Bridging Science and Policy: A Global Review of Socio-ecological Indicators Guiding Biodiversity Action

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ABSTRACT

1. Biodiversity continues to decline despite a proliferation of indicators intended to inform conservation policy. We asked which socio-ecological indicators are actually reaching decision-makers, how they are used, and where critical gaps persist.
2. Following a scoping-review protocol and PRISMA workflow, we screened 906 documents in Web of Science and Scopus and analyzed 43 studies that explicitly linked indicators, biodiversity targets and policy processes.
3. Most indicators (54%) rely on landscape-level data, primarily using land-cover proxies as biodiversity surrogates. Ecosystem-level scale dominates over population-species studies, while genetic studies were not identified. Remote sensing (n=23) and economic variables (n=25) were frequently integrated, though evidence for their comparative policy uptake remains limited. The Millennium Ecosystem Assessment dominates as the most conceptual framework used (n=18 of 43 studies), whereas Post-2020 Global Biodiversity (n=1 of 43 studies) remains largely confined to theoretical discourse rather than practical application. Local scales predominated (53% of studies), with subnational applications adding another 23%, creating potential mismatches with national biodiversity targets. Local Communities' participation was more evident in the Global South, making up 21.2%, emphasizing community-driven engagement. In the Global North, participation mainly involved academics and civil servants as experts (15.7%), reflecting a more formal, technical approach.
4. We conclude that accelerating the uptake of socio-ecological indicators requires: (i) improved long-term socio-ecological time series and monitoring systems to address widespread data limitations; (ii) expanding beyond land-cover proxies to span scales from

genetic to ecosystem-based metrics; (iii) developing multi-scale integration approaches that bridge local applications with national biodiversity targets; and (iv) institutionalizing stakeholder engagement in indicator development, particularly incorporating local and Indigenous knowledge systems. To enable the next step—from documenting indicator availability to assessing the effectiveness of decision-making processes—future syntheses should also systematically capture the conditions of use (decision arena, institutional mandates, accountability, capacity, and incentives), the depth and timing of participation across the indicator cycle, and transparent effectiveness criteria (e.g., salience, credibility, legitimacy, and equity) that allow influence on real decisions and downstream outcomes to be traced rather than inferred. Closing these gaps would shift indicators from predominantly academic exercises toward actionable policy instruments that genuinely inform biodiversity decisions.

RESUMEN

1. La biodiversidad sigue disminuyendo a pesar de la proliferación de indicadores destinados a informar las políticas de conservación. Nos preguntamos qué indicadores socioecológicos llegan realmente a los responsables de la toma de decisiones, cómo se utilizan y dónde persisten los vacíos críticos.

2. Siguiendo el protocolo de revisión sistemática y el flujo de trabajo PRISMA, examinamos 906 documentos en Web of Science y Scopus y analizamos 43 estudios que vinculaban explícitamente los indicadores, los objetivos de biodiversidad y los procesos políticos.

3. La mayoría de los indicadores (54 %) se basan en datos a nivel de paisaje, utilizando principalmente proxies de cobertura del suelo como sustitutos de la biodiversidad. La escala a nivel de ecosistema predomina sobre los estudios de poblaciones/especies, mientras que

no se identificaron estudios genéticos. La teledetección (n = 23) y las variables económicas (n = 25) se integraron con frecuencia, aunque las pruebas de su adopción comparativa en las políticas siguen siendo limitadas. La Evaluación de los Ecosistemas del Milenio predomina como el marco conceptual más utilizado (n=18 de 43 estudios), mientras que la Marco Global de Biodiversidad Post-2020 (n=1 de 43 estudios) sigue limitándose en gran medida al discurso teórico, en lugar de a la aplicación práctica. Las escalas locales predominaron (53 % de los estudios), con aplicaciones subnacionales que suman otro 23%, lo que crea posibles desajustes con los objetivos nacionales de biodiversidad. La participación de las comunidades locales fue más evidente en el Sur Global, con un 21,2 %, lo que pone de relieve el compromiso impulsado por la comunidad. En el Norte Global, la participación estuvo principalmente compuesta por académicos y funcionarios públicos como expertos (15,7 %), lo que refleja un enfoque más formal y técnico.

4. Concluimos que para acelerar la adopción de indicadores socioecológicos es necesario: (i) mejorar las series temporales socioecológicas a largo plazo y los sistemas de seguimiento para hacer frente a las limitaciones generalizadas de los datos; (ii) ir más allá de los indicadores sustitutivos de la cobertura del suelo para abarcar escalas que vayan desde métricas genéticas hasta métricas basadas en los ecosistemas; (iii) desarrollar enfoques de integración multiescala que conecten las aplicaciones locales con los objetivos nacionales de biodiversidad; y (iv) institucionalizar la participación de las partes interesadas en el desarrollo de indicadores, incorporando en particular los sistemas de conocimiento locales e indígenas. Para dar el siguiente paso, que consiste en pasar de documentar la disponibilidad de los indicadores a evaluar la eficacia de los procesos de toma de decisiones, las síntesis futuras también deberían recoger sistemáticamente las condiciones

de uso (ámbito de decisión, mandatos institucionales, rendición de cuentas, capacidad e incentivos), la profundidad y el momento de la participación a lo largo del ciclo de los indicadores, y criterios de eficacia transparentes (por ejemplo, relevancia, credibilidad, legitimidad y equidad) que permitan rastrear, en lugar de inferir, la influencia en las decisiones reales y los resultados posteriores. Cerrar estos vacíos permitiría que los indicadores pasaran de ser ejercicios predominantemente académicos a convertirse en instrumentos políticos viables que realmente sirvan de base para las decisiones sobre biodiversidad.

KEYWORDS: conservation, co-production, global biodiversity framework, governance, multi-scale, sustainability, policy-making.

1. INTRODUCTION

The rapid decline of biodiversity, as one of the broader planetary crises, highlights the growing threat to the planet's capacity to sustain life-support systems. Despite decades of consensus and international political efforts, biodiversity continues to decline(Burgass et al., 2021a). Current species extinction rates are estimated to be 10 to 100 times higher than natural background levels, indicating a profound global loss of biodiversity (De Vos et al., 2015). At the same time, global trends have shown an average reduction of about 70% in vertebrate populations (WWF, 2024). International agreements such as the Kunming–Montreal Global Biodiversity Framework (GBF; CBD/COP/DEC/15/4, CBD/COP/DEC/15/5) aim at creating pressure and legal pathways, thereby strengthening obligations to halt biodiversity loss (Ekardt et al., 2023). However, significant implementation gaps remain, and questions about the effectiveness of these agreements persist.

Biodiversity governance refers to the institutions, structures, and processes that determine how and by whom decisions affecting biodiversity are made (Schwerdtner Máñez et al., 2025; N. J. Bennett & Satterfield, 2018). Traditionally, governments have played the central role in conservation decision-making, even as new actors and mechanisms become increasingly significant. In this environment, governments at different levels participate in a wide range of decision-making activities, from international negotiations to national policies and local community projects (Young, 2002). Their participation also impacts the definition and use of policy instruments, which are structured activities aimed at achieving long-term environmental goals (Schwerdtner Máñez et al., 2025).

