Long-Term Environmental and Social Monitoring in the Andes: State of the Art, Knowledge Gaps, and Priorities for an Integrated Agenda

Authors: Carilla, Julieta, Aráoz, Ezequiel, Acosta, Oriana Osinaga, Malizia, Agustina, Malizia, Matilde, et al.

Source: Mountain Research and Development, 43(2)

Published By: International Mountain Society

URL: https://doi.org/10.1659/mrd.2022.00018

Mountain Research and Development (MRD)
An international, peer-reviewed open access journal
published by the International Mountain Society (IMS)
www.mrd-journal.org

MountainAgenda
Target knowledge

Long-Term Environmental and Social Monitoring in the Andes: State of the Art, Knowledge Gaps, and Priorities for an Integrated Agenda

Julieta Carilla[1], Ezequiel Aráoz[1,2,]*, Oriana Osinaga Acosta[1], Agustina Malizia[1], Matilde Malizia[3], Yohana Jimenez[1], Manuel Peralvo[4], Alexandra Garces[4], Geovanna Lasso[4], and Luis Daniel Llambí[4,5]

* *Corresponding author: ezequielaraoz@gmail.com*

[1] *Instituto de Ecología Regional (IER), Universidad Nacional de Tucumán (UNT)–Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), 4107 Yerba Buena, Tucumán, Argentina*
[2] *Facultad de Ciencias Naturales e Instituto Miguel Lillo (FCN e IML), Universidad Nacional de Tucumán (UNT), 4000 San Miguel de Tucumán, Tucumán, Argentina*
[3] *Instituto de Investigaciones Territoriales y Tecnológicas para la Producción del Hábitat (INTEPH), Universidad Nacional de Tucumán (UNT)–Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), 4000 San Miguel de Tucumán, Tucumán, Argentina*
[4] *Consorcio para el Desarrollo Sostenible de la Ecorregión Andina (CONDESAN), 170504 Quito, Ecuador*
[5] *Instituto de Ciencias Ambientales y Ecológicas, Universidad de Los Andes, 5101 Mérida, Venezuela*

Andean social–ecological systems (SES) play a key role in the livelihoods of South American people by conserving biodiversity, providing natural resources, and regulating water supply. Long-term social–ecological monitoring (LTSEM) of Andean SES needs to be coordinated to inform sustainable management and increase resilience. We combined quantitative and qualitative approaches to identify the state of the art, knowledge gaps, and monitoring priorities for a research agenda targeted toward Andean LTSEM. We carried out participatory and transdisciplinary meetings to design a conceptual model of the functioning and monitoring of Andean SES. This was contrasted with the themes and labels of LTSEMs identified through an electronic survey and active searches of bibliographies and montane monitoring networks. Most LTSEM addressed biophysical issues, with a minor fraction addressing social aspects; participatory efforts were very rare. By combining both approaches, we identified research priorities that were grouped into 5 categories. Our main proposals advocate: (1) the development of integrated models of Andean SES to frame a transdisciplinary approach in long-term studies, (2) the coordination of independent LTSEMs to forecast the functioning of Andean SES under environmental change scenarios, (3) the inclusion of external dynamics and drivers on Andean systems, (4) the promotion of science–policy dialogue to attain a more effective governance of mountain SES, and (5) the increase of information accessibility to improve the adaptive management of Andean SES.

Keywords: *conceptual model; codesign; comanagement; global change; adaptive management; participatory monitoring; social–ecological systems.*

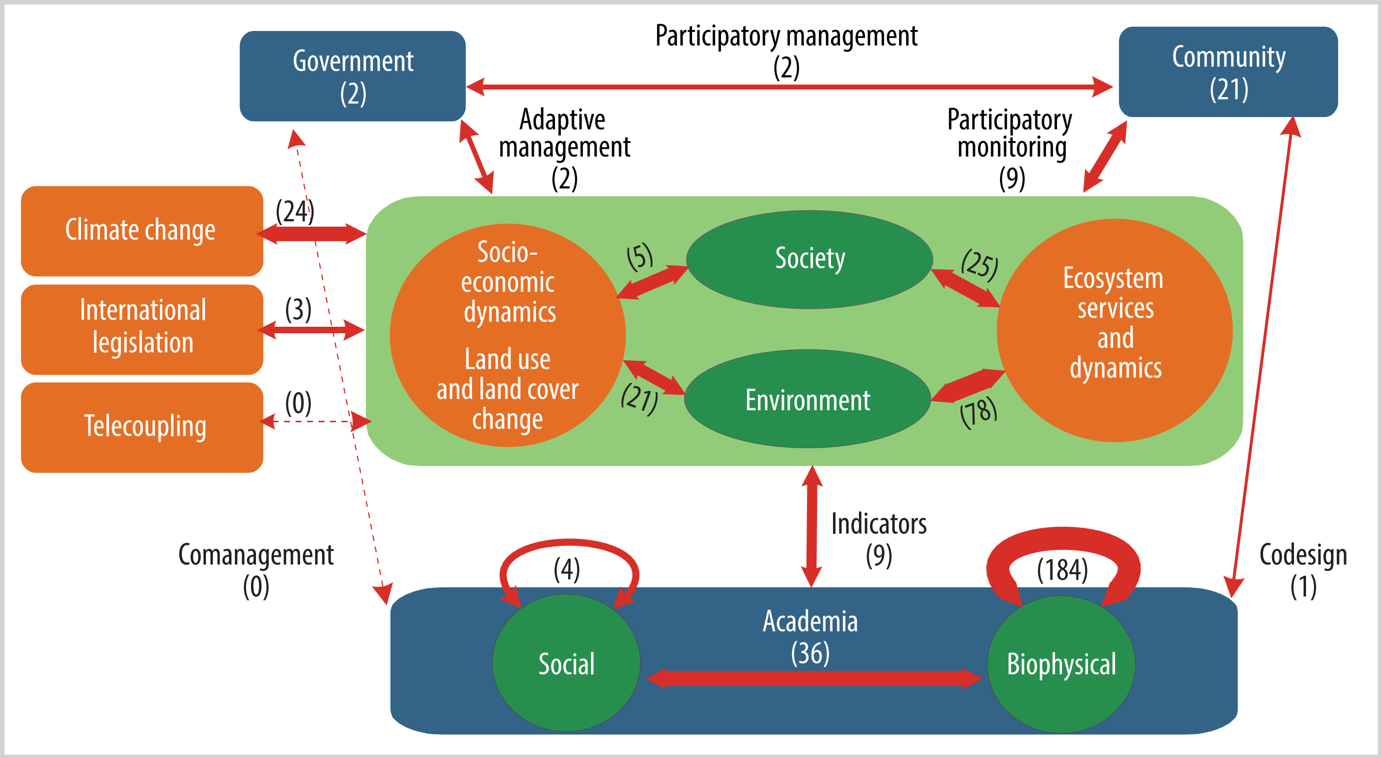
Received: *11 May 2022* ***Accepted:*** *15 March 2023*

Introduction

The coordination of long-term social and environmental monitoring systems should be a core component of any strategy to study social–ecological responses to climate and land-use changes in mountain regions. Ecosystems are essential to the functioning of societies (Isbell et al 2017), and societies in turn influence ecosystems directly (eg through land-use changes) and indirectly (eg through actions that cause climate change; Krausmann et al 2013). Globally, different initiatives focused on mountain regions have highlighted the role that long-term monitoring of social–ecological systems (SES) should play in understanding their dynamics (eg Björnsen Gurung et al 2012; Peralvo and Bustamante 2015; Gleeson et al 2016; Adler et al 2018). Long-term social–ecological monitoring (LTSEM) efforts are expensive and demanding in terms of their institutional governance. Therefore, it is important to coordinate their objectives and logistics across spatial scales, so they can answer relevant questions and inform management policies ranging from the local to the national and continental contexts (Wymann et al 2018; Llambí et al 2019).

