

Review

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[Cesar Augusto Ruiz-Agudelo](#)* and Angela Maria Cortes- Gomez

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Review

Socioecological Resilience Assessment: Current State and Future Challenges

Cesar Augusto Ruiz-Agudelo ^{1,*} and Angela María Cortes-Gomez ²

¹ RINA-Consulting, Universidad Jorge Tadeo Lozano, Colombia

² Natural Offset Solutions S.A.S, Colombia

* Correspondence: cesara.ruiza@utadeo.edu.co or cesaraugusto.ruiz@rina.org; Tel.: +(57)-314-3963697 or 0000-0002-1380-2884

Abstract

The classic conceptualization of resilience refers to a system attribute that helps us understand the extent to which systems can withstand pressures and impacts without altering their constitutive or intrinsic characteristics. In recent years, resilience has become the subject of profound debate in international academic literature. Nevertheless, the concept—particularly socio-ecological resilience—remains a research topic with limited academic consensus. What do we mean when we speak of socio-ecological resilience? How can it be measured and interpreted adequately or efficiently? What tools are available to assess it? Based on a critical review of 146 papers published between 2011 and 2025, this study defines the current state of concepts, methods, tools, and approaches to socio-ecological resilience. Beyond identifying research trends, the analysis critically evaluates existing methods to formulate recommendations for future research and to highlight promising lines of inquiry that better capture the multidimensional complexity of socio-ecological systems.

Keywords: resilience; socioecological systems; socioecological resilience; review; methods; trends; recommendations

1. Introduction

Since its initial conceptualization in 1973, resilience has acquired heuristic, symbolic, and normative dimensions [1–4], in addition to its original role as a descriptor of complex ecological processes [5]. In general terms, Allenby and Fink [6] defined resilience as “the ability of a system to remain in a practical state and to degrade gracefully in the face of internal and external changes.” According to [7], the diverse literature on resilience identifies two contrasting concepts.

The first, described by [8] as *engineering resilience*, refers to the capacity of a system to persist through a disaster with minimal damage. As noted by [9], engineering resilience emphasizes a system’s ability to return to its previous state after a disturbance, considering both the recovery time and the recovery trajectory.

The second, more widely adopted concept is ecological resilience, defined as the degree of perturbation a system can withstand without altering its structure and function [1,5,10]. Ecological resilience incorporates the notion of regime shifts—non-linear, abrupt transitions between alternative system states that differ in configuration and properties [11,12]. Overall, resilience can be understood as a system’s capacity to adapt to perturbations, thereby supporting sustainable development [10].

The concepts, applications, and methodological developments of resilience have diversified to encompass multiple research dimensions [7]. For example, incorporating social analysis, Bruneau et al. [13], and later Cimellaro et al. [14], defined resilience as “the ability of social units to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities to minimize social disruption and mitigate the effects of future earthquakes.” Similarly, Cimellaro et al. [15] introduced the PEOPLES framework, a top-down theoretical model that addresses all aspects of a community. These aspects

are categorized into seven dimensions: Population, Environment, Organized government services, Physical infrastructure, Lifestyle, Economy, and Social capital. Subsequently, the PEOPLES framework was upgraded into a quantitative model for measuring community resilience [16,17]. Collectively, these studies emphasize social resilience, particularly in the context of natural disasters [18].

In contrast, more recent works have examined social resilience from a regional perspective, focusing on the systems that sustain local livelihoods [19]. These approaches have drawn the attention of economists and have emerged as a research hotspot in regional economics and economic geography.

As a result of this conceptual and methodological multiplicity, Socio-ecological resilience assessment has developed from diverse conceptual and methodological approaches [7], expanding on traditional resilience theory, which evaluates how socio-ecological systems (SES) endure shocks through their interconnections [20,21]. Franco-Gaviria et al. [22] emphasize that SES resilience is central to resource management and to resolving socio-environmental conflicts. Research has examined ecosystem resilience across disciplines, including ecology, resource management, food security, community planning, and disaster response [23–25]. Applications and measurements vary and often lack a strong theoretical grounding [7,22]. One of the few points of consensus in this field is that resilience must encompass three capacities—absorption, adaptation, and transformation [26,27]—all of which are vital for SES assessments.

Since the 1990s, resilience studies have increasingly focused on socioeconomic systems [19]. However, most remain discipline-specific, overlook multiple levels of resilience, and neglect the interdisciplinary complexity of the concept [28]. According to the Stockholm Resilience Center and related literature [29], resilience thinking is guided by seven core principles that enable socio-ecological systems to adapt, recover, and transform in the face of change. These principles emphasize diversity, connectivity, adaptive learning, and inclusive governance as foundations for long-term sustainability. This comprehensive vision of SES resilience necessarily incorporates a transdisciplinary perspective. Overall, the literature calls for adaptive, quantitative, and cross-disciplinary assessments that integrate network perspectives to better capture the dynamic nature of SES under environmental and social change [6,7,19–22].

The central questions of the review were: (1) What are the publication trends in the research on Socioecological Resilience?; (2) To what extent are the seven principles of resilient thinking considered in the SES resilience research? (3) What are the methods and modeling techniques most applied for understanding and assessing the SES resilience? (4) What are the most commonly applied resilience approaches in the studies reviewed? (5) What is studied in socioecological resilience, resilience of what, and against what? and (6) What are the current challenges, recommendations, and future directions for improving our understanding and assessment of the SES resilience?

The review is structured as follows. Section 2 presents the materials and methods (literature search, database, and classification) used for the review, while Section 3 provides the review's results, including publication trends and findings from the database analysis. We also explore the common methods, modeling techniques, and tools used to understand and assess SES resilience. In Section 4, we discuss the research challenges and ways to proceed to improve our understanding of SES resilience. Section 5 concludes with the main findings.

