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DOI
10.5751/ES-16726-300451

Publication date
2025

Document Version
Final published version

Published in
Ecology and Society

Citation (APA)
Hirata Sanches, V., Quiñones, R., Vivas, J., Guillaume, J. H. A., Iwanaga, T., Kwakkel, J. H., Quinlan, A. E., Rocha, J. C., Crépin, A. S., & More Authors (2025). Integrating diversity and agency into social-ecological resilience metrics. *Ecology and Society*, *30*(4), Article 51. https://doi.org/10.5751/ES-16726-300451

Hirata Sanches, V., R. Quiñones, J. Vivas, J. H. A. Guillaume, T. Iwanaga, J. H. Kwakkel, A. E. Quinlan, J. C. Rocha, A.-S. Crépin, V. Dakos, J. F. Donges, and S. J. Lade. 2025. Integrating diversity and agency into social-ecological resilience metrics. Ecology and Society 30(4):51. https://doi.org/10.5751/ES-16726-300451

Research

Integrating diversity and agency into social-ecological resilience metrics

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ABSTRACT. Resilience is an increasingly popular concept in research and practice, but quantitative resilience analyses are often disconnected from resilience theory. For example, previous studies argue that diversity, a key attribute for building resilience, and agency, essential for understanding local adaptation and transformation, are critical to understanding resilience. Despite significant progress in integrating them into qualitative frameworks, diversity and agency are rarely incorporated into quantitative social-ecological resilience metrics. This omission is concerning, given the critical role of quantitative resilience metrics in informing resilience-oriented decision-making. This study examines how diversity and agency are represented in quantitative resilience metrics across disciplines, with the goals of (a) assessing how research on social-ecological resilience currently integrates these concepts into quantitative metrics and (b) identifying future opportunities to enhance their inclusion using insights from other fields. Using topic modelling to identify different research fields and facilitate the screening process, we performed a multidisciplinary systematic meta-review of resilience metrics. To understand what types of resilience metrics are used across disciplines and where diversity and agency are more commonly included, we identified six categories of resilience metrics, with "performance under disruption" being the most used category (35%). We found that a limited number of quantitative resilience metrics include diversity and agency, with "system structure" and "compound indicators" being the main sources of diversity and agency, respectively. We further reviewed simulation models applying resilience metrics. The prevalence of performance under disruption metrics is stronger than in reviews (67%) and a similar quantity of metrics including diversity (14%) and agency (5%) was found. Drawing on insights from multiple disciplines, we outline five potential pathways to improve the inclusion of diversity and agency in social-ecological resilience metrics: using network-based metrics, using response and pathway diversity, including diversity and agency in compound indicators, integrating quantitative methodologies outside resilience theory, and improving the application of resilience in simulation models.

Key Words: *agency; diversity; resilience; systematic review; topic modelling*

INTRODUCTION

The concept of resilience has gained increasing prominence in scientific literature and policy discussions (Folke 2006, Walker et al. 2004). Resilience introduced a complex systems perspective to social-ecological systems analyses, emphasizing that system responses to changes can be nonlinear and include regime shifts (Folke 2006, Walker et al. 2004). Numerous definitions and metrics have been developed to operationalize resilience (Baggio et al. 2015, Dakos and Kéfi 2022). However, there are challenges to measuring resilience and being consistent with theoretical work (Allen et al. 2019, Quinlan et al. 2016).

Diversity and agency are recognized as important concepts in the resilience literature. Diversity, broadly defined as the range of components within a system (e.g., species, functions, or institutions, Stirling 2007), has been fundamental to shaping the resilience concept, with evidence from ecology and economics demonstrating how diversity can enhance system stability and adaptability (Biggs et al. 2015, Elmqvist et al. 2003, Walker et al. 2023). Agency, broadly understood as the capability of individuals and institutions to act and make decisions (Duncan 2019), gained importance in resilience theory recently, as it acknowledges the critical roles these actors play in building resilience, shifting the focus toward local-level analyses (Brown and Westaway 2011, Cote and Nightingale 2012, Hahn and Nykvist 2017). Although diversity and agency are recognized as important, incorporating them into resilience metrics can be challenging because metrics often use simpler conceptualizations of resilience (Allen et al. 2019). In this study, we conducted a systematic review to assess how research on social-ecological resilience currently integrates diversity and agency into quantitative metrics and identify future opportunities to enhance their inclusion using insights from other research fields. In this study, we outline our focus on social-ecological resilience and quantitative resilience metrics, discuss the significance of diversity and agency for resilience, and provide an overview of our methodological approach.

Social-ecological resilience is an interdisciplinarity concept

Social-ecological resilience is rooted in ecological resilience (Folke 2006, Walker et al. 2004). Ecological resilience was first introduced in Holling's (1973) seminal paper, which emphasized ecosystem stability and the existence of systems with multiple stable states. With the recognition of the intertwined relationship

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of humans and nature (Adger 2000, Berkes et al. 2002), the concept of ecological resilience was expanded to incorporate theories and methods from social sciences (Brown 2014, Carpenter et al. 2001, Walker et al. 2004). Social-ecological resilience theory builds on this long ecological tradition, which has influenced definitions of resilience along multiple research fields (Brand and Jax 2007, Folke 2006, Quinlan et al. 2016). A citation network analysis shows that social-ecological resilience is highly interdisciplinary and more frequently connected to other research fields than alternative conceptualizations of resilience, being strongly linked to ecology, but also with social sciences, psychology, and to a lesser extent, engineering fields (Baggio et al. 2015).

Definitions of resilience vary widely across research fields, although some common ideas are shared. Resilience is understood as the capacity of a system to deal with disturbances across different fields (Baggio et al. 2015). The concept of recovery from disturbance is relevant to most research fields: in engineering, e.g., recovery of water provision after a pipe failure (Pagano et al. 2019); in psychology, e.g., recovery of well-being after a traumatic event (Davydov et al. 2010); and in social-ecological systems, e.g., recovery of grass in rangelands after intense grazing (Anderies et al. 2002). Many fields, including psychology, community, and social-ecological resilience focus on adaptability, transformability, and learning besides recovery capabilities (Brown and Westaway 2011, Davydov et al. 2010, Walker et al. 2004). Social-ecological resilience, for example, focuses on maintaining structure and function against disruptions, which may require transformations rather than simply recovering pre-disturbance configurations (Folke 2006, Walker et al. 2004). Mathematical formalizations of resilience also show metrics from different fields are correlated in specific contexts (Dakos and Kéfi 2022, Meyer 2016, Krakovská et al. 2023); for instance, recovery time is related to probability of regime shift when computed across the entire basin of attraction (Meyer 2016). One relevant difference in how resilience is understood across fields is whether it is considered a descriptive system property, as in social-ecological resilience, or a normative and inherently desirable condition, as in disaster and development resilience (Brand and Jax 2007, Baggio et al. 2015, Hahn and Nykvist 2017). For instance, a system locked in a poverty trap that quickly returns to that state after interventions has high resilience under many social-ecological resilience definitions but low under development resilience (Lade et al. 2020).

We adopted social-ecological resilience as our primary focus while incorporating resilience definitions from other research fields to learn how they address diversity and agency. Social-ecological resilience is inherently interdisciplinary (Baggio et al. 2015, Beichler et al. 2014), valuing insights across fields and recognizing that diverse knowledge systems are essential to addressing complex, real-world environmental challenges (Allen et al. 2019, Beichler et al. 2014, Folke 2006). As discussed in the previous paragraph, different fields define resilience in distinct ways, but they also share a basic definition and have similarities. Therefore, resilience can function as a boundary object, sharing foundational concepts while being adapted for specific fields, thus facilitating communication and breaking down silos between research fields (Baggio et al. 2015). Diversity and agency are also recognized as important elements in resilience applications across multiple fields (Bandura 2006, Fabozzi et al. 2002, Pagano et al. 2019). Accordingly, by analyzing which properties of these concepts are integrated in resilience metrics in different contexts and research fields we can gain insights to improve how future social-ecological resilience applications include diversity and agency.