Assessing the impact of policies and progress toward international, national, and local actions depends on having key resources: representative tools that reflect the current status and trends (Jetz et al., 2019). Indicators have emerged as a structured framework to serve this purpose. They guide data collection and analysis, ensuring measurements are reliable, reproducible, and accurate, while also providing vital information that supports various levels of action—whether international, national, or regional (Canedoli et al., 2024). The concept of using indicators to measure sustainability has gained significant popularity, as numerous governments, NGOs, and academic groups invest considerable resources into developing and testing these indicators (Bell & Morse, 2008). An example of that is the global indicators of change, such as the suite of GEO-BON-endorsed biodiversity indicators (Pereira et al., 2015), realm-specific indicators, like the marine biodiversity indicators (Teixeira et al., 2016) or specific indicators that represent the Well-being among Indigenous Peoples (IWIP) (Cruz et al., 2020). The challenge is to identify which indicators are effective in achieving the goals at multiple scales.

An increasing body of research also emphasizes that maintaining biodiversity depends on ecological knowledge that integrates insights from the social sciences and humanities. (Díaz et al., 2018). These disciplines offer valuable perspectives through social analysis tools and theories that help reveal how human values, institutions, and behaviours influence conservation outcomes. (Pascual et al., 2021; Mace, 2014). Recent scholarship also highlights the need to incorporate principles of social justice within conservation planning (Montgomery et al., 2024). Additionally, consider that understanding the world is much broader than the typical perspectives found in the global North, Western, and Eurocentric contexts (Santos, 2016). This involves recognizing approaches developed in other countries, such as those considered part of the Global South (Ocampo-Ariza et al., 2023), as well as acknowledging the central role of local communities and Indigenous knowledge in enhancing legitimacy, ownership, and long-term success (McAllister et al., 2025). This integration is essential for promoting inclusive decision-making and creating policies that effectively balance environmental sustainability with human well-being. (Cumming, 2023).

The Social-ecological systems (SES) frameworks provide a valuable insight for tackling these challenges. This is an emerging concept that originated in the 1990s and began to describe the interconnectedness of human and natural systems (Mace, 2014; Reyers & Bennett, 2025). A search in the Web of Science using 'social-ecological' words from 1990 to 2025 shows that the vast majority of publications (around 97%) appeared in the last two decades, reflecting a sharp increase in research interest over this period. Social-ecological systems research is now a recognized interdisciplinary field within this perspective, revealing that decision-making and governance must incorporate both ecological knowledge and social dynamics in sustainability science (Biggs et al., 2021). It also underscores the need for multi-level governance systems that can operate coherently across scales (Reyers & Bennett, 2025). Next steps lie in integrating all these complex structures with diverse social and ecological processes (Bell & Morse, 2008).

While previous studies have explored biodiversity governance and socio-ecological systems, there remains a limited understanding of how socio-ecological knowledge is integrated into decision-making, especially through the application of indicators to assess progress and inform policy (Cruz et al., 2020; Stephanson & Mascia, 2014). By doing so, we ask the following questions: 1) What socio-ecological indicators have been developed to support biodiversity-related decision-making, and what evidence exists on their practical effectiveness?, 2) Which dimensions of biodiversity (genes, population/species, communities, ecosystems, landascape) and policy targets do these indicators address, and what evaluation approaches are most commonly applied?, 3) Are participatory approaches used differently across regions (Global South–Global North) and actor types in the cases where indicators were applied? and d) What methodological, governance or data gaps constrain the operational use of socio-ecological indicators, and what priorities emerge to close the science–policy implementation gap? This study does not aim to evaluate the effectiveness of decision-making processes in socioecological research. Instead, it focuses on understanding the conditions under which the socioecological approach integrates decision-making. and also allows for the identification of biases and gaps in terms of space-time, variables, conceptual frameworks, among others. We seek to understand how scientific efforts have attempted to bridge the gap between research findings and real-world decision-making.

We anticipate a dominant focus on ecosystem-level attributes—such as land-usce-land-cover integrity, connectivity, and resilience—while genetic metrics will remain markedly under-represented, surfacing in fewer than one in ten studies. Evaluation methods are expected to be predominantly descriptive or comparative *ex-post*, with contrafactual or quasi-experimental designs constituting a clear minority. Indicators will most often be reported as applied during the diagnostic and monitoring phases at local to sub-national scales, whereas their application in option appraisal or implementation, particularly at national or transboundary levels, will appear only sporadically.

2. METHODS

Scope of review

We performed a scoping review to evaluate the existing literature on socio-ecological systems, indicators and biodiversity goals. To structure the query, we analyzed the frequency of the words used in the indicators proposed in the Kunming–Montreal Global Biodiversity Framework (KMGBF; CBD/COP/DEC/15/5) and we identified 61 key terms (Supporting Information Fig S1). For the selection, we constructed a cloud word by merging full words and eliminating punctuation, along with semantically related words such as prepositions, conjunctions, adverbs, and pronouns. For example, Goal A of the GBF, in the headline indicator A, target two, one of the component indicators is called *Maintenance and restoration of connectivity of natural ecosystems*. Then, we used “maintenance”, “restoration”, “connectivity”, “natural”, and “ecosystem” as possible keywords. We also examined the most common stem of each word, removing the ending letters—for example, “fishing” and “fisheries” have the same base but different terminations (Supporting Information Table S1).

The group of words was organized into three categories: biological or ecological processes, social dynamics, and types of measurement. Additionally, the query evaluation included the terms decision-making and indicators because they are vital to answering our questions. The articles were found on the Web of Science and Scopus platforms by searching for the words in the Title and Abstract fields. Finally, to increase the specificity of the literature obtained, the search queries were improved by removing keywords related to health sciences (e.g. "clinical trial", "therapy", "disease") and specific environmental areas (e.g. "urban air quality", "renewable energy"). The queries used are provided in Supporting Information Text S1. To ensure transparency, this systematic scoping review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021). The systematic review was conducted using the Covidence software package (www.covidence.org), which efficiently screens and extracts information for development reviews and facilitates tracking. The PRISMA reporting workflow is shown in Supporting Information Figure S2.

Scoping criteria

We screen papers in two stages. *First*, we reviewed the abstracts and exclude (i) those that focus solely on biological or ecological topics, such as species or interactions, (ii) papers related to other fields not relevant to the objectives of these papers, such as health, engineering, or education, and (iii) opinion, conference or theoretical papers. After the *second phase*, we reviewed the whole paper and exclude articles that (i) did not include indicators or didn't refer to policy/policymakers in the methods, (ii) did not employ a social or biological or ecological approach in their methods, and (iii) were written in a language other than English or Spanish.

Extraction of information

We define 22 categories that are associated with each of the four questions. Additionally, we have defined each possible option for each category. For example, in the geographical scale category, the options were local, subnational, national, regional, or global. Similarly, for the management implications category, the options were whether the study refers to best practices to improve economic activity or if it offers environmental policy and governance. All the categories defined can be consulted in Table 1. For more details regarding the options for each category, see the Supplementary Data S1.