Due to their steep topographic environmental gradients and wide spatiotemporal variability, Andean SES are particularly vulnerable to environmental changes (Cuesta et al 2020). Thus, different management challenges arise because Andean SES play a key role in the sustenance and functioning of human societies at local to continental scales (Schoolmeester et al 2016). Around 84 million people live in the Andes, and the welfare of a significant portion of lowland inhabitants depends on Andean ecosystem services (Devenish and Gianella 2012). Andean systems act as biodiversity refuges and are crucial to climate regulation and water provision for lowlands; they also provide food, fiber, and forest resources for local populations (Buytaert et al 2011). A thorough understanding of the functioning of the Andes requires long-term interdisciplinary monitoring

FIGURE 1 Conceptual model of Andean SES functioning and associated knowledge management. Systems are indicated in green, actors are in blue, processes are in orange, and interactions are indicated with red arrows. Arrow thickness represents the number of database records referring to that interaction based on the labels assigned to the 239 records compiled (electronic surveys, literature review, and compiled networks) for Andean LTSEM systems. See definition of terms in Appendix S1 (*Supplemental material*, https://doi.org/10.1659/mrd.2022.00018.S1).



efforts integrating approaches that consider multiple spatial and temporal scales (Llambí and Garcés 2021).

A recent research agenda for Andean forest landscapes identified major knowledge gaps around the interactions between social and environmental dynamics (Mathez-Stiefel et al 2017). Other synthesis works have highlighted the importance of coordinating monitoring efforts of Andean SES at a continental scale to inform policies and sustainable management programs, and to design effective conservation strategies (Cuesta et al 2012; Llambí et al 2019). LTSEM, the systematic recording of social and environmental indicators over an extended period (Lindenmayer and Likens 2009), can provide valuable information for understanding the nonlinear responses of complex SES under ongoing climate change, through the use of indicators that, being locally relevant, allow comparison across studies (Maldonado et al 2012; Huggel et al 2015). However, to coordinate Andean monitoring efforts and achieve sustainable management, it is necessary to identify the main information gaps and questions to be addressed from a transdisciplinary perspective.

The aim of this study was to identify knowledge gaps and monitoring priorities that can inform the design of a research agenda for LTSEM to understand the response of Andean SES to climate and land-use changes. Specifically, we: (1) proposed a simple conceptual model integrating the relationships between the processes of social and environmental change and the main stakeholders involved in knowledge generation and management; (2) identified and reviewed available long-term monitoring systems across the region and analyzed their congruence with the conceptual model; and (3) combined quantitative methods and experts' perceptions to identify knowledge gaps, research priorities, and key thematic areas for Andean LTSEM.

Methods

To identify knowledge gaps and research priorities for Andean LTSEM, we combined quantitative methods with expert knowledge. We built a conceptual model to be contrasted with existing LTSEM in the region in terms of the addressed topics (climate and hydrology, environmental quality, fauna, vegetation and disturbances, land-use and land-cover change, social–environmental, and social analyses). We conducted 2 virtual interdisciplinary meetings (IER 2021a, 2021b) to collect the opinions of experts and knowledge demands of key Andean stakeholders. The first meeting was a discussion panel designed to promote the dialogue between scientists and decision-makers, share monitoring experiences, and identify challenges to integrating Andean LTSEM systems. The outputs of this meeting, which gathered 53 actors from all the Andean countries, the United States, Switzerland, and the UK, were synthesized into a conceptual model describing the processes of knowledge generation on the dynamics of Andean SES. The description and labeling (Figure 1) of the main relationships identified in the model were used to classify existing Andean LTSEM systems. We also conducted an immersive session that gathered researchers from natural and social sciences and decision-makers from public and private sectors from all Andean countries. Five of the 17 participants with a range of backgrounds combined the conceptual model with their knowledge and experience of the region to identify the main constraints to implementing efficient LTSEMs and to integrating them into decision processes.

To analyze the state of the art of Andean LTSEM, we compiled a database of existing efforts, including an electronic survey, a literature search, and a compilation of active research networks (see Appendixes S1, S2, and S3, *Supplemental material*, https://doi.org/10.1659/mrd.2022.00018.S1). We surveyed Andean LTSEM systems through an open questionnaire implemented in Google Forms and distributed through email to 425 experts and decision-makers known to be involved in research, monitoring, or policy design in the Andes. Besides providing feedback about the nature of their monitoring systems, experts also indicated key publications. To complement these publications, we performed a literature search using Google Scholar to identify published articles and reports based on Andean LTSEM. The results of this search, driven through different word combinations (see Appendix S2, *Supplemental material*, https://doi.org/10.1659/mrd.2022.00018.S1), constituted a representative sample of key issues considered in Andean LTSEM literature. We also compiled and systematized LTSEM platforms, networks, observatories programs, and projects in the region (ie existing networks), identified through diverse mechanisms (eg our research experience, expert opinion, the electronic survey, and the literature review). We compiled and mapped the geographic locations of the study sites reported in the electronic survey and publications. Each LTSEM system (ie record) was assigned to one or more topics and labels identified in the conceptual model. To assess agreement between the model and the LTSEM database, we quantified the frequency of records corresponding to each label.

Results and discussion

Conceptual model

The conceptual model graphically represents how different stakeholders are articulated in the management of Andean SES in a context of global environmental change, and the related flows of information relevant to LTSEM (Figure 1). It includes 4 types of elements: systems, stakeholders (ie actors), processes, and their interactions, which were labeled and contrasted with existing LTSEM. This model is a conceptual tool with which to explore knowledge generation and governance of Andean SES and the equitable distribution of decision-making power, as it includes the main mechanisms that involve actors in research and knowledge production and its application to informed decision-making (Ariza-Montobbio and Cuvi 2020).