Measuring resilience is important for decision-making

Social-ecological resilience is a multifaceted concept that is notably challenging to measure but central to decision-making. Questions have been raised about the limitations of understanding such a complex and dynamic concept using only quantitative analysis (Brown and Westaway 2011, Quinlan et al. 2016, Leslie and McCabe 2013). We acknowledge the value of qualitative approaches in providing a deeper understanding of resilience. However, when quantitative metrics are grounded in theory, appropriately contextualized and explicit about their assumptions and limitations, they have great potential to guide policies (Carpenter et al. 2001, Quinlan et al. 2016). Quantitative resilience measures are critical in comparative studies, policy evaluations, and decision-making processes (Béné 2013, Grafton et al. 2019). Moreover, although diversity and agency are critical in both qualitative and quantitative resilience analyses, we suspect they are primarily addressed in qualitative approaches and rarely operationalized in quantitative metrics. Interdisciplinary works with social scientists have progressed in including agency in qualitative resilience assessments (Bohle et al. 2009, Haider and Cleaver 2023), but due to its subjectivity it is challenging to capture the role of agency in quantitative resilience measures, which also usually focus on system and not on agent level dynamics (Brown and Westaway 2011, Otto et al. 2020). Similarly, despite its quantitative nature, diversity is more commonly used as part of resilience frameworks. For these reasons, we focus on quantitative resilience metrics in this review.

Diversity and agency are critical for resilience

Diversity has been a central concept in the development of ecological resilience, with evidence suggesting it enhances resilience across various social-ecological systems. In ecology, debates on the relationship between biodiversity, ecosystem function, and stability have a long history (Elmqvist et al. 2003, Holling et al. 1995, McCann 2000). Besides biodiversity, the importance of diversity to resilience extends to other contexts, such as the diversity of land use, livelihoods, cognitive capacity, knowledge systems, and institutions (Biggs et al. 2015, Freeman et al. 2020, Page 2010). Studies that synthesized lists of properties or principles critical to resilience across domains and systems consistently highlight the importance of diversity, with it included in the so-called resilience principles, attributes and others (Biggs et al. 2015, Carpenter et al. 2012, Rockström et al. 2023, Walker et al. 2006). In general, systems composed of many elements are more resilient than more homogeneous systems (Biggs et al. 2015, Walker et al. 2006), though the impact of diversity can vary depending on the context and its distribution across scales (Biggs et al. 2015, Walker et al. 2023). In some cases, too much diversity might undermine resilience (Biggs et al. 2015, Mori et al. 2013).

The concept of response diversity offers a mechanistic explanation for why diversity can enhance resilience (Elmqvist et al. 2003, Walker et al. 2023). Systems with components that respond differently to disruptions are only partially affected by disruptions, allowing other components to continue functioning and maintaining the system's resilience (Elmqvist et al. 2003, Walker et al. 2023). This effect has been observed in empirical ecological studies and has also been extended to social and social-ecological systems, as well as local and global scales (Leslie and McCabe 2013, Walker et al. 2023). For example, species diversity is important to seed dispersal in tropical forests. As different species responsible for seed dispersal respond differently to disruptions, events like a cyclone or wildfire only affect some species, preserving the seed dispersal function (Elmqvist et al. 2003, Biggs et al. 2015). Similarly, traditional farmers in some tropical regions choose crops with varying tolerances to water scarcity and flooding, using agricultural diversity to increase their resilience to floods or droughts and maintain some level of crop production (Lin 2011).

The central role of agency in contributing to social-ecological resilience is well-documented in the literature. The integration of social-ecological resilience with social science theories lead to the recognition of the importance of agency for resilience (Bohle et al. 2009, Brown 2014, Brown and Westaway 2011, Cote and Nightingale 2012, Coulthard 2012) and recent resilience frameworks have incorporated agency as a key component (Bohle et al. 2009, Hahn and Nykvist 2017, Haider and Cleaver 2023, Zhang et al. 2025). In multiple contexts, adaptive capacity is built locally, and we need to understand agents' motivations, practices, history and worldviews, besides systemic factors affecting their agency like power and governance structures, to understand their decision-making and how they respond to change (Brown and Westaway 2011, Cote and Nightingale 2012, Haider and Cleaver 2023). Actor motivation and agency can undermine resilience, for example, if a few powerful actors promote their self-interest over collective resilience, but when agency is aligned with resilience-building objectives it can be a powerful mechanism to develop resilience (Zhang et al. 2025). For instance, Bohle et al. (2009) use an agency-based resilience framework to argue that informal food vendors, their social capital and personal compromise are crucial for the resilience of Dhaka's food system to droughts and resilience-building strategies should focus on enabling their capability and well-being.

Agency is particularly important for building transformative capacities in social-ecological systems. Key actors and institutions are essential for guiding and promoting transformations and social-technical innovation (Brown and Westaway 2011, Westley et al. 2011, Westley et al. 2013). These actors provide leadership, identify leverage points, develop shared visions and coordinate actions (Olsson et al. 2014, Westley et al. 2011). Furthermore, different types of agency and capabilities are important at various stages of the transformation process. Knowledge carriers and innovators are critical in the early phases when new ideas are being developed, while reinforcers and organizers become more relevant in later stages when proposals are scaling (Olsson et al. 2014, Westley et al. 2013).

Diversity and agency are also important for resilience in fields beyond social-ecological systems. In economics, portfolio theory highlights the importance of asset diversification for managing risk (Fabozzi et al. 2002). In engineering and critical infrastructure resilience, researchers recognize the importance of having diverse ways of delivering water in water distribution networks (Pagano et al. 2019). Psychological research investigates how both external and internal factors influence individual agency and the ability to cope with disruptions (Bandura 2006). In business, researchers analyze preparedness and the capability of organizations to act and respond to crises (Rose 2007).

Methodological approach

Here we assess with what frequency and how resilience metrics from multiple fields include diversity and agency with the goals of assessing how research on social-ecological resilience currently integrates these concepts into quantitative metrics and identifying future opportunities to enhance their inclusion using insights from other fields. We choose to analyze these specific concepts and not other concepts relevant to resilience for four reasons. First, there is strong evidence and agreement on their importance, as discussed in subsection - Diversity and agency are critical for resilience. Second, researchers have called for more studies to incorporate social science and agency theories into resilience analysis (Cote and Nightingale 2012, Olsson et al. 2015) and highlight the need to better understand and quantify the relationship between diversity and resilience (Biggs et al. 2015, Mori et al. 2013). Third, they bridge debates from the two main communities of social-ecological systems, the ecology, for diversity, and the social sciences, for agency. Finally, we suspect there is a noticeable gap in operationalizing these concepts in quantitative metrics, as these concepts are mainly used in theoretical and qualitative frameworks, as discussed in subsection - Measuring resilience is important for decision-making. As such, by analyzing how these two concepts are included in resilience metrics across different fields, we aim to identify gaps in the literature and suggest pathways to improve social-ecological resilience metrics.

To assess the inclusion of diversity and agency in quantitative resilience metrics, we first conducted a meta-review. By focusing on review articles, we aimed to capture a broader landscape of resilience metrics across multiple fields without needing to analyze individual case studies. This approach allowed us to understand how different research fields operationalize resilience and engage with agency and diversity, which is critical since resilience is an interdisciplinary concept (subsection: Subsection Social-ecological resilience is an interdisciplinarity concept). Additionally, selecting review articles enabled us to capture diverse quantitative resilience applications, including empirical studies, theoretical frameworks, and simulation models. One outcome of the meta-review was the identification of six categories of resilience metrics. The primary goal of this categorization is to provide a structure for analyzing how resilience metrics include agency and diversity as methodological constraints can make it challenging to include these concepts in certain types of metrics.

We further explore the operationalization of agency and diversity in resilience metrics through their use in simulation models. Analyzing case studies allows us to better understand the context of each problem and how each metric is used. We focus on simulation (or process-based) models — i.e., models which explicitly and often quantitatively generate results showing how systems change over time, often based on theoretical assumptions and mathematical descriptions of systems (Cuddington et al. 2013) — because of their key role in theory development, scenario exploration, and policy design (Cuddington et al. 2013).

Moreover, despite their importance in both contexts, we hypothesize that the absence of diversity and agency in resilience metrics is more pronounced in simulation models than in statistical or exclusively data-based analyses. For instance, community resilience metrics from small-scale empirical studies often capture the role of agency (Sharifi et al. 2016). However, simulation models typically operate at broader scales, making it difficult to account for agency, a property defined at the individual or agent level (Macy and Willer 2002).

