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Key Points:
- Mountain social-ecological systems (MtSES) worldwide face climatic, economic, and governance threats; policies made by outsiders are a critical challenge
- Mountains that support subsistence-oriented livelihoods deliver abundant cross-scale ecosystems services, but these MtSES are also most threatened
- Addressing threats to MtSES requires the united effort of policymakers, land users, scientists, and practitioners at local to global scales

Supporting Information:
- Supporting Information S1

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Catalyzing Transformations to Sustainability in the World's Mountains

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Abstract Mountain social-ecological systems (MtSES) are vital to humanity, providing ecosystem services to over half the planet's human population. Despite their importance, there has been no global assessment of threats to MtSES, even as they face unprecedented challenges to their sustainability. With survey data from 57 MtSES sites worldwide, we test a conceptual model of the types and scales of stressors and ecosystem services in MtSES and explore their distinct configurations according to their primary economic orientation and land use. We find that MtSES worldwide are experiencing both gradual and abrupt climatic, economic, and governance changes, with policies made by outsiders as the most ubiquitous challenge. Mountains that support primarily subsistence-oriented livelihoods, especially agropastoral systems, deliver abundant services but are also most at risk. Moreover, transitions from subsistence- to market-oriented economies are often accompanied by increased physical connectedness, reduced diversity of cross-scale ecosystem services, lowered importance of local knowledge, and shifting vulnerabilities to threats. Addressing the complex challenges facing MtSES and catalyzing transformations to MtSES sustainability will require cross-scale partnerships among researchers, stakeholders, and decision makers to jointly identify desired futures and adaptation pathways, assess trade-offs in prioritizing ecosystem services, and share best practices for sustainability. These transdisciplinary approaches will allow local stakeholders, researchers, and practitioners to jointly address MtSES knowledge gaps while simultaneously focusing on critical issues of poverty and food security.

Plain Language Summary Mountain ecosystems and the human communities that inhabit them deliver critical resources—such as fresh water and timber—to over half the planet's human population. Despite their importance, there has been no global assessment of threats to mountain systems, even as they face unprecedented challenges to their sustainability. With survey data from 57 mountain sites worldwide, we test our understanding of the types of stresses that are threatening mountain systems as well as the resources and benefits that come from mountains. We find that mountain systems worldwide are experiencing both gradual and abrupt climatic, economic, and governance changes. One of the most ubiquitous challenges facing mountain systems is that policies directly affecting mountain systems are being made by those living outside of the mountains themselves. Mountains that support primarily subsistence-oriented livelihoods in the developing world, especially mixed agriculture and animal husbandry systems, deliver abundant services but are also most at risk. Addressing the complex challenges facing mountain systems will require partnerships among researchers, stakeholders, and decision makers to jointly identify the types of futures they desire and the actions to achieve these. This approach will address knowledge gaps in mountains while simultaneously focusing on critical issues of poverty and food security.

1. Introduction

Mountains are iconic social-ecological systems (MtSES) that are globally ubiquitous yet locally unique. As critical sentinels of climate change, mountains are more than just lands at high elevation. MtSES provide key ecosystem services (ES) to over half the planet's human population (Körner & Oshawa, 2005), most of whom live in the lowlands. Characterized by vertical gradients of climate, hydrology, population, and biocultural diversity, mountains are often isolated social-ecological systems surrounded by a sea of lowlands, analogous to islands. Their rugged landscapes may form forbidding and contested political boundaries and are home to marginalized communities, or conversely, offer elite vacation destinations. MtSES provide a disproportionate amount of ES to humanity relative to their physical extent, the number of people who live in mountains, and the economic and political power of those living in the mountains; yet, MtSES are vulnerable to degradation and extreme events.

Recent global syntheses that focused on mountains have consisted of literature reviews of global change impacts (Löffler et al., 2011), elevation-dependent warming (Pepin et al., 2015), the importance of glacier water for mountain societies (Carey et al., 2017), how changes in land-use intensity influence the supply of ES (Locatelli et al., 2017), and the impacts of anticipated climate change on the alpine cryosphere, hydrosphere, and biosphere (Huss et al., 2017). Carey et al. (2017) conclude that future work on these important topics requires a social-ecological approach. Alessa et al. (2018) present diverse examples of successful SES work in mountains but with a focus on the western United States. Data-oriented global mountain syntheses have focused on the elevational distributions of protected areas in mountains using high-resolution digital elevation models (Elsena et al., 2018), the mapping and classification of mountains (Körner et al., 2017; Price et al., 2018; Sayre et al., 2018), continental-scale syntheses of observed alpine flora changes over time (Gottfried et al., 2012), estimates of future changes to biophysical aspects of the cryosphere (Huss et al., 2017), and trade-offs in clusters of ES over time (Locatelli et al., 2017). No concerted efforts have synthesized the complex threats to MtSES worldwide or highlighted opportunities to address these challenges, partly due to the diverse sociocultural, political, and economic contexts in which mountains occur. Understanding and synthesizing MtSES dynamics across spatial and temporal scales is a grand challenge and a first step toward identifying pathways toward sustainability within and across MtSES.