Andean social–ecological systems: Since societies depend on functioning ecosystems, and there is almost no ecosystem free from anthropic influence, it is essential to consider SES as a single unit of analysis (Petrosillo et al 2015), highlighting the complex interactions among biophysical and social components (Llambí and Llambí 2001; Pulver et al 2018). LTSEM of Andean systems depends on the identification of sensitive indicators and variables that are easy to measure and summarize the state of the SES (Turnhout et al 2007; Maggino and Zumbo 2012). For example, land-use and land-cover changes are key indicators of the effects of society on ecosystems (Potschin 2009); moreover, the provision of ecosystem services should be assessed with indicators quantifying their demand by society (Burkhard et al 2012).

Stakeholders: Three groups of actors interact with SES and are involved in their conceptualization, research, and monitoring (Young et al 2006). These groups, with different spheres of action (public and private) and scales (local to global), conceptualize and influence the system differently (Villamor et al 2014).

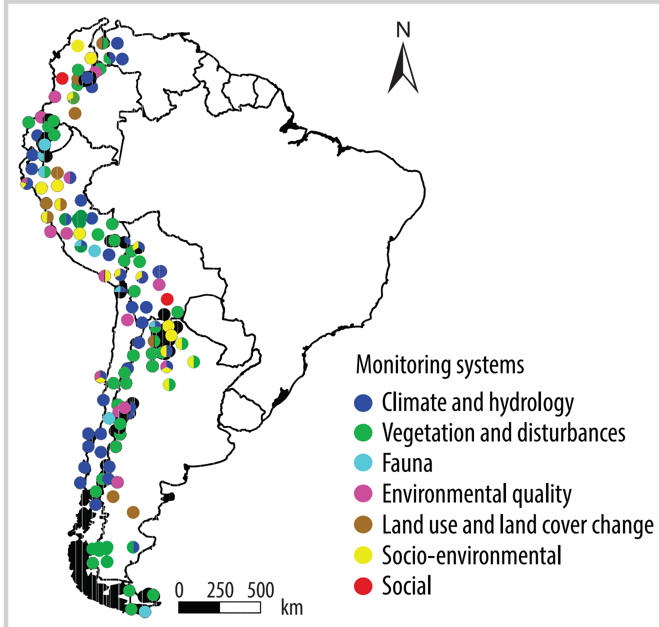
- Academia: Scientists usually describe systems through the quantification of indicators (Carpenter et al 2005), with a clear distinction between biophysical and social spheres. However, transdisciplinary studies are increasingly deemed to be better sources for informing decision-making processes (Mathez-Stiefel et al 2017). Thus, scientists are increasingly interacting with other stakeholders, considering alternative visions of SES (eg Tengö et al 2014), and promoting research codesign, which confers a greater decision power to the community (Moser 2016). Moreover, transdisciplinary research can facilitate the integration of scientific knowledge, governmental requirements, and community demands and perspectives (Holzer et al 2018).
- Governments: Governments have traditionally been responsible for managing SES through legislation, policies, and so forth (Ebbesson 2010). However, in recent years, the increasing complexity of SES has fostered the implementation of participatory and adaptive management (Dupuits 2021), in which governments and society define goals and policies. These are assessed on the basis of expected results and observed data (Vos et al 2000). Community involvement in LTSEM increases the transparency and usability of data, favoring effective governance and comanagement (Armitage et al 2009).
- Community: Community includes groups with diverse visions of SES and knowledge demands (eg local and Indigenous communities, private sector, nongovernmental organizations; Tengö et al 2014). These groups are increasingly involved in research design (Moser 2016) and participatory monitoring (Staddon et al 2014), which is facilitated by automatized data collection (eg Conrad and Hilchey 2011). With increased access to information, Andean communities can be involved in participatory management and local policy design and decision-making (Dupuits et al 2022).

Processes: Andean SES are influenced by external factors such as climate change, telecouplings, and international legislation (Young et al 2006). The widespread manifestations of climate change (Parmesan 2006) are magnified in Andean SES because of the steep gradients and vulnerable social–ecosystems (Carey 2010). Telecouplings, the exchange of material, money, information, and people between distant systems (Hull and Liu 2018), increasingly influence Andean dynamics (eg farmers' decisions are influenced by global food markets; Llambí and Llambí 2001; Zimmerer et al 2018). Andean SES are also influenced by international legislation (ie agreements that regulate global relations and standards) driven by supranational organizations and conventions (eg United Nations Framework Convention on Climate Change, Intergovernmental Panel on Climate Change, Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services), intended to coordinate policies and minimize environmental injustices through the use of scientific information (Galaz et al 2012; Biermann et al 2016).

Characterization of monitoring efforts and identification of knowledge gaps

We analyzed 239 records of Andean LTSEM systems that resulted from 65 responses to the electronic survey, 124 published studies (from a total of 2443 publications) that passed scrutiny to ensure they addressed Andean LTSEM, and 50 active networks including Andean LTSEM systems (see Appendixes S1, S2, and S3, respectively, *Supplemental material*, https://doi.org/10.1659/mrd.2022.00018.S1). Each record was assigned one or more labels from the conceptual model, which allowed the fit between expected and existing monitoring efforts to be identified (Figure 1). We acknowledge that some monitoring efforts may be overrepresented (eg literature records or networks reported in the electronic survey). However, rather than performing a formal numerical analysis, we aimed to identify general patterns and research gaps, depicting the most infrequent (eg unpublished) labels within our conceptual model (eg those involving community-based approaches). The inclusion of all the available sources of information increased the likelihood of detecting these gaps. In addition, to visually assess the geographic representativeness of our study and of the LTSEM efforts in the region, we mapped every record (survey and published studies with known study area; Figure 2).

FIGURE 2 Geographic distribution of monitoring systems and temporal studies in the Andean region detected through electronic surveys and literature search. More than one location could be reported by an electronic survey.



Tabulating the labels assigned to the 239 LTSEM records and their graphical representation in the model (Figure 1) allowed us to identify research gaps around Andean SES dynamics. While most Andean LTSEM systems are related to environmental issues (235 records considered some environmental aspect, and 162 records did not consider any social aspect at all), with vegetation ($n = 106$) and climate ($n = 100$) being the most studied topics, social aspects were underrepresented. The effect of climate change was considered in 24 LTSEM systems, and international legislation was explicit in only 3 of these systems. Social–environmental studies were mainly focused on environmental quality (eg water and air conditions and urban solid wastes, $n = 28$), ecosystem services ($n = 25$; eg Fernández-Turiel et al 2003), or the quantification of land-use and land-cover changes ($n = 24$), and social aspects were usually disregarded (eg studies monitor environmental quality but do not explicitly quantify its effects on human health; Gramsch et al 2006). Only 4 of the identified LTSEMs focused solely on the social sciences (eg López-Sandoval and Maldonado 2019).