Table 1. Categories were evaluated to answer the question in the reviewed papers, as well as the explanation. To check all evaluated options and the full definition for each category, see Supporting Data S1.

Question	Categories	Explanation
	Framework Used	Framework used to explain or to categorize the relationship between the socioecological system (e.g. Pst-2020 Global Biodiversity or DPSIR Framework)
	Indicator used	Category of the indicator. It could be more than one (e.g. economic, social, biological/ ecological)
	Result level	Effect of the indicator(s) used (e.g. output or impact)
	Management implications	Summarize what the results mean in terms of actions (e.g. best practices to improve the economic activity or environmental policy and governance)
Q1	outcomes or outputs to support decision making	The scope of the study includes scenario development, policy support, monitoring over time, and decision-making relevance.
Q2	Geographical Scale	Politico administrative boundaries defined. (e.g. local, subnational, regional or global)

	Hierarchical biodiversity	Biological unit used in the study (e.g. genes, population or communities) (adapted from (Noss, 1990))
	Habitat type	General type of habitat described in the study (e.g. Freshwater, marine, or forest)
	Revealed Preferences	Empirical variables obtained to answer the goals of the papers (e.g. Ecological surveys, remote sensing or economic model)
	Stated preferences	information obtained from individuals through systems (e.g. interviews, participatory mapping or focus group)
	Country	Country where the study was developed
	Participant types	Type of contributors who participated in the study (e.g. Local people, academic or civil servants)
Q3	Role	Role of the participants in the study. It must be explicit in the methods (e.g. stakeholder or experts)
	Limitations in the study	Limitations described by the authors in the study (e.g. data availability or conceptual issues)
Q4	Challenges or suggestions for the future	challenges or suggestions offers by the authors (e.g. applicability, more empirical research or others)

The data and figures were processed using R software (R Development Core Team, 2022). The *tidyverse* package (Wickham, n.d.) was used for data handling, while *ggplot2* (Wickham, 2016) facilitated graph visualization, with multi-panel layouts assembled with *patchwork* (Pedersen, 2024) version 1.2.0. To ensure clarity and accessibility, colour schemes were chosen from *scico* (Pedersen & Crameri, 2025) in the version v1.5.0.9 and *viridis* (Garnier et al., 2023) in the version v0.6.4. Alluvial and Sankey diagrams were created using *easyalluvial* (Koneswarakantha, 2023), version v0.3.2 and *ggsankey* (Sjoberg, 2025), version v0.0.9. Finally, for spatial data and mapping, we employed *geodata* (Hijmans et al., 2023) using the version v0.5-9 and *tmap* (Tennekes, 2018).

3. RESULTS AND DISCUSSION

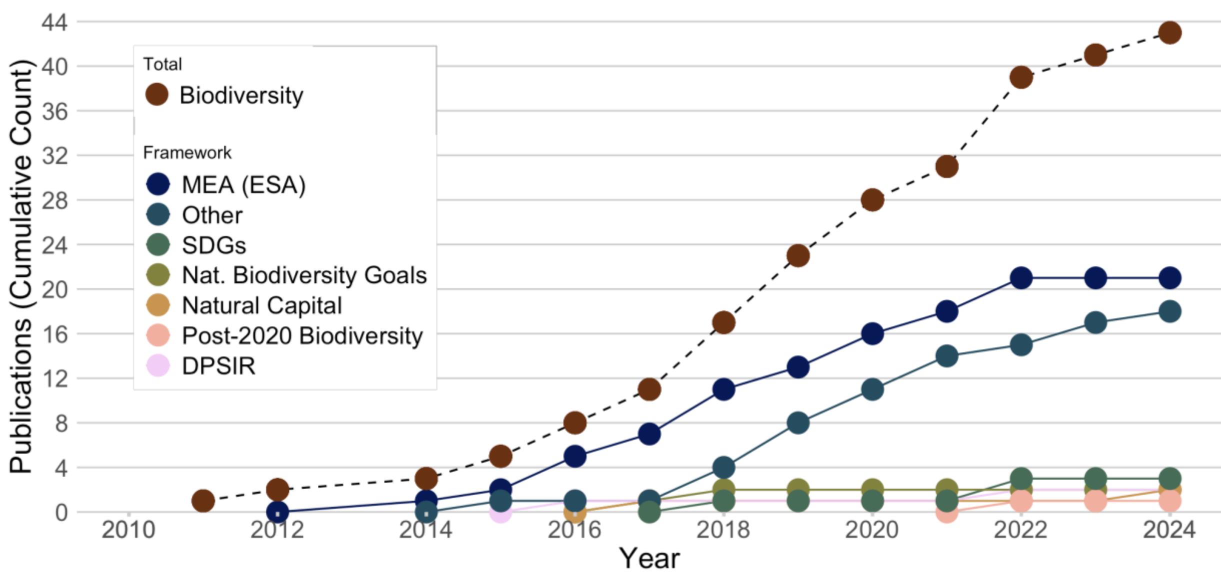
A total of 906 references were imported and screened based on their titles and abstracts (Supporting Information Figure S2). Three duplicates were identified manually, and 226 were identified by the Covidence tool. After the abstract review, 165 studies were included and 512 were excluded. In this phase, all included studies were related to the environment and decision-making. Finally, in the full-text review of the paper, we selected 43 papers.

3.1. Co-designed indicators show higher policy uptake.

What socio-ecological indicators have been developed to support biodiversity-related decision-making, and what evidence exists on their practical effectiveness?

Socio-ecological indicators have become central tools for supporting biodiversity-related decision-making. Since the 1980s, frameworks have sought to integrate environmental, economic, and social dimensions into management and policy processes (Stokstad, 2020). The most common framework we identified has been the Millennium Ecosystem Assessment (Fig.

1, *Top*, Dark Cyan Blue, n = 18) (MEA, 2003). Surprisingly, other methods, such as Natural Capital, Driver-Pressure-State-Impact-Response (DPSIR) Framework, and the Sustainable Development Goals, have not been widely consolidated in research focused on decision-making (less than 4; see Fig. 1). Instead, it is often the case that alternative methodologies have been proposed to support decision-making in socioecological processes through indicators (Fig. 1 *Top*, "Others" category shown in Dark Cyan Blue, n = 18). Despite their wide application and an increasing number of studies demonstrating their potential usability, global environmental conditions continue to decline (Winkler et al., 2021). This ongoing challenge raises important questions about how effectively these indicators translate into concrete actions that improve biodiversity outcomes and inform sustainable management.