2. Material and Methods

2.1. Literature Search

To examine the rise and trends in research on socioecological systems resilience (SES resilience) in international peer-reviewed journals, a systematic literature search was conducted. Journal articles published between 2011 and 2025, as well as those forthcoming in 2026, were included if they contained the following search terms: resilience, ecological resilience, social resilience, socioecological resilience, resilience modeling tools, qualitative/descriptive resilience assessment techniques,

matrices, mapping resilience, resilience statistical modeling methods, resilience and machine learning, and resilience and Bayesian networks. Spelling variants were considered, and each search term was combined individually with the terms ecosystem services, multiple ecosystem services, ecology, social, socioecological systems, and case studies to capture literature at the core of the review aim (i.e., case studies on the assessment of socioecological systems resilience).

Articles were sourced from five major scientific databases—ScienceDirect, SCOPUS, SCIELO, ISI Web of Knowledge, and Google Scholar—between January and December 2025.

In total, 622 scientific papers were identified. After excluding those that did not explicitly measure resilience or socioecological systems resilience, a final set of 146 documents was reviewed and systematized in a database (Supplementary Material S1).

2.2. Database and Classification

1. Key information was recorded for each study, including descriptors of the publication (e.g., citation, year, and journal), the scale of analysis (local, regional, national, continental, or global), and geographic details (location, country, and continent). This dataset provided valuable insights into publication trends related to socioecological systems resilience (SES resilience).
2. To assess whether the case studies engaged with the seven principles of resilience thinking, we documented both the number and type of principles addressed. The principles are conceptualized as follows [29,30]:
 - a. **Principle 1 – Diversity and redundancy:** Systems that include many components, such as species, actors, or knowledge sources, tend to be more resilient than those with fewer elements. Diversity provides options for adaptation, while redundancy ensures that if one component fails, others can compensate. Resilience is strengthened when components respond differently to disturbances [29,31].
 - b. **Principle 2 – Connectivity management:** Connectivity can influence ecosystem functioning in both positive and negative ways. Well-connected systems often recover more quickly from shocks, but excessive connectivity can accelerate the spread of disturbances. Landscape connectivity is particularly important for sustaining biodiversity [32,33].
 - c. **Principle 3 – Slow variables and feedback:** Interactions among system components shape configurations that deliver ecosystem services. Managing slow variables and feedback helps maintain systems in desired states. Once a system shifts to an alternative configuration, reversing the change can be extremely difficult [29,30].
 - d. **Principle 4 – Complex adaptive systems perspective:** Viewing social-ecological systems as complex adaptive systems (CAS) highlights the multiple, simultaneous connections across scales. This perspective embraces unpredictability, uncertainty, and diverse viewpoints, recognizing that coupled human–natural systems are nonlinear, evolutionary, and characterized by feedback [34,35].
 - e. **Principle 5 – Learning and experimentation:** Because social-ecological systems are dynamic, knowledge must be continually revised. Adaptive and collaborative management fosters experimentation and collective learning, which are essential for building resilience [29,30].
 - f. **Principle 6 – Broad participation:** Inclusive participation in planning and governance enhances trust, shared understanding, accountability, and legitimacy. Active stakeholder involvement integrates diverse perspectives and supports collective action. A key challenge is establishing durable communication structures that reflect the diversity of complex socioecological contexts [30].
 - g. **Principle 7 – Polycentric governance:** Polycentric governance involves multiple organizations and stakeholders working together to create and enforce rules. This approach strengthens collective action, enhances connectivity, and supports learning across scales and cultures. Well-connected governance systems can respond quickly to disturbances

when the right actors are engaged. Effective coordination requires clear and widely accessible information [36].

It should be noted that case studies addressing two or more principles are not inherently superior or more desirable. The essential point is that socioecological systems encompass multiple dimensions; therefore, including more principles increases the likelihood of achieving a more comprehensive understanding of socioecological system resilience.

3. To analyze trends in methods for assessing socioecological systems (SES) resilience, the methods used in the case studies were classified into the following categories:
 - a. **Qualitative / descriptive tools:** These include participatory mapping, sociocultural approaches, and surveys with open-ended questions designed to capture individuals' perceptions of system resilience [37].
 - b. **Indices and indicators:** This category encompasses case studies that employ environmental, socioeconomic, or social indices and indicators commonly used across disciplines. The aim is to establish a static, concrete measure of resilience within a defined conceptual framework [38–44].
 - c. **Ecosystem services assessment and indicators:** Case studies in this group evaluate the resilience of specific ecosystem services, applying indices and indicators traditionally used in ecosystem service characterization and assessment as proxies for resilience [45–49].
 - d. **Dynamic and remote-sensing indices:** These studies apply indices and indicators from a multi-temporal perspective, using geographic information system (GIS) tools or tracking changes in resilience measures over time [50–53].
 - e. **Dynamic ecological models:** This category includes studies that use system dynamics approaches, either through data-driven modeling (DDM) based on machine learning with empirical data [54], or integration techniques such as semantic meta-modeling, which employs Unified Modeling Language to address the complexity of SES resilience evaluation [55–57].
 - f. **Bayesian and ecological networks:** Case studies here explicitly apply Bayesian networks or ecological networks to model hypotheses and measure resilience in socioecological systems [58,59].
 - g. **Emerging methods:** This group refers to specialized case studies employing novel approaches, such as the stochastic cusp model (CUSPRA), to measure and interpret SES resilience [60].
 - h. **Other methods:** Additional approaches include the development of ecological or socioecological frameworks, experimental field measures, meta-analyses, resilience economic valuation methods, and review studies that assess resilience in diverse ways [61–65].
4. To determine which domains of resilience approaches are applied in the case studies reviewed, we draw on the conceptual framework outlined in [66], as follows:
 - a. **Engineering resilience approach:** Focuses on the speed with which a system returns to equilibrium after a shock. Key elements include recovery time, efficiency, and equilibrium [67].
 - b. **Ecological resilience approach:** Emphasizes a system's ability to withstand shocks while maintaining critical relationships and functions. Central aspects are buffer capacity, persistence, robustness, and the ability to absorb disturbances [68].
 - c. **Community resilience approach:** Defined as a process that links adaptive capacities to a positive trajectory of functioning and adaptation following a disturbance. The emphasis is on adaptive capacity, responses to disturbances, and social dimensions [69].
 - d. **Social-ecological resilience approach:** Encompasses (i) the extent of disturbance a system can absorb while remaining within its domain of attraction, (ii) its capacity for learning and