The disproportion between biophysical and social monitoring efforts is likely explained by methodological issues; some biophysical indicators have been used to summarize the state of an environmental system for a long time (eg rainfall, temperature). By contrast, the complexity and spatial variability of social systems and rapid technological and economic changes complicate the use of single indicators through time and space. Some additional aspects may contribute to the low representation of social aspects: (1) long-term social studies are seldom integrated into formal monitoring networks; (2) most social monitoring efforts are part of official statistics and programs such as national censuses, which were not detected explicitly in our search, although they are important sources of information for social–ecological research; and (3) social research is still infrequently integrated explicitly into social–environmental initiatives.

We found that community participation is scarce in the design, implementation, and operation of Andean LTSEM systems. Only one LTSEM, led by ProYungas Foundation in collaboration with governments and private companies, implemented codesigned research. This is also 1 of the 2 records that involved adaptive management (the other one is a risk management project in Colombia; Alzate Buitrago 2010). Participatory monitoring was more frequent in the implementation of Andean LTSEM; local communities participated in data collection for 9 LTSEM systems, but they were not involved in data analysis or interpretation. Most examples of community participation involved hydrological monitoring (eg Saavedra Daza et al 2020; Ulloa et al 2021) and took advantage of cell phone applications and web-based data collection (eg World Water Monitoring Challenge or the Litterati platform for surveying urban solid waste). Collaboration with local communities is deemed essential for successful social–environmental monitoring, as it promotes knowledge appropriation and increases the social relevance and applicability of research. However, the implementation of community participation poses big challenges, such as creating an effective dialogue between technical quantification and community knowledge. Participatory monitoring seems to be more likely when interests are transparent and homogeneous (eg private sector with clearly formulated goals or when some resource [eg water] is essential for the whole group) and when the participatory methods are accessible to local stakeholders (eg Litterati citizen science).

Although academics are frequently consulted by governments, and LTSEM systems depend on public funds, none of the records presented effective comanagement between academia and government; it is possible that the lack of common expectations, language, and time frames is a source of mutual distrust (Karam-Gemael et al 2018). Policymakers usually need rapid technical responses, while scientists are interested in novel and abstract problems, which are not always linked with social demands. Adaptive management (reported in 2 records; a single publication of Dallmeier et al 2002), considered an efficient tool to deal with uncertainty, implies a continuous reassessment of policies by contrasting expected and observed results (which need to be monitored). Most of the time, policymakers must address pressing problems and have no time or resources to monitor the impacts of implemented policies or revisit past problems that are assumed to be solved (eg crisis of water scarcity). This may raise a problem in coordinating and implementing effective adaptive management and policy implementation across scales (see Dupuits et al 2022). Even though policies are usually implemented in single geographic systems, their results could provide information across multiple spatiotemporal scales, a benefit that is usually beyond the scope of short-term policymaking. In this context, strengthening communication between policymakers and academics (eg comanagement of information platforms, explicit social–environmental science–policy dialogues) is key to reinforcing monitoring networks and regional political platforms and actions (eg within the framework of the Andean Mountain Initiative and other continental policy forums).

Collaborative networks promote the use of indicators in LTSEM, facilitating comparison and integration of different case studies (eg Carilla et al 2013; Cuesta et al 2020; Malizia et al 2020) and different areas of knowledge (Jimenez et al 2021). However, some constraints may arise in the selection of comparable variables because most LTSEM systems choose indicators based on specific social–ecological problems (eg changes in plant diversity, water pollution). Biophysical sciences have identified indicators that are easy to measure (eg the normalized difference vegetation index [NDVI] indicates vegetation activity, and the abundance of some organisms is deemed to be a good proxy of the health of an ecosystem; Linares Arias et al 2019). By contrast, social–environmental and social indicators enabling the comparison between sites are difficult to identify due to the diversity of social actors and conditions between Andean countries and landscapes (Bustamante et al 2014). The lack of core social indicators and networks focused on social issues reduces the opportunity to perform integrative analyses and create regional maps with adequate resolution. Although social studies might be underrepresented in our search, there are at least 2 objective aspects that make the integration of social studies more difficult. On the one hand, social issues are more complex than biophysical systems and present multiple nonlinear responses, so simple models incapable of extrapolation are generally less useful. On the other hand, the narrative approach, widely used in social areas, permits accurate characterization of complex systems, but their inclusion in quantitative comparisons and meta-analyses, particularly across wide spatial scales, is difficult.

Global changes affecting Andean SES highlight the importance of LTSEM because they generate nonanalogous conditions precluding the extrapolation of results. While most LTSEM systems only mention the potential effects of climate change on the Andean SES, some LTSEM systems assess these effects on environmental dynamics (eg Gloria or RBA networks; Morales et al 2015; Carilla et al 2018; Fadrique et al 2018). In contrast, we found no assessments of telecoupling effects, even though they are considered to be relevant drivers of Andean land-use changes (Aide et al 2019). International agreements advocate knowledge-based policies to handle problems that cannot be addressed by local governments (eg Aichi Biodiversity Targets; O'Connor et al 2015), and some LTSEM systems are considered to inform these policies: At least 3 networks were involved in the transference of knowledge to inform international agreements (Global Change in Mountain Regions or GLOCHAMORE, World Glacier Monitoring Service, and Global Cryosphere Watch, from the United Nations Educational, Scientific and Cultural Organization and World Meteorological Organization, which are specialized agencies of the United Nations). Information from LTSEM in the Andean region has informed international reports aimed at decision-makers such as those of the Intergovernmental Panel on Climate Change (eg Adler et al 2022). Recent efforts have also aimed to integrate LTSEM results into policy briefs and facilitate communication mechanisms of regional policy platforms such as the Andean Mountain Initiative (eg see iam-andes.org).

Research priorities for the development of an agenda for integrated social–environmental monitoring in the Andes and conclusions

Andean LTSEM systems constitute the best source of information to understand SES responses to unprecedented global changes and to increase their resilience. We combined a conceptual model representing interactions within Andean SES with an active search of LTSEM systems (through an electronic survey, literature review, and search of existing networks) to characterize monitoring efforts in terms of the topics addressed and the actors involved. This characterization of existing studies is necessary to coordinate efforts to fulfill existing knowledge gaps, facilitate information sharing, summarize complex processes at different spatial and temporal scales, and inform local social–environmental policies and international agreements.

The combination of our quantitative approach with the experts' opinions compiled from 2 interdisciplinary workshops allowed us to identify some research priorities for Andean LTSEM. We classified them into 5 categories (Table 1). (1) System conceptualization: The characterization of Andean SES, identifying main stakeholders, economic activities, ecological elements, and their interactions, should form the basis for analytical classifications of Andean SES (eg social–ecological land systems; Zarbá et al 2022). This classification, based on unified indicators and conceptual approaches, will permit more accurate integration of SES knowledge and the establishment of LTSEM at representative learning sites. (2) System functioning: The integration of systematic social–ecological information gathered through unified protocols with alternative proxies to fill geographic gaps (eg derived from remote sensing) and modeling approaches will allow a comprehensive understanding of Andean SES. The integration of

TABLE 1 Research priorities for integrated monitoring of Andean SES identified from the perception of experts representing academia, government, and private sectors of different Andean countries (compiled during 2 interdisciplinary workshops), and from the analysis of different information sources on the state of the art of environmental and social monitoring along the Andes (surveys, literature, and networks) and the ways in which they are linked with the proposed conceptual model. Each priority was assigned with a recommendation type: "What" refers to the content of monitoring, "How" refers to the strategy, and "Why" refers to the purpose of the monitoring. (Table continued on next page.)