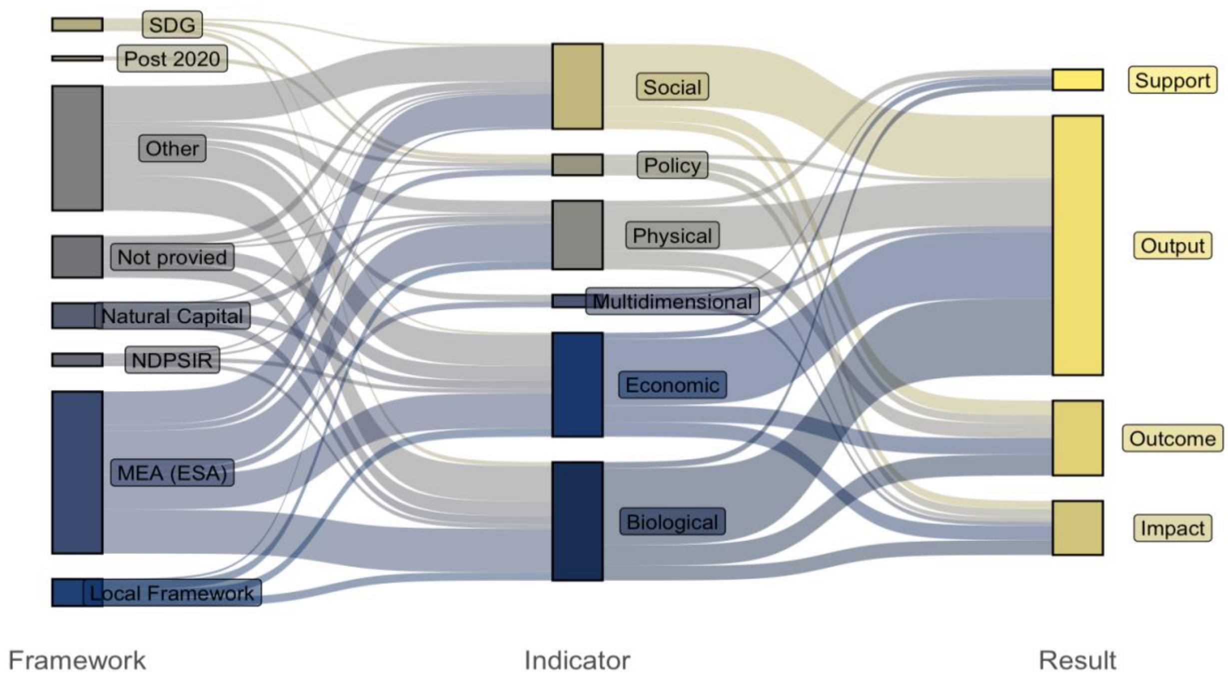


Figure 1, *Top*. The frameworks used in the research are evaluated. The most prevalent framework was the MEA, followed by various approaches for analyzing socioecological systems. The remaining frameworks have been used less frequently, despite being proposed before 2018, except for the Post-2020 Biodiversity framework. Dashed lines indicate the total cumulative number of papers. *Down*: Connections among the defined conceptual model, the indicators used, and the types of results obtained. The colours on the right help identify connections with the middle column, while the colours in the middle categories are organized to aid in recognizing these connections with the results.

The adoption of the framework to construct specific indicators across different socio-ecological categories reflects the growing interest in aligning different fields with the global frameworks (Burgass et al., 2021b). Biological information was the most common base indicator used to construct the results (n=36), followed by economic indicators. (n=32) as the input (Fig 1, down). In turn, we found that the use of multidimensional indicators, which uniquely integrate all categories into a single measure, was less common (five of the studies, Fig 1, down). Although proposed during a specific period, the policy indicators emerged as a novel category that can be related to different frameworks.

Across the six socio-ecological indicator categories (Fig 1, down), the most common results generated by them are the development of tools, workflows, or approaches to understand socio-ecological processes (n=32; Fig. 1). These studies primarily reflect academic interests in developing theories and creating new methodologies for studying the subject. These results are essential, offering a picture of biodiversity, which helps to establish the state of the system (Conroy et al., 1997). Additionally, historical information based on economic and social records, and stakeholder insights were essential for understanding changes and future solutions (Bornmann, 2013).

A second level is characterized by research that generates "socially robust" knowledge, evaluated well beyond the initial user stage (Bornmann, 2013). In the last decade, policymakers have increasingly focused on the societal impacts of research, including its contributions to the economy, society, culture, public administration, health, environment, and quality of life, and not only on knowledge (Fecher & Hebing, 2021). At this secondary user level, our findings indicate that researchers who approach evaluation in this manner are less common (Fig 1, down; n = 9 for outcomes and n = 8 for impact). This type of study is becoming important for understanding the best way to make decisions because it offers us the opportunity to comprehend what happens beyond the outputs generated by researchers. In contrast, the least common result involves support efforts related to support programs that track the state of systems over time (Fig. 1, down; n=2). This pattern aligns with previous critiques that highlight the necessity to guide the use of indicators to capture ecological and social effectiveness, rather than proposing procedural progress limits their capacity to reflect real conservation impact (Beher et al., 2024).

Our review shows that the type of management implications reflected by indicators often determines their potential impact on decision-making. Ecological and economic management implications were the most common outcomes reported per indicator, whereas social aspects appeared less frequently (Table 2). Although indicators are widely incorporated into public policy documents—particularly through future change scenarios, which were recurrent at regional and national levels (n = 28.3%; Table 2)—they seldom lead to direct actions or strategies aimed at improving local economic or environmental conditions. Being explicitly action-oriented, for instance, in evaluating environmental risks or improving resource management practices, was relatively uncommon. The most frequent outcomes supporting decision-making involved the development or approval of policy documents, mostly at regional and national scales (Table 2). In these cases, land or vegetation cover was the most common proxy for biodiversity, applied across multiple ecosystems.

Table 2. Outlines of the management implications, outcomes, and outputs that support decision-making in the reviewed studies.

Category	Options	n	%
Management implications	Ecological management	22	22.9
	Environmental policy and governance	22	22.9
	Economic improvement	21	21.9
	Water / soil management	15	15.6
	Environmental risk assessment	9	9.4

	Climate Change Vulnerability and Adaptation	3	3.1
	Other	3	3.1
	Not provided	1	1
Outcomes or outputs to support decision-making	Future change scenarios	15	28.3
	Public policy to improve activities	15	28.3
	Results from time-monitored characteristics	11	20.8
	Other	9	17
	Not provided	3	5.7

These findings indicate that, although indicators generate useful information for decision-making, their influence on real-world management remains limited (Díaz et al., 2020). A key reason is the insufficient integration of perspectives from the political, economic, and social sciences (Leadley et al., 2022). Research in these disciplines offers alternative ways of understanding how knowledge supports decision-making, highlighting the roles of institutions, governance, and power dynamics (Leadley et al., 2022). However, such perspectives are not yet fully reflected in biodiversity indicators or in the processes that guide their use and development (Butchart et al., 2010). The economy remains the most common social dimension included. At the same time, approaches that integrate policy or governance aspects are still scarce (Fig. 1 down). Drawing more extensively on insights and tools from the social sciences and humanities could enhance the legitimacy, relevance, and effectiveness of these indicators (Liu et al., 2023; Díaz et al., 2018).

While they provide valuable ecological and economic information, they often fail to capture the complexity of human–nature interactions that shape management outcomes (Holden et al., 2024). Strengthening the interdisciplinary foundations of indicator frameworks, fostering participatory approaches, and aligning indicators more closely with governance contexts could help ensure that they not only describe environmental conditions but also promote transformative and sustainable actions (Krebs et al., 2025).

3.2. Socioecological studies underrepresent the dimension of biodiversity

Which dimensions of biodiversity (genes, population/species, communities, ecosystems, landscape) and policy targets do these indicators address, and what evaluation approaches are most commonly applied?