Here, we describe the suite of characteristics and paradoxes that create particular challenges for MtSES. We present an a priori, expert-based conceptual model highlighting threats to MtSES dynamics and their ES. We then use survey data from 57 MtSES worldwide (Figure 1 and supporting information [SI] Table S1) to explore the conceptual model and address the following: How do MtSES characteristics relate to critical challenges within and across MtSES? What are the biophysical and socioeconomic drivers and ES that are most prevalent within and across MtSES, and what are their spatiotemporal dimensions? and What features are common worldwide and what differences emerge according to contrasting economies and principal MtSES land uses?

We consider a sustainable system to be one that maintains its essential desired SES structure and function in the face of change (e.g., high resilience/low vulnerability) or undergoes the necessary transformations (e.g., via adaptation pathways; Colloff et al., 2017; Wise et al., 2014) toward desired sustainable futures, which are the normative desired visions or scenarios for the future (e.g., goals, objectives, outcomes, and conditions) that represent the values and preferences of relevant stakeholders and are based on sustainability principles (Bibri, 2018). We recognize, however, that these concepts are variously defined and encompass different origins, methods, and applications (Miller et al., 2010).

2. Methods

2.1. Expert Workshop

Experts working in 12 MtSES worldwide convened at a workshop funded by the Mountain Research Initiative and led by Klein and Nolin—who each have decades of experience working in and publishing on MtSES in Asia and North America, respectively. Following a broad call to the mountain community for applications, the organizers selected the experts based on their extensive, highly cited MtSES research, geographic and disciplinary diversity, and interdisciplinary experience. The workshop experts were joined by a selected group of early career participants, graduate students, and postdoctoral scholars working in MtSES. At the workshop, the participants identified common characteristics, paradoxes (i.e., apparent contradictions), drivers, and ES across MtSES.

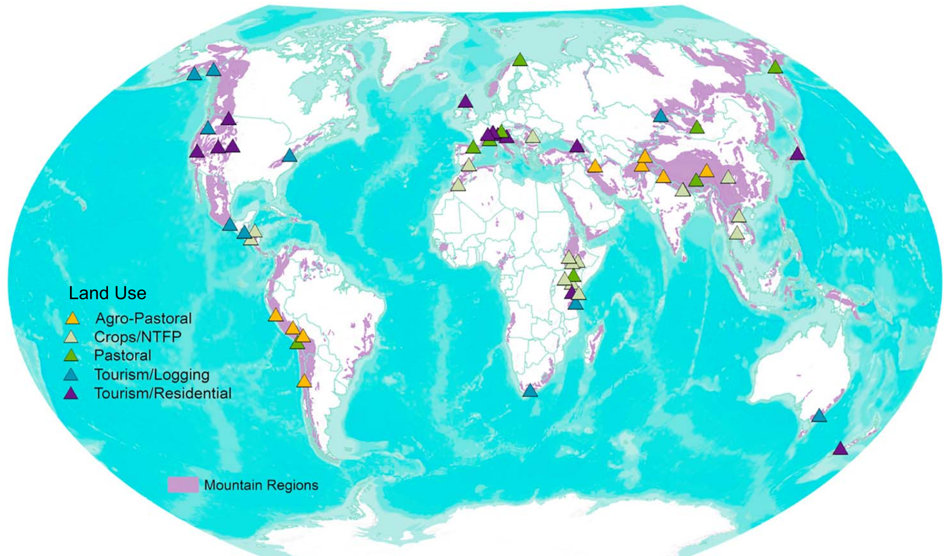

Figure 1. Map of the 57 case study sites included in this analysis. Mountain regions of the world are depicted in purple, based on Körner et al. (2017). Triangles indicate sites, and colors represent mountain land use groups (see supporting information Figure S3 and Table S1). NTFP = nontimber forest products.

From these, we developed key elements of a MtSES conceptual model. The workshop laid the foundation for the U.S. National Science Foundation-funded Mountain Sentinels Collaborative Network (mountainsentinels.org) led by Klein, Nolin, Reid, and Tucker. Coauthors include workshop participants and additional active members of the Mountain Sentinels network, which conducts syntheses, holds in-person and virtual workshops, develops tools, and communicates about ways to address critical mountain issues and identify potential pathways toward sustainability (e.g., Klein et al., 2019).

2.2. Survey

To explore the applicability of this expert-based conceptual model for MtSES globally, we surveyed an expanded group of experts working in MtSES worldwide (Table S1), with a goal of broad coverage across mountain regions (as defined by Körner et al., 2017; Figure 1). The workshop leaders and experts directly reached out to the potential respondents, who are well known for their scholarship and long-term expertise in MtSES. In limited cases where we lacked direct contacts, we conducted a literature search and reached out to authors on MtSES sustainability topics from regions that were geographically underrepresented in our initial group of respondents. Our final set of responses of 57 sites encompasses 6 continents and 37 countries (see Text S1 Methods and Table S1 for more details about survey respondents and sites).