Category/number	Research priority	Recommendation type
1. System conceptualization		
1.1	Document and integrate into long-term monitoring efforts the perceptions, cultural values, identities, and knowledge of different stakeholders.	What
1.2	Identify and incorporate into long-term monitoring the main anthropic activities and their effects on landscape dynamics and ecosystem functioning (eg degradation, land-use change, and changes in disturbance regimes).	What
1.3	Analyze the perceptions on natural assets and the demand for ecosystem services by local communities and urban populations (within and beyond the Andes).	What
1.4	Characterize Andean social–ecological systems by identifying and describing the main processes, stakeholders, livelihoods, and social–ecological interactions to permit the comparison between study cases.	How
1.5	Promote and strengthen the establishment of long-term research in learning sites where more integrated social–ecological monitoring approaches are developed and tested.	How
2. System functioning		
2.1	Identify social indicators relevant for sustainable management and systematize their quantification in long-term research and learning sites across regions and countries.	What
2.2	Generate comparable information on long-term demographic and social processes at multiple spatial scales (local to continental), considering historical dynamics of settlement and transformation of Andean landscapes.	What
2.3	Monitor the main economic activities and their effects on land cover, ecosystem functioning, disturbance regimes, and provision of ecosystem services.	What
2.4	Monitor the effects of environmental, social, and economic policies implemented in SES across the Andes.	What
2.5	Identify indicators that transversally link economic, social, institutional, and environmental dynamics and that take into account the social–ecological heterogeneity of the Andes.	What
2.6	Generate systematic and comparable climatic and hydrological information, identifying underrepresented geographic areas.	How
2.7	Complement climate or vegetation observational data with experimental designs, modeled scenarios, and remote-sensing proxies to overcome the scarcity of instrumental/field data.	How
2.8	Incorporate standardized protocols to monitor ecosystem functioning, including indicators based on remote sensing.	How
2.9	Incorporate analytical and modeling techniques that allow scaling and extrapolation of results derived from local studies and long-term monitoring sites.	How
3. Influences of external dynamics on Andean social–ecosystems		
3.1	Analyze the consequences of global socioeconomic changes (eg commodity prices, demand for natural resources such as lithium) on resource access and use.	What
3.2	Monitor flows of information, goods, services, money, and people between Andean systems and distant regions (telecouplings) and evaluate their local social–ecological consequences.	What
3.3	Strengthen monitoring of the responses of natural and transformed ecosystems to climate change through long-term integrated efforts (eg Global Observation Research Initiative in Alpine Environments in the Andes, better known as GLORIA-Andes, and the Andean Forest Network).	How
3.4	Promote regional analyses to inform international agreements and design monitoring systems to assess the local effects of their implementation.	Why

TABLE 1 Continued. (First part of Table 1 on previous page.)

Category/number	Research priority	Recommendation type
4. Governance and social–ecosystem interactions		
4.1	Strengthen regional, national, and local capacities in planning, execution, and management of research, monitoring, and technological development projects in social–environmental matters, including innovative strategies for promoting citizen science through the use of new technologies (eg cell phone applications).	How
4.2	Promote a more effective integration of results from long-term monitoring processes into regional science–policy dialogs, considering community demands.	Why
4.3	Generate joint research agendas, in the medium and long term, involving the public and private sectors, local communities, and academia, promoting research and monitoring codesign and comanagement.	Why
4.4	Promote the use of environmental and social monitoring information for the design of more inclusive, equitable, and sustainable governance systems adapted to local realities.	Why
4.5	Identify the needs and demands for financial resources and cofinancial strategies for social–ecological research and monitoring for the coming years from both the public and private sectors (companies, research centers, universities, among others) at national and regional levels.	Why
4.6	Develop research and funding strategies to enhance replicability and comparability of social and environmental research at a continental scale that can inform global policies.	Why
5. Information accessibility		
5.1	Promote regional integration of existing networks with different scopes and approaches (social, environmental), based on a comprehensive action plan that involves cooperation mechanisms, promotion of learning sites, integration of scales, capacity building, and identification of key indicators to guide the various monitoring efforts.	How
5.2	Systematize available regional and multiscale information (eg through regional comparative analyses and social–ecological indicator systems accessible to different stakeholders through virtual platforms).	How
5.3	Strengthen collaborative regional long-term monitoring systems and efforts to integrate environmental information into regional-scale analyses, which are widely communicated (eg via scientific publications, integrative web portals, policy briefs, science–policy dialogs) and incorporated into social–ecosystem management.	How, why

monitoring approaches and protocols will allow the coordination of individual LTSEM systems and the analysis of different-scale processes that cannot be inferred from single case studies (eg Llambí et al 2019). (3) Influence of external dynamics: Although climate change is considered in Andean research, the effect of other global drivers of change, such as international trade, must be monitored. Since the responses of mountain SES to environmental changes are particularly complex in mountain landscapes, Andean LTSEM should actively provide information to global agreements and legislation. (4) Governance: The assessment of the effects of policies and management strategies through LTSEM and the implementation of participatory research through the use of new technologies will ensure a more socially relevant understanding and governance of Andean SES. The coordination of different LTSEM systems (eg through the consolidation of long-term integrated learning sites including multiple stakeholders) will increase Andean social–ecological resilience and sustainable management by facilitating the dialogue and flow of information between technicians and community-based knowledge systems. (5) Information accessibility: The growing availability of data and information (eg via integrated social–ecological indicator platforms; see Adaptación en las Alturas et al n.d.) will strengthen existing research networks, foster knowledge coproduction, support science–policy dialogue, and facilitate science-based governance. Making coherently gathered information accessible is necessary for regional synthesis analyses (eg Malizia et al 2020), which are key pieces in understanding complex systems.

In summary, the foundation and the point of departure for the consolidation of the integrated monitoring agenda advocated here should be a reconceptualization of Andean SES, focusing on social–ecological interactions and considering the views of different stakeholders. It should also involve the integration of different disciplines and spatiotemporal scales. The identification of unified indicators leading to regional comparisons and providing relevant information for decision-making at multiple spatial scales remains a central challenge for LTSEM in the Andes. Research networks and long-term learning sites will play key roles in generating field information, measuring integrative indicators, and performing analytical syntheses (combining observational, experimental, and remote-sensing data), which can better inform science-based policies. Moreover, the participation of diverse stakeholders in knowledge production and system management is essential to strengthen governance and to promote the resilience of

Andean SES to global changes that will increasingly influence these systems.