3.2.1. Indicators, Scales, and Evaluation Approaches in Socioecological Systems

Building on these patterns, the choice of indicators and the scale of analysis are tightly linked to data availability and decision contexts. Much socioecological and decision-oriented research is conducted at local scales (n = 23; Fig. 2a–b), where fine-scale ecological variables and rates can be measured (Schneider, 2001) and community-level economic information (e.g., small-scale fishers, local farmer surveys) is most informative (Basurto et al., 2025; Agardy, 2000). At the same time, many socioeconomic and development datasets exist only at regional or national resolutions, producing scale mismatches with ecological processes and governance boundaries (Diogo & Koomen, 2016; Scholes et al., 2013). Because decision-making problems typically require analysis of causality and trade-offs, studies should therefore combine local measurements with coarser socioeconomic data and explicitly reconcile scales (Butchart et al., 2010).

In most studies, the most common approach is to operate at the landscape level, using the Land Use and Land Cover (LULC) as a proxy for biodiversity (54% of reviewed studies; Fig. 2a). This is because LULC provides spatially consistent data that links social and ecological aspects across various scales (Diogo & Koomen, 2016). However, this proxy predominance is mainly terrestrial: in marine and freshwater systems, population and community level metrics are used more frequently (Fig. 2b–c). In these habitats, it is not always possible to use LULC, so using ecosystem or watershed boundaries shows that it is possible to adapt the scales based on the systems studied (Teixeira et al., 2016).

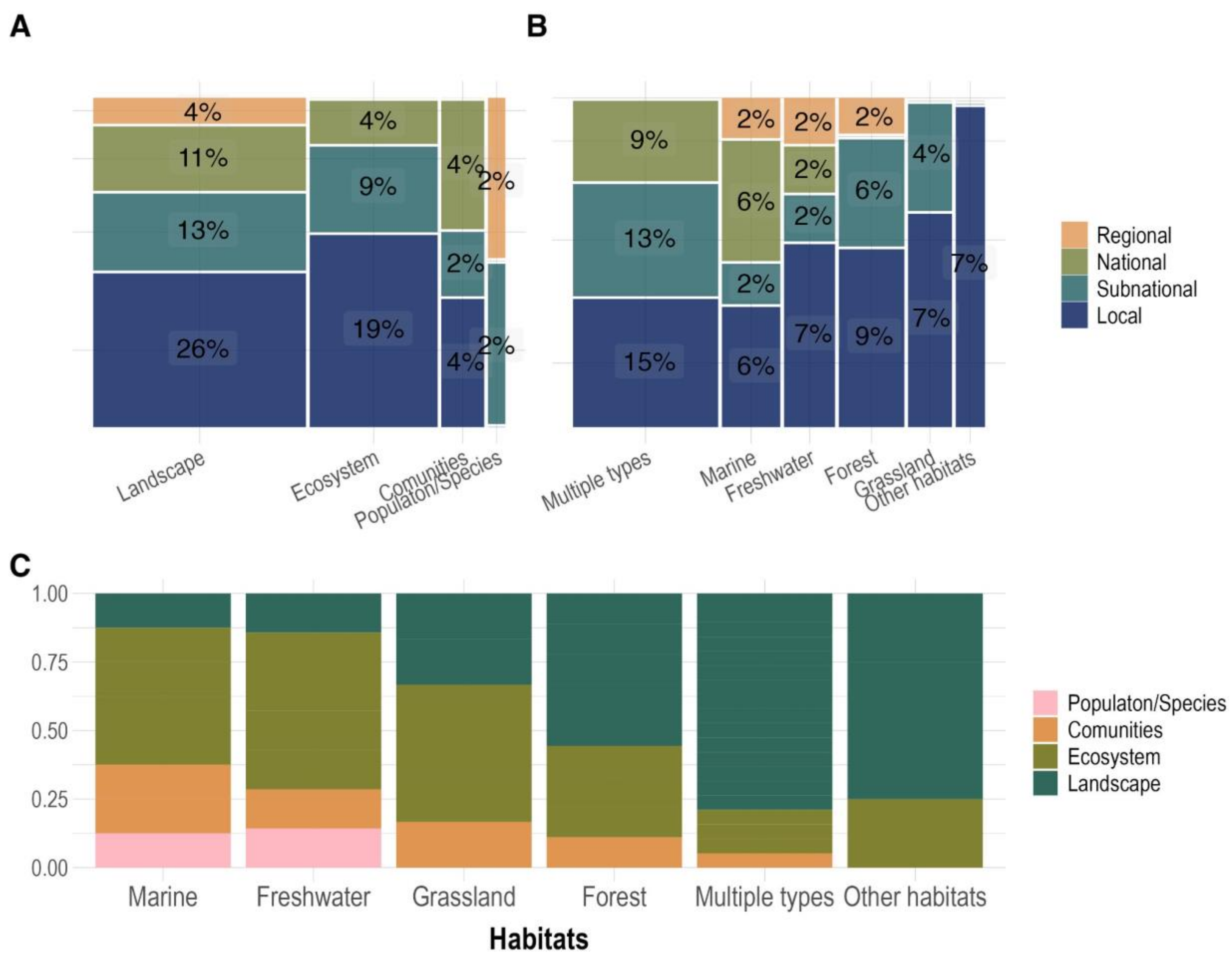


Figure 2. The relationship between the ecological (a) and habitat (b) scale, contrasted at the geographical scale. The size of the box represents the number of papers related to the valued categories. Freshwater and marine systems primarily advocate for biodiversity boundaries to define the group of interest (c). Instead, in land ecosystems, the use of landscape was more predominant. The genetic category was not identified in the analyzed studies.

Socioecological studies also often neglect genetic approaches. In our study, we did not find research that integrates genetic perspectives within a socioecological framework and decision-making. Genetic assessments are essential for international conservation initiatives, such as the Convention on Biological Diversity, and they help governments and managers monitor conservation progress while also prioritizing species and populations for preservation and recovery of their genetic diversity (Pereira et al., 2013). One of the main challenges is that direct DNA-based assessments are resource-intensive and not feasible at scale for many species. For that reason, new indicators such as the "Proportion of populations (or range) maintained" and the "Proportion of populations with Ne < 500" have emerged as practical solutions (Sean et al., 2024). These indicators provide a roadmap for implementation, making the contribution not just theoretical but also applicable in real-world conservation contexts.

Accordingly, evaluation approaches in the reviewed literature range from spatial correlation and modelling using LULC to more robust quasi-experimental designs that better support causal inference (for example Before-After-Control-Impact, difference-in-differences, and matching approaches) (De Palma et al., 2018). These stronger designs are especially useful where policies or interventions need impact evaluation, but they depend on adequate baseline or counterfactual data (Christie et al., 2020). Finally, stakeholder ownership across scales is essential for credible assessments and for translating indicators into action (Cruz et al., 2020). Even when adequate data exist, political and social barriers can hinder implementation (Krebs et al., 2025). This raises the practical question: do we act on imperfect data, or restrict conclusions to what our data can robustly support?