- adaptation, and (iii) its ability to self-organize. This approach highlights adaptive capacity, learning, and innovation [26].
- e. **Socioeconomic/livelihood resilience approach:** Refers to the policy-driven ability of an economy to recover from or adjust to adverse external shocks, while also benefiting from positive ones. It focuses on economic response capacity [70]. At the household or individual level, it includes the capacity to avoid poverty despite stressors and repeated shocks over time [71].
 - f. **Ecosystem services resilience approach:** Proposed in this review as a new domain, this approach is based on the characterization and modeling of specific ecosystem services using established methodological frameworks. It examines how these services are affected by shocks and pressures, such as land-use change, climate change, and socioeconomic drivers. This perspective introduces a novel way to evaluate resilience by explicitly integrating ecosystem service methodologies.
5. To define, in a concrete way, the trends in resilience assessment (resilience of what?), each of the 146 case studies was analyzed, and the objects of resilience assessment were classified into the following general categories:
- a. Terrestrial ecosystems
 - b. Human communities
 - c. Socio-ecological systems
 - d. Ecosystem services
 - e. Agroecosystems
 - f. Marine ecosystems
 - g. Water ecosystems
 - h. Coastal ecosystems
 - i. Urban areas
 - j. Urban and natural areas
 - k. General systems
 - l. Groundwater systems
 - m. Island ecosystems
 - n. Seafood businesses
6. To define trends in response to the question “resilience against what?”, 146 documents were reviewed and classified into the following general categories:
- a. Climate change and climate variability.
 - b. Habitat fragmentation and human changes.
 - c. Natural disasters (Droughts, floods, tornadoes, cyclones, storms).
 - d. Fire frequency increased.
 - e. Climate change, population growth and infrastructure.
 - f. Sea-level rise.
 - g. Urban Growth.
 - h. Economic shocks.
 - i. Invasive species and changing wildfire regimes.
 - j. Nanoplastics Pollution.
 - k. Sea warming.

7. Finally, to identify the challenges and potential avenues for improving our understanding of the resilience of socioecological systems, the conclusions, recommendations, and limitations of each case study were critically analyzed. This step highlighted methodological gaps, conceptual constraints, and practical insights that can guide future research directions and strengthen the assessment of socioecological systems resilience.

3. Results and Discussion

3.1. Publication Trends: An Overview

The number of scientific papers on socioecological systems resilience, including measurement and conceptual frameworks, has increased since 2010. The 146 papers we evaluated were published across 69 journals, with eight journals accounting for 42% of the total: *Ecological Indicators*, *Journal of Environmental Management*, *International Journal of Disaster Risk Reduction*, *Science of the Total Environment*, *Climate Risk Management*, *Biological Conservation*, *Global Ecology and Conservation*, and *Journal of Cleaner Production*.

The countries with the most resilience studies were China (29), the USA (15), the UK (6), and India (5). Together, these countries contributed 38% of current knowledge on resilience and socio-ecological resilience (Figure 1). It is important to note that, in this review, 36 studies (25%) correspond to global assessments of resilience, either through the use of global databases or the proposal of ecological and sociological frameworks (e.g., [42,72–76]). This tendency clearly demonstrates the dominance of global publications that test methods, apply models, or seek to homogenize concepts when evaluating the resilience of socio-ecological systems.

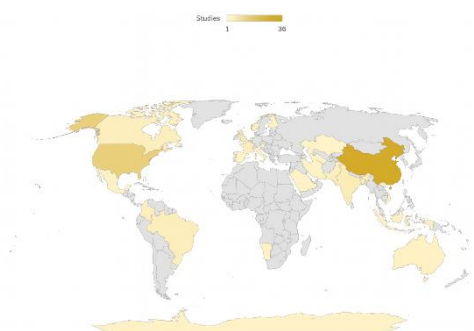


Figure 1. Global distribution of study locations by country, where tools were applied to assess resilience and socioecological systems resilience. The categorization of the number of studies was based on natural breaks.

3.2. Findings from the Database Analysis

3.2.1. Resilience of What and Against What

An analysis of resilience assessments, encompassing both the types of resilience examined and the contexts in which they are applied, was conducted to identify the dominant themes in the reviewed literature.

The evidence highlights a strong focus on terrestrial ecosystems (26%) and their resilience to climate change (53%). Studies that address, at least in part, the resilience of socio-ecological systems under climate change scenarios are also relatively frequent (Figure 2).

The resilience of human communities, across both urban and rural settings, to natural disasters and extreme weather events remains a central area of investigation (Figure 2).

Moreover, the growing emphasis on evaluating the resilience of ecosystem services to climate change and extreme weather events underscores this as an increasingly prominent research trend (Figure 2).

Finally, several columns reveal consistently low or negligible values for certain stressors, including nanoplastic pollution, ocean warming, and sea-level rise, in specific systems, thereby delineating priority areas for future resilience research (Figure 2).