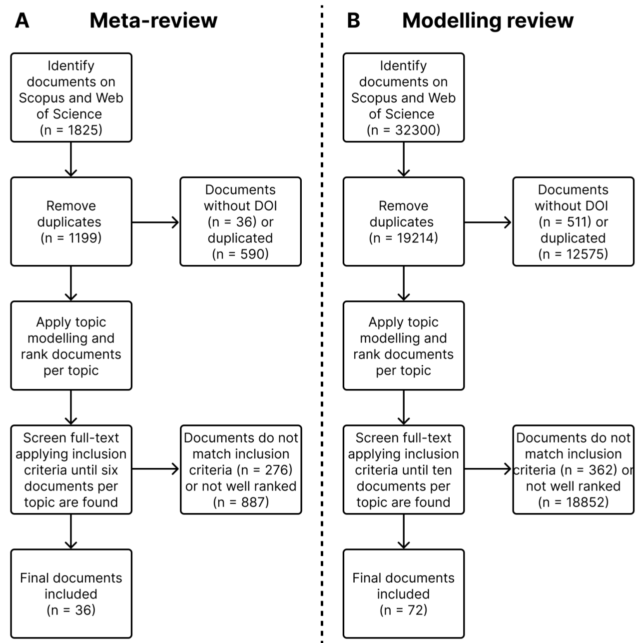
METHODS

We performed two systematic reviews (Fig. 1): (A) A meta-review of resilience metrics to capture domain-specific reviews and understand how different research fields measure resilience and (B) a review of resilience metrics applied in simulation models. We first describe the aspects of our methods common to both reviews, then review-specific methods. Across both reviews, we utilized the Web of Science and Scopus databases, adopting DOIs as unique identifiers to merge the databases and excluding documents without DOIs.

Given the large number of results, 1825 for reviews and 32,300 for modelling, we used topic modelling in each review component to facilitate the screening process and filter selective reading (Blei et al. 2003). This statistical modelling technique identifies clusters (or topics) among a set of documents to group similar documents. Topic modelling assumes that when authoring a text, an author discusses one or more topics. A topic is a vector of probabilities for each word in the corpus. So, a specific topic can be interpreted as a set of words ranked according to their probability of occurrence, while each document is a mixture of one or more topics. Given a corpus, statistical techniques can infer the topics presented in the corpus and the mixture of topics in each document. Specifically, we used Latent Dirichlet Allocation (LDA; Blei et al. 2003) as our statistical technique for topic modelling due to its stability and widespread adoption. We trained the LDA model with titles, abstracts, and author's keywords as inputs. Then, we computed the topic distribution probability for each document and assigned the topic with the highest probability to that document. To select the number of topics we evaluate the topic coherence - a quantitative measure of the interpretability of a topic - and the topic diversity - measured as the percentage of unique words in the top 20 words of all topics - and select the value that maximizes the product of the two indicators, as done by Dieng et al. (2020). Note that the modelling review and meta-review have different topic models because they use different datasets.

The first three authors read the documents included in this study to collect three key data for each metric in both reviews: the metric category, whether the metric incorporates agency and diversity elements and how these two concepts are included. After the reading process, we validated a random sample of the results, addressing disagreements in discussions with a larger group of co-authors. We included in our final sample any resilience metrics the authors of the analyzed documents defined as resilience, to include how multiple research fields define and operationalize resilience. Because not all papers directly mention diversity and agency, we adopted specific criteria to define when a metric includes these concepts (subsections: Agency criteria, and Diversity criteria). More details on the reading process can be found in Supplementary Methods (Appendix 1).

Fig. 1. Flowchart of the process to obtain the included documents in two reviews: (A) meta-review and (B) modelling review. The diagram covers the database search to the final selection of documents, adapted from PRISMA (Page et al. 2021). An alternative validation methodology was performed in parallel with B but was not included here because we only report these results in the Supplementary Methods in Appendix 1.



Meta-review

The search terms utilized for the meta-review are provided in Table 1. We adopted a shorter year range for the meta-review to ensure we selected reviews that provide an up-to-date perspective on each research field, a common practice in systematic reviews (Gough et al. 2017). Older reviews would miss newer approaches to measure resilience, and most of their metrics are already captured in more recent reviews. In addition, the literature on resilience is recent, and we would increase the sample size by less than 10% by widening the year range (Appendix 1: Fig. S1).

We ran the LDA algorithm with seven topics, merging two psychological topics due to their similarity. The algorithm yielded the following topics: urban, community and disaster; health and psychology; supply-chain; environmental science and food; energy and power-grid; ecological, soil, and animal. Then, for each topic, we performed two sortings: by number of citations and by year of publication. The first sorting aimed to identify influential and well-known publications on the topic, while the latter aimed to capture newer publications that might present fresh perspectives not found in the most influential works. Finally, we read the ordered list of documents, stopping when we identified three documents that satisfied the inclusion criteria for each combination of topic and sorting. The process resulted in six documents per topic model - three from the most cited list and three from the most recent list - with 36 documents overall. The

Table 1. Search terms used to get the initial set of documents in the meta-review and modelling review.

	Meta-review search	Modelling review search
Title	resilienc*	------
Title-abstract-keywords	(metric OR measure* OR quant* OR indicat* OR index OR score OR scale OR criter*)	resilienc* AND (metric OR measure* OR quant* OR indicat*) AND (model* OR simulat*)
Document type	Review	Article
Language	English	English
Date of publication	2010 - 2023	2000 - 2023
Search date	8th March 2023	16th March 2023
Database	Scopus and Web of Science	Scopus and Web of Science

inclusion criteria were (1) the document presented multiple quantitative resilience metrics, and (2) it provided sufficient information on most of the metrics, at least sufficient for categorizing the metric and determining if it includes agency and diversity. We considered as a quantitative resilience metric any type of indicator or index, whether composite or single, that assigns numerical values to resilience and enables comparison across different systems, scenarios, or points in time. In the meta-review we lack the context that would allow us to assess inclusion of agency and diversity in individual metrics. Therefore, we classified how frequently applications of metrics in each category take diversity and agency into account, based on our understanding of the literature. We provide more details on how this score was computed in the Supplementary Methods (Appendix 1).

Modelling review

The terms used for the modelling component are provided in Table 1. We followed a similar procedure to the meta-review, using topic modelling to group different documents and select documents from each topic. We ran the LDA algorithm with six topics and merged two psychological topics due to their similarity. The algorithm yielded the following topics: urban, community and disaster; health and psychology; environmental science; energy and power-grid; and ecological. Then, we used the same two sorts from the meta-review, by number of citations and by year of publication. To cover a broader range of applications, we chose a larger sample size than in the meta-review in which each document already covered a wider range of metrics from a research field. We read the ordered list of documents, and for each combination of topic and sorting, we stopped when we identified ten documents that satisfied the inclusion criteria or when fifty documents were read. We added a second stopping criterion because some topics showed a low percentage of valid papers (<20%), mainly due to a low use of simulation models. The process resulted in 72 documents. We had twelve documents for the urban, community and disaster topic and zero for the health and psychology topic. For the remaining topics, we had twenty documents, ten from the most cited list and ten from the most recent list. To cross-validate the results using an alternative methodology, in Supplementary Methods (Appendix 1), we categorized documents from selected journals. We selected at least one journal from each topic, except for the health and psychology topic. For more information, consult Appendix 1.

The inclusion criterion was that the document presents a simulation (or process-based) model that computes a numerical value for resilience at some stage. The exclusion criteria were that the document (1) applies statistical models to data or conceptual models or (2) presents a metric but does not apply it in a simulated model. Example criteria for including a paper include the paper's ability to present and apply an equation defining resilience in a simulation model, graphically communicate resilience, or provide numeric values of resilience measures. Compared with the meta-review, on the simulation review there is more context available on how the metric is used. Thus, while for the meta-review, we provide a classification of inclusion of diversity and agency by category, for the modelling review we provide a case-by-case classification for each metric.

Agency criteria

To assess whether a resilience metric incorporates agency elements, we applied Anthony Giddens' structuration theory. Giddens sought to bridge the duality between social structure and agency, arguing that individuals both reproduce and change the structure through their actions, while also being constrained by structural rules and resources (Duncan 2019, Giddens 1984). He identifies *knowledgeability* and *capability* as the fundamental characteristics of human agency (Duncan 2019, Whaley 2018). Given the challenges of capturing knowledgeability in our sampled metrics, we focused on capability, which is defined as the capacity of agents to "command relevant skills, access to material and non-material resources and engage in particular organising practices" (Whaley 2018). Based on this formal understanding of agency, capability, and agent, we used the following criterion: does the metric measure agents' capability to act? Examples of measures of agents' capability include measures of agents' capital, options, responses or paths available for the agents, and measures that consider how social structure, norms, power, and agents' knowledge can limit the agents' actions and capability. More details on how this was applied can be found in Appendix 1.

