Policy Implementation Challenges of UNESCO's Man and the Biosphere Program, Illustrated by Science–Society Interactions in 18 Mountain Biosphere Reserves

Authors: Mitrofanenko, Alexander, Thaler, Thomas, and Gugerell, Katharina

Source: Mountain Research and Development, 45(4)

Published By: International Mountain Society

URL: https://doi.org/10.1659/mrd.2025.00037

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

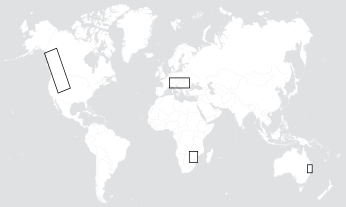
MountainResearch
Systems knowledge

Policy Implementation Challenges of UNESCO's Man and the Biosphere Program, Illustrated by Science–Society Interactions in 18 Mountain Biosphere Reserves

Alexander Mitrofanenko [1,2]*, ***Thomas Thaler*** [1,2,3], ***and Katharina Gugerell*** [1,2,4]

* *Corresponding author: alexander.mitrofanenko@boku.ac.at*

[1] BOKU University, Institute of Landscape Planning, Department of Landscape, Water and Infrastructure, Peter-Jordan-Str. 65, 1180 Vienna, Austria
[2] BOKU University, Transitions to Sustainability (T2S) Doctoral School, Gregor-Mendel-Str. 33, 1180 Vienna, Austria
[3] International Institute for Applied Systems Analysis, Population and Just Societies Program, Schlossplatz 1, 2361 Laxenburg, Austria
[4] University of Johannesburg, Department of Geography, Environmental Management & Energy Studies, Auckland Park, 2092 Johannesburg, South Africa



Mountain regions are increasingly vulnerable to the converging global crises of climate change, biodiversity loss, and land degradation. These socioecological challenges demand not only incremental adaptation but also broader societal transformation processes, including in knowledge production. Science–society interactions (SSIs) are increasingly recognized as a promising pathway toward the coproduction of context-specific, actionable knowledge that can support such transformations. In recent years, the United Nations Educational, Scientific and Cultural Organization's (UNESCO's) Man and the Biosphere (MAB) program has positioned its biosphere reserves (BRs), most of which are in mountain regions, as model sites for sustainability transformations and for advancing SSIs. However, despite a strong emphasis on SSIs in MAB policy directives, little is known about whether and how these have been implemented in practice. This paper investigates the policy implementation gaps between the aims of the MAB program and reality on the ground, based on qualitative content analysis of periodic review reports from 18 mountain BRs across Africa, Australia, Europe, and North America and 14 semistructured interviews with BR representatives. Findings reveal that SSIs in mountain BRs remain predominantly ecology-focused, characterized by one-way, short-term information transfer, with limited involvement of local actors or incorporation of nonacademic knowledge. Main challenges to the international policy goals include resource and capacity constraints, weak institutional anchoring, fragmented governance, and sociopolitical resistance. Although participatory approaches are widely valued, their practical execution remains challenging. The results underscore the need for context-sensitive policy frameworks, increased resources, and capacity-building to strengthen mountain BRs as model regions for SSIs and sustainability transformations.

Keywords: *science–society interactions; biosphere reserves; mountain regions; UNESCO Man and the Biosphere program; policy implementation; implementation gap; knowledge coproduction; sustainability transformation.*

Received: *30 June 2025* ***Accepted:*** *31 October 2025*

Introduction

The polycrisis, driven by interconnected issues such as climate change, biodiversity loss, and land degradation, is threatening ecosystems and giving rise to major socioeconomic and political consequences (IPCC 2022; Lawrence et al 2024). Mountain regions, home to more than a billion people, are particularly vulnerable due to their biophysical characteristics and exposure to rapid environmental change and socioeconomic pressures (Adler et al 2022; Aquerreta et al 2022). They often represent ecological and cultural hotspots, supporting unique ecosystems and traditional livelihoods that are increasingly at risk (Wyss et al 2022). Climate change is accelerating glacier melt, altering species distributions, and increasing the frequency of extreme weather events, heightening risks not only for mountain ecosystems and communities but also for downstream lowland regions that depend on mountain resources (Steiger et al 2024; Tripathi et al 2024). Additionally, biodiversity loss and land degradation in mountain areas are compounded by land use changes, overexploitation of natural resources, and the frequent marginalization of mountain regions, where limited economic opportunities and political influence increase vulnerability (Chand and Leimgruber 2016; Gupta et al 2022; Wyss et al 2022).

Given the urgency and complexity of these challenges, incremental adaptation is increasingly considered

insufficient, prompting calls for transformative changes in governance, knowledge production, and socioeconomic systems (Folke et al 2021; Vogel and O'Brien 2022; Voulvoulis et al 2022). Such calls have gained momentum across science, policy, and civil society (Bennett et al 2019), highlighting the need for approaches that integrate scientific expertise with other knowledge systems (eg local, Indigenous, practitioner) (Wyss et al 2022; Horcea-Milcu et al 2024). Traditional scientific approaches to knowledge generation often fall short by overlooking local needs and knowledge (Lang et al 2012). Science–society interactions (SSIs) offer a promising pathway, bringing together scientific and societal actors to generate context-specific, actionable knowledge (Schneider et al 2021; Barth et al 2023). SSIs encompass a variety of activities, ranging from minimal, one-way exchanges such as interviews or consultations to intensive, participatory processes, such as transdisciplinary research (Steger et al 2021; Knott et al 2022; Mitrofanenko et al 2025). The more participatory forms are increasingly recognized for their potential to foster peer learning and thereby offer new pathways to support societal transformation (Schneider et al 2019; Kok et al 2021).

The role of SSIs in advancing sustainability transformations is increasingly acknowledged across diverse sectors, from climate change adaptation and agriculture to public health and innovation policy (Fontana et al 2021; Schwarz et al 2021; Hellin et al 2022). This emphasis is also evident in conservation and protected area management, where participatory approaches to knowledge production are considered essential for addressing socioecological challenges (Durán et al 2023). A notable example is the United Nations Educational, Scientific and Cultural Organization's (UNESCO's) Man and the Biosphere (MAB) program and its global network of biosphere reserves (BRs) pioneered as model regions for sustainable development and transformation (Dabard et al 2025; Leibenath et al 2025). BRs provide a unique framework for experimenting with and institutionalizing SSIs (Reed 2016). Unlike conventional protected areas, which primarily emphasize conservation, BRs operate under a tripartite mandate: conservation of biodiversity, promotion of sustainable development, and facilitation of research and education (UNESCO 1996).

Established in the 1970s to promote global collaboration in conservation, research, and ecological monitoring, BRs have evolved alongside growing recognition of the need for more inclusive, participatory, and place-based approaches to sustainability (Price et al 2010). This shift was formalized with the adoption of the 1995 Seville Strategy that redefined BRs as learning sites for sustainability and explicitly called for the involvement of local communities in knowledge production (UNESCO 1996; Reed and Massie 2013). This trajectory continued with the MAB Strategy 2015–2025 and the 2017 Lima Action Plan (UNESCO 2017), which guide the development and functioning of BRs in the current decade, and has now been further advanced through the Hangzhou Strategic Action Plan for 2026–2035 (UNESCO 2025). These policy documents not only reaffirm the importance of SSIs, but also strengthen the emphasis on collaborative forms, explicitly calling for SSIs through meaningful collaboration among policymakers, scientists, and citizens to generate context-specific knowledge (Goodrich et al 2020; UNESCO 2025). However, it remains unclear whether and how this emphasis has been translated into practice.