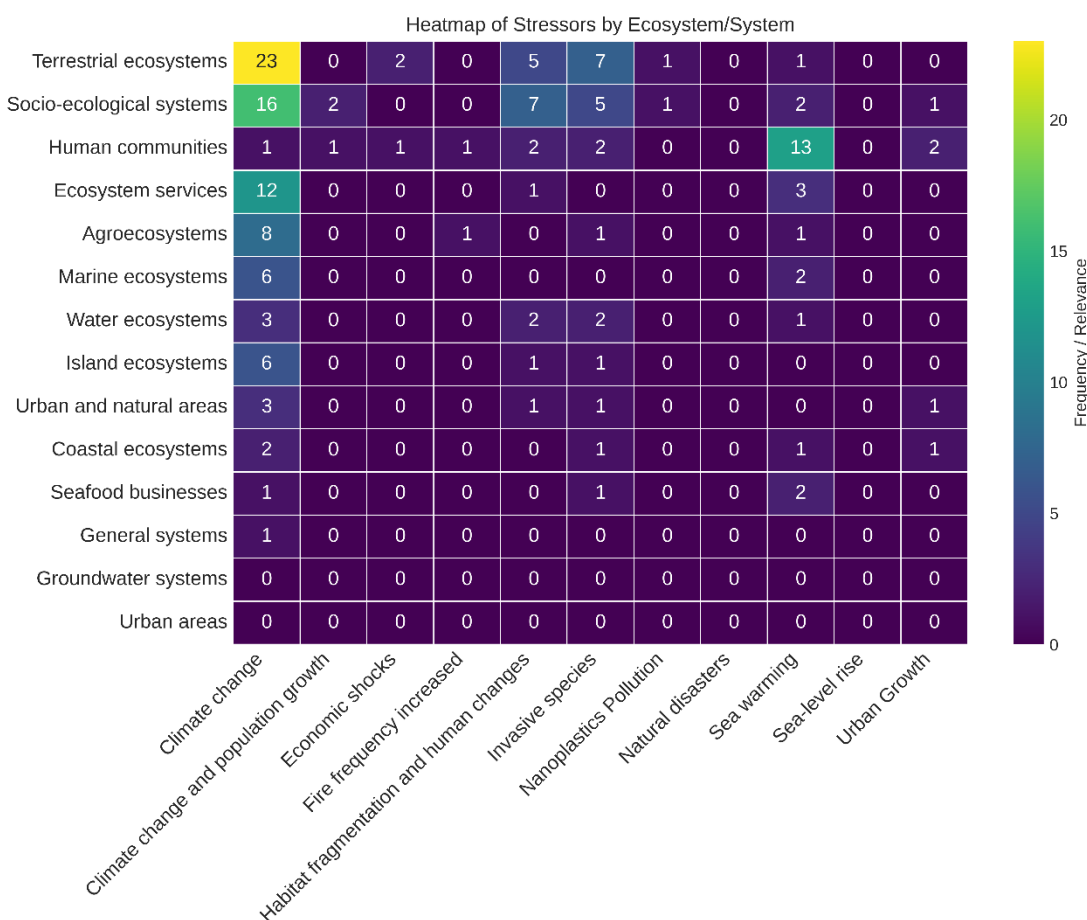


Figure 2. Resilience of what and against what.

3.2.2. Inclusion of the Seven Principles of Resilience Thinking

Decades of research on resilience in social–ecological systems have identified a set of strategies that strengthen and sustain resilience. These strategies highlight the unique characteristics of resilient social–ecological systems, rather than those of complex systems more broadly, and have significant implications for the measurement and assessment of resilience. Seven core strategies are consistently recognized as enhancing resilience: 1. Maintaining diversity and redundancy. 2. Managing connectivity. 3. Addressing slow variables and feedbacks. 4. Fostering an understanding of social–ecological systems as complex adaptive systems. 5. Encouraging learning and experimentation. 6. Broadening participation. 7. Promoting polycentric governance structures [29,30].

According to the present review (Figure 3), 22% of the studies (133 cases) incorporate the principle of managing slow variables and feedbacks, defining sub-criteria that consider system components (e.g., flow regulation, slow variables, feedbacks). Eighteen percent (110 studies) address connectivity management and the definition of relationships between environmental elements (e.g., the connectivity of ecosystem functions). Seventeen percent of the reviewed studies evaluate maintaining diversity and redundancy, establishing appropriate sub-criteria and metrics that account for these aspects. 15% of the studies focus on fostering complex adaptive systems thinking and on defining sub-criteria and metrics for robustness, redundancy, rapidity, and durability. Twelve percent of the studies emphasize encouraging learning, defining sub-criteria using multiple tools and methods for social analysis.

Finally, it is important to note that the principles of broadening participation and promoting polycentric governance systems (9% and 7%, respectively) remain the least addressed in socio-ecological resilience studies (Figure 2). Studies that incorporate these principles typically apply indices and metrics for social analysis.

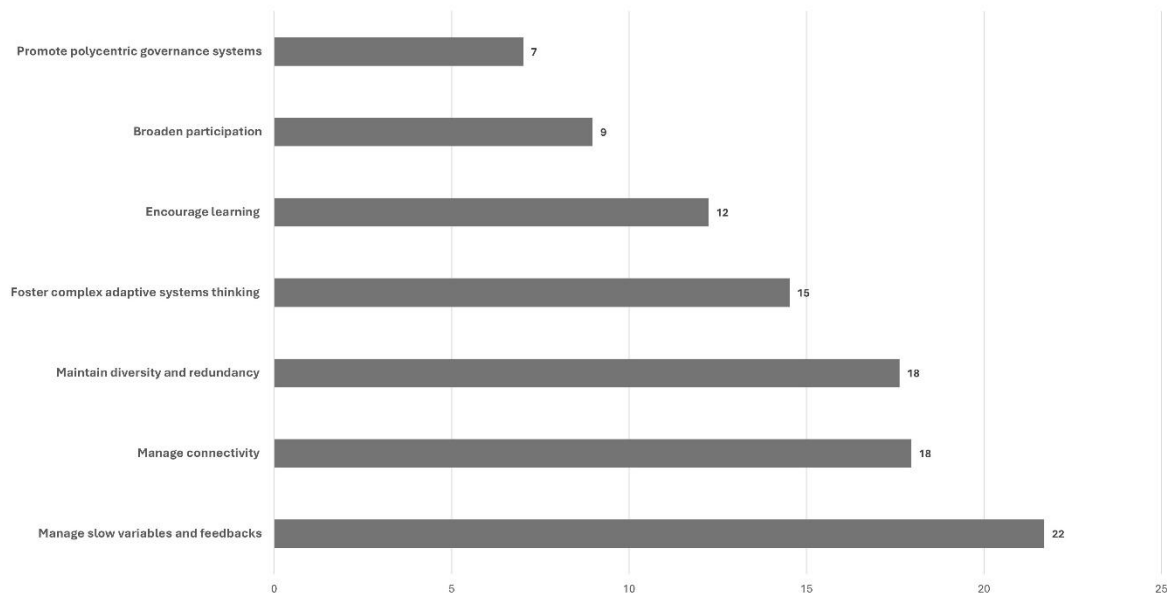


Figure 3. Principles of resilience thinking addressed in the case studies included in this review.