We make two notes on how we considered other definitions of agency and interpreted this concept. First, we expanded Giddens' definition of agency to incorporate groups of individuals. Specifically, we considered an agent to be the entity responsible for the decision-making process, encompassing individuals, households, groups of individuals, and formal institutions. We made this adaptation because, in methodological trials, the sampled metrics commonly focused on composite agents. Furthermore, social psychology and sociology studies recognize the importance of collective actors' agency (Bandura 2006, Morris et al. 2001, Otto et al. 2020). Second, we acknowledge the significance of non-human agency, which includes the agency of non-human living creatures and materials (Contesse et al. 2021, Duncan 2019). However, we limited our focus to human and groups of humans' agency due to the challenges associated with defining and identifying non-human agency.

Diversity criteria

Diversity is an attribute of any system composed of elements that can be subdivided into categories (Stirling 2007, Page 2010). These categories may encompass a wide range of entities, such as biological species in an ecosystem, assets in a portfolio, or available actions when facing a problem. Here, we interpret diversity in terms of the three properties identified by Stirling

Table 2. Description of the six resilience metric categories identified in the meta-review. The focus reflects whether the category emphasises persistence, adaptation, or transformation capacities of resilience and was determined based on the descriptions provided in the reviews. The review articles cited in the last column are examples that captured that category particularly well.

Category	Description	Purpose	Focus	Data needed	Examples of metrics	Research fields	Review articles
Shape of potential landscape	Measures geometrical properties of the potential landscape	Identify proximity to critical transition	Persistence	Critical threshold or mathematical model defining potential landscape	Distance to the basin threshold, potential depth, size of the basin of attraction	Social-ecological, Ecology, environmental science	Meyer 2016, Dakos and Kéfi 2022
Early-warning signal	Measures statistical signatures in a time-series	Identify the risk of critical transition	Persistence	Long time series of system state	Variance, autocorrelation, skewness	Social-ecological, Ecology, environmental science	Scheffer et al. 2015, Dakos and Kéfi 2022
Performance under disruption	Measures performance during the disturbance-recovery process to analyse the effect of disturbances	Measure the impact or loss caused by disturbance	Persistence	Time series of system state	Recovery time, performance loss (resilience triangle), ratio of performance recovered	Engineering, supply-chain, economics, management	Hosseini et al. 2016, Cheng et al. 2022, Steinmann et al. 2024
System structure	Measures the quantity of or relations between system constituents	Measure potential impact and propagation of disturbance	Persistence	Quantity or relation between system constituents	Number of elements in the system, average node degree, average shortest path length	Power-grid, supply-chain	Jufri et al. 2019, Zhou et al. 2019, Liu et al. 2022
Compound indicator at the system level	Groups multiple independent indicators (mostly) at the system level	System capacity to deal with disruptive events	Adaptation and Transformation	Socioeconomic indicators, infrastructure indicators, biological indicators	Resilience Index Measurement and Analysis, The Australian Natural Disaster Resilience Index	Urban, community, and disaster	Sharifi 2016, Laurien et al. 2022
Compound indicator at the individual level	Groups multiple independent indicators (mostly) at the individual level	Individual capacity to deal with disruptive events	Adaptation and Transformation	Questionnaires answered by one individual	Connor-Davidson Resilience Scale, Resilience Scale for Adults	Psychology, medicine, psychiatry	Pangallo et al. 2015, Satapathy et al. 2022

(2007): variety, balance, and disparity. Variety refers to the number of distinct types of elements the system has, for example, the number of species in an ecosystem. Balance relates to the distribution of types in the system or how much of each type of element the system has, for example, the evenness in the distribution of species. Disparity refers to how different from each other are the type of elements the system has, for example, the average genetic distance between all species. We employed a binary classification to evaluate the incorporation of diversity in resilience metrics. A metric incorporates diversity if it explicitly quantifies the variety, balance, or disparity of a specific element within the system.

RESULTS

We present the systematic review results based on its two components. The first two subsections (Identification and categorization of resilience metrics, and Inclusion of diversity and agency in resilience metrics), cover the meta-review results on metric categorization and inclusion of diversity and agency, and the last subsection cover the modelling review. More detailed information on the documents and metrics analyzed can be found in Appendix 1: Table S1.

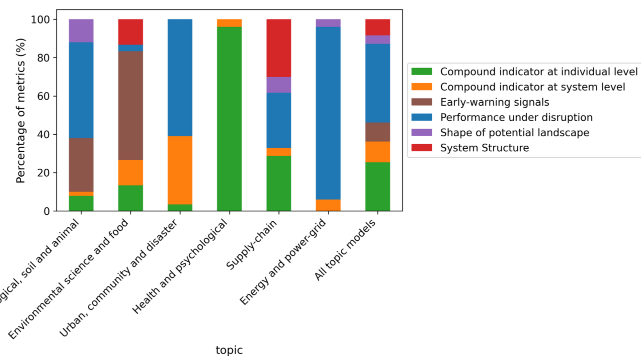
Identification and categorization of resilience metrics

Based on the trial readings of the meta-review corpus and discussions with the co-authors, we developed six categories of resilience measures, each of which describes a distinct process to measure resilience (Table 2). From the 36 included documents, we collected 312 metrics, averaging 8.6 metrics per document, with each metric classified into one category. Note that the complete set of 312 metrics can contain duplicate metrics, as different documents can present the same metric, and we did not merge them when this happened.

Two metric categories have origins in ecology and are commonly used in research in social-ecological resilience. The shape of potential landscape category holds historical significance as one of the earliest approaches to analyzing resilience in ecology (Holling 1973, Walker et al. 2004). Early-warning signals is a recent model-free approach to analyze the system's stability based on statistical patterns in the time series of the system state (Scheffer et al. 2015). These two categories were mainly limited to the two topics most associated with social-ecological systems, shown on the left of Figure 2, with early-warning signals accounting for 57% of the metrics in the environmental science and food topic. Surprisingly, they were not the most common categories in two topics closely related to social-ecological systems: ecology, soil, and animal and the urban, community and disaster topics. A possible explanation for this result is the predominance of qualitative approaches in social-ecological resilience research (González-Quintero and Avila-Foucat 2019, Polain de Waroux et al. 2024). In the absence of more operational metrics, researchers often rely on performance under disruption metrics, which are easier to apply.

In the engineering domain, it is possible to distinguish between performance and structure-based resilience metrics (Pagano et al. 2019). The first is represented by the performance under disruption category, which encompasses a wide range of metrics that measure resilience by analyzing the performance of a system over time under disruptive events (Cheng et al. 2022, Steinmann et al. 2024). The second is represented by the system structure category, which assess resilience by measuring the relationships between the system's elements, encompassing primarily network topology measures (Jufri et al. 2019, Liu et al. 2022). The most mentioned metric category in our sample was the performance under disruption category, accounting for 35% of all sampled metrics (Fig. 2). It was most mentioned in topics closer to engineering, such as energy and power-grid (90%), and urban, community and disaster (61%) topics. Systems structure metrics were mentioned most frequently in the supply-chain topic (30%, Fig. 2).

Fig. 2. Percentage of each metric category mentioned in the six topics and total corpus. The figure was generated using the meta-review corpus (N = 312 metrics). Topics closer to the social-ecological field are on the left.



Lastly, we have compound indicators that encompass metrics that aggregate multiple indicators into a single metric. In compound indicators at the system-level category, metrics typically aggregate socioeconomic, demographic, and infrastructure indicators to derive a comprehensive resilience metric (Sharifi 2016, Laurien et al. 2022). In compound indicators at the individual level measures protective factors associated with coping well with disruptive events or evaluate individuals' previous experiences in stressful situations (Davydov et al. 2010). These two categories are the only ones that focus on adaptation and transformation capacities (Table 2), emphasizing the need to include multiple research fields to capture different aspects relevant to resilience, as the remaining metrics focus primarily on persistence. Compound indicators at the individual level were largely confined to the health and psychology topic, where they appeared most and dominated (96%). Compound indicators at the system levels appeared most on urban, community and disaster topic (48%, Fig. 2).

Inclusion of diversity and agency in resilience metrics

In the ecology, soil and animal and environmental science and food topics, the topics more aligned with social-ecological systems resilience, we observed a predominance of performance under disruption and early-warning signal categories, which have a low and very low inclusion of diversity and agency, respectively (Table 3). Most metrics closer to social-ecological resilience incorporating diversity and agency were found in compound indicators at the system level, especially if we consider part of the documents in the urban, community and disaster topic. A common element included in compound indicators at the system level that included diversity is economic diversity, such as the diversity of employment sectors, income levels, and livelihoods (Laurien et al. 2022, Sharifi 2016). The City Resilience Profiling Tool considers that a diversified employment base increases the capability to deal with disasters as industries are affected differently, an example of response diversity promoting resilience (UN-Habitat 2018, Walker et al. 2023). The Natural Hazard Resilience Screening Index considers that a diverse pool of skills can support recovery and rebuilding efforts, an example of functional diversity promoting resilience (Summers et al. 2018, Walker et al. 2006). Regarding agency, metrics typically included factors such as population preparedness, training, and access to essential physical resources needed to effectively respond to catastrophic events (Laurien et al. 2022, Sharifi 2016). The Australian Disaster Resilience Index considers that the lack of prior planning, limited access to crucial information, physical resources, and agentic constructs at higher scales, such as community engagement, governance and leadership, can alter the community resilience to disasters, as they affect the agency of individual actors (Parsons et al. 2016, 2020, 2021).