Several studies have broadly explored MAB policy implementation in BRs, highlighting the importance of institutional structures, governance arrangements, and professional expertise, while also pointing to legislative misalignment, the need for multisectoral collaboration, and the role of legal frameworks in shaping accountability (Schliep and Stoll-Kleemann 2010; Elbakidze et al 2013; Klaver et al 2024). However, the implementation of MAB policy directives concerning SSIs remains underexplored. The few studies that do touch on SSIs in BRs suggest that their potential remains largely untapped, pointing to a policy implementation gap between the ambitions of the MAB program and their realization in practice (Reed 2019; Pool-Stanvliet and Coetzer 2020; Dabard et al 2024; Sandström et al 2025). In this article, we address this gap by (1) examining the extent to which the Seville Strategy and the latest UNESCO MAB policy directives on SSIs have been operationalized within mountain BRs, as well as (2) identifying the challenges associated with the implementation of these policies on the ground. Mountain BRs make up a substantial share of the global network, with the majority of the sites located in mountain areas, and since 2021 they have been formally recognized through the World Network of Mountain Biosphere Reserves as strategic hubs for international research collaboration and cross-border cooperation (UNESCO 2023; Köck et al 2025; WNMBR n.d.). Hosting many Indigenous communities with rich knowledge systems, they offer particularly fertile ground for experimenting with coproductive approaches to sustainability and advancing SSIs (Otero et al 2020; Mason et al 2022). To frame this analysis, the following section outlines how policy implementation gaps and challenges are understood in the broader governance literature. Although UNESCO's MAB framework articulates an ambitious vision for collaborative and participatory approaches to SSIs, its practical realization depends on a complex interplay of institutional capacities, political incentives, and socioeconomic contexts. Understanding these underlying dynamics provides a foundation for analyzing how MAB policy directives on SSIs are implemented within mountain BRs.

Policy implementation gaps and challenges

The policy implementation gap, understood as the divergence between policy objectives and their realization in practice, can emerge from a combination of structural and procedural shortcomings (Hudson et al 2019; Hill and Hupe 2021). These are shaped by implementation challenges arising from the institutional, political, and socioeconomic conditions that hinder or delay the effective translation of policy into action, including overly optimistic expectations, fragmented governance systems, and inadequate resource allocation (Osmani et al 2022; Ferraro and Failler 2024).

Ambition–feasibility mismatch

Policies, understood as deliberate courses of action developed and followed by actors to address specific issues (Anderson 1975; Hill and Hupe 2021), often underestimate the complexity of implementation, leading to mismatched timelines, underestimated risks, and overestimated benefits. This overoptimism frequently undermines the practicality of policies and their outcomes (Hudson et al 2019). This is

particularly evident in transformative or sustainability-related policy frameworks, which often articulate broad ambitions without providing concrete institutional measures and mechanisms for implementation and accountability (Haddad et al 2022).

Institutional fragmentation and coordination challenges

Policies formulated at national or international levels often fail to account for local contexts, resulting in inconsistencies in how they are applied at subnational levels (Sala et al 2024). Efforts to implement policies at local levels can result in unclear divisions of responsibility and fragmented coordination (Hill and Hupe 2021). This is further exacerbated when local governments or implementing organizations lack resources and capacities, such as contextual knowledge or decision-making authority, to adapt broad policies (Biesbroek 2021; Papamichail et al 2023). Such conditions exemplify a form of institutional hollowing out, where responsibilities are devolved without adequate support (Bevir 2022). Rather than following a clear top-down structure, implementation often unfolds within polycentric settings. These are characterized by multiple actors involved in decision-making that interact, cooperate, or compete with one another across scales and sectors (Thiel et al 2019). Although such settings offer potential for innovation, learning, and contextual adaptation, they also introduce complexity, ambiguity, and coordination challenges (Stephan et al 2019; Thiel et al 2019). In these settings, the distribution of responsibilities, information, and incentives is often uneven, which can result in fragmented implementation, overlaps, or gaps in responsibilities, as well as varying and competing interpretations of policy objectives.

Resource and capacity constraints

Another challenge is the lack of financial and human resources required for effective implementation (Chasek et al 2019; Lee 2024). Many policies, including those related to the Sustainable Development Goals, require substantial investment in capacity-building, training, and infrastructure (Zhan and Santos-Paulino 2021). This is particularly pronounced in low- and middle-income countries, where financial and technical support from external actors is often inadequate (Breuer et al 2023). Collaboration, or the lack thereof, also plays a critical role in policy failures. Policies often require intersectoral coordination to address cross-cutting issues effectively (Biesbroek 2021). However, traditional siloed approaches to policymaking hinder collaboration, creating redundancies, inefficiencies, and sometimes conflict (Hudson et al 2019; Scott and Gong 2021). Without a framework for continuous collaboration and communication, policies risk losing their legitimacy and face resistance during implementation (Stupak et al 2021). Furthermore, success in implementation is often contingent on local interest and the willingness of local actors to collaborate (Dupuits et al 2022; Hui and Smith 2022).

Political cycles and accountability gaps

In addition, the unpredictability and fluctuations associated with political cycles present a significant challenge. The short-term focus of political leaders often leads to a preference for quick results over long-term, sustainable outcomes (Hudson et al 2019; Allen et al 2021). Decision-makers are frequently incentivized to push policies through quickly to gain immediate recognition, neglecting the complexities of implementation. This short-sighted approach often results in poorly planned execution strategies that falter once organizational or political attention shifts to other priorities. These issues are amplified during crises, when overlapping disruptions overwhelm institutions and policy focus becomes selective and politicized, undermining coherence in implementation (Zaki et al 2024). Furthermore, the absence of robust accountability structures, such as mechanisms for monitoring, evaluation, and enforcement, undermines implementation and enables persistent inefficiencies, thereby exacerbating the policy implementation gap (Biesbroek 2021; Haddad et al 2022).

Temporal dynamics and implementation lags

Time lags represent another challenge. These lags arise from the time required to establish institutional mechanisms, build capacity, and allow actors to adapt to anticipated changes (Di Maria et al 2012). Although often unavoidable, such delays can undermine policy effectiveness by allowing gaps between the policy's goals and on-the-ground realities, potentially leading to unintended consequences as actors adjust their behaviors during the interim period (Di Maria et al 2012). Moreover, policy impacts are often distributed over time, with the effects becoming apparent only after substantial delays, further complicating coordination and decision-making (Bian et al 2021). These lags can destabilize systems, erode community trust, and undermine policy relevance.

Adaptive dimensions of policy implementation

Overall, policy implementation is not merely a matter of translating goals into action, but a socially and institutionally embedded process shaped by the interactions of diverse actors, governance structures, resources, and capacities, as well as the characteristics of the systems in question (Sager and Gofen 2022). Implementation challenges often emerge from misalignments between institutional authority and responsibility, limited access to credible or relevant information, and deeply held norms or beliefs that shape how problems are understood and addressed (Boehnke et al 2023). They can manifest at multiple stages of the implementation process, ranging from problem recognition and planning to execution and evaluation. Importantly, many implementation challenges are not fixed limits but rather contingent and malleable constraints that can be addressed through iterative learning, adaptive management, and collaboration (Moser and Ekstrom 2010; Månsson et al 2023).

Materials and methods

This study employed a qualitative, multimethod approach, applied sequentially, focusing on 2 data sources: periodic review reports and qualitative interviews with BR representatives. Periodic reviews are official self-assessments submitted by BRs to UNESCO every 10 years to evaluate how the reserves meet the goals of the MAB program. They provide data on BR activities, including research, actor involvement, projects, and the implementation of MAB strategies in general.

We first identified BRs located in mountainous regions. The World Network of Mountain Biosphere Reserves lists 474 such BRs (WNMBR n.d.). To refine this, we adopted the global mountain classification of Grêt-Regamey and Weibel (2020), which integrates elevation, climate, and major mountain range data. Using this framework, we identified 19 major mountain systems worldwide and cross-referenced them with the full BR list, narrowing our sample to 273 BRs in clearly defined mountainous areas.

Although the UNESCO MAB program promotes transparency and information sharing (UNESCO 2017), periodic reviews are for the most part not publicly available. Only 10 periodic reviews could be obtained from the individual BR websites directly. To obtain further reports, 257 of the 273 identified mountain BRs were contacted via email, with contact details obtained primarily from the UNESCO MAB website and, where necessary, from the websites of the respective BRs. Of these, 121 email addresses were inactive. The remaining BRs were contacted with 3 follow-up emails, but only 8 responses were received. In the end, we obtained periodic reviews from 18 mountain BRs in Australia (1 BR), Austria (3), Canada (2), Germany (3), Italy (1), Serbia (1), Slovenia (1), South Africa (1), Switzerland (1), the United States (2), Ukraine (1), and Zimbabwe (1). All of the reports obtained were available in English and dated from 2010 to 2022.