3.2.2. Empirical and Participatory Tools for Socioecological Decision Support

In economics, the terms "stated preferences" and "revealed preferences" are used to describe two ways of understanding people's choices (Shang & Chandra, 2023). *Stated preferences* refer to the information people give directly, such as their opinions, values, or feelings. This type of data is often collected through interviews, surveys, or participatory activities. *Revealed preferences*, on the other hand, refer to behaviour that can be observed or measured. These are based on real actions and are obtained through direct observation or empirical methods. In this review, we use *stated preferences* to group the tools that collect people's perceptions and *revealed preferences* to group those that gather measurable, real-world data.

Among revealed preference tools, the most common data sources were the economic and environmental variables used to describe how resources, goods, or services are produced and shared (n = 26; Fig. 3a). Remote sensing was the second most common method (n = 24). It was widely used as a flexible tool that combines social and ecological information through the analysis of land use and cover (Diogo & Koomen, 2016). Policy data were less frequent (n = 4) and usually appeared in models that included institutions or laws that shape how decisions are made.

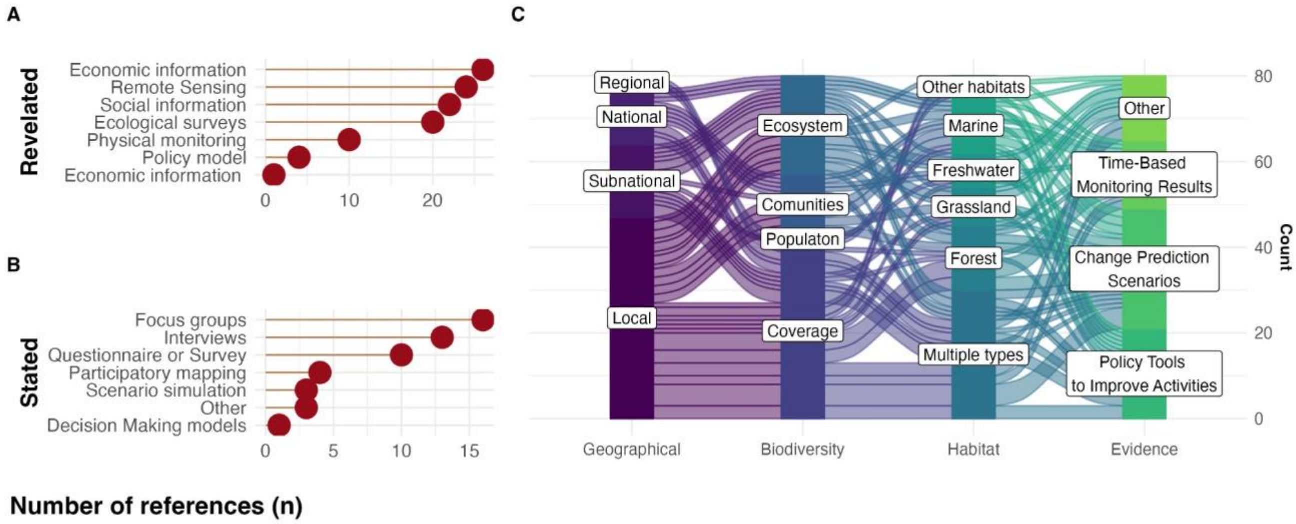


Figure 3. In revealed preferences (a), economic data were the most frequently followed by remote sensing analyses of social and ecological surveys. For stated preferences (b), the participatory process with various actors was the main method, with focus groups and interviews being the most cited. Scenario or decision-making models emerged as less frequent alternatives for generating analytical information. (c). Relationship between the *geographical*, *biodiversity*, and *habitat* scales, with the *evidence* presented in the paper reviewed. The count on this axis Y reflects category occurrences rather than unique documents, because individual studies may be assigned to multiple categories (e.g., different habitats within a single study).

For stated preference tools, the most frequent approach was the use of participatory processes that include different actors. Among these, focus groups (n = 15) and interviews (n = 13) were the most common (Fig. 3b). Less frequent were scenario models (n = 3) and decision-making models (n = 1), but these were valuable because they helped generate information that could later be used for analysis and planning. For more details on the definition of each category, please see Supplementary Data 1.

Remote sensing and time-series data are still key tools for creating scenarios and monitoring changes over time (Vihervaara et al., 2017). Community studies provide essential information at the local level, helping to understand social and ecological changes in specific areas (Magurran et al., 2010), Fig. 3c). Larger scales, such as subnational or national levels, rely more on policy data to support decision-making. However, most studies that evaluated impacts were not directly linked to policy design (Fig. 3c). This shows that there is still a gap between scientific monitoring and how information is used to guide public policy (Tobias et al., 2025).

Hébert et al (2025) identified that most biodiversity indicators are used at national or subnational levels, leaving a gap in monitoring local and short-term changes (Hébert et al., 2025). In our review, we found the opposite pattern: most studies apply indicators at the local scale (Fig. 3c). This could mean that research is starting to fill that gap, but it also adds some challenges. Many of the indicators we found come from other frameworks, such as ecosystem services or land-use and land-cover (LULC) studies, instead of the Global Biodiversity Framework.

These approaches focus more on understanding the local context and how people and nature interact, rather than just measuring biological changes. For that reason, our results may help reduce the spatial gap mentioned by Hébert et al. (2025), but they also show that we still miss the temporal side of biodiversity change, since our review did not evaluate how indicators vary over time. Finally, socioecological systems are complex and dynamic, involving many interactions between nature and society (Winkler et al., 2021). Future research should use mixed approaches —combining participatory work, remote sensing, and modelling—to design indicators and solutions that are both practical and sustainable (Fig. 3c).

3.3. Patterns of Participation and Knowledge Integration Across Scales

Are participatory approaches used differently across regions (Global South–Global North) and actor types in the cases where indicators where applied?

Indicators were used to map our findings onto the North–South highlighting how participatory approaches and multi-scale integration differ across regions. These patterns contribute to understanding how local applications connect to national biodiversity targets and broader governance frameworks. Research was identified across all continents (Fig. 4), demonstrating the global reach of multi-scale biodiversity governance studies. China accounted for the highest number of studies (n = 8), followed by Brazil (n = 4), and then Canada, Ecuador, France, and the United States (n = 3 each). The primary observation indicates that nations with a greater number of case studies incorporating socio-ecological indicators into decision-making processes also coincides to the countries that experience higher income growth and reduced inequality (Chrisendo et al., 2025). The examples of China, which has the highest number of studies, and Brazil serve as particularly illustrative cases.