The survey inquired about characteristics, paradoxes, drivers, ES, land uses, and the role of local environmental knowledge. Respondents (Table S1) assigned Likert scores (scale: 1–5) to denote the importance of each category in their MtSES. For drivers and ES, we also asked about spatiotemporal dimensions. For example, we asked respondents to identify the spatial scales (local, regional, and global) at which each ES is used and at which drivers originate. Drivers were further categorized by whether they were shorter term and episodic (pulses) or longer term and incremental (presses). While the time frame is variable and difficult to quantify, pulse drivers tend to occur on the order of a few years or less, while press drivers tend to occur on the order of a decade or more. For example, economic change drivers were pulses (e.g., economic shocks) or presses (e.g., globalization).

2.3. Analyses

We empirically confronted the expert-based MtSES characteristics, paradoxes, and conceptual model with the survey data at three levels. First, we considered the global scale, using all survey responses (n = 57). Second, we compared subsistence-oriented (n = 32) versus market-oriented (n = 25) MtSES, based on respondent selections. Third, we split the MtSES into five land use groups using hierarchical clustering in SAS (v. 9.3). To obtain the groups, we created a dissimilarity matrix for all sites based on squared

Euclidean distances between land use importance scores and applied Ward's clustering algorithm to the matrix to identify MtSES groups with similar land uses.

We assessed whether importance scores differed significantly between subsistence and market-oriented sites and among land use groups using Wilcoxon rank-sum tests. We conducted follow-up pairwise comparisons between land use groups using Kruskal-Wallis tests. We determined the strength of each variable for the different groups based on their median importance scores. To test for significant differences among spatial scales of drivers and ES, we conducted chi-square goodness of fit tests. We used Spearman's rank order correlation to examine ES correlations. Survey and analysis details are in Text S1.

3. Results

3.1. An Expert-Based Description of the MtSES Characteristics and Paradoxes That Create Challenges for Sustainability

A combination of characteristics (*mountain characteristics*, MCs) illustrates why MtSES are fundamentally different from other regions, even while being connected with them; why MtSES are vulnerable to global changes yet provide examples of resilience and why sustaining MtSES requires an approach embracing multiple domains and their interactions across scales. Mountains are biophysically and culturally complex systems (MC1: *complexity*; Alessa et al., 2018), characterized by steep vertical gradients and climatic, hydrologic, and topographic complexity. Such features generate high cultural and biophysical diversity (Körner & Oshawa, 2005), as well as abundant ES. MtSES supply essential ES—including water, hydropower, and timber—from local to global scales (MC2: *cross-scale ES*; Grêt-Regamey et al., 2012). Because of their tectonic or volcanic origins and climatic extremes, mountains are dynamic and prone to hazards, such as floods, debris flows, avalanches, and wildfires (MC3: *hazards*). Physical isolation (MC4: *isolation*) forms barriers and borders. This presents challenges for trade, migration, and other aspects of connectivity but contributes to high levels of endemism and biocultural diversity. Physical isolation and distance from centers of power and decision-making contribute to socioeconomic and political isolation and marginalization (MC5: *marginalization*).

Nonlinear interactions among these characteristics create multidimensional problems that defy clear definitions and optimal solutions, so-called "wicked problems" (Chapin et al., 2008). We identify these as *paradoxes* (P1–6, below), which refer to surprising and contradictory aspects of MtSES. These interrelated MtSES paradoxes present challenges that must be considered when developing pathways toward sustainable futures.

The first paradox that emerges from MC1–5 is that MtSES are resource rich but income poor (P1: *resource rich*, *income poor*). Mountain peoples are among the world's poorest. A study by the Food and Agricultural Organization of the United Nations found that while roughly 13% of the population in the developing world globally is considered to be food insecure, 39% of urban and rural mountain inhabitants in developing countries were vulnerable to food insecurity in 2012 and that this rose to 50% for rural mountain inhabitants (Romeo et al., 2015). Thus, many mountain people experience scarcity despite mountains' abundance of timber, water, and minerals (Veith & Shaw, 2011). In some cases these resources are acquired by "outsiders" who have the necessary capital to make use of the services that mountains provide. For example, kinetic energy is abundant in mountains, but expensive hydropower generation infrastructure generally transports the electricity to the populous lowlands.

Policies affecting mountain systems are often made by outsiders (P2: *policies by outsiders*) even when they have little understanding of local MtSES dynamics. Despite mountain-dwelling peoples' extensive resource management knowledge, valuable mountain ES—including energy and water—are frequently managed by and for distant decision makers and markets. Policies intended to reduce vulnerability to drivers like climate change may introduce barriers to traditional coping strategies, exacerbate scarcities, and make mountain people more reliant on outside interventions (Yeh et al., 2014). These dynamics are facilitated by power imbalances that stem from MtSES's political and economic marginalization.

On mountain "islands" globally, diverse species and human communities that developed in relative physical isolation are now confronted by global change (P3: *remote but vulnerable to global change*). Some mountain ecosystems are buffered against drivers such as climate change by topographic complexity that creates microclimatic refugia (Scherrer & Körner, 2010). MtSES resilience also stems from mountain dwellers' long-developed coping strategies in marginal, extreme, and hazardous environments (Young & León, 2009). Now, however, high exposure to climate change (Pepin et al., 2015) and diminishing adaptive capacity—largely due to perverse policies by outsiders, marginalization (Midgley et al., 2002), and increasing reliance of previously self-sufficient MtSES on outside funding, employment, markets, and infrastructure—can exacerbate MtSES vulnerability to stressors.