We observed a limited inclusion of diversity in our complete sample, with four out of six metric categories showing low or very low inclusion of diversity (Table 3). Shape of potential landscape and early-warning signal showed the lowest inclusion of diversity, with no positive example found (Table 3). On the other hand, the system structure category, which is highly used in supply-chain resilience, featured the highest inclusion of diversity in resilience metrics (Table 3). In this category, metrics related to the number and density of nodes and links in a network measured resilience by considering the diversity of elements within the system. For instance, in analyzing the resilience of public transportation networks to events like failures at specific train stations, metrics like the average shortest path indicate the impact of removing nodes and whether this leads to the segmentation of the network (Berche et al. 2009, Zhou et al. 2019). Generally, networks with a higher number of nodes performing similar functions depend less on individual components and are more tolerant to failures or targeted attacks on specific nodes or links (Han et al. 2020, Zhou et al. 2019).

We also observed a limited inclusion of agency in our complete sample, with four out of six metric categories showing low or very low inclusion of agency in our sample (Table 3). Shape of potential landscape, early-warning signal and system structure showed the lowest inclusion of agency, with no positive example found (Table 3). On the contrary, agency is most frequently included within the compound indicator at the individual level category, particularly within psychological resilience (Table 3). By placing the individual at the center of the process, psychological resilience typically measures individual resilience by quantifying the presence of protective factors or personality traits associated with a better capability to overcome stressful events (Davydov et al. 2010, Friborg et al. 2003). Measurements encompass aspects ranging from internal factors like emotions and self-esteem to external elements such as relationships within the community and family cohesion, all of which influence an individual's adeptness at navigating stressful events (Davydov et al. 2010, Pangallo et al. 2015). In these measures, the individual is conceptualized as constantly acting and using available resources to adapt to disruptive or stressful situations, with their agency serving as a core component of the resilience measure.

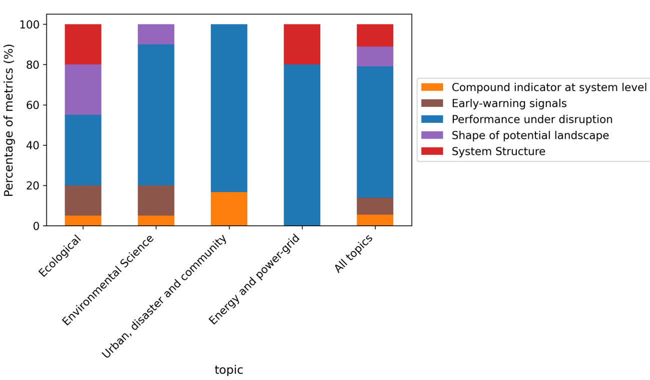
Resilience metrics in simulation models

In the modelling review, the predominance of the performance under disruption category is even more substantial, with 65% of all sampled metrics categorized as such (Fig. 3). In the ecological and environmental science topics, which are more aligned with social-ecological systems, we observe more traditional ecological and social-ecological resilience metrics such as metrics based on shape of potential landscape (25% of the ecological topic) and early-warning signal (15% of the environmental science topic), though there is a high use of performance under disruption

Table 3. How and with what frequency resilience metric categories include diversity and agency, based on the meta-review results. The supplementary material in Appendix 1 discusses how the scores were computed.

Category	Frequency of diversity inclusion	How did metrics include diversity?	Example of a metric that includes diversity	Frequency of agency inclusion	How did metrics include agency?	Example of a metric that includes agency
Shape of potential landscape	Very low	Into the model's state, but diversity elements are rarely incorporated into the state	No example found	Very low	Into the model's state, but agency elements are rarely incorporated into the state	No example found
Early-warning signal	Very low	Into the model's state or early-warning indicator, but diversity elements are rarely incorporated into the state	No example found	Very low	Into the model's state or early-warning indicator, but agency elements are rarely incorporated into the state	No example found
Performance under disruption	Low	Into the performance indicator. Metrics can assess performance based on network measures related to the system diversity	Metric is the cumulative impact on performance. Performance is measured based current traffic flow and disrupted traffic flow between nodes of a transportation network (Zhou et al. 2019)	Low	Into the performance indicator. Metrics can have agent capability as performance indicator or measure the agent capability to influence the performance	Metric is how much recovery actions avoid performance loss compared to business-as-usual (Rose 2007)
System structure	Very high	Metrics typically capture diversity by measuring the diversity of nodes and links	Metric is the average shortest path or the number of nodes in the biggest network component (Zhou et al. 2019)	Very low	Depends on the system and its elements, but agency elements are rarely incorporated	No example found
Compound indicator at the system level	High	Metrics commonly incorporate elements such as economic diversity	The City Resilience Profiling Tool considers economic, transportation and biological diversity indicators to measure urban resilience (UN-Habitat 2018).	High	Metrics commonly incorporate elements that influence agent capability, such as access to information and infrastructure	The Australian Disaster Resilience Index considers information and infrastructure access as structural factors to individual action (Parsons et al. 2016, 2020, 2022).
Compound indicator at the individual level	Low	Metrics can include factors such as diversity of social support or access to different resources	The Resilience Index Measurement and Analysis uses dietary diversity to assess household resilience (FAO 2016)	Very high	Metrics typically include the role of self-reflection, traits that help individuals cope with stressful events, and the individual's relationship with family, friends, and community.	The Resilience Scale for Adults evaluates elements such as perception of self, personal competence, family cohesion, and social resources (Friborg et al. 2003)

Fig. 3. Percentage of metrics category mentioned in the modelling review corpus per topic (N = 72 metrics). Based on the classification of all resilience metrics from the modelling review, we show the most common metrics category per topic. The category compound indicator at the individual level was not found in this corpus. For the urban, disaster, and community topic we used a smaller sample size (12 instead of 20), as discussed in subsection: Modelling review. Topics closer to the social-ecological fields are on the left.

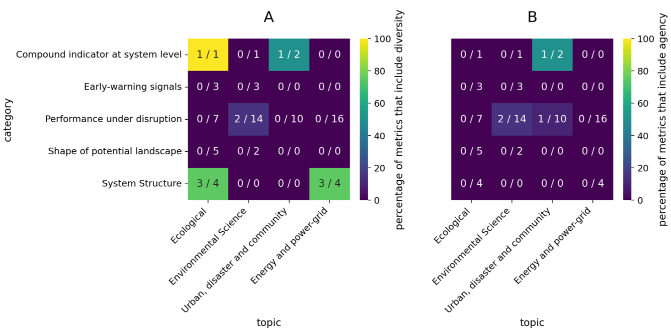


metrics. Performance under disruption metrics were the most used across all topics, likely due to the ease of operationalizing metrics of this category within simulation models. This metric category is especially predominant in the urban, disaster, and community (83%) and energy and power-grid (80%) topics. Compound metrics at the system and individual levels showed the highest overall percentual reduction when compared with the meta-review, 5% and 25% respectively, with the latter being completely absent from this corpus due to the low use of simulation models in psychology. When classifying resilience metrics in five selected journals from different topics, we obtained a similar result, validating our document selection methodology. Performance under disruption is used on 70% of metrics and is predominant in all journals except for Ecology and Society, where the shape of potential landscape category is predominant (54%, Appendix 1: Fig. S5).

In the ecological and environmental science topics, the topics more aligned with social-ecological resilience, we observe a limited inclusion of diversity and agency (15% for diversity and 5% for agency, Fig. 4). Here are a few notable examples of the inclusion of these concepts in social-ecological articles. Bitterman and Bennett (2016) measure the resilience of agricultural systems using a bi-dimensional potential landscape composed of the landscape diversity, which is considered to provide greater functional and response diversity, and the mean net profit, which reflects farmers' capability to overcome disruptions. Estrada and Bodin (2008) measure the resilience of a landscape in Madagascar to patch loss using the size of the largest network component and clustering coefficient, which capture the diversity and density of links between habitat patches. Lankford et al. (2023) measure the resilience of irrigated agriculture in South Africa to droughts using a performance indicator that captures farmers' capabilities to respond to droughts.