The reviewed literature reveals differing levels of engagement with the seven core resilience principles in social-ecological systems. Only 12% of the case studies systematically and comprehensively address all seven principles (Figure 4). In contrast, 77% of the studies incorporate three to five principles, most commonly focusing on managing slow variables and feedbacks, managing connectivity, maintaining diversity and redundancy, and fostering complex adaptive systems thinking.

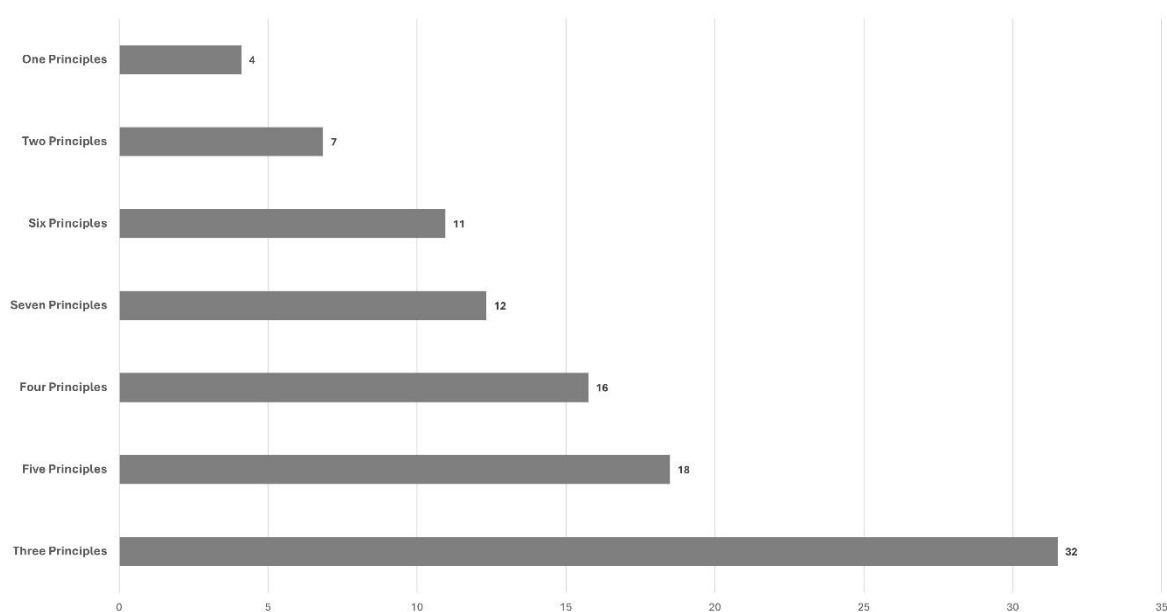


Figure 4. Distribution of studies addressing multiple principles of resilience thinking.

A range of social, political, cultural, economic, and environmental factors influences the resilience of socio-ecological systems. Previous reviews [77] indicate that many studies fail to fully integrate these dimensions into a comprehensive socio-ecological framework. Although research on the seven resilience principles has expanded during the period analyzed, our findings align with earlier reviews [65,66,77,78] and indicate that these principles are rarely quantified to assess or enhance socio-ecological resilience.

Among these principles, encouraging learning and experimentation, broadening participation, and promoting polycentric governance [79–81] are particularly vital for strengthening social resilience. These principles build the human and institutional capacities required to navigate uncertainty and change. Learning enhances adaptability by integrating lessons from past disruptions and fostering innovation in crisis response. Participation ensures inclusive decision-making, enabling diverse stakeholders to contribute perspectives and resources. Polycentric governance, characterized by nested and interconnected structures, facilitates flexible, multi-level coordination, improving responsiveness to both local and systemic challenges. Collectively, these principles reinforce a system's ability to self-organize, recover, and transform in the face of shocks, thereby ensuring long-term social resilience [80,81].

The primary objective of most resilience research is to design adaptive management strategies that enable ecological and social-ecological systems to address increasingly complex environmental challenges. This requires a strong emphasis on understanding and enhancing their capacity to persist and transform in response to dynamic global changes [82,83]. As previously noted, case studies that incorporate more principles are not necessarily superior or more desirable. The critical point is that socio-ecological systems are multidimensional; therefore, integrating more principles increases the likelihood of achieving a comprehensive understanding of resilience.

This review identifies a significant gap in literature: few studies operationalize resilience theory by systematically applying its principles to inform practical solutions. According to [79], the limited real-world implementation of these principles constrains progress in strengthening ecological, socio-economic, and infrastructural resilience.

3.2.3. About the Resilience Approaches' Findings

As noted in [79], contemporary ecosystem management is marked by rapid transformations and considerable uncertainty. Since its emergence, the concept of resilience has been examined, debated, and defined through diverse lenses, reflecting a wide range of scholarly perspectives. This review concentrates on approaches used to assess the resilience of socio-ecological systems, with the aim of determining the extent to which system complexity is effectively integrated and of identifying potential actions or recommendations.

Consistent with the methodological framework of this review and the guidelines outlined in [66], our analysis revealed that 47% of the studies examined (67 cases) employed an ecological resilience assessment (Figure 5). This approach focuses on evaluating a system's capacity to absorb disturbances and, if necessary, shift to alternative stable states [68]. In such studies, the emphasis is placed primarily on ecological and biophysical variables (Figure 6), while cultural, socioeconomic, and participatory dimensions receive limited attention (e.g., [40,84–92]). Nonetheless, certain studies adopting an ecological resilience perspective have, at least qualitatively, incorporated aspects of socioeconomic and cultural contexts (e.g., [72,93–99]). The predominance of this approach (47%) underscores its continued prevalence, while also highlighting a tendency to address socioeconomic and cultural dimensions only sporadically or superficially, without systematic measurement or analysis.