MtSES are experiencing destabilizing demographic fluxes from migration into and out of mountains (P4: *in- and out-migration*). In many mountain regions, people leave their communities for educational opportunities or employment in lowland cities (McEvoy et al., 2012), which impacts gender and power dynamics and contributes to agricultural abandonment and declining population. Yet other MtSES experience population growth or urbanization (Hansen et al., 2014). With climate change, people are moving into higher elevations to escape disease and to grow traditional crops under suitable temperatures (Boone et al., 2002). Mountains are also subject to amenity migration, with the wealthy moving in for recreation and tourism. Rapid migration flows can lead to social conflict and environmental problems (Körner & Oshawa, 2005).

Mountains can be remote and difficult to access but still attract diverse actors (P5: *remote but attracts actors*), creating challenges for equitable decision making and resource management. Mountains serve as refugia for marginalized or indigenous peoples attempting to escape from or pushed out of centralized states (Maurer et al., 2006) and as destinations for the wealthy seeking vacation homes and recreation. The challenge of managing these complex relationships over large, remote land areas can result in inequities between local mountain communities and the “elite” stakeholders and national or global systems to which they provide services.

To capture their complexity, MtSES require fine-scale data, which are often lacking (P6: *data needed but lacking*). Complex mountain environments produce high biophysical and cultural diversity (Körner & Oshawa, 2005), requiring transdisciplinary, high-resolution spatial and temporal data, and integration of scientific and local knowledge (Klein et al., 2014). Several factors amplify the problem of data scarcity in mountain regions: remoteness and inaccessibility, political barriers, and inadequate funding for robust data collection infrastructure.

3.2. An Expert-Based Conceptual Model of ES From Mountains and Their Threats

MtSES characteristics and paradoxes suggest the need for a mountain-specific framework to address their complex problems, just as a drylands framework has been developed (Reynolds et al., 2007). Building on previous SES work (e.g., Collins et al., 2011), we present a conceptual model (Figure 2) of MtSES's cross-scale ES and the drivers affecting them. It considers drivers that are episodic (pulse) or sustained (press) and which affect not only the quality and amount of ES but also the timing of their provision. Because ES link social and ecological domains and connect MtSES to other systems, problems resolved at local scales can generate new drivers within that system or new drivers that are exported to other MtSES, particularly to places with weaker institutions (Lambin & Meyfroidt, 2011). Such feedbacks and cascading effects interact with MtSES characteristics and give rise to the paradoxes described above (Figure 3c). Next we examine these interactions, using survey data to indicate the domains and scales at which the most critical interactions are likely to occur.

3.3. An Empirical Examination of MtSES Characteristics, Paradoxes, and the Conceptual Model

We present survey results from all 57 sites (the “global model”), compare between subsistence versus market-oriented MtSES (the “economic model”) and among sites distinguished by land use classification (the “land use model”).

3.3.1. The Global Model: Climate Change, Extreme Events, and Governance Challenge MtSES Worldwide

The 57 MtSES are experiencing high exposure to climate change (global press) and extreme weather events (local pulse). Coupled with their isolation (MC4) and marginalization (MC5), these factors support the importance of P3, “isolated but vulnerable to global change,” (Figures 3 and 4a). MtSES are experiencing additional challenges in the form of economic presses and shocks and through political transformations. Changes in governance, markets, and land tenure across all sites typically emerge at regional scales, indicating that they are driven by decision makers outside MtSES themselves. This reinforces the most ubiquitous

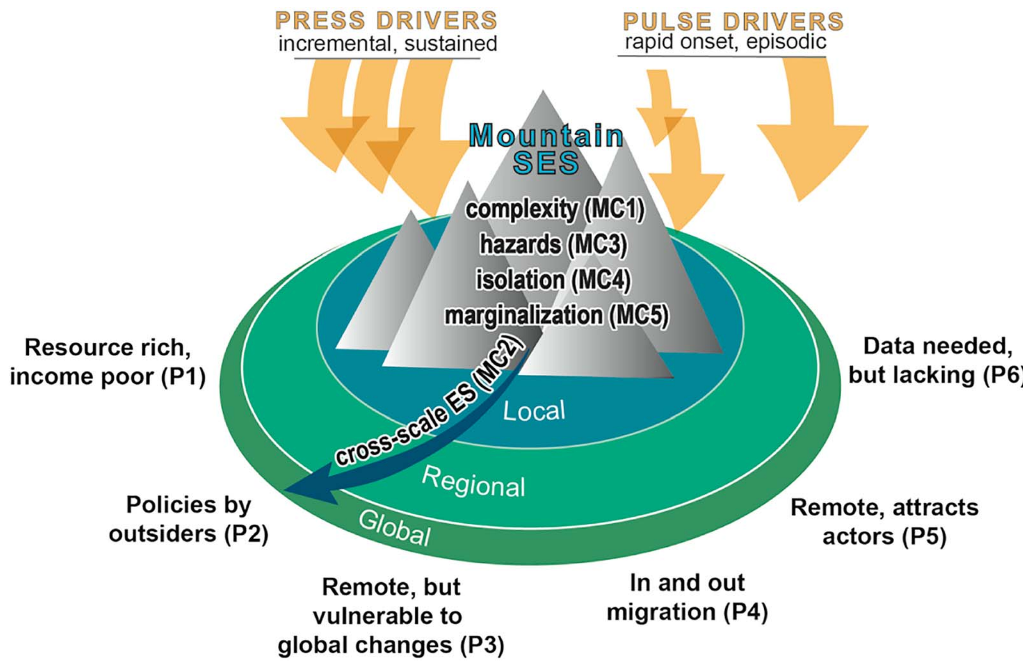

Figure 2. Expert-based conceptual model of mountain social-ecological systems that highlights mountain characteristics, paradoxes, press/pulse drivers, and cross-scale ecosystem services.