Few metrics in the complete simulation model sample include diversity measures (14% of all metrics, Fig. 4a). Similar to the meta-review, metrics that include diversity reside predominantly in the

Fig. 4. Heat map of (A) the percentage of resilience metrics that include diversity (B) the percentage of resilience metrics that include agency, per category and topic in the modelling review corpus (N = 72 metrics). In the text inside each cell, the numerator is the number of metrics that include diversity (A), or agency (B) and the denominator is the total number of metrics in the cell. For the urban, disaster, and community topic we used a smaller sample size (12 instead of 20), as discussed in subsection: Modelling review. Topics closer to the social-ecological fields are on the left.



system structure category. Metrics in this category predominantly analyze critical infrastructure networks such as power-grid and water distribution networks. For example, systems with energetic redundancy, where water flows can reach nodes from multiple alternative routes, will be more resilient to pipe failure (Pagano et al. 2019). We found a smaller number of metrics including diversity in the compound indicator category — where a metric includes transportation routes diversity during disasters (Hosseini and Barker 2016) as a way to provide response diversity to the analyzed systems — and the performance under disruption category — where a metric includes vegetation diversity as a performance indicator (Gustafson et al. 2023).

Compared to diversity, we observe even fewer metrics including agency in the complete simulation model sample (5% of all sampled metrics, Fig. 4b). Performance under disruption and compound indicators at the system level are the primary source of metrics including agency in the modelling review. Availability of resources during disruptions emerges as a recurrent theme in these metrics, encompassing aspects like the availability of human resources, equipment, and knowledge during disasters (Hosseini and Barker 2016, Pagano et al. 2017). Covering more subjective elements, one metric considered both “real” and “perceived” resilience, with the latter guiding decision-makers’ actions to build disaster recovery plans (Zobel 2011). Multiple articles in the ecological and environmental science topics focused solely on non-human ecological elements, recognizing the human impact but not modelling it. Most articles from other topics had models with agents making decisions. However, they do not consider the agents’ capability to act when measuring resilience.

DISCUSSION

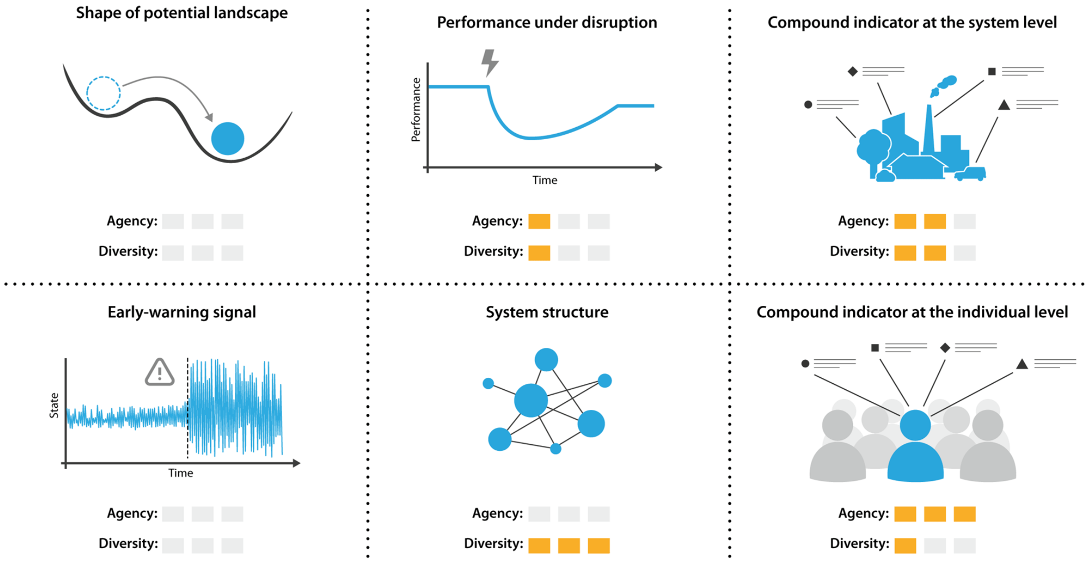
Prominent works have identified the importance of diversity and agency in social-ecological resilience (Biggs et al. 2015, Brown and Westaway 2011). Significant progress has been made in integrating these concepts within qualitative and theoretical contexts (González-Quintero and Avila-Foucat 2019, Hahn and Nykvist 2017). However, studies suggest that there are challenges to operationalizing these concepts in resilience quantitative metrics (Cote and Nightingale 2012, Leslie and McCabe 2013). Our findings confirm the limited use of these concepts: for the sampled documents, we observe that quantitative resilience metrics rarely incorporate diversity and agency (Fig. 5). For instance, in the meta-review, over 60% of metrics fall into categories with low or very low inclusion of either diversity or agency (Fig. 2 and Table 3). Metrics incorporating diversity were predominantly found in the system structure and compound indicators at the system level categories, while agency was primarily included in compound indicators at both the individual and system levels. Simulation models exhibited an even greater disparity, with more than 80% of metrics falling into categories with less than 20% inclusion of either diversity or agency (Fig. 4). The lower inclusion of these concepts in simulation models is largely due to the reduced presence of compound indicators. An interesting next step would be to assess whether the observed lack of diversity and agency in simulation models also applies to empirical application of resilience metrics.

Differences in how research fields conceptualize resilience help explain the inclusion of diversity and agency in Figure 5. Metrics closer to ecological and social-ecological resilience (Fig. 5, left) tend to focus on ecosystem processes and often overlook individual dimensions such as agency. While ecological and social-ecological resilience frequently recognizes the importance of diversity as a property that confers resilience, it typically does not include it explicitly in metrics. Metrics closer to engineering fields (Fig. 5, middle) are highly varied but tend to prioritize recovery of performance indicators and often neglect human dimensions, resulting in a low inclusion of agency. However, surprisingly, system structure metrics, which commonly measure infrastructure and supply-chain network indicators, show the highest inclusion of diversity between all categories (Fig. 5). Compound indicators at the individual level are primarily used in psychology resilience, where humans are central, leading to a high inclusion of agency (Fig. 5). Compound indicators at the system level are predominantly used in community, urban and disaster resilience, where metrics tend to incorporate multiple dimensions such as social, organizational, infrastructure, ecological, and others. The use of multiple indicators and adoption of a multifactorial perspective result in a moderate inclusion of both diversity and agency (Fig. 5), showing a possible pathway to increase the inclusion of these concepts in social-ecological resilience metrics.

Why should social-ecological resilience metrics include diversity and agency?

The failure of many social-ecological resilience metrics to include diversity overlooks a key determinant of resilience and risks poorly designed management. In the subsection: Diversity and agency are critical for resilience, we summarized literature showing the importance of diversity for social-ecological systems. For example, social-ecological systems with greater diversity are often more resilient than homogeneous ones, though not always (Biggs et al. 2015). Our literature reviews subsequently showed that metrics often neglect this important feature of social-ecological resilience. Unintended consequences of omitting diversity include: (1) Metrics focused on detecting proximity or risk of critical threshold can lead to management strategies

Fig. 5. Quantitative resilience metrics rarely address agency and diversity. We present a summary of our results showing how frequently the sampled documents of this study use resilience metrics that include agency and diversity, for six metric categories. We determine scores (Supplementary Methods in Appendix 1) that range from rare to high inclusion of agency and diversity based on the results of the meta-review (Table 3) and modelling review (Fig. 4). Illustration made by Azote.



focused on increasing stability and reducing disturbances, which can reduce variability and stop the system from building response diversity (Carpenter et al. 2015). (2) Management based on these metrics can improve resilience against specific disruptions but can undermine the system's capacity to handle unknown events and deep uncertainty, while diversity is an emergent property associated with general resilience (Carpenter et al. 2012, Walker et al. 2023). The importance of diversity to resilience depends on the resilience questions: resilience of what and to what (Carpenter et al. 2001). Highly specialized and more homogenous systems might be necessary to handle resilience to specific disruptions, as diversity can increase system complexity and reduce efficiency (Biggs et al. 2015, Carpenter et al. 2012). Generally, including diversity in resilience metrics is especially important when analyzing systems composed of multiple actors or components, as they will likely act differently and respond differently to disturbances. For example, perceptions of reality and cognitive diversity, together with the capability of agents to generate shared goals and diffuse conflict, are a mechanism to solve common-pool problems, promote cooperation and resilience (Freeman et al. 2020, Cronin and Weingart 2019). Overall, diversity is related to resilience in most social-ecological systems at appropriate temporal and spatial scales (Biggs et al. 2015, Walker et al. 2023).