According to this review, 26 studies (18%) adopted a community resilience approach, focusing on processes linking adaptive capacities to positive trajectories of functioning and adaptation following disturbances (Figure 5). These studies emphasize adaptive capacity, responses to disturbances, and social dimensions [69]. They range from qualitative analyses of community resilience [100] to research proposing specific models that incorporate socioeconomic variables

related to community progress under multiple stressors [101] (Figure 6). A defining characteristic of this body of work is the effort to identify and measure the adaptive capacity of communities or livelihoods in response to changes in socioeconomic, natural, and environmental contexts (e.g., [18,41,43,75,102–108]). Consistent with recent reviews such as [78], ecological studies remain fundamental for understanding the biophysical foundations of socio-ecological systems; however, integrating social perspectives broadens these insights, and it is encouraging to observe their increasing presence in international literature. Nevertheless, most community resilience studies reviewed do not substantially incorporate ecological dimensions, suggesting a shift in research priorities toward social aspects, which may come at the expense of fully capturing the inherent complexity of socio-ecological systems.



Figure 5. Distribution of studies according to different resilience research approaches.

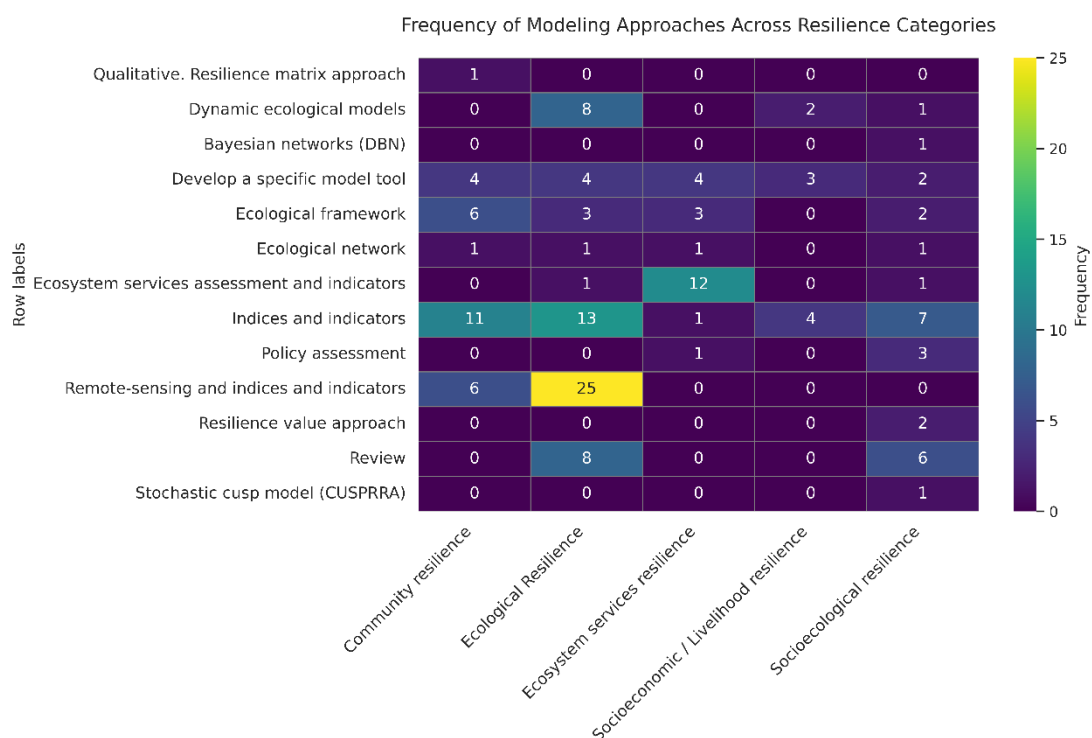


Figure 6. Frequency of modeling and methodological types across resilience approaches.

This review identified 16 studies (11%) using a hybrid Ecosystem Services Resilience framework (Figure 5). These studies advance resilience evaluation by explicitly integrating ecosystem service methodologies and modeling responses to shocks, such as land-use change, climate change, and socioeconomic drivers (Figure 6).

Studies were classified in this category because they go beyond ecological resilience by operationalizing ecosystem services and incorporating relevant socioeconomic and cultural factors, while maintaining a primary focus on established ecosystem services models (primarily InVEST). This approach spans from general indicator assessments under stressors (e.g., [45,47]) to targeted modeling of ecosystem service resilience to environmental and socioeconomic pressures (e.g., [109–111]) (Figure 6).

The conceptual and operational boundaries between ecosystem services and socio-ecological systems are, in practice, blurred [112]. Ecosystem services are commonly defined as the multiple benefits that human societies derive from ecosystem functioning, establishing a critical link between natural ecosystems and social systems by integrating both tangible goods and intangible services produced by nature [112,113]. In contrast, socio-ecological systems (SES) are understood as complex, integrated systems in which humans are embedded within nature [114], and where nature itself encompasses both human and non-human components [115]. SES thus refers to the dynamics and evolution of coupled human–ecological systems [23].

From this perspective, studies of ecosystem service resilience acknowledge the interconnections between environmental and social systems, with particular emphasis on changes in the availability of services to society. However, their approach tends to be static or time-bound, and the methods reviewed do not adequately capture the dynamic evolution of resilience within these coupled systems. While examining the resilience of ecosystem services represents a significant conceptual and methodological advance, bringing us closer to understanding the resilience of socio-ecological systems, it nonetheless falls short of encompassing the full dynamic complexity of these systems and their multifaceted responses to diverse stressors.

On the other hand, this review identified 11 studies (8%) that adopt a socioeconomic or livelihood resilience perspective (Figure 5). This approach seeks to understand economic response capacity at the household or individual level, including the ability to avoid poverty despite stressors and repeated shocks over time [70,71]. Studies in this category emphasize the responses of agroecosystems to multiple stressors. The reviewed works range from the application of indices and indicators (e.g., [44,61,116–118]) to dynamic modeling [119,120] (Figure 6).