and important paradox across our case studies, “policies by outsiders” (P2). Presses are characterized as global almost twice as much as pulses (14% vs. 8%, respectively, SI Figures S1 and S2). Pulses—especially biophysical pulses including wildfire, landslides, avalanches, floods, and pest outbreaks—are most prevalent at local scales. The most important ES provided locally are food, forage, and spiritual/aesthetics; ES provided locally/regionally are water, biocultural diversity, timber, and fuel/power; ES provided regionally are tourism/recreation.

3.3.2. The Economic Model: Subsistence-Based MtSES Deliver More ES and Face More Challenges

Key differences emerge depending on economic orientation (Figures 3 and 4b). Subsistence-oriented MtSES are more complex (MC1), isolated (MC4), and provide more cross-scale ES (MC2) than market-oriented sites. Biocultural diversity (a regional ES, produced and maintained by high complexity and isolation) ranks as more important in subsistence-oriented sites and is accompanied by biodiversity loss as a strong local/regional press. ES used locally—including food, forage, nontimber forest products (NTFP), and traditional medicines—are also more important in subsistence-oriented sites; resource extraction is a more important local pulse in these systems. The subsistence-based orientation of this group and its higher number of ES provided across scales can at least partially explain the greater importance of P1, “resource rich, income poor,” in subsistence-oriented sites. Isolation, complexity, and provision of critical ES also contribute to the paradox “requires data but lacking” (P6) and the greater importance of local knowledge within subsistence-oriented sites (Table S4). Our findings suggest that transitions from subsistence- to market-oriented economies are often accompanied by increased physical connectedness, reduced diversity of cross-scale ES, lowered importance of local knowledge, and shifting vulnerabilities to paradoxes.

3.3.3. The Land Use Model: Agropastoral MtSES Land Use Is Most Dynamic and Most at Risk

MtSES cluster into five land use groups (Figure S3), each exhibiting unique expressions of the conceptual model (Figure 5). Here we describe features that distinguish land use groups and highlight drivers and ES within them that are less prevalent in the global and economic models described above.

Agropastoral systems are experiencing the greatest number of “very important” drivers and ES. Biodiversity loss, hazards, and water scarcity are the most acute drivers within the agropastoral land use group, while biodiversity, hazard protection, and water are among their most important ES. NTFP are most important for agropastoral and crop-NTFP groups, where minerals are also relatively important. Glacier melt prevails in agropastoral and tourism-residential groups, where hazard protection is an important local ES.