The periodic reviews were deductively coded in MAXQDA and analyzed using deductive qualitative content analysis (Elo and Kyngäs 2008), guided by a coding framework grounded in literature on SSIs. This approach was selected to analyze the extent to which the Seville Strategy and subsequent UNESCO MAB policy directives on SSIs have been operationalized in mountain BRs. The SSI literature provided a conceptual foundation for identifying and categorizing the forms and characteristics of SSIs, such as actor constellations, types of knowledge involved, and degrees of participation (Enengel et al 2012; Pohl et al 2017; Bergmann et al 2021; Kok et al 2021; Rogga and Zscheischler 2021; Zurba et al 2022), enabling a systematic description of how interactions between science and society are realized in practice (see Appendix S1, *Supplemental material*, https://doi.org/10.1659/mrd.2025.00037.S1). This analysis of how SSIs are enacted within the BRs provided the basis for examining the institutional and contextual factors that shape their implementation.

To contextualize the findings from the periodic reviews, we conducted semistructured interviews with representatives involved in the management and governance of the mountain BRs whose periodic reviews we had analyzed. We contacted all 18 BRs in our sample and received positive responses from 14 individuals representing 11 different BRs (Table 1). The roles of the interviewees included BR directors, scientific/research coordinators, department heads, and steering committee chairs.

An interview guideline was developed based on established literature on qualitative interviews (DiCicco-Bloom and Crabtree 2006; Kallio et al 2016), informed by the study's conceptual focus, and structured to cover core themes while allowing for open-ended exploration. We tested it in a pilot interview with a representative of a BR outside the main sample and refined it accordingly (Kallio et al 2016). Prior and informed consent was obtained from all participants in line with General Data Protection Regulation requirements, ensuring participants were informed about data use, storage, and their rights, with all interviews anonymized and securely stored. Conducted via Zoom and lasting 30–60 minutes, the interviews were recorded with consent, transcribed verbatim, and deductively coded in MAXQDA. The coding framework was derived from the policy implementation literature outlined under "Policy implementation gaps and challenges" above (Moser and Ekstrom 2010; Chasek et al 2019; Hudson et al 2019; Biesbroek 2021; Ferraro and Failler 2024), with its subsections informing the categorization of underlying factors shaping implementation of the MAB policy on SSIs. Analysis followed the same deductive qualitative content analysis approach applied to the periodic reviews (Elo and Kyngäs 2008).

TABLE 1 Overview of interviewees by geographical area.

Interviewee	Geographical area
1	Southern Africa
2	Eastern Europe
3	Eastern Europe
4	Eastern Europe
5	Eastern Europe
6	Eastern Europe
7	North America
8	North America
9	North America
10	North America
11	Western Europe
12	Western Europe
13	Western Europe
14	Western Europe

Results

The coding of the 18 periodic reviews yielded 2530 entries across 8 categories and 27 subcategories reflecting dimensions of SSIs (breakdowns by subcategory are presented in Table 2). The findings illustrate that SSIs were predominantly concerned with ecology and monitoring, with a strong focus on flora and fauna surveys and conservation activities. Ecological issues represented the majority of societal–scientific problems addressed, whereas social, economic, and governance-related challenges received comparatively little attention. Academic actors were most prominent, followed by strategic case actors, particularly politicians and public authorities, and BR representatives, whereas local nonacademic actors played only a marginal role. Scientific knowledge dominated as the main input, with smaller contributions from practitioner knowledge and other forms of local knowledge, including

TABLE 2 Overview of SSIs reported in periodic reviews of 18 mountain BRs, showing coded references across 8 categories and 27 subcategories with short descriptions of key patterns. Numbers in parentheses indicate total coded instances per subcategory. Categories reflect core SSI dimensions, based on relevant literature and established frameworks (Enengel et al 2012; Pohl et al 2017; Rogga and Zscheischler 2021; Kok et al 2021; Bergmann et al 2021; Zurba et al 2022).

Category	Subcategories (number of coded instances)	Short description
Societal–scientific problem	Ecological (337) Social (114) Economic (64) Governance (25)	Most reported SSIs addressed ecological issues, especially biodiversity monitoring, conservation, and climate impacts, often tied to directives. Social aspects centered on participation, identity, education, and cultural values, usually linked to conservation or development. Economic topics focused on tourism, ecosystem services, and regional branding, whereas governance was least reported and mainly related to management plans and regulations.
Actors	Academic (319) Strategic case (279) Local (86) BR representatives (81)	Academic actors dominated SSIs, largely through research projects. Strategic case actors (governments, nongovernmental organizations, businesses) featured mainly as regulators or supporters, whereas BR administrations mediated between research and practice. Local actors (farmers, youth, community groups) were noted in awareness and education but remained peripheral to research agendas.
Knowledge input	Scientific (57) Local, including Indigenous (38) Practitioner (19)	Scientific knowledge was most frequently reported, especially in ecological research and monitoring. Local and Indigenous knowledge appeared in relation to traditions, resource use, and cultural practices, whereas the expertise of practitioners (eg farmers, rangers, craft workers) was noted in SSIs on land management, forestry, and agriculture.
Form of research	Contract (49) Academic qualification (40) Competitive (7)	SSIs were most often conducted through contract studies tied to management or monitoring, alongside many academic theses (most frequently BSc and MSc theses). Competitive projects were rarer but connected BRs to broader sustainability and climate networks.
Intensity of interaction	Information (109) Coproduction (37) Consultation (26)	Most reported interactions were information-oriented, such as surveys, exhibitions, excursions, and awareness events. Coproduction (citizen science, workshops, joint planning) was less frequent and often experimental, whereas consultation through meetings or perception studies mainly served data collection rather than joint decision-making.
Scale	Local (116) Microlevel (83) International (72) National (50)	Most SSIs took place at the local level, including monitoring, education campaigns, surveys, and municipal partnerships. Microlevel SSIs, in parts of BRs, included habitat studies and species surveys. International projects connected BRs via networks, comparative research, and cross-border cooperation, whereas national initiatives often involved thematic studies and collaborations with universities.
Duration	Research projects (161) Short-term (160) Long-term relations (66)	Most SSIs were tied to research projects, running 2–5 years through external funding. Others were linked to short-term activities, such as contract studies, surveys, or one-off workshops, typically lasting only months to 1 year. Long-term relations were least common but included multidecade monitoring schemes and institutional partnerships with universities.
Knowledge output	Systems (93) Target (28) Transformation (14)	Most SSIs resulted in systems knowledge, including ecological baselines, monitoring data, and scientific publications for conservation and management. Some produced target knowledge, such as recommendations, action plans, awareness campaigns, and guides. Very few yielded transformation knowledge, linked to sustainability transitions, governance innovations, and capacity-building.

Indigenous. Where mentioned, local or Indigenous knowledge was treated mainly as support for ecological monitoring or conservation, rather than as an equal knowledge system. Information on the form of research was largely absent in the periodic reviews; where noted, it mainly referred to contract research and academic qualification work, with very little mention of competitive project-based research. Overall, our coding suggests that most SSIs took the form of one-way engagements. Information-sharing activities, such as data collection through surveys or semistructured interviews conducted by researchers, as well as awareness-raising events (eg school excursions), were much more frequent than knowledge coproduction or consultation. Although rare, some examples of more participatory approaches exist, such as citizen science initiatives or participatory modeling exercises, but these remain exceptions. SSIs were largely reported in the context of short-term activities, such as research projects, contract studies, or academic qualification (eg student theses), rather than as part of long-term collaborations and institutionalized relationships between actors. In terms of scale, SSIs were most often reported at the local level of the individual BRs, followed by microlevel activities within specific parts of BRs. Nevertheless, there were also national and international collaborations, such as the Swiss-Ukrainian FORZA project on sustainable forest management in the Carpathian region, which involved local practitioners and authorities, and the global HIGHLANDS.3 network coordinated by an Austrian university, which links mountain BRs to international sustainability research (Sarkki et al 2019; Universität Innsbruck n.d.). Furthermore, a consistent pattern across the reports was the absence of direct interaction between scientists and local communities: instead, scientists primarily interacted with BR representatives, whereas local communities were mostly engaged by the BRs outside of SSIs.

Insights from the interviews reinforced these findings. Most described SSIs as centered on biodiversity monitoring, often with limited community involvement (Interviews 1–3, 6, 9–11, 13). Where local actors were engaged, participation was often limited to passive roles (eg awareness-raising). Although there were some examples of more participatory approaches to SSIs, these were small-scale and time-bound, often depending on specific projects or individuals (Interviews 4, 8, 12–14). Furthermore, the interviews highlighted significant discrepancies in how the MAB program's policy directives on SSIs were implemented. Although the overarching goals related to SSIs and community involvement were acknowledged, implementation often faced substantial challenges.