ACKNOWLEDGMENTS

We thank the 2 reviewers and Editor Susanne Wymann von Dach for their very valuable suggestions and comments. Special thanks go to all the experts and decision-makers who participated in the workshops and provided us with their insights on the challenges for integrated monitoring in the Andes. We also want to acknowledge the financial support of the Adaptation at Altitude and Andean Forest Programmes (SDC) and the Scientific and Technological Research Fund of Argentina (FONCyT, PICT 2020 03355).

OPEN PEER REVIEW

This article was reviewed by Jere L. Gilles and Elizabeth Jiménez. The peer review process for all MountainAgenda articles is open. In shaping target knowledge, values are explicitly at stake. The open review process offers authors and reviewers the opportunity to engage in a discussion about these values.

REFERENCES

Adaptación en las Alturas, Bosques Andinos, SDC [Swiss Agency for Development and Cooperation], CONDESAN [Consorcio para el Desarrollo Sostenible de la Ecorregión Andina]. N.d. *Plataforma de indicadores socioambientales en la region Andina*. Lima, Peru: Adaptación en las Alturas, Bosques Andinos, SDC, CONDESAN. https://indicadores-andinos.condesan.org/; accessed on 1 March 2023.

Adler C, Palazzi E, Kulonen A, Balsiger J, Colangeli G, Cripe D, Forsythe N, Goss-Durant G, Guigoz Y, Krauer J, et al. 2018. Monitoring mountains in a changing world: New horizons for the Global Network for Observations and Information on Mountain Environments (GEO-GNOME). *Mountain Research and Development* 38(3):265–269.

Adler C, Wester P, Bhatt I, Huggel C, Insarov GE, Morecroft MD, Muccione V, Prakash A. 2022. Cross-Chapter Paper 5: Mountains. *In*: Pörtner HO, Roberts DC, Tignor M, Poloczanska ES, Mintenbeck K, Alegría A, Craig M, Langsdorf S, Löschke S, Möller V, et al, editors. *Climate Change 2022: Impacts, Adaptation, and Vulnerability*. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom: Cambridge University Press, pp 2273–2318.

Aide TM, Grau HR, Graesser J, Andrade-Nuñez MJ, Aráoz E, Barros AP, Campos-Cerqueira M, Chacon-Moreno E, Cuesta F, Espinoza R, et al. 2019. Woody vegetation dynamics in the tropical and subtropical Andes from 2001 to 2014: Satellite image interpretation and expert validation. *Global Change Biology* 25(6):2112–2126.

Alzate Buitrago A. 2010. El proceso de reconstrucción post sismo 1999, un desafío para la sostenibilidad de la gestión del riesgo en los procesos de desarrollo: Lecciones por aprender en el municipio de Pereira. *Entre Ciencia e Ingeniería* 4(8):96–114.

Ariza-Montobbio P, Cuvi N. 2020. Adaptación basada en ecosistemas en Ecuador: Buenas prácticas para el co-manejo adaptativo. *Ambiente & Sociedade* 23. https://doi.org/10.1590/1809-4422asoc20180315r2vu2020L4AO.

Armitage DR, Plummer R, Berkes F, Arthur RI, Charles AT, Davidson-Hunt IJ, Diduck AP, Doubleday NC, Johnson DS, Marschke M, et al. 2009. Adaptive co-management for social–ecological complexity. *Frontiers in Ecology and the Environment* 7(2):95–102.

Biermann F, Bai X, Bondre N, Broadgate W, Arthur Chen CT, Dube OP, Erisman JW, Glaser M, van der Hel S, Lemos MC, et al. 2016. Down to earth: Contextualizing the Anthropocene. *Global Environmental Change* 39:341–350.

Björnsen Gurung A, Wymann von Dach S, Price MF, Aspinall A, Balsiger J, Baron JS, Sharma E, Greenwood G, Kohler T. 2012. Global change and the world's mountains: Research needs and emerging themes for sustainable development. *Mountain Research and Development* 32(S1). https://doi.org/10.1659/MRD-JOURNAL-D-11-00084.S1.

Burkhard B, Kroll F, Nedkov S, Müller F. 2012. Mapping ecosystem service supply, demand and budgets. *Ecological Indicators* 21:17–29.

Bustamante M, Carrera M, Cossio V, Crespo M, Ferreira W, Herbas M, Jimenez J, Peralvo M, Postigo JC, Vargas C. 2014. *Protocolo de monitoreo de modos de vida a escala local*. Serie de protocolos de monitoreo. Quito, Ecuador: CONDESAN [Consortium for the Sustainable Development of the Andean Ecoregion], COSUDE [Agencia Suiza para el Desarrollo y la Cooperación], Rumbol SRL, Centro Agua, Universidad Mayor de San Simón.

Buytaert W, Cuesta F, Tobón C. 2011. Potential impacts of climate change on the environmental services of humid tropical alpine regions. *Global Ecology and Biogeography* 20:19–33.

Carey M. 2010. *In the Shadow of Melting Glaciers: Climate Change and Andean Society*. Oxford, United Kingdom: Oxford University Press.

Carilla J, Grau HR, Paolini L, Morales M. 2013. Lake fluctuations, plant productivity, and long-term variability in high-elevation tropical Andean ecosystems. *Arctic, Antarctic, and Alpine Research* 45(2):179–189.

Carilla J, Halloy S, Cuello S, Grau A, Malizia A, Cuesta F. 2018. Vegetation trends over eleven years on mountain summits in NW Argentina. *Ecology and Evolution* 8(23):11554–11567. https://doi.org/10.1002/ece3.4602.

Carpenter SR, Westley F, Turner MG. 2005. Surrogates for resilience of social–ecological systems. *Ecosystems* 8(8):941–944.

Conrad CC, Hilchey KG. 2011. A review of citizen science and community-based environmental monitoring: Issues and opportunities. *Environmental Monitoring and Assessment* 176(1):273–291.

Cuesta F, Baez S, Ramírez J, Tovar C, Devenish C, Buytaert W, Jarvis A. 2012. Síntesis de los impactos y estado del conocimiento de los efectos del cambio climático en la biodiversidad de los Andes tropicales. *In*: Cuesta F, Bustamante M, Becerra MT, Postigo J, Peralvo J, editors. *Panorama Andino de cambio climático: Vulnerabilidad y adaptación en los Andes tropicales*. Lima, Peru: CONDESAN [Consortium for the Sustainable Development of the Andean Ecoregion], SGCAN [Secretaría General de la Comunidad Andina de Naciones], pp 60–139.

Cuesta F, Tovar C, Llambí LD, Gosling WD, Halloy S, Carilla J, Muriel P, Meneses RI, Beck S, Ulloa Ulloa C, et al. 2020. Thermal niche traits of high alpine plant species and communities across the tropical Andes and their vulnerability to global warming. *Journal of Biogeography* 47(2):408–420.