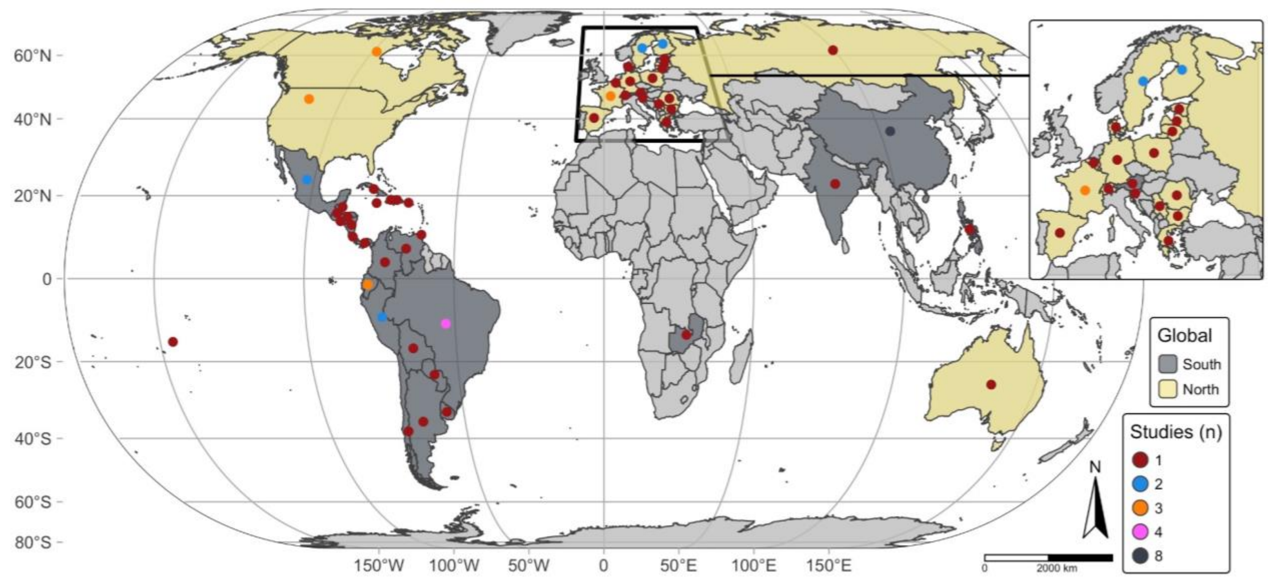


Figure 4. Distribution of the number of papers per country registered in this study. Countries were also categorized according to the relationship of the sources with respect to the Global South and North. The small rectangle in the corner shows a zoomed-in view of the European area.

Most of the reviewed studies were conducted at a local scale (n = 23), while only a few integrated information across countries (n = 3). This dominance of local-scale research suggests that biodiversity governance remains strongly place-based, with limited efforts to connect findings across national or regional levels (E. M. Bennett et al., 2021; Tengö et al., 2014). Strengthening comparative and multi-level research could enhance understanding of how local actions contribute to global biodiversity goals. Across studies, local communities and civil servants were the most common participant types (19.1%), followed by members of academia (16.4%) (Supporting Information Fig. 1). The roles of participants varied according to the group: local communities were primarily identified as stakeholders (11.8%), whereas academics often acted as experts (10%).

These patterns reflect how knowledge production and authority remain unevenly distributed among actors (Newig et al., 2023). Participation was more prominent in the Global South, where Local Communities represented a greater proportion of stakeholders (21.2%, Fig. 5b), underscoring the importance of community-based engagement. In contrast, in the Global North, the region with more in high-income (Chrisendo et al., 2025), participation was dominated by academics and civil servants acting as experts (15.7%, Fig. 5a), suggesting a more institutionalized and technical approach. This North–South difference illustrates two complementary but imbalanced trends: while the Global South, the region with higher inequality (Chrisendo et al., 2025) demonstrates stronger inclusion of local actors, the Global North, which has the high-income countries, relies more heavily on formal institutions and technical expertise. Such divergence highlights the need for governance models that balance expert-driven analysis with participatory inclusion, ensuring that diverse perspectives contribute to biodiversity indicators and management outcomes (Newig et al., 2023).

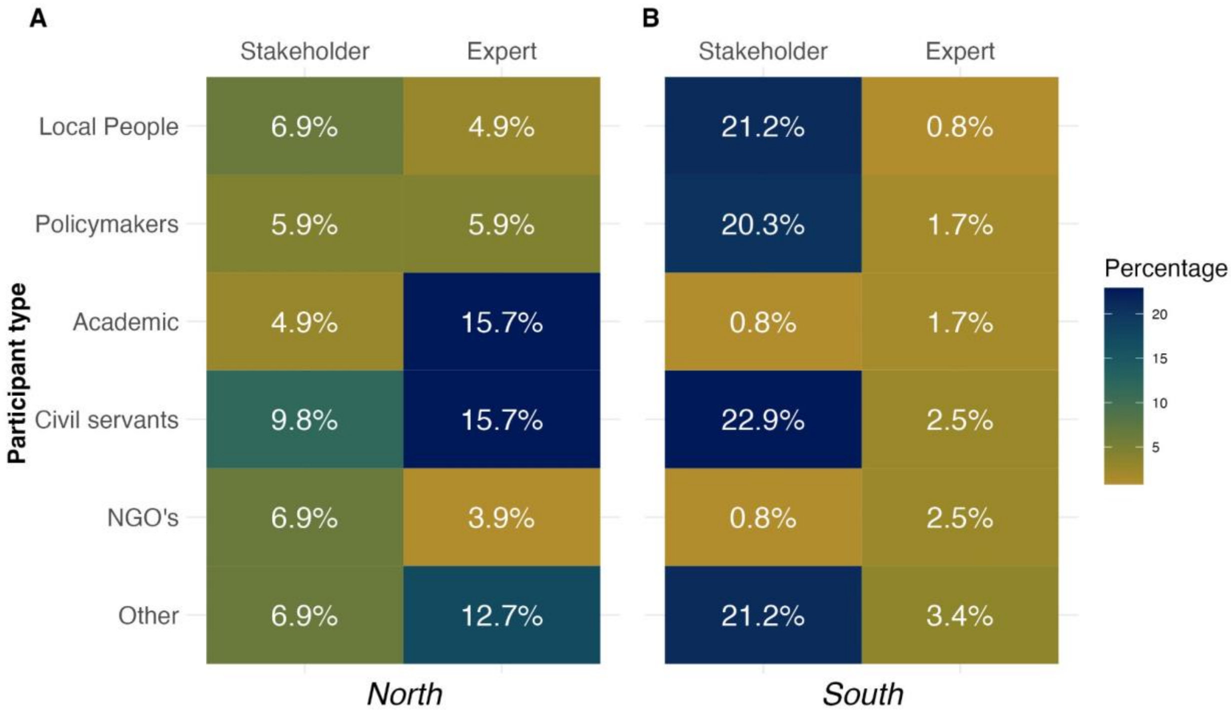


Figure 5. Regarding the role of participants in the Global North (A), there was more heterogeneity among the actors involved in the processes, while in the South (B), the inclusion of local people and civil servants was predominant.

Although participation by local communities remains limited overall, its importance is increasingly recognized in both regions (Tengö et al., 2014). Traditional and local communities hold knowledge systems developed through generations of direct interaction with ecosystems (Campbell & Gurney, 2024). Integrating this knowledge can improve the relevance and legitimacy of biodiversity indicators, yet challenges persist due to differences between scientific and local epistemologies. A case from the Amazon region of Colombia demonstrates this integration: Indigenous communities developed their own indicators to inform policy decisions and ensure autonomy in managing information (Cruz et al., 2020). This example shows the potential of participatory indicator frameworks to enhance representation and accountability within decision-making processes.