Institutional arrangements and resource constraints

According to the interviewees, the perceived governance structures of BRs significantly shaped how MAB policy directives were interpreted and enacted. In some cases, the institutional setup of a BR itself constrained implementation, with direct implications for SSIs. One interviewee explained that, as an employee of a ministry governing the BR, they were required to operate strictly within the ministry's legal mandate, restricting collaboration with local actors and their inclusion in research (Interview 6). Others reported institutional voids, due to either administrative neglect or lack of capacity (Interviews 1, 9, 10). For one BR, the original board of directors dissolved over time, and no formal management body was reestablished, despite proposals and support from local organizations (Interview 1). The interviewee attributed this partly to the regional MAB office's focus on developing a new BR in the country, which sidelined revitalization efforts (Interview 1). As a result, SSI activities were left unsupported, lacking both coordination and institutional backing from the National Committee and the MAB program. In another BR, administrative fragmentation was reported as a challenge, as the reserve spanned multiple jurisdictions; coordination of research and actor engagement was complicated by overlapping mandates and differing state-level priorities (Interview 12). Furthermore, several interviewees described unclear institutional responsibilities for coordinating BR activities, which they felt weakened accountability for implementing MAB mandates and left SSI coordination largely to individual actors or organizations (Interviews 1–3, 9, 10).

Conversely, some interviewees described their BRs as being better embedded within national or regional institutional frameworks, citing factors such as legal recognition, dedicated management structures, or more stable funding. They reported more structured approaches to SSIs, including long-standing collaborations with universities, themed advisory groups, and interactive projects codesigned with local actors (Interviews 7, 8, 12–14). In one case, flexible endowment resources supported participatory initiatives, such as Indigenous-led restoration of shellfish gardens that combined water quality testing with youth programs, and a decade-long citizen-science sea-star–monitoring project that culminated in public data-sharing; the same funding also enabled twice-yearly regional science forums on Indigenous territory (Interview 7). In another case, a transdisciplinary initiative convened cross-sector advisory groups to coproduce research questions and methods on sustainable life quality and future scenarios, with the outcomes later presented in a museum exhibition where residents deliberated on these themes (Interview 14). Nevertheless, according to these interviewees, their BRs still faced issues in implementing SSIs, including difficulties in sustaining relationships beyond the scope of individual projects and challenges in engaging a wider cross section of local society. One interviewee noted that, in their BR, the citizen-science coordinator for a specific SSI initiative was project-funded; when the term ended, associated volunteer engagement and outputs lost institutional support, highlighting difficulties in sustaining involvement and dissemination beyond the project period (Interview 12).

Across nearly all sites, the lack of stable financial and human resources to conduct SSIs emerged as a major challenge. As one interviewee noted: "It's a bit difficult to get funding for these activities [SSIs], to be honest . . . maybe UNESCO has an idea for that, for financing the research activities that they wish to have in our programs" (Interview 11). The challenge of obtaining funding for research activities is exacerbated by short-term funding cycles and competitive research funding streams (Interviews 1, 4–6, 9–11). A concrete example from one BR involves a 3-year knowledge-transfer initiative aimed at improving practitioner uptake through workshops, interviews, a dedicated website, and practice briefs; despite positive interim outputs, the initiative was discontinued when the grant ended, illustrating the fragility of SSI projects built around fixed-term funding (Interview 13). Furthermore, respondents noted that despite formal

commitments to SSIs, implementation was constrained by limited staff capacity, the need to prioritize other operational demands, and the absence of dedicated roles to coordinate actor engagement. As one interviewee put it: "It's a lot easier to care or to involve the people if you have 1 person that is actually responsible for that" (Interview 12). Moreover, SSIs often depended on existing university links, which were frequently reliant on personal networks (Interviews 2, 3, 9, 10, 13). Several interviewees underscored that SSIs, especially those involving knowledge coproduction (eg transdisciplinary projects), require long-term investments in staff, training, facilitation, and relationship-building, resources that are often unavailable (Interviews 6, 8, 11–14). As one interviewee noted, "In a 10-year period, you can maybe make 2, maximum 2, TD [transdisciplinary] projects, true TD projects" (Interview 14), highlighting how resource- and time-intensive such efforts are.

Although mentioned in only a few cases, interviewees also pointed to challenges specific to mountain regions. The remoteness and high costs of accessing some of the sites made research logistically demanding and often transient, discouraging long-term engagement and complicating efforts to involve local actors (Interview 6). One interviewee mentioned that their BR sought to counter this by providing logistic support such as field cabins, equipment, and volunteer coordination to enable research in mountainous areas (Interview 7).

Engagement with MAB policy

Several interviewees described engagement with MAB policies, including those on SSIs, as largely symbolic or procedural, focused on fulfilling reporting requirements (Interviews 4, 6, 8, 9, 12). Rather than serving as practical tools for management, the Seville Strategy and Lima Action Plan were frequently viewed as abstract and ambitious guiding frameworks with limited relevance to day-to-day decision-making. Respondents emphasized that locally developed strategies, more attuned to regional needs and actor priorities, were often prioritized over MAB directives. In some cases, MAB policy engagement was instead framed within broader agendas, such as the Sustainable Development Goals, to align with national priorities and facilitate tapping of funding opportunities (Interviews 2, 3, 8, 11). Underlying these dynamics was a recurring sense that global MAB policies were disconnected from local realities and offered little concrete support for advancing SSIs on the ground: "You've got a massive Western Europe–centered global bureaucracy that you're supposed to be connected to, and there are obviously lots of tensions there. In some cases, things seem, at best, just like a kind of a funny disconnect, and at worst, like blatantly at odds" (Interview 7).

However, other interviewees stressed that the generality of these frameworks can be enabling, because UNESCO guidelines are considered "not that strict," leaving room for interpretation and allowing SSI priorities to be negotiated with regional actors (Interview 13). Directives were understood as broad cues, from which the BR selectively drew elements most relevant to local realities (Interview 12). A further account described the BR designation as an "open-sky laboratory," where SSIs could be advanced through coproduced place-based solutions, with broader agendas serving as loose guides rather than strict templates (Interview 8).

Community trust and legitimacy

Some BRs, as well as the MAB directives, have at times been met with skepticism or resistance, being perceived as "top-down" international frameworks (Interviews 1, 4–7, 12, 13). As one respondent explained: "It was also seen as a threat. We already have [name of the national park] and then all the private organizations which are working in the region, and no one wants this extra layer of management. So, it wasn't very well received" (Interview 1). The results show that BR representatives perceived local communities as at times viewing MAB initiatives and associated activities with caution, questioning their legitimacy, relevance, or added value. In some cases, this resistance reflected a deeper concern about jurisdiction and autonomy; as one example illustrates, a First Nation refused to have a part of their territory included in a BR, rejecting what they described as "another non-Indigenous, not-from-here designation" (Interview 7). Several interviewees pointed out that overcoming these challenges requires more than policy alignment; it demands trust, time, and sustained relationship-building (Interviews 4, 5, 7, 8, 14).

Discussion and conclusions

The findings of this study strongly resonate with insights from the policy implementation literature, which emphasize the complex, nonlinear, and contingent nature of translating policy ambitions into practice (Hudson et al 2019; Osmani et al 2022; Ferraro and Failler 2024). In the context of the UNESCO MAB program's vision for SSIs in mountain BRs, the results underscore the persistence of a policy implementation gap. Although MAB policy directives promote participatory knowledge production and engagement with local actors, in practice, SSIs remain predominantly unidirectional and oriented toward expert-driven data collection, with limited local-actor involvement. This pattern is not unique to our sample. A recent synthesis of BR research found that of 3304 publications since 1975, only 336 explicitly adopted transdisciplinary approaches, with participation mostly consultative rather than coproductive (Dabard et al 2024).

A key challenge is the mismatch between policy ambition and practical feasibility (Hudson et al 2019). Most BR representatives saw MAB directives as abstract, overly ambitious, and lacking operational value. This highlights how policies are often designed with overly optimistic assumptions about implementation, underestimating institutional complexity and local constraints (Hudson et al 2019; Haddad et al 2022). The generic, top-down nature of global MAB policies does not always reflect the localized social and institutional realities within which BRs operate, contributing to implementation inconsistencies (Hill and Hupe 2021; Sala et al 2024). This echoes broader critiques of international sustainability policies becoming decoupled from local governance processes and instead functioning as administrative obligations with limited transformative effect (Biesbroek 2021; Haddad et al 2022).