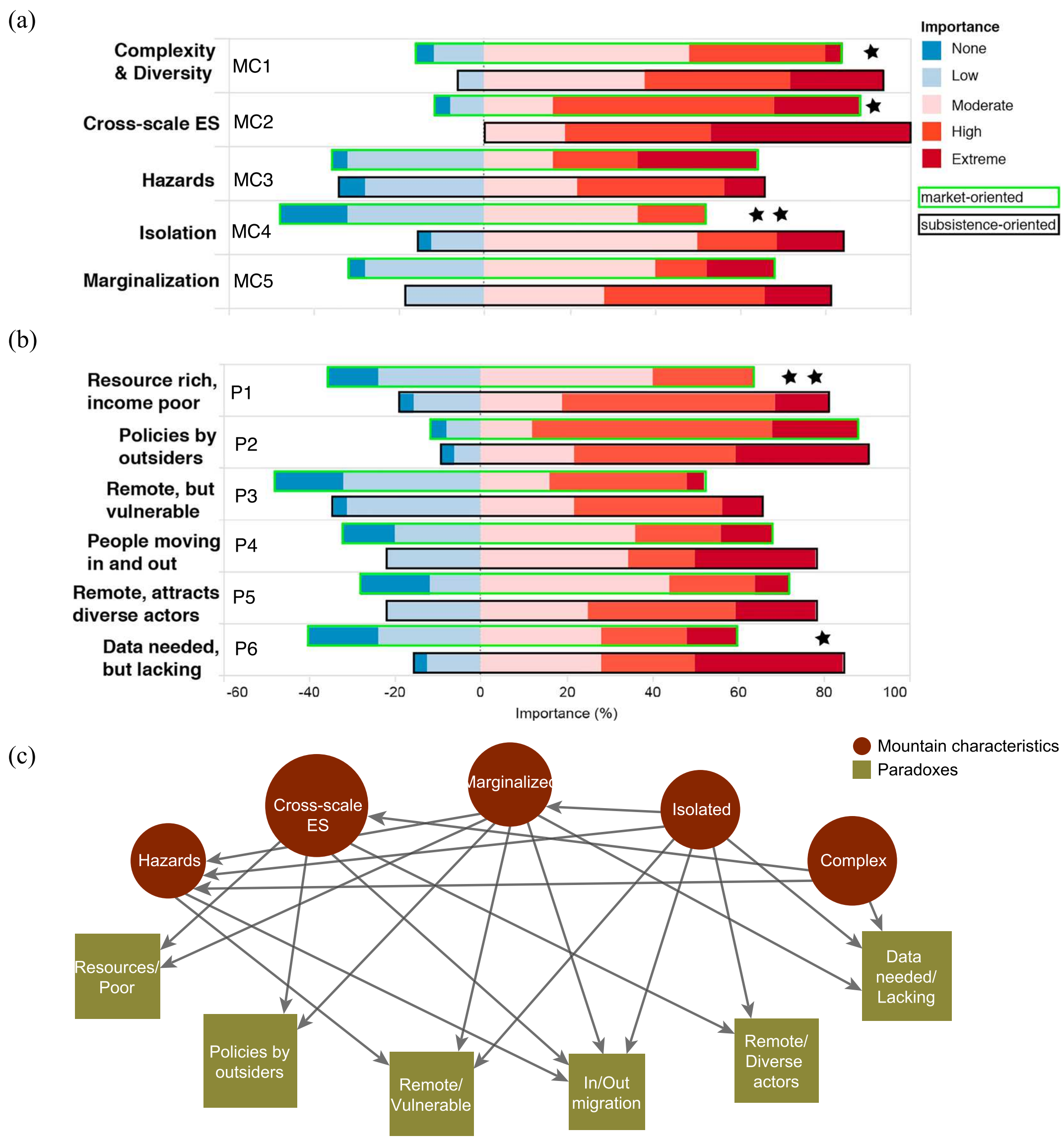

Figure 3. The survey-based relative importance of mountain characteristics (a) and paradoxes (b) across subsistence-oriented (black box) and market-oriented (green box) mountain case study sites. Stars indicate a statistically significant difference between subsistence-oriented and market-oriented sites (Table S2). Two stars represent $p < 0.05$; one star represents $0.05 < p < 0.10$. (c) Conceptual network diagram linking mountain characteristics with paradoxes. Each characteristic or paradox is scaled by mean importance score across all sites. Arrows represent conceptual understanding of the links between characteristics and paradoxes. MC = mountain characteristic.

Spiritual/aesthetic ES are particularly important in the agropastoral and pastoral groups, which are typically the most marginalized. The paradoxes of “remote, attracts diverse actors,” “requires data but lacking”, and “people moving in and out,” are especially important within the agropastoral group. Across groups, out-migration is most important for agropastoral MtSES; in-migration is more important in tourism-residential MtSES (pulse) and crops-NTFP MtSES (press).

The pastoral land use group ranks the MCs of isolated, marginalized, and cross-scale ES as most important. Governance is an important driver, and cultural change is significant. Land tenure change is a prevalent driver for pastoral and agropastoral MtSES. Most paradoxes, especially “policies by outsiders”, are important within pastoral MtSES. The paradox “isolated, vulnerable to global change” is of highest importance within the pastoral and agropastoral groups, where factors including marginalization, perverse policies, and land tenure change constrain opportunities to adapt.