Likewise, the failure of many social-ecological resilience metrics to include agency risks poorly designed management actions. The literature highlights the importance of understanding agents' motivations for building resilience at local scales (subsection: Diversity and agency are critical for resilience). Neglecting agency in resilience metrics can underestimate actors' roles in producing change and the factors influencing this capability. For example, (1) Simpler metrics such as performance loss and recovery time often ignore agency and taking management decisions based on them can lead to solutions that ignore how conflicts and power dynamics constraining agency affect the system, favoring the status-quo, a depoliticized description of resilience and missing who benefits from enhancing resilience (Brown 2014, Cote and Nightingale 2012, Semplici et al. 2024, Parsons 2024). Without a deeper understanding of the local level, improving the resilience of fishing communities can promote solutions such as exiting fishing that might reduce performance loss but does not match the community values and undermines their long-term well-being (Coulthard 2012). (2) Beyond these practical implications, neglecting agency can increase the already noticeable gap between practical application and theoretical works (Quinlan et al. 2016, Reyers et al. 2022), as well as making resilience analyses less relevant to social scientists, causing communication problems and making knowledge integration harder (Brown and Westaway 2011, Olsson et al. 2015, Parsons 2024). Analyzing agency is especially relevant when the gap between the agent and system level is small and when differentials of power and influence between agents are low. For example, agency is crucial to resilience in small-scale communities where few agents can each have a considerable influence on their shared natural resources. The impact of each agent in the system is less evident in large-scale and decentralized systems, but even in large-scale systems decision-making and power imbalances make agency relevant (Cote and Nightingale 2012).

Our review shows diversity and agency are underrepresented in quantitative resilience metrics, leading practitioners and researchers to overlook critical aspects of social-ecological resilience. We recognize that other concepts not assessed here, such as feedbacks, governance, and slow and fast variables, may also be important for resilience. However, our findings demonstrate that diversity and agency are important for resilience metrics in multiple social-ecological contexts and are frequently missing from metrics. We, therefore, recommend improvement on the inclusion of diversity and agency into quantitative resilience metrics. Next, we discuss the challenges involved and potential pathways for incorporating diversity and agency into resilience metrics.

Challenges to include diversity and agency in social-ecological resilience metrics

We identify three major challenges to incorporating more diversity and agency in social-ecological resilience metrics. First, metrics need to better represent individual elements. To include diversity or agency, resilience measures must capture individual elements, be it systems components, for diversity, or agent characteristics, for agency. However, metric categories such as shape of potential landscape, early-warning signal, and performance under disruption usually focus on analyzing system-scale dynamics and neglect lower-scales. Indeed, our results show these categories rarely include diversity and agency. Metrics in these categories have valid use cases, but researchers should be aware that choosing a metric can limit what elements it can capture. This challenge is stronger for simulation models, where the choice of models further limits the capacity to include individual elements.

Second, metrics need to account for the complexity of resilience, diversity and agency. Compared to ecological resilience, social-ecological resilience tends to focus on qualitative assessments (González-Quintero and Avila-Foucat 2019, Polain de Waroux et al. 2024). The limited attention to developing better quantitative social-ecological resilience metrics means that simpler and easier-to-apply metrics tend to be used, such as the predominant performance under disruptions metrics observed in this review. However, these metrics rarely include diversity and agency. There are also challenges to better capture the complexity of diversity and agency in metrics that already include them. Our results showed that agency is mainly captured by assessing individual capitals. However, research argues agency analyses should go beyond and include structural elements such as power and relational and dynamic capabilities (Cote and Nightingale 2012, Reyers et al. 2022). These elements are harder to quantify, and there is limited data available, especially at higher scales, which explains why they are rarely included in resilience metrics. Similarly, many studies analyze the relationship between biodiversity and resilience (Biggs et al. 2015, McCann 2000). However, we know less about how this translates to social systems and the diversity of other elements that might be more relevant to promote resilience (Leslie and McCabe 2013, Mori et al. 2013). Improvements are also necessary to use diversity-based analysis to provide concrete management and policy recommendations (Mori et al. 2013).

Third, to include diversity and agency requires integrating knowledge from diverse research fields. Many studies argue for better integrating social theories into social-ecological resilience (Brown 2014, Cote and Nightingale 2012). Resilience can work with different theories of agency, including more established or collective and non-human agency (Contesse et al. 2021, Duncan 2019). More integration between social science knowledge and resilience is necessary to choose relevant agency theories aligned with the purpose of the research (Cote and Nightingale 2012, Semplici et al. 2024). Similarly, to better include diversity in resilience metrics, we need to adapt ecology results to social and social-ecological systems (Leslie and McCabe 2013, Mori et al. 2013).

Pathways to improve inclusion of diversity and agency in social-ecological resilience metrics

We suggest five promising pathways, informed by this article's results and insights from multiple research fields, for improving the inclusion of diversity and agency in social-ecological resilience metrics and addressing the three previous challenges.

- **Using network-based metrics**: Networks are a methodology that can capture both local and system-level elements. They can also be a common language to bridge research fields, as they are used in social science, ecology and engineering, and include agency and diversity in resilience metrics (Janssen et al. 2006). The system structure category was the main source of metrics including diversity in this review (Fig. 5). Recent works used networks to estimate the likelihood of reaching critical thresholds (Domínguez-García et al. 2019, Liu et al. 2022, Rocha et al. 2018) and the impact on system performance time series (Meng et al. 2018, Zhou et al. 2019), showing a pathway to expand network-based metrics methodology to include diversity to other categories. Network methodologies have also been used to favor a more relational, less individual-focused understanding of agency (Semplici et al. 2024, West et al. 2024). As such, allowing new insights into how structural properties, such as power and inequalities, influence agency and adaptive and transformative capacities (Barnes et al. 2025, Semplici et al. 2024, West et al. 2024).
- **Using response and pathway diversity**: These metrics are particularly effective in incorporating both diversity and agency but were rarely found in our review. Response diversity directly incorporates diversity and, in social-ecological systems, frequently involves agent response diversity, thus also including agency. The response diversity concept is originally from ecology but has been extended to include social and economic systems (Leslie and McCabe 2013, Walker et al. 2023). It is not commonly recognized and applied as a metric, though promising efforts are being made to operationalize it (Ross et al. 2023). Pathway diversity builds upon response diversity and previous resilience theories to capture both system and agent components of resilience. The metric defines resilience as higher if more agents' actions are currently available and can be maintained and enhanced into the future (Lade et al. 2020, Sellberg et al. 2024). It was designed as an operational metric that can work in different social-ecological contexts, and it incorporates diversity and agency. Because it is a new approach, new studies still need to refine it and implement it in different empirical case studies.
- **Including diversity and agency in compound indicators**: It is relatively easy to include more diversity and agency in compound indicators, and we have already observed a moderate inclusion of these elements in this review (Fig. 5). However, more metrics could include these concepts and their whole complexity. For agency, most approaches include individual capital assessment but neglect structural and subjective elements such as power and dynamic capacities (Cote and Nightingale 2012, Reyers et al. 2022). Multiple psychology resilience metrics capture how external relationships affect individual capability to act and other subjective individual factors. These metrics, or other

psychological and sociological assessments, can be adapted for social-ecological problems to guarantee more effective incorporation of agency in social-ecological resilience metrics (Reyers et al. 2022). For diversity, most approaches include biodiversity or economic diversity. However, they are not necessarily the main promoters of response and functional diversity in different systems. More empirical and contextual studies are necessary to identify the key diversity elements causing a system to be resilient before including them on metrics.

- **Integrating quantitative methodologies outside resilience theory:** Different theories are used to analyze social-ecological problems, and resilience theory can benefit from them. For example, the field of Decision-Making under Deep Uncertainty (DMDU) analyzes how systems can cope with uncertainties in environmental, political, and social variables, dealing with similar problems as resilience (Marchau et al. 2019). In the DMDU literature, methods such as portfolio theory have been used to promote a diversity of strategies and resources (Crowe and Parker 2008), and exploratory modelling has been used to analyze cooperation in regional water management and how power and agency might affect it (Gold et al. 2022).
- **Improving the application of resilience in simulation models:** Dynamical systems models are heavily used in ecology but usually focus on the system level and consider simplified aggregated agents (Macy and Willer 2002). Agent-based, integrated assessment and network models are more flexible and allow simulation models to focus on the agent perspective (Bianchi and Squazzoni 2015, Liu et al. 2022, Otto et al. 2020). They show a pathway to use behavioral theories and analyze how structural elements influence agent capability to take actions as well as capture agent heterogeneity.