Resource and capacity constraints were among the most frequently cited challenges by BR representatives, aligning closely with findings in the literature (Chasek et al 2019; Lee 2024). Despite widespread recognition of the value of SSIs, especially more collaborative forms, many BRs lack the

stable financial and human resources required for their implementation. Interviewees emphasized the difficulty of securing long-term funding as well as the shortage of trained personnel to facilitate SSIs. These findings suggest that shifting responsibilities to local actors without adequate support, whether in terms of capacity, expertise, or coordination, can undermine implementation and lead to institutional hollowing out (Bevir 2022). In mountain regions, these resource limitations can be further compounded by remoteness and high logistic costs, which discourage sustained engagement and complicate efforts to involve local actors.

Capacity issues were often compounded by fragmented and weak institutional arrangements. As the analysis illustrates, BR management structures vary considerably, ranging from voluntary initiatives led by nongovernmental organizations to public agencies embedded in government hierarchies. Polycentric governance settings frequently led to overlapping mandates, ambiguous accountability, and coordination challenges, resulting in ad hoc implementation practices and limited engagement with MAB policies (Hudson et al 2019; Thiel et al 2019; Biesbroek 2021). In some contexts, even basic administrative infrastructure to support SSIs was absent, leaving BR managers to navigate conflicting institutional priorities with little guidance or support. Moreover, reliance on short-term projects, rather than institutionalized structures, makes implementation fragile and person-dependent (Allen et al 2021; Papamichail et al 2023).

Institutional setup and support also varied across regions. Mountain BRs in Western Europe stood out as comparatively better resourced and more likely to have dedicated research or scientific coordination roles, facilitating more consistent and structured forms of SSIs. Interviewees from this region described long-standing collaborations with universities and efforts to coproduce projects with local actors. Although challenges persist, their institutional foundations generally support more consistent engagement and structured implementation practices (Zhan and Santos-Paulino 2021). In contrast, BRs in Eastern Europe were less well-resourced and often lacked dedicated staff or clear mandates, resulting in limited capacity to implement participatory research. MAB policies, in these cases, were often treated as aspirational rather than actionable, with BR managers lacking the authority or support to operationalize them effectively. Similar challenges were also observed in a North American BR and the Southern African BR from the sample, both of which reported institutional neglect and the absence of stable mechanisms for coordination. Hence, implementation outcomes are shaped not only by the clarity of international policy frameworks, but also by their alignment with domestic legal and administrative systems (Sager and Gofen 2022; Månsson et al 2023).

Time lags were another challenge to implementing MAB directives on SSIs. Although BR representatives expressed support for participatory approaches, they emphasized that building trust, capacity, and collaborative relationships takes time, often exceeding the scope of project funding or political cycles. These challenges are compounded by a reliance on specific individuals to drive more participatory forms of SSIs, making initiatives vulnerable to staff turnover and shifting priorities. More fundamentally, the findings point to a structural time lag in the institutional adaptation of BRs. Many appear to still be in the slow process of transitioning from their original, pre-Seville strategy role, focused primarily on conservation and ecological monitoring, toward the expanded MAB vision of BRs as model regions for knowledge coproduction and sustainability transformations. Delays in adaptation and the slow emergence of policy impacts can erode trust and credibility, reducing the perceived relevance and transformative potential of MAB SSI directives (Di Maria et al 2012; Bian et al 2021).

Last, questions of legitimacy also hindered implementation. Several BR representatives noted that local communities and institutional actors were skeptical of the MAB framework, viewing it as a top-down imposition disconnected from regional needs. This illustrates that implementation is not only a technical or administrative matter but also hinges on the cultural and political resonance of policies. Local interest, ownership, and willingness to collaborate are key determinants of successful policy implementation (Dupuits et al 2022; Hui and Smith 2022). Building trust requires more than consultation or participation; it necessitates sustained, reciprocal relationships and shared decision-making. Without these, even well-designed policies may fail to gain traction or may be selectively adopted in ways that diverge from their original intent.

Despite these challenges, the results also highlight considerable potential. Some mountain BRs reported SSI initiatives that were interactive and participatory, ranging from Indigenous-led research and citizen-science monitoring to transdisciplinary projects that engaged diverse local actors and institutions. These examples demonstrate that, when conditions such as stable funding, trust, and supportive governance are in place, BRs can foster sustained forms of coproduction. Importantly, several representatives also noted that the generality of MAB directives can be enabling, as it provides orientation and legitimacy while leaving flexibility to adapt SSI principles to local realities and priorities.

For the MAB program to realize its vision of BRs as model regions for sustainability transformation in mountain regions and beyond, a shift is needed from prescriptive policy frameworks toward more enabling, context-sensitive approaches to SSIs. This includes strengthening institutional capacity at the local level, coproducing policy directives with implementers and communities, and investing in long-term forms of engagement that foster trust, continuity, and accountability. Embedding dedicated SSI coordination roles, expanding capacity-building initiatives in participatory methods and knowledge coproduction, and facilitating peer learning across BRs can support more consistent implementation and help address regional disparities. At the same time, advancing BRs as effective knowledge–action networks requires more durable support for coordinated infrastructure of collaboration and data exchange, as current efforts have been constrained by fragmented research infrastructure and an emphasis on site designation over sustained scientific networking (Barraclough et al 2023). Monitoring mechanisms also require rethinking. The

10-year periodic reviews, although central to MAB governance, tend to encourage procedural compliance more than meaningful reflection (Ferreira et al 2018), thus offering limited insight into the evolving dimensions of SSIs. More flexible, regular tools that capture the nature of collaboration, continuity of engagement, and diversity of knowledge systems would be better suited to support adaptive learning. In this vein, some BRs and networks are piloting complementary self-assessments and peer learning between periodic review cycles (Matar and Anthony 2022).

Mountain BRs are particularly well positioned to lead advancements in SSIs, given their exposure to pressing socioecological challenges and their long-standing traditions of place-based knowledge and stewardship (Otero et al 2020; Mason et al 2022; Wyss et al 2022). Their embeddedness in culturally diverse and ecologically sensitive, yet threatened, landscapes offers unique opportunities to pilot participatory approaches that should be both innovative and grounded. Furthermore, the relatively new World Network of Mountain Biosphere Reserves offers a platform to scale out such efforts by providing a knowledge platform and facilitating experimentation, thoughtful policy transfer, research support, and (peer) learning across mountainous BRs globally (UNESCO 2023; Köck et al 2025; WNMBR n.d.). Taken together, these features position mountain BRs as key arenas for testing and refining participatory SSI approaches, generating insights that can inform sustainability transformations beyond mountain regions.

A critical prerequisite, however, is stable funding. BRs require resources for both short- and long-term research to effectively engage in SSIs and to act as knowledge brokers. Research funding frameworks need to acknowledge this role, ensuring that BRs are recognized and supported as full partners in research programs, with adequate resources for SSI facilitation and transdisciplinary collaborations. At present, UNESCO MAB strategies and policies can appear somewhat detached from the realities on the ground. Without more concrete support for BRs, it may be more realistic to adjust high-level policies and expectations to better align with BR practices and constraints they face in their daily work. Otherwise, policy aspirations and everyday realities in BRs risk drifting further apart, making UNESCO goals increasingly sophisticated but elusive. This disconnect might be a call for a stronger representation of BRs and local-level perspectives in high-level policy, alongside meaningful cross-scale interaction and feedback. If this gap continues to grow, UNESCO MAB policies may become more sophisticated on paper but even less relevant in practice, resulting in vague implementation and monitoring outcomes and, ultimately, a weakening of the role of BRs themselves, as they become detached from the umbrella policy framework.

Finally, although this study offers indicative insights into the implementation of UNESCO MAB directives on SSIs in mountain BRs, it draws on periodic review reports from 18 BRs and interviews with representatives from 11 of them, a small share of the global network. Given the predominance of European and North American BRs in the sample, the findings should be interpreted as illustrative of broader tendencies in these regions rather than representative of all BRs worldwide. Moreover, periodic reviews, though standardized and longitudinal, are difficult to obtain and vary considerably in depth and quality. Strengthening validity and better capturing lived experiences requires follow-up studies that combine data from periodic reviews and BR manager perspectives with interviews involving local communities, Indigenous knowledge holders, and practitioners.