Dallmeier F, Alonso A, Campbell, P. 2002. Biodiversity monitoring and assessment for adaptive management: Linking conservation and development. *Journal of Environmental Monitoring and Assessment* 76:1–156.

Devenish C, Gianella C. 2012. *Regional Report. Sustainable Mountain Development in the Andes: From Rio 1992 to 2012 and Beyond*. Lima, Peru: COSUDE [Agencia Suiza para el Desarrollo y la Cooperación]–CONDESAN [Consortium for the Sustainable Development of the Andean Ecoregion] Mountain Partnership.

Dupuits E. 2021. *Climate Change Policies in the Andes: Dialogue Between Scales and Perspectives for Adaptation*. Propuestas Andinas 18. Quito, Ecuador: Adaptation at Altitude, Andean Forests Programme, CONDESAN [Consortium for the Sustainable Development of the Andean Ecoregion].

Dupuits E, Llambí LD, Peralvo M. 2022. Implementing climate change adaptation policies across scales: Challenges for knowledge coproduction in Andean mountain socio-ecosystems. *Mountain Research and Development* 42(2):A1–A11.

Ebbesson J. 2010. The rule of law in governance of complex socio-ecological changes. *Global Environmental Change* 20(3):414–422.

Fadrique B, Báez S, Duque Á, Malizia A, Blundo C, Carilla J, Osinaga Acosta O, Malizia L, Silman M, Farfán-Ríos W, et al. 2018. Widespread but heterogeneous responses of Andean forests to climate change. *Nature* 564(7735):207–212.

Fernández-Turiel J, Pérez-Miranda C, Almada G, Medina M, Riviere C, Gordillo MA. 2003. Surface-water quality for the Salí River watershed in NW Argentina. *Environmental Geology* 43:941–949.

Galaz V, Biermann F, Crona B, Loorbach D, Folke C, Olsson P, Nilsson M, Allouche J, Persson Å, Reischl G. 2012. Planetary boundaries: Exploring the challenges for global environmental governance. *Current Opinion in Environmental Sustainability* 4(1):80–87.

Gleeson EH, Wymann von Dach S, Flint CG, Greenwood GB, Price MF, Balsiger J, Nolin A, Vanacker V. 2016. Mountains of our future Earth: Defining priorities for mountain research. A synthesis from the 2015 Perth III conference. *Mountain Research and Development* 36(4):537–548.

Gramsch E, Cereceda-Balic F, Oyolac P, von Baerd D. 2006. Examination of pollution trends in Santiago de Chile with cluster analysis of PM10 and ozone data. *Atmospheric Environment* 40(28):5464–5475.

Holzer JM, Carmon N, Orenstein DE. 2018. A methodology for evaluating transdisciplinary research on coupled socio-ecological systems. *Ecological Indicators* 85:808–819.

Huggel C, Scheel M, Albrecht F, Andres N, Calanca P, Jurt C, Khabarov N, Mira-Salama D, Rohrer M, Salzmann N, et al. 2015. A framework for the science contribution in climate adaptation: Experiences from policy-science processes in the Andes. *Environmental Science and Policy* 47:80–94.

Hull V, Liu J. 2018. Telecoupling: A new frontier for global sustainability. *Ecology and Society* 23(4):41. https://doi.org/10.5751/ES-10494-230441.

IER [Instituto de Ecología Regional]. 2021a. Memorias de la sesión de inmersión: Desarrollo de una agenda de investigación para el análisis integrado de monitoreos socioambientales en los Andes. XXIX Reunión Argentina de Ecología (RAE). https://condesan.org/recursos/memorias-de-la-sesion-de-inmersion-desarrollo-de-una-agenda-de-investigacion-para-el-analisis-integrado-de-monitoreos-socio-ambientales-en-los-andes/; accessed on 2 April 2023.

IER [Instituto de Ecología Regional]. 2021b. Memoria del conversatorio: Hacia una agenda de investigación para el monitoreo integrado de ecosistemas andinos: Aportes para la sostenibilidad en escenarios de cambio ambiental. Quito, Ecuador: CONDESAN [Consortium for the Sustainable Development of the Andean Ecoregion]. https://condesan.org/recursos/hacia-una-agenda-investigacion-monitoreo-integrado-ecosistemas-andinos-aportes-la-sostenibilidad-escenarios-cambio-ambiental/; accessed on 2 April 2023.

Isbell F, Gonzalez A, Loreau M, Cowles J, Díaz S, Hector A, Mace GM, Wardle DA, O'Connor MI, Duffy JE, et al. 2017. Linking the influence and dependence of people on biodiversity across scales. *Nature* 546:65–72.

Jimenez YG, Aráoz E, Grau HR, Paolini L. 2021. Linking forest transition, plant invasion and forest succession theories: Socioeconomic drivers and composition of new subtropical Andean forests. *Landscape Ecology* 36(4):1161–1176.

Karam-Gemael M, Loyola R, Penha, Izzo T. 2018. Poor alignment of priorities between scientists and policymakers highlights the need for evidence-informed conservation in Brazil. *Perspectives in Ecology and Conservation* 16(3):125–132.

Krausmann F, Erb KH, Gingrich S, Haberl H, Bondeau A, Gaube V, Lauk C, Plutzar C, Searchinger TD. 2013. Global human appropriation of net primary production doubled in the 20th century. *Proceedings of the National Academy of Sciences of the United States of America* 110(25):10324–10329.