The findings also emphasize the importance of linking governance across scales. National and regional institutions act as intermediaries that connect global biodiversity frameworks with local implementation (Allen et al., 2023). Where such coordination is weak, local initiatives risk being isolated from national targets, limiting their long-term impact (Allen et al., 2023). Strengthening these connections—through co-production of indicators and dialogue between knowledge systems—can make biodiversity governance more adaptive and inclusive. Overall, the analysis reveals persistent asymmetries between the Global North and South, but also growing recognition of the value of local participation and multi-scale integration (E. M. Bennett et al., 2021; Newig et al., 2023; Tengö et al., 2014). Building effective biodiversity governance will depend on balancing scientific expertise with local knowledge, enhancing the connections between local and global scales, and developing indicators that reflect both ecological realities and social priorities.

3.4. The lack of information which could be integrated in the new socioecological dimensions

What methodological, governance or data gaps constrain the operational use of socio-ecological indicators, and what priorities emerge to close the science–policy implementation gap?

We identified multiple, recurrent information gaps that constrain socio-ecological integration and science–policy implementation, indicating the need to quantify governance and data gaps (Table 3). A substantial portion of studies did not report limitations (21.1%) and an equal proportion did not report lack-of-information issues (21.1%) (Table 3). Among the specific data needs reported were: long-term time series to strengthen inference (e.g., (Chen et al., 2022; Darvill & Lindo, 2016), uneven information availability between regions and countries (Czúcz et al., 2018; Manners & Varela-Ortega, 2017), finer-scale data (Xu et al., 2019), and explicit recognition of data limitations (Arlidge et al., 2020; Dietz et al., 2023; Kourantidou et al., 2020; Malmborg et al., 2021). Conceptual problems were least frequently cited (8.5%), reflecting continuing interest in methodological innovations for socio-ecological analysis (Fig. 2).

Table 3. Limitations reported by the researchers, as well as challenges or suggestions for the future.

Category	Options	n	%
Limitations in the study	Data availability	15	21.1
	Not provided	15	21.1
	Other Limitations	14	19.7
	Methodological approach	12	16.9
	Need to include social aspects	9	12.7
	Conceptual issues	6	8.5
Challenges or suggestions for the future	Other suggestions	22	28.9
	Participation of multiple actors or disciplines	16	21.1
	Applicability	14	18.4
	More empirical research	12	15.8
	Communicative tools	7	9.2
	Not provided	5	6.6

Researchers suggested future actions clustered around broad, practical priorities: increasing participation of multiple actors or disciplines (21.1%), improving applicability of results (18.4%), and conducting more empirical research (15.8%) (Table 3). The recurrent call to integrate multiple actors underscores a perceived need to strengthen the legitimacy and usability of outputs for decision-makers. When conceptual limitations were identified, authors emphasized translating high-level frameworks into usable methodological procedures (Fontaine et al., 2014), acknowledged the difficulty of reducing complex social–ecological interactions to simplified valuation methods (Sajeva et al., 2020), and noted management challenges highlighted elsewhere (Arlidge et al., 2020). The absence of a dominant single challenge or recommendation (28.9% “other”) suggests heterogeneity in both contexts and priorities across studies.

Integrating biological and social data in ways that preserve coherence across knowledge systems requires improved communication tools and plural epistemological approaches (Campbell & Gurney, 2024; Richter et al., 2022). Drivers that affect communities and natural areas operate over time and across scales (Fig. 3c), so robust, long-term time series and monitoring are essential to detect trends, evaluate interventions, and inform adaptive management (Dornelas et al., 2025; Knapp et al., 2012). Although biological and social data availability is increasing through new initiatives, persistent problems remain: many datasets are spatially, temporally, or demographically unrepresentative and often provide only short-term snapshots rather than continuous records (Bowler et al., 2025; Krebs et al., 2025). These limitations complicate the translation of ecological signals into actionable policy, particularly because required solutions are frequently social and political as much as ecological (Krebs et al., 2025).

Social-science data streams (e.g., education, health, demographics, economic indicators) are expanding and can support frameworks such as ecosystem services, but integrating knowledge that departs from Western epistemologies remains a common and unresolved request (Urbina-Cardona et al., 2023; Muradian & Gómez-Baggethun, 2021; Díaz et al., 2018; Adams et al., 2014). This omission reduces the capacity of global frameworks to capture system complexity in many contexts (Gonzalez-Redin et al., 2024) and contributes to persistent questions about whether scientific outputs align with policy processes and decision-maker needs (Greenhalgh et al., 2022).

In sum, our results show clear, actionable gaps: (1) frequent non-reporting of study limitations and data shortages; (2) a strong demand for long-term, finer-scale, and regionally representative datasets; and (3) a need for methods and communication tools that bridge epistemic differences. Quantifying governance and data gaps—by region, actor type, and data domain—should be a priority to evaluate the Q4 and to guide investments in monitoring, co-production, and policy-relevant research.

4. CONCLUSION

Advancing the uptake of socio-ecological indicators requires strengthening long-term monitoring to address data gaps, moving beyond land-cover proxies to capture ecosystem processes, and incorporating community-based measures that explain biodiversity change. While biodiversity indicators are improving at regional and national scales, and socio-ecological indicators capture local dynamics, the main challenge is to develop integration processes that connect local applications with national goals, rather than seeking a single universal measure. Equally important is embedding stakeholder participation in indicator development, particularly through the inclusion of local and Indigenous knowledge systems in participatory settings that recognize their expertise. Addressing these gaps would transform socio-ecological indicators from academic exercises into practical tools that effectively inform biodiversity policy and decision-making.

Building on this initial research, a future review aiming to better understand the conditions under which a socio-ecological indicator approach genuinely integrates decision-making should consider expanding the evidence base beyond what is typically reported in academic articles. In particular, it would be valuable to systematically capture (i) the stage of uptake of indicators (from conceptual proposal to institutionalized use), (ii) the decision context and governance arrangements in which indicators are embedded (mandates, accountability, capacity, incentives, and rights/legitimacy), and (iii) the quality and intensity of participation across the full indicator cycle (co-design, implementation, interpretation, and adaptive revision). With these elements in place, the field would be better positioned to move from describing indicators to evaluating the effectiveness of decision-making processes in socio-ecological research—using transparent criteria (e.g., salience, credibility, legitimacy, equity) and, where feasible, designs that can trace influence on decisions and downstream outcomes rather than relying solely on reported intentions or inferred relevance.

AUTHOR CONTRIBUTIONS

Cristian Alexander Cruz-Rodríguez, Maria C. Londoño and Timothée Poisot conceived the idea; Cristian Alexander Cruz-Rodríguez, J. Nicolas Urbina-Cardona, Maria Cecilia Londoño Murcia and Timothée Poisot designed the methodology; Cristian Alexander Cruz-Rodríguez collected and analyzed the data; Cristian Alexander Cruz-Rodríguez wrote a first draft of the manuscript; All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

We have no conflicts of interest to disclose.

DATA AVAILABILITY STATEMENT

The data utilized to generate the figures, as well as the R script required to obtain them, are available at the following GitHub repository.

https://github.com/crcruzr/Socioecologic_rev/tree/main

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