Overall, the socioeconomic approach, as reflected in the literature, focuses on the specific responses of agroecosystems to stressors. Nevertheless, studies employing dynamic modeling remain scarce, reinforcing the tendency toward partial evaluations of socio-ecological resilience, particularly in relation to production systems (Figure 6).

Finally, this review identified 24 studies (17%) that focus on measuring and understanding resilience in socio-ecological systems (Figure 5). This category encompasses studies that examine (i) the extent of disturbance a system can absorb while remaining within its domain of attraction, (ii) its capacity for learning and adaptation, and (iii) its ability to self-organize. This approach emphasizes adaptive capacity, learning, and innovation [26].

The methodological spectrum for assessing socio-ecological resilience, as documented in the literature, is highly diverse. It ranges from studies that employ indicator systems to capture environmental, social, economic, and cultural dimensions (e.g., [7,20,42,82,121,122]), to those that integrate complex networks [123], system dynamics [124], Bayesian networks [59], and complex stochastic models [60] (Figure 6).

One of the findings of this review is that studies seeking to measure the resilience of socio-ecological systems using indicators and indices are far more common, whereas those employing system dynamics, Bayesian networks, or other complex modeling approaches remain relatively rare (Figure 5). These results are consistent with the arguments presented by [59,60], which suggest that

the absence of robust methodologies for empirically estimating socio-ecological resilience has contributed to its limited integration into ecosystem-based management frameworks.

Socio-ecological systems are highly complex. Their ability to absorb, adapt, and transform can be viewed as a function that underlies resilience assessment [125]. However, using these measures is challenging in practice because of the nonlinear dynamics arising from the interactions between disturbances and environmental, ecological, economic, and socio-cultural processes over time [1]. While functionality suggests socio-ecological resilience, its evaluation must still address uncertainties in biology, society, and system knowledge. This review supports recent studies [7,30,59,60,122–124] that call for heuristic frameworks and integrative approaches. These could help address system uncertainties and the dynamic processes behind socio-ecological resilience.

3.2.4. Socio-Ecological System Resilience Assessments: Methods, Tools, Current Status, and Future Challenges

In this review, we analyzed the tools employed to assess socio-ecological system resilience and the types of information on which they rely. A substantial proportion of studies (25%) utilize satellite imagery in combination with indices and indicators to evaluate resilience, drawing primarily data related to the physical environment and geographic locations. Within this group, however, only 6% integrate both physical and socio-economic information (Figure 7).

Beyond remote sensing approaches, 23% of the reviewed studies depend on environmental, socio-economic, or social indices and indicators that are widely applied across disciplines. Although these studies incorporate coupled socio-economic and biophysical data, their objective is to produce static and well-defined measures of resilience situated within specific conceptual frameworks [38–44] (Figure 7).

Taken together, these findings corroborate earlier research [7,60,66], which highlights that much of the scholarship on socio-ecological resilience remains oriented toward the development of metrics that combine social and environmental indicators. Contemporary methodologies continue to emphasize statistical signals, such as critical slowing down, that emerge when ecosystems approach thresholds and transition into alternative stability states [93–99,126].

This review also identified a growing number of assessments of socio-ecological system resilience that are grounded in the evaluation of ecosystem services (9%). These studies typically integrate both biophysical and socio-economic information, with an emphasis on analyzing how ecosystem services respond to diverse stressors (Figure 7).

Finally, the review identified a limited number of assessments of socio-ecological system resilience that employ dynamic modeling (6%), ecological networks, Bayesian networks, and other systems dynamics approaches (1–2%). These methodologies integrate coupled biophysical and socio-economic information (Figure 7). Nevertheless, such approaches remain scarce in the reviewed literature.

Recent studies suggest that resilience cannot be reduced to a single value or outcome. Rather, it constitutes an emergent property that manifests in diverse ways across the multiple domains comprising a system. Resilience is inherently contextual, depending on the subsystem under analysis and the specific questions being addressed [7,59,65,66,77,127].

This review acknowledges the value of all approaches to assessing socio-ecological resilience, ranging from qualitative methods to those based on individual or coupled indices, as well as dynamic and stochastic models. In many contexts, decision-makers are required to monitor and measure the systems they manage, underscoring the importance of research on metrics and indicators. Such approaches facilitate the identification of changes across different dimensions of socio-ecological resilience. Nevertheless, it is essential to recognize that, when applied to complex systems, measurement—though useful—carries inherent limitations. By privileging easily quantifiable, manipulable performance indicators, these approaches risk overlooking deeper, more nuanced objectives that are difficult to capture with conventional metrics.