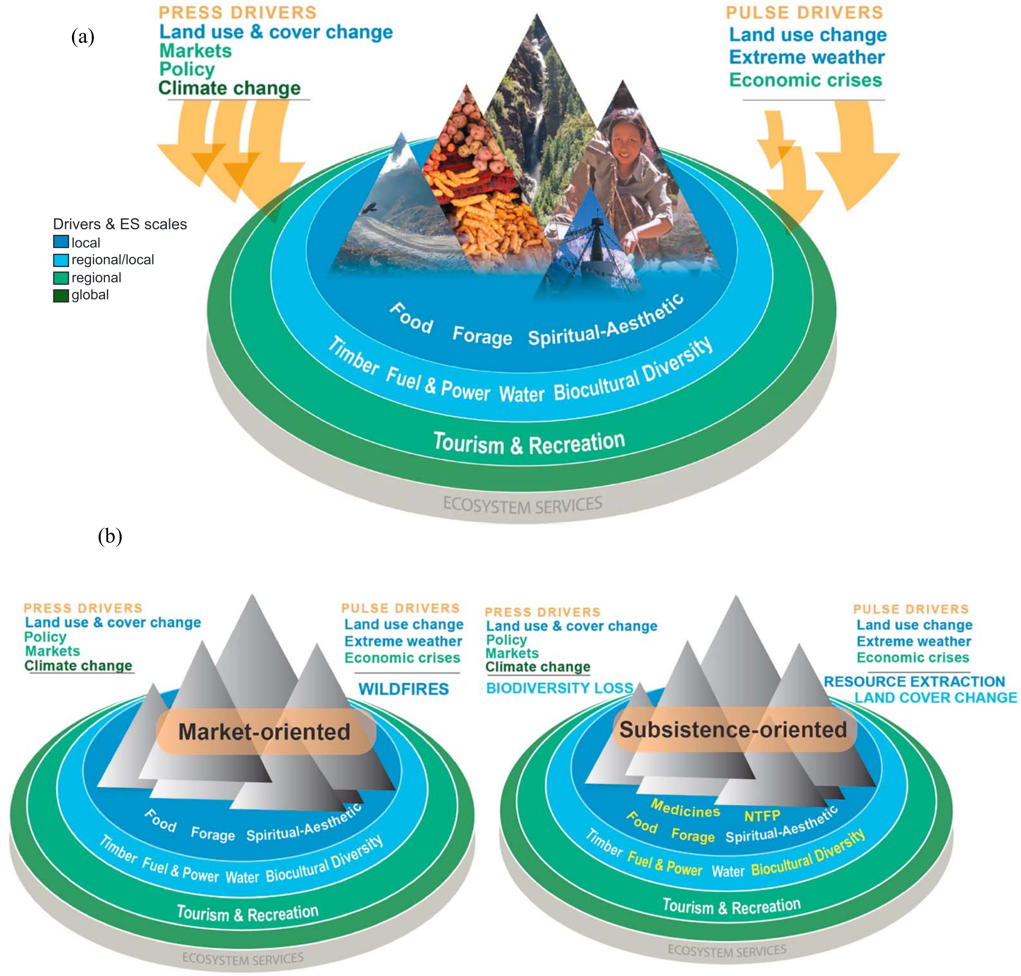

Figure 4. Survey-based results for key cross-scale press/pulse drivers and ES for (a) all sites, the "global model," and (b) subsistence-oriented and market-oriented sites, the "economic model." The scale at which the drivers originate is indicated by the color of the text. The scale at which the ES are utilized is indicated by the band color on which the ES is written. In panel (b), the drivers that are significantly more important in the subsistence-based or market-oriented models (and not very important in the global model) are presented in capital letters. The ES that are significantly more important in subsistence-oriented sites ($p < 0.05$) are in yellow text. ES = ecosystem services; NTFP = nontimber forest products.

Tourism-dominated land use groups experience fewer key drivers, deliver fewer ES, and rank local knowledge as less important than resource-dominated land use groups. The tourism-residential group is the least isolated and marginalized and is the only group for which "resource rich, income poor" is not important. Yet, land use change and governance are important drivers in tourism-residential and crop-NTFP MtSES, the land uses where in-migration is occurring. The tourism-logging MtSES—the only land-use group with timber as a very important ES and where only a single driver, climate change, is considered important—have the lowest importance scores for paradoxes, including "policies by outsiders" and "requires data but lacking". The ES of tourism/recreation are most important within both tourism-based land uses and in the agropastoral MtSES.

The local ES of food and forage (which are particularly important across resource-based MtSES), NTFP, spiritual/aesthetics, and medicines and the regional ES of biocultural diversity are correlated with each other and strongly associated with the importance of local knowledge (SI Table S6). Water is also associated with several ES in this grouping. A separate, smaller grouping of ES includes fuel/power, timber, and minerals, with water also strongly associated with minerals. Tourism tends to stand alone as an ES, sharing a weak, positive association with hazard protection. Notably, tourism exhibits a weak, negative association with

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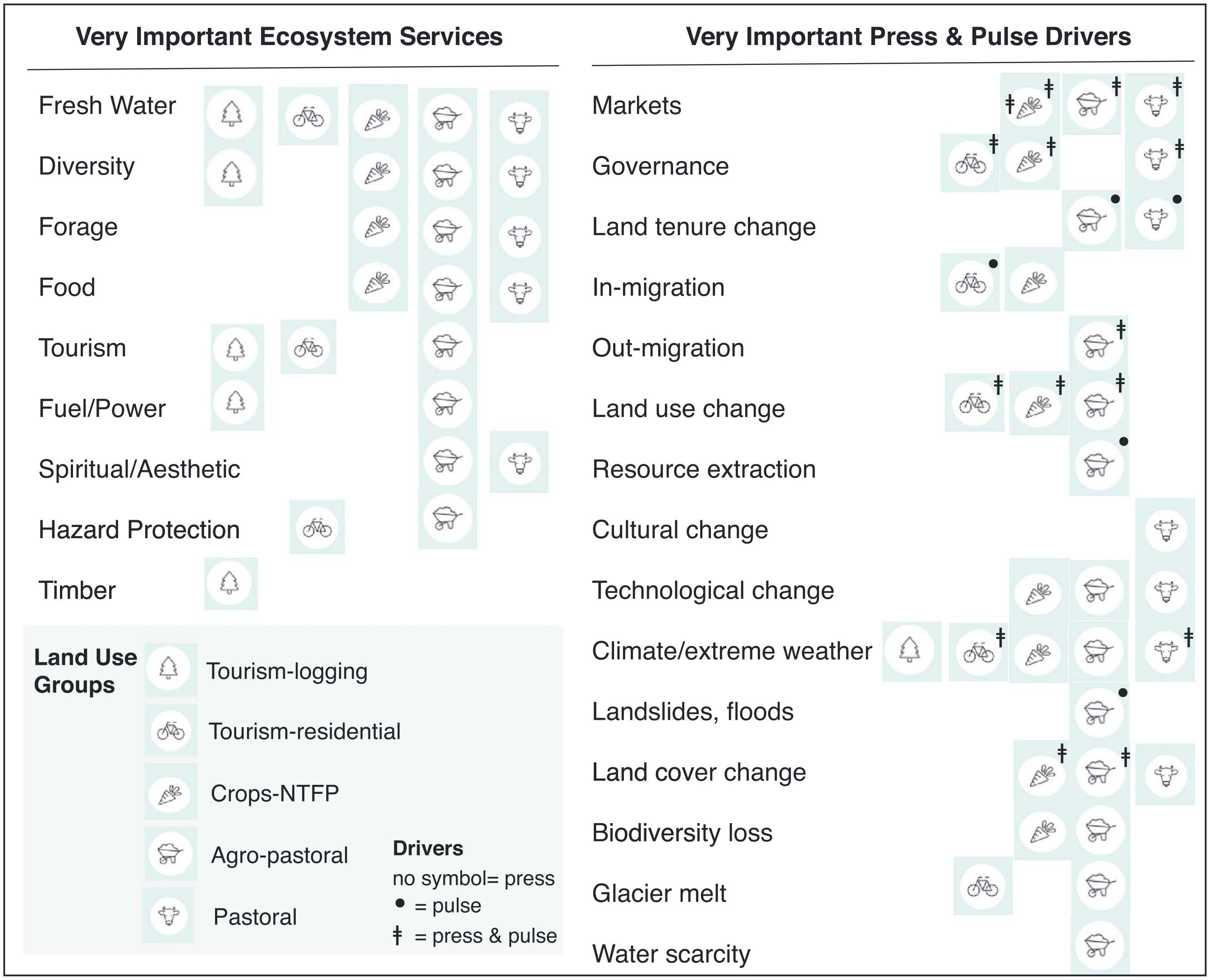