Linares Arias JC, Carrillo Fajardo MY, González CM, Vergara Doria LE, Prioló MC, Vargas Pérez A, Martínez JA, Chica Vargas JP, Mercado Pérez JD, Martínez A, et al. 2019. *Informe final sobre monitoreo a la rehabilitación del socioecosistema anfibio en La Mojana, con énfasis en monitoreo comunitario*. Bogotá, Colombia: Instituto de Investigación de Recursos Biológicos Alexander von Humboldt.
Lindenmayer DB, Likens GE. 2009. Adaptive monitoring: A new paradigm for long-term research and monitoring. *Trends in Ecology and Evolution* 24(9):482–486.
Llambí L, Llambí LD. 2001. A transdisciplinary framework for the analysis of tropical agroecosystem transformations. *In:* Lawrence G, Higgins V, Lockie S, editors. *Environment, Society and Natural Resource Management: Theoretical Perspectives from Australasia and the Americas*. Cheltenham, United Kingdom: Edward Elgar, pp 53–69.
Llambí LD, Becerra MT, Peralvo M, Avella A, Baruffol M, Díaz LJ. 2019. Monitoring biodiversity and ecosystem services in Colombia's High Andean ecosystems: Toward an integrated strategy. *Mountain Research and Development* 39(3):A8–A20.
Llambí LD, Garcés A. 2021. *Adaptation to Climate Change in the Andes: Gaps in Understanding and Opportunities for Knowledge Management*. Quito, Ecuador: CONDESAN [Consortium for the Sustainable Development of the Andean Ecoregion].
López-Sandoval M, Maldonado P. 2019. Change, collective action, and cultural resilience in páramo management in Ecuador. *Mountain Research and Development* 39(4):R1–R9.
Maggino F, Zumbo BD. 2012. Measuring the quality of life and the construction of social indicators. *In:* Land KC, Michalos AC, Sirgy MJ, editors. *Handbook of Social Indicators and Quality of Life Research*. Dordrecht, the Netherlands: Springer, pp 201–238.
Maldonado G, Becerra MT, Cuesta F. 2012. Marco institucional y normativo en los países de la subregión andina para abordar el tema de cambio climático en el marco de la Convención Marco de Naciones Unidas sobre Cambio Climático. *In*: Cuesta F, Bustamante M, Becerra MT, Postigo J, Peralvo J, editors. *Panorama andino de cambio climático: Vulnerabilidad y adaptación en los Andes tropicales*. Lima, Peru: CONDESAN [Consortium for the Sustainable Development of the Andean Ecoregion], SGCAN [Secretaría General de la Comunidad Andina de Naciones], pp 221–261.
Malizia A, Blundo C, Carilla J, Osinaga Acosta O, Cuesta F, Duque A, Young KR. 2020. Elevation and latitude drives structure and tree species composition in Andean forests: Results from a large-scale plot network. *PloS One* 15(4):e0231553.
Mathez-Stiefel SL, Peralvo M, Báez S, Riest S, Buytaert W, Cuesta F, Fadrique B, Feeley KJ, Groth AA, Homeir J, et al. 2017. Research priorities for the conservation and sustainable governance of Andean forest landscapes. *Mountain Research and Development* 37(3):323–339.
Morales MS, Carilla J, Grau HR, Villalba R. 2015. Multi-century lake area changes in the Southern Altiplano: A tree-ring-based reconstruction. *Climate of the Past* 11(9):1139–1152.
Moser SC. 2016. Can science on transformation transform science? Lessons from co-design. *Current Opinion in Environmental Sustainability* 20:106–115.
O'Connor B, Secades C, Penner J, Sonnenschein R, Skidmore A, Burgess ND, Hutton JM. 2015. Earth observation as a tool for tracking progress towards the Aichi Biodiversity Targets. *Remote Sensing in Ecology and Conservation* 1(1):19–28.
Parmesan C. 2006. Ecological and evolutionary responses to recent climate change. *Annual Review of Ecology, Evolution, and Systematics* 37:637–669.
Peralvo M, Bustamante M. 2015. CONDESAN: Promoting long-term monitoring at different scales to support natural resource governance in the Andean countries. *Mountain Research and Development* 35(1):90–92.
Petrosillo I, Aretano R, Zurlini G. 2015. Socioecological systems. *In:* Fath, B, editor. *Encyclopedia of Ecology*. 2nd edition. Amsterdam, the Netherlands: Elsevier, pp 419–425. https://doi.org/10.1016/B978-0-12-409548-9.09518-X.
Potschin M. 2009. Land use and the state of the natural environment. *Land Use Policy* 26:S170–S177.
Pulver S, Ulibarri N, Sobocinski KL, Alexander SM, Johnson ML, McCord PF, Dell'Angelo J. 2018. Frontiers in socio-environmental research. *Ecology and Society* 23(3):23. https://doi.org/10.5751/ES-10280-230323.
Saavedra Daza NV, Sandoval Sierra JS, Galeano Soto PD. 2020. *Aplicación web y móvil para el proyecto "Plataforma comunitaria para la medición de la calidad del agua en la región de Samacá, Boyacá.*" Boyaca, Colombia: Universidad Santo Tomás Seccional Tunja.
Schoolmeester T, Saravia M, Andresen M, Postigo J, Valverde A, Jurek M, Alfthan B, Giada S. 2016. *Outlook on Climate Change Adaptation in the Tropical Andes Mountains*. Mountain Adaptation Outlook Series. Nairobi, Kenya, Arendal, Norway, Vienna, Austria, Lima, Peru: UNEP [United Nations Environment Programme], GRID-Arendal, CONDESAN [Consortium for Sustainable Development of the Andean Ecoregion].
Staddon SC, Nightingale A, Shrestha SK. 2014. The social nature of participatory ecological monitoring. *Society & Natural Resources* 27(9):899–914.
Tengö M, Brondizio ES, Elmqvist T, Malmer P, Spierenburg M. 2014. Connecting diverse knowledge systems for enhanced ecosystem governance: The multiple evidence base approach. *Ambio* 43(5):579–591.
Turnhout E, Hisschemöller M, Eijsackers H. 2007. Ecological indicators: Between the two fires of science and policy. *Ecological Indicators* 7(2):215–228.
Ulloa A, Godfrid J, Damonte G, Quiroga C, López AP. 2021. Monitoreos hídricos *comunitarios*: Conocimientos locales como defensa territorial y ambiental en Argentina, Perú y Colombia. *Íconos Revista de Ciencias Sociales* 69:77–97.
Villamor GB, Palomo I, Santiago CAL, Oteros-Rozas E, Hill J. 2014. Assessing stakeholders' perceptions and values towards social–ecological systems using participatory methods. *Ecological Processes* 3(1):1–12.
Vos P, Meelis E, Ter Keurs WJ. 2000. A framework for the design of ecological monitoring programs as a tool for environmental and nature management. *Environmental Monitoring and Assessment* 61(3):317–344.
Wymann von Dach S, Bracher C, Peralvo M, Perez K, Adler C, and a group of contributing authors. 2018. *Leaving No One in Mountains Behind: Localizing the SDGs for Resilience of Mountain People and Ecosystems*. Issue Brief on Sustainable Mountain Development. Bern, Switzerland: Centre for Development and Environment and Mountain Research Initiative, with BOP [Bern Open Publishing].
Young OR, Berkhout F, Gallopin GC, Janssen MA, Ostrom E, Van der Leeuw S. 2006. The globalization of socio-ecological systems: An agenda for scientific research. *Global Environmental Change* 16(3):304–316.
Zarbá L, Piquer-Rodríguez M, Boillat S, Levers C, Gasparri I, Aide TM, Álvarez-Berríos NL, Anderson LO, Aráoz E, Arima E, et al. 2022. Mapping and characterizing social–ecological land systems of South America. *Ecology and Society* 27(2):27. https://doi.org/10.5751/ES-13066-270227.
Zimmerer KS, Lambin EF, Vanek SJ. 2018. Smallholder telecoupling and potential sustainability. *Ecology and Society* 23(1):30. https://doi.org/10.5751/ES-09935-230130.

Supplemental material

APPENDIX S1 Electronic survey.
APPENDIX S2 Literature search.
APPENDIX S3 Monitoring networks.

Found at: https://doi.org/10.1659/mrd.2022.00018.S1