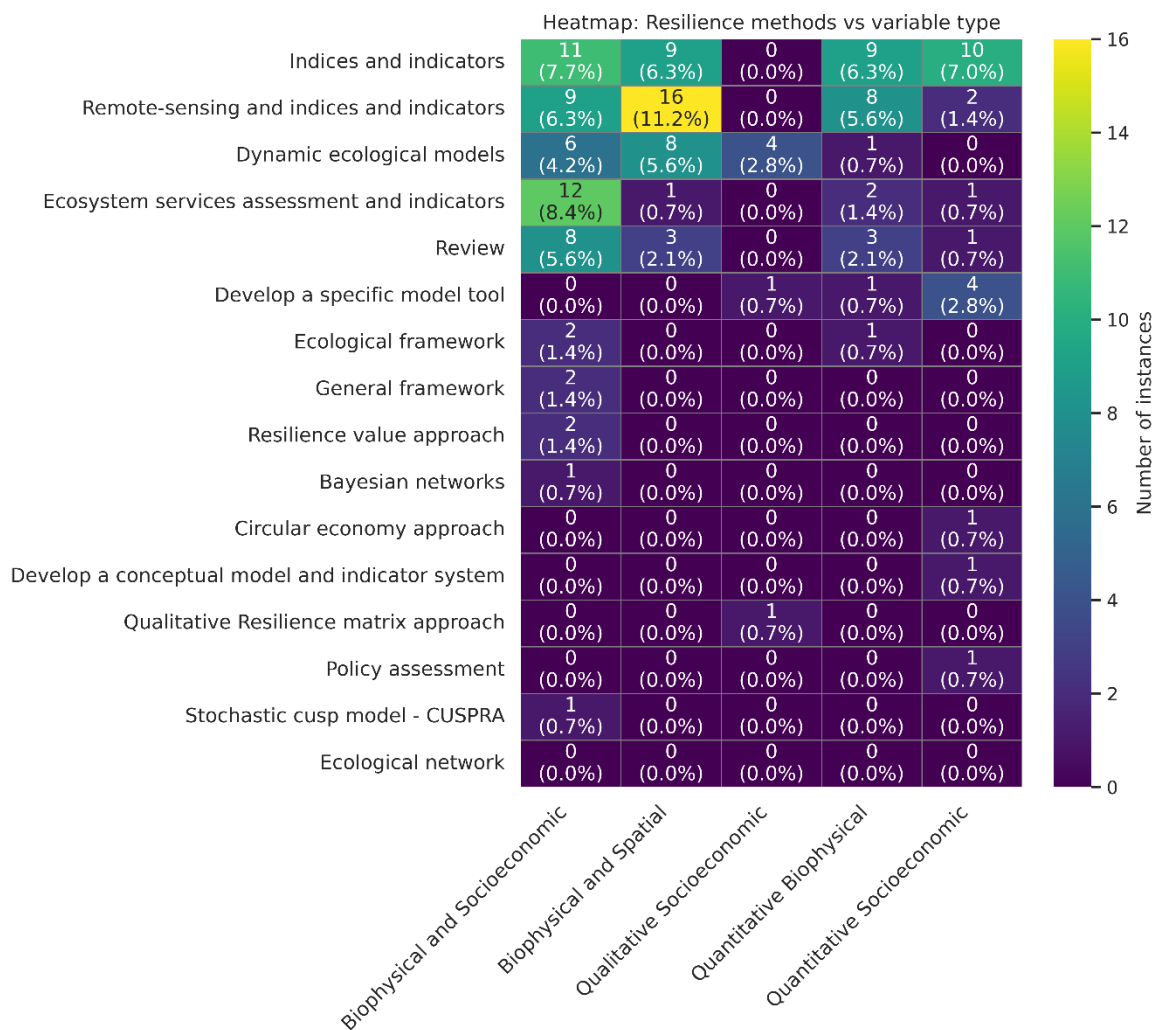


Figure 7. Resilience methods and Type of variables and information.

This review recommends a broader, more complex academic perspective on resilience. Such a perspective accounts for multiple nonlinear interactions, which enable a deeper understanding of system dynamics. From this point of view, several key studies illustrate the relevance of complexity-oriented approaches:

1. Case study [120] (2021) provides a notable example of applying systems dynamics to assess socio-ecological resilience. The research developed a dynamically coupled modeling framework designed to be replicable and stakeholder-friendly, enabling the quantification of resilience metrics in a dynamic agroecosystem subject to diverse socio-environmental shocks. The model incorporates (i) comparative analyses of variable resilience and (ii) the identification of potential regime shifts, transformations, and previously unrecognized system vulnerabilities. By employing a group-built physical systems model, the study generated feedback loops and complex variable linkages that other models have struggled to capture reliably.
2. Study [59] (2022) presents a dynamic Bayesian network approach for constructing temporally robust models of socio-environmental resilience in the Colombian Andes. This methodology adopts a long-term perspective, integrating diverse data sources and interdisciplinary approaches spanning paleoecology, archaeology, anthropology, and history.
3. A novel empirical approach to resilience estimation is introduced in [60] (2024) using the stochastic cusp model from catastrophe theory. This model identifies inflection points linked to cusp bifurcations and distinguishes between stable and unstable states in complex systems. The assessment includes three features: (i) estimating the probability a system will cross a hysteresis-

marked tipping point; (ii) evaluating resilience relative to multiple external drivers; and (iii) providing management-oriented results for ecosystem governance.

A central insight from these cases is that resilience evaluations employing Bayesian systems dynamics or network approaches can identify strategic opportunities and strengthen arguments for transformation and polycentric governance of socio-ecological systems (SES). These methods are adaptive, quantitative, interdisciplinary, and participatory, and can be refined as new system knowledge emerges. By highlighting the relationships among actions, knowledge, uncertainty, and causality, they incorporate management variables that shape both social and ecological components. Overall, dynamic, stochastic, and Bayesian models better reflect the complexity of SES and support resilience assessments under multiple shocks.

This review highlights additional challenges for research aimed at comprehensively and consistently assessing the resilience of socio-ecological systems. One major challenge concerns the limited funding available for interdisciplinary work, a constraint that is particularly critical in developing countries, regions that are simultaneously the most biodiverse and the most vulnerable to climate change as well as political and socio-economic shocks [7]. Another challenge involves the application of Bayesian network models. As noted in [59], integrating the Bayesian Network approach with the Hidden Markov Model (HMM) can capture transitions among network structures, thereby offering deeper insights into resilience dynamics in complex, evolving contexts.

4. Conclusions

This review of 146 papers (2011–2025) outlines the current state of socio-ecological resilience concepts, methods, and tools. Most studies were conducted in China (29), the USA (15), the UK (6), and India (5). Notably, 36 studies (25%) addressed global assessments, reflecting the dominance of publications that test methods, apply models, or seek to standardize concepts.

Research shows a strong focus on terrestrial ecosystems (26%) and resilience to climate change (53%). Engagement with the seven core resilience principles is uneven: only 12% of case studies address all principles, while 77% apply three to five, typically emphasizing slow variables, connectivity, diversity, redundancy, and adaptive systems thinking. Few studies operate resilience theory to guide practical solutions.

Methodologies are diverse, but indicator-based approaches dominate. Complex modeling methods (system dynamics, Bayesian networks) remain rare, limiting empirical integration into ecosystem-based management. Bayesian system dynamics and network approaches, however, can identify strategic opportunities and support polycentric governance. These adaptive, quantitative, and participatory methods highlight relationships among actions, knowledge, uncertainty, and causality, better capturing SES complexity and resilience under multiple shocks.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org.

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