ACKNOWLEDGMENTS

We thank the representatives of the participating mountain biosphere reserves for their time and valuable insights during the interviews. The research project "Biosphere Reserves as Models for Science-Society Interaction to Spur Sustainability Transformations in Mountainous Areas and Beyond" (BIOSS), which led to this paper, is funded by the Austrian Academy of Sciences (ÖAW) through the Earth System Sciences (ESS) research program, grant number ESS22-11-BIOSS. We also gratefully acknowledge the Transitions to Sustainability (T2S) Doctoral School at BOKU University for supporting this research.

REFERENCES

Adler C, Wester P, Bhatt I, Huggel C, Insarov GE, Morecroft MD, Muccione V, Prakash A. 2022. Cross-chapter paper'5: Mountains. *In*: Pörtner H-O, 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, and New York, NY: Cambridge University Press, pp 2273–2318. https://doi.org/10.1017/9781009325844.022.

Allen C, Metternicht G, Wiedmann T, Pedercini M. 2021. Modelling national transformations to achieve the SDGs within planetary boundaries in small island developing states. *Global Sustainability* 4:e15. https://doi.org/10.1017/sus.2021.13.

Anderson JE. 1975. *Public Policy-Making*. Praeger University Series Vol 805. London, United Kingdom: Praeger.

Aquerreta R, Vivien L, Adler CE, Cárdenas MR, Chávez E, Price MF. 2022. *Harnessing the Socio-Ecological Potential of Mountain Biosphere Reserves for Biodiversity Conservation: Policy Brief*. Paris, France: UNESCO [United Nations Educational, Scientific and Cultural Organization]. https://doi.org/10.48350/178535.

Barraclough AD, Reed MG, Coetzer K, Price MF, Schultz L, Moreira-Muñoz A, Måren I. 2023. Global knowledge–action networks at the frontlines of sustainability: Insights from five decades of science for action in UNESCO's World Network of biosphere reserves. *People and Nature* 5(5):1430–1444. https://doi.org/10.1002/pan3.10515.

Barth M, Jiménez-Aceituno A, Lam DP, Bürgener L, Lang DJ. 2023. Transdisciplinary learning as a key leverage for sustainability transformations. *Current Opinion in Environmental Sustainability* 64:101361. https://doi.org/10.1016/j.cosust.2023.101361.

Bennett NJ, Blythe J, Cisneros-Montemayor AM, Singh GG, Sumaila UR. 2019. Just transformations to sustainability. *Sustainability* 11:3881. https://doi.org/10.3390/su11143881.

Bergmann M, Schäpke N, Marg O, Stelzer F, Lang DJ, Bossert M, Gantert M, Häußler E, Marquardt E, Piontek FM, Potthast T. 2021. Transdisciplinary sustainability research in real-world labs: Success factors and methods for change. *Sustainability Science* 16:541–564. https://doi.org/10.1007/s11625-020-00886-8.

Bevir M. 2022. What is the decentered state? *Public Policy and Administration* 37(1):3–21. https://doi.org/10.1177/0952076720904993.

Bian Z, Zuo F, Gao J, Chen Y, Venkata SSCP, Bernardes SD, Ozbay K, Ban X, Wang J. 2021. Time lag effects of COVID-19 policies on transportation systems: A comparative study of New York City and Seattle. *Transportation Research Part A: Policy and Practice* 145:269–283. https://doi.org/10.1016/j.tra.2021.01.019.

Biesbroek R. 2021. Policy integration and climate change adaptation. *Current Opinion in Environmental Sustainability* 52:75–81. https://doi.org/10.1016/j.cosust.2021.07.003.

Boehnke D, Jehling M, Vogt J. 2023. What hinders climate adaptation? Approaching barriers in municipal land use planning through participant observation. *Land Use Policy* 132:106786. https://doi.org/10.1016/j.landusepol.2023.106786.

Breuer A, Leininger J, Malerba D, Tosun J. 2023. Integrated policymaking: Institutional designs for implementing the sustainable development goals (SDGs). *World Development* 170:106317. https://doi.org/10.1016/j.worlddev.2023.106317.

Chand R, Leimgruber W. 2016. Introduction: Globalization and marginalization in mountain regions. *In:* Chand R, Leimgruber W, editors. *Globalization and Marginalization in Mountain Regions. Perspectives on Geographical Marginality*, Vol 1. Cham, Switzerland: Springer, pp 1–15. https://doi.org/10.1007/978-3-319-32649-8_1.

Chasek P, Akhtar-Schuster M, Orr BJ, Luise A, Ratsimba HR, Safriel U. 2019. Land degradation neutrality: The science–policy interface from the UNCCD to

national implementation. *Environmental Science & Policy* 92:182–190. https://doi.org/10.1016/j.envsci.2018.11.017.

Dabard CH, Gohr C, Weiss F, von Wehrden H, Neumann F, Hordasevych S, Arieta B, Hammerich J, Meier C, Jargow J, et al. 2024. Biosphere reserves as model regions for transdisciplinarity? A literature review. *Sustainability Science* 19:2065–2081. https://doi.org/10.1007/s11625-024-01542-1.

Dabard CH, Mann C, Martín-López B. 2025. Biosphere reserves as catalysts for sustainability transformations: Five strategies to support place-based innovation. *Current Opinion in Environmental Sustainability* 73:101508. https://doi.org/10.1016/j.cosust.2025.101508.

DiCicco-Bloom B, Crabtree BF. 2006. The qualitative research interview. *Medical Education* 40(4):314–321. https://doi.org/10.1111/j.1365-2929.2006.02418.x.

Di Maria C, Smulders S, Van der Werf E. 2012. Absolute abundance and relative scarcity: Environmental policy with implementation lags. *Ecological Economics* 74:104–119. https://doi.org/10.1016/j.ecolecon.2011.12.003.

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. https://doi.org/10.1659/MRD-JOURNAL-D-21-00040.1.

Durán AP, Kuiper JJ, Aguiar APD, Cheung WW, Diaw MC, Halouani G, Hashimoto S, Gasalla MA, Peterson GD, Schoolenberg MA, Abbasov R. 2023. Bringing the nature futures framework to life: Creating a set of illustrative narratives of nature futures. *Sustainability Science* 1–20. https://doi.org/10.1007/s11625-023-01316-1.

Elbakidze M, Hahn T, Mauerhofer V, Angelstam P, Axelsson R. 2013. Legal framework for biosphere reserves as learning sites for sustainable development: A comparative analysis of Ukraine and Sweden. *Ambio* 42:174–187. https://doi.org/10.1007/s13280-012-0373-3.

Elo S, Kyngäs H. 2008. The qualitative content analysis process. *Journal of Advanced Nursing* 62(1):107–115. https://doi.org/10.1111/j.1365-2648.2007.04569.x.

Enengel B, Muhar A, Penker M, Freyer B, Drlik S, Ritter F. 2012. Co-production of knowledge in transdisciplinary doctoral theses on landscape development: An analysis of actor roles and knowledge types in different research phases. *Landscape and Urban Planning* 105(1–2):106–117. https://doi.org/10.1016/j.landurbplan.2011.12.004.

Ferraro G, Failler P. 2024. Understanding the "implementation gap" to improve biodiversity governance: An interdisciplinary literature review. *Journal of Sustainability Research* 6(2):e240009. DOI: https://doi.org/10.20900/jsr20240009.

Ferreira AF, Zimmermann H, Santos R, von Wehrden H. 2018. A social–ecological systems framework as a tool for understanding the effectiveness of biosphere reserve management. *Sustainability* 10(10):3608. https://doi.org/10.3390/su10103608.

Folke C, Polasky S, Rockström J, Galaz V, Westley F, Lamont M, Scheffer M, Österblom H, Carpenter SR, Chapin FS III, et al. 2021. Our future in the Anthropocene biosphere. *Ambio* 50:834–869. https://doi.org/10.1007/s13280-021-01544-8.

Fontana L, Fasano A, Chong YS, Vineis P, Willett WC. 2021. Transdisciplinary research and clinical priorities for better health. *PLoS Medicine* 18(7):e1003699. https://doi.org/10.1371/journal.pmed.1003699.

Goodrich KA, Sjostrom KD, Vaughan C, Nichols L, Bednarek A, Lemos MC. 2020. Who are boundary spanners and how can we support them in making knowledge more actionable in sustainability fields? *Current Opinion in Environmental Sustainability* 42:45–51. https://doi.org/10.1016/j.cosust.2020.01.001.

Grêt-Regamey A, Weibel B. 2020. Global assessment of mountain ecosystem services using earth observation data. *Ecosystem Services* 46:101213. https://doi.org/10.1016/j.ecoser.2020.101213.