Conclusion

Through this systematic review, we contribute to the debate by showing diversity and agency are central concepts for understanding social-ecological resilience and highlight a critical gap in quantitative resilience metrics: few quantitative resilience metrics sampled include agency and diversity. While resilience definitions and qualitative frameworks incorporate agency and diversity, their translation into operationalized metrics remains rare. This review underscores the need for novel approaches and metrics that explicitly embrace agency and diversity as integral components of resilience measures. The inclusion of these concepts in quantitative methodologies has the potential to promote a more coherent understanding of social-ecological resilience.

Author Contributions:

V.H.S and S.J.L. designed the study. V.H.S., R.Q., and J.V. gathered the data. V.H.S. made initial data analysis and visualizations. V.H. S. wrote the first draft of the manuscript. All authors contributed with discussion of the methodology, interpretation of the results, revision of the manuscript, and approved the final version of the manuscript.

Acknowledgments:

The research leading to these results has received funding from the Australian Government (Australian Research Council Future Fellowship FT200100381 to SJL), and the Rasmussen Foundation (project "Strengthening the theoretical basis of resilience in practice" granted to the Resilience Alliance to support working groups led by Resilience Alliance Young Scholars). J.F.D acknowledges support from the European Research Council Advanced Grant project ERA (Earth Resilience in the Anthropocene, ERC-2016-ADG-743080). We also thank Jamila Haider for her contributions during our workshop and feedback on the manuscript.

Data Availability:

The data and code that support the findings of this study are openly available in Zenodo at https://doi.org/10.5281/zenodo.15672560.

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Supplementary Methods

This document is the Supplementary Methods for the paper "Integrating Diversity and Agency into Social-Ecological Resilience Metrics". Here, we provide additional details on the methodology of the paper. In section 1, we explain the process of developing the methodology and the reading process. In section 2, we show a histogram of the year of publication for all documents in both the meta-review and the modelling review. In section 3, we show how the number of topics was selected and the details of the topic modelling results. In section 4, we show how the frequency of diversity and agency inclusion in the meta-review was determined. In sections 5 and 6, we show a codebook with the application of agency and diversity criteria, respectively. In section 7, we present the figure of the metric category mentioned per discipline. In section 8 we present an alternative methodology and results, using selected journals, to validate the modelling review. In section 9, we present how we determine the scores for the summary figure (Figure 5).

1. Determination of the methodology and reading process

To develop the methodological design, we organised two in-person workshops and several online meetings. The process started with the first workshop in early 2023 and involved the presentation of the paper proposal, the trial of the methods and the refinement of the methodological design. Following the workshop, VHS elaborated a protocol, defining the inclusion criteria, all the data to be collected and the criteria to classify the metric categories, diversity and agency, including examples. After the presentation of the protocol and further discussion of the criteria with all co-authors, we started coding the data in a spreadsheet, starting with the meta-review. VHS, RQ and JV were involved in the reading process. During the data collection, readers tagged the metrics they did not know how to classify the category or agency and diversity inclusion. VHS later read these metrics and, if needed, discussed them with the reader or the whole group. After the data collection, VHS selected a random sample of around 30% of metrics to reevaluate the criteria to classify metrics and agency and diversity inclusion. When disagreements were found, they were discussed by VHS, RQ, JV and AEQ. In the second in-person workshop in mid-2023, we discussed disagreements and chose a consensual opinion. A similar process was followed for the modelling review. However, we adopted a smaller sample to reevaluate the criteria, around 10%, because we considered we had a better comprehension of the criteria's application by that time.

2. Document's year of publication for meta-review and modelling review

Most papers on the meta-review and modelling review were published recently (Figure S1). In both the meta-review and modelling review, more than 50% of the total sample was published in the last five years (2019-2023).

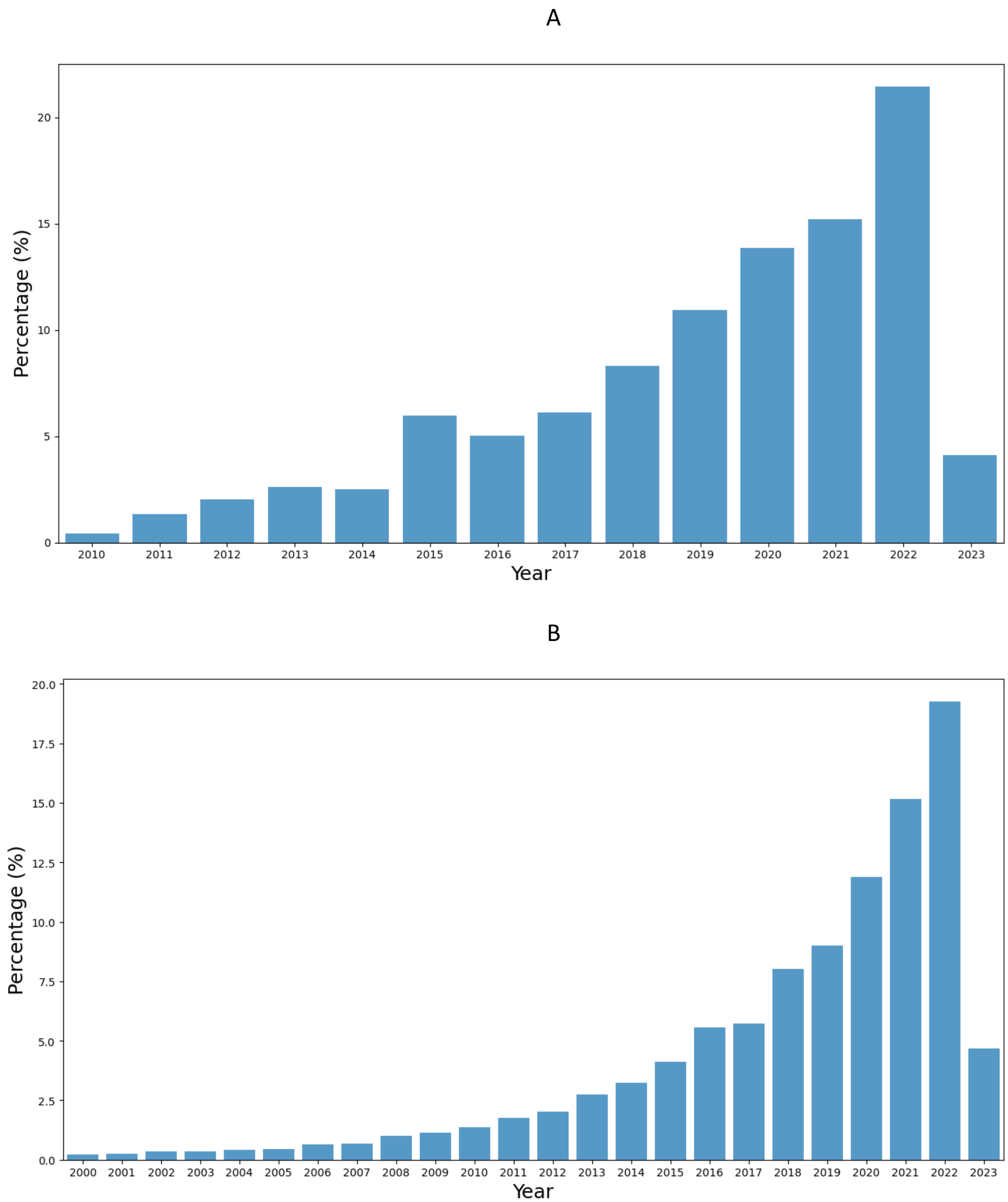


Figure S1: Histogram of the year of publication of documents in (A) the meta-review and (B) the modelling review. The year 2023 is incomplete and only covers papers published up to March (see Table 1 for the exact search date for each review).

3. Selection of the number of topics and topic modelling results

To select the optimal number of topics, we applied a combination of two metrics that assess the quality of the topic modelling results: topic coherence and topic diversity. Topic coherence is a measure of the interpretability of a topic; the basic idea is that coherent topics will have words that are used in the same document, so that "the most likely words in a coherent topic should have high mutual information" (Dieng et al., 2020). We also use topic diversity to measure how topics differ. The metric is computed by taking the percentage of unique words in the main n topic words, in our case n=20 (Dieng et al., 2020). Our final metric is the product of the two indicators, as done in Dieng et al. (2020). To select the number of topics, we varied its value between 2 and 20 and selected the number that maximises the product of topic coherence and topic diversity (Figure S2). In the meta-review, we selected seven topics, and in the modelling review, we selected six topics. For more details on the topics' results for each review component, see Table S1.