Figure 5. Land use groups and the number of very important drivers and ecosystem services (median score ≥4). For drivers, no symbol on the icon represents a press, a solid circle indicates a pulse, and a cross indicates that the driver is very important both as a press and as a pulse. For example, a cross for climate change indicates that both longer-term climate change (press) and extreme weather events (pulse) are very important for that land use (see SI Tables S4 and S5 and Figure S3). NTFP = nontimber forest products.

ES such as food and forage, with implications for decision making and identifying trade-offs in ES (e.g., Locatelli et al., 2017).

4. Conclusions

4.1. Catalyzing Transformations to Sustainability

Our assessment of 57 MtSES reveals that gradual and abrupt changes in climate, governance, and economies are key drivers in MtSES worldwide. These threats include local system shocks and chronic, incremental regional and global transformations. One of the greatest challenges facing MtSES is that the policies that directly influence MtSES are made by those living outside of mountains. To overcome this challenge, local stakeholders should have a voice in decision making for building resilience and adaptive transformations. Our findings also demonstrate that the fate of MtSES is critical not only to their inhabitants but also to much of humanity living beyond MtSES who rely on their ES. Therefore, it is imperative to more effectively communicate the importance of MtSES and to highlight local MtSES knowledge, experience, and innovations.

MtSES challenges are typically more numerous and formidable within subsistence-oriented MtSES, which are also bioculturally more diverse and deliver more cross-scale ES than market-oriented MtSES. The importance of the paradoxes "resource rich but income poor" and "requires data but lacking" underscores the need for transdisciplinary approaches, where local stakeholders, researchers, and practitioners can jointly address MtSES knowledge gaps while simultaneously focusing on critical issues of poverty and food security.

Resource-based MtSES land use groups, especially agropastoral MtSES, contain high biocultural diversity and cross-scale ES; these systems also face the greatest number of threats and should be considered priority regions for supporting and building resilience and catalyzing transformation. Moreover, maintenance of local ES—such as food, forage, NTFP, and medicines—may have co-benefits of simultaneously conserving a grouping of associated ES, such as water. In contrast, sustaining tourism alone may be associated with reduced ES and loss of local knowledge. These linkages require further study.

We found common challenges and features of our conceptual model across 57 MtSES worldwide, with key differences depending on economic orientation and land use. Through examining multiple stressors, ES, and their spatiotemporal scales, we can begin to assess system interactions and feedbacks and the conditions that maintain or lead to resilience and adaptive transformation. Acting on these opportunities requires the united effort of policymakers, land users, scientists, and practitioners working together in local to international knowledge-action networks.

The use of MtSES global, economic, and land use groupings to identify areas of convergence can serve as a catalyst for sharing knowledge, tools, experiences, and best practices within and across MtSES. This international, collaborative process can serve as an example for other knowledge-action networks seeking to address "wicked problems," especially in marginal SES (Maru et al., 2014).

Author Contributions

All authors (except C. S., R. M., and J. T.) helped conceive of the initial conceptual model and paradoxes at a workshop. K. A. H. and C. S. conducted data analysis along with J. A. K. All authors (except G. G., J. T., and T. S.) contributed to survey data. All authors contributed to writing.

Data Deposition

The associated data are deposited in the CSU data repository (https://hdl.handle.net/10217/194492 and https://doi.org/10.25675/10217/194492).

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