Gupta H, Nishi M, Gasparatos A. 2022. Community-based responses for tackling environmental and socio-economic change and impacts in mountain social–ecological systems. *Ambio* 51:1123–1142. https://doi.org/10.1007/s13280-021-01651-6.

Haddad CR, Nakić V, Bergek A, Hellsmark H. 2022. Transformative innovation policy: A systematic review. *Environmental Innovation and Societal Transitions* 43:14–40. https://doi.org/10.1016/j.eist.2022.03.002.

Hellin J, Amarnath G, Challinor A, Fisher E, Girvetz E, Guo Z, Hodur J, Loboguerrero AM, Pacillo G, Rose S, Schutz T, Valencia L, You L. 2022. Transformative adaptation and implications for transdisciplinary climate change research. *Environmental Research: Climate* 1(2):023001. https://doi.org/10.1088/2752-5295/ac8b9d.

Hill M, Hupe P. 2021. *Implementing Public Policy: An Introduction to the Study of Operational Governance*. 4th edition (1st edition 2002). London, United Kingdom: Sage Publications.

Horcea-Milcu AI, Dorresteijn I, Leventon J, Stojanovic M, Lam DP, Lang DJ, Moriggi A, Raymond CM, Stålhammar S, Weiser A, Zimmermann S. 2024. Transformative research for sustainability: Characteristics, tensions, and moving forward. *Global Sustainability* 7:e14. https://doi.org/10.1017/sus.2024.12.

Hudson B, Hunter D, Peckham S. 2019. Policy failure and the policy-implementation gap: Can policy support programs help? *Policy Design and Practice* 2(1):1–14. https://doi.org/10.1080/25741292.2018.1540378.

Hui I, Smith G. 2022. Private citizens, stakeholder groups, or governments? Perceived legitimacy and participation in water collaborative governance. *Policy Studies Journal* 50(1):241–265. https://doi.org/10.1111/psj.12453.

IPCC [Intergovernmental Panel on Climate Change]. 2022. *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, and New York, NY: Cambridge University Press, pp 3–37. https://doi.org/10.1017/9781009325844.

Kallio H, Pietilä AM, Johnson M, Kangasniemi M. 2016. Systematic methodological review: Developing a framework for a qualitative semi-structured interview guide. *Journal of Advanced Nursing* 72(12):2954–2965. https://doi.org/10.1111/jan.13031.

Klaver M, Currie B, Sekonya JG, Coetzer K. 2024. Exploring the implementation of UNESCO's MAB program in South Africa: A case study of the Cape Winelands Biosphere Reserve. *Environmental Management* 74(6):1207–1222. https://doi.org/10.1007/s00267-024-02048-3.

Knott E, Rao AH, Summers K, Teeger C. 2022. Interviews in the social sciences. *Nature Reviews Methods Primers* 2(1):73. https://doi.org/10.1038/s43586-022-00150-6.

Köck G, Aquerreta R, Castro N, Sánchez-Cruzado J, Weihua X. 2025. The evolution of the World Network of Mountain Biosphere Reserves (WNMBR): Bridging science and practice for sustainable mountain management. *Journal on Protected Mountain Areas Research and Management* 17:19–24. https://doi.org/10.1553/eco.mont-17-2s19.

Kok KPW, Gjefsen MD, Regeer BJ, Broerse JE. 2021. Unraveling the politics of 'doing inclusion' in transdisciplinarity for sustainable transformation. *Sustainability Science* 16:1811–1826. https://doi.org/10.1007/s11625-021-01033-7.

Lang DJ, Wiek A, Bergmann M, Stauffacher M, Martens P, Moll P, Swilling M, Thomas CJ. 2012. Transdisciplinary research in sustainability science: Practice, principles, and challenges. *Sustainability Science* 7:25–43. https://doi.org/10.1007/s11625-011-0149-x.

Lawrence M, Homer-Dixon T, Janzwood S, Rockström J, Renn O, Donges JF. 2024. Global polycrisis: The causal mechanisms of crisis entanglement. *Global Sustainability* 7:e6. https://doi.org/10.1017/sus.2024.1.

Lee H. 2024. Strategic types, implementation, and capabilities: Sustainability policies of local governments. *Public Administration* 102(1):264–284. https://doi.org/10.1111/padm.12917.

Leibenath M, Diemunsch N, Pregizer M, Bergsträßer JC. 2025. Biosphere reserves as landscape laboratories for sustainability transitions. *Landscape Research* 50(3):491–504. https://doi.org/10.1080/01426397.2024.2421336.

Månsson J, Eriksson L, Hodgson I, Elmberg J, Bunnefeld N, Hessel R, Johansson M, Liljebäck N, Nilsson L, Olsson C, Pärt T. 2023. Understanding and overcoming obstacles in adaptive management. *Trends in Ecology & Evolution* 38(1):55–71. https://doi.org/10.1016/j.tree.2022.08.009.

Mason CW, Carr A, Vandermale E, Snow B, Philipp L. 2022. Rethinking the role of Indigenous knowledge in sustainable mountain development and protected area management in Canada and Aotearoa/New Zealand. *Mountain Research and Development* 42(4):A1–A9. https://doi.org/10.1659/mrd.2022.00016.

Matar DA, Anthony BP. 2022. BREMi—A new tool for the evaluation of UNESCO Biosphere Reserve management effectiveness: Case-study in the Arab Man and Biosphere (ArabMAB) regional network. *Environmental Management* 70:730–745. https://doi.org/10.1007/s00267-022-01711-x.

Mitrofanenko A, Thaler T, Radinger-Peer V, Fiala V, Penker M, Gugerell K. 2025. Understanding science-society interactions (SSI): Diverse viewpoints from mountain biosphere reserves. *Journal of Integrative Environmental Sciences* 22(1):2537242. https://doi.org/10.1080/1943815X.2025.2537242.

Moser SC, Ekstrom JA. 2010. A framework to diagnose barriers to climate change adaptation. *Proceedings of the National Academy of Sciences* 107(51):22026–22031. https://doi.org/10.1073/pnas.1007887107.

Osmani M, Kolaj R, Borisov P, Arabska E. 2022. Why agricultural policies fail and two cases of policy failures in Albania. *Agricultural and Resource Economics: International Scientific e-Journal* 8(2):86–104. http://doi.org/10.22004/ag.econ.322722.

Otero I, Darbellay F, Reynard E, Hetényi G, Perga ME, Rüegg J, de Bellefroid B. 2020. Designing inter- and transdisciplinary research on mountains: What place for the unexpected? *Mountain Research and Development* 40(4):D10. https://doi.org/10.1659/MRD-JOURNAL-D-20-00036.1.

Papamichail G, Rosiello A, Wield D. 2023. Addressing public policy implementation challenges in lagging regions through the analytical lens of smart specialisation. *Journal of the Knowledge Economy* 14(1):356–381. https://doi.org/10.1007/s13132-021-00874-y.

Pohl C, Truffer B, Hirsch Hadorn G. 2017. Addressing wicked problems through transdisciplinary research. *In:* Frodeman R, Klein JT, Pacheco R, editors. *The Oxford Handbook of Interdisciplinarity*. 2nd edition (1st edition 2010). Oxford, United Kingdon: Oxford Academic, pp 319–331. https://doi.org/10.1093/oxfordhb/9780198733522.013.26.

Pool-Stanvliet R, Coetzer K. 2020. The scientific value of UNESCO biosphere reserves. *South African Journal of Science* 116(1–2):1–4. https://doi.org/10.17159/sajs.2020/7432.

Price MF, Park JJ, Bouamrane M. 2010. Reporting progress on internationally designated sites: The periodic review of biosphere reserves. *Environmental Science & Policy* 13(6):549–557. https://doi.org/10.1016/j.envsci.2010.06.005.

Reed MG. 2016. Conservation (in) action: renewing the relevance of UNESCO biosphere reserves. *Conservation Letters* 9(6):448–456. https://doi.org/10.1111/conl.12275.

Reed MG. 2019. The contributions of UNESCO Man and Biosphere Programme and biosphere reserves to the practice of sustainability science. *Sustainability Science* 14:809–821. https://doi.org/10.1007/s11625-018-0603-0.
Reed MG, Massie MM. 2013. Embracing ecological learning and social learning: UNESCO biosphere reserves as exemplars of changing conservation practices. *Conservation and Society* 11(4):391–405. https://doi.org/10.4103/0972-4923.125755.
Rogga S, Zscheischler J. 2021. Opportunities, balancing acts, and challenges: Doing PhDs in transdisciplinary research projects. *Environmental Science & Policy* 120:138–144. https://doi.org/10.1016/j.envsci.2021.03.009.
Sager F, Gofen A. 2022. The polity of implementation: Organizational and institutional arrangements in policy implementation. *Governance* 35(2):347–364. https://doi.org/10.1111/gove.12677.
Sala S, Lostrangio MC, Zampatti M, De Luca G, Landoni M, Giorgi A. 2024. What governance for sustainable development in the mountains? Insights from the alpine region. *Mountain Research and Development* 44(3):A1–A10. https://doi.org/10.1659/mrd.2023.00042.
Sandström C, Mancheva I, Laudon H. 2025. Unlocking the potential of biosphere reserves: A review of structural, institutional, and ideational challenges to transformational learning. *Current Opinion in Environmental Sustainability* 75:101543. https://doi.org/10.1016/j.cosust.2025.101543.
Sarkki S, Parpan T, Melnykovych M, Zahvoyska L, Derbal J, Voloshyna N, Nijnik M. 2019. Beyond participation! Social innovations facilitating movement from authoritative state to participatory forest governance in Ukraine. *Landscape Ecology* 34:1601–1618. https://doi.org/10.1007/s10980-019-00787-x.
Schliep R, Stoll-Kleemann S. 2010. Assessing governance of biosphere reserves in Central Europe. *Land Use Policy* 27(3):917–927. https://doi.org/10.1016/j.landusepol.2009.12.005.
Schneider F, Giger M, Harari N, Moser S, Oberlack C, Providoli I, Schmid L, Tribaldos T, Zimmermann A. 2019. Transdisciplinary co-production of knowledge and sustainability transformations: Three generic mechanisms of impact generation. *Environmental Science & Policy* 102:26–35. https://doi.org/10.1016/j.envsci.2019.08.017.
Schneider F, Tribaldos T, Adler C, Biggs RO, de Bremond A, Buser T, Krug C, Loutre MF, Moore S, Norström AV, Paulavets K. 2021. Co-production of knowledge and sustainability transformations: A strategic compass for global research networks. *Current Opinion in Environmental Sustainability* 49:127–142. https://doi.org/10.1016/j.cosust.2021.04.007.
Schwarz G, Vanni F, Miller D. 2021. The role of transdisciplinary research in the transformation of food systems. *Agricultural and Food Economics* 9(1):35. https://doi.org/10.1186/s40100-021-00207-2.
Scott I, Gong T. 2021. Coordinating government silos: Challenges and opportunities. *Global Public Policy and Governance* 1(1):20–38. https://doi.org/10.1007/s43508-021-00004-z.
Steger C, Klein JA, Reid RS, Lavorel S, Tucker C, Hopping KA, Marchant R, Teel T, Cuni-Sanchez A, Dorji T, et al. 2021. Science with society: Evidence-based guidance for best practices in environmental transdisciplinary work. *Global Environmental Change* 68:102240. https://doi.org/10.1016/j.gloenvcha.2021.102240.
Steiger R, Knowles N, Pöll K, Rutty M. 2024. Impacts of climate change on mountain tourism: A review. *Journal of Sustainable Tourism* 32(9):1984–2017. https://doi.org/10.1080/09669582.2022.2112204.
Stephan M, Marshall G, McGinnis M. 2019. An introduction to polycentricity and governance. *In:* Thiel A, Blomquist WA, Garrick DE, editors. *Governing Complexity: Analyzing and Applying Polycentricity*. Cambridge, United Kingdom: Cambridge University Press, pp 21–44. DOI: https://doi.org/10.1017/9781108325721.003.
Stupak I, Mansoor M, Smith CT. 2021. Conceptual framework for increasing legitimacy and trust of sustainability governance. *Energy, Sustainability and Society* 11:1–57. https://doi.org/10.1186/s13705-021-00280-x.
Thiel A, Blomquist WA, Garrick DE, editors. 2019. *Governing Complexity: Analyzing and Applying Polycentricity*. Cambridge, United Kingdom: Cambridge University Press. https://doi.org/10.1017/9781108325721.
Tripathi S, Bhadouria R, Garkoti SC. 2024. Warming mountains: Challenges and opportunities. *In:* Tripathi S, Bhadouria R, Garkoti SC, editors. *Warming Mountains*. Cham, Switzerland: Springer, pp 1–15. https://doi.org/10.1007/978-3-031-62197-0_1.
UNESCO [United Nations Educational, Scientific and Cultural Organization]. 1996. *Biosphere Reserves: The Seville Strategy and the Statutory Framework of the World Network*. Paris, France: UNESCO. https://unesdoc.unesco.org/ark:/48223/pf0000103849; accessed on 22 May 2025.
UNESCO [United Nations Educational, Scientific and Cultural Organization]. 2017. *New Roadmap for the Man and the Biosphere (MAB) Programme and Its World Network of Biosphere Reserves*. Paris, France: UNESCO. https://unesdoc.unesco.org/ark:/48223/pf0000247418; accessed on 22 May 2025.
UNESCO [United Nations Educational, Scientific and Cultural Organization]. 2023. *Mountain Biosphere Reserves in a New Era for Resilient Socio-Ecological Systems*. Paris, France: UNESCO. https://www.unesco.org/en/articles/mountain-biosphere-reserves-new-era-resilient-socio-ecological-systems, accessed on 16 September 2025.
UNESCO [United Nations Educational, Scientific and Cultural Organization]. 2025. *Hangzhou MAB Strategic Action Plan for UNESCO's Man and the Biosphere (MAB) Programme and Its World Network of Biosphere Reserves (2026–2035).* Paris, France: UNESCO. https://www.biosphere2025.org.cn/HANGZHOU%20STRATEGIC%20ACTION%20PLAN-UK.pdf; accessed on 17 October 2025.
Universität Innsbruck. n.d. *HIGHLANDS.3: Collective Approach of Research and Innovation for Sustainable Development in Highland*. Innsbruck, Austria: Universität Innsbruck. https://www.uibk.ac.at/en/geography/projects/highlands3/; accessed on 16 September 2025.
Vogel C, O'Brien K. 2022. Getting to the heart of transformation. *Sustainability Science* 17:653–659. https://doi.org/10.1007/s11625-021-01016-8.
Voulvoulis N, Giakoumis T, Hunt C, Kioupi V, Petrou N, Souliotis I, Vaghela CJGE. 2022. Systems thinking as a paradigm shift for sustainability transformation. *Global Environmental Change* 75:102544. https://doi.org/10.1016/j.gloenvcha.2022.102544.
WNMBR [World Network of Mountain Biosphere Reserves]. n.d. *Mountain Biosphere Reserves*. Madrid, Spain: UNESCO Chair on Sustainable Mountain Development, Technical University of Madrid. https://www.mountainbiosphere.org/en/; accessed on 20 May 2025.
Wyss R, Luthe T, Pedoth L, Schneiderbauer S, Adler C, Apple M, Acosta EE, Fitzpatrick H, Haider J, Ikizer G, Imperiale AJ. 2022. Mountain resilience: A systematic literature review and paths to the future. *Mountain Research and Development* 42(2):A23–A36. https://doi.org/10.1659/MRD-JOURNAL-D-21-00044.1.
Zaki B, Pattyn V, Wayenberg E. 2024. Policy learning from evidence during polycrises: A case of EU environmental policy. *Policy Design and Practice* 7(4):390–408. https://doi.org/10.1080/25741292.2024.2344822.
Zhan JX, Santos-Paulino AU. 2021. Investing in the sustainable development goals: Mobilization, channeling, and impact. *Journal of International Business Policy* 4(1):166. https://doi.org/10.1057/s42214-020-00093-3.
Zurba M, Petriello MA, Madge C, McCarney P, Bishop B, McBeth S, Denniston M, Bodwitch H, Bailey M. 2022. Learning from knowledge co-production research and practice in the twenty-first century: Global lessons and what they mean for collaborative research in Nunatsiavut. *Sustainability Science* 17(2):449–467. https://doi.org/10.1007/s11625-021-00996-x.

Supplemental material

APPENDIX S1 Overview of categories reflecting different dimensions of SSIs, including background and sources used in the coding of the periodic reviews.

Found at: https://doi.org/10.1659/mrd.2025.00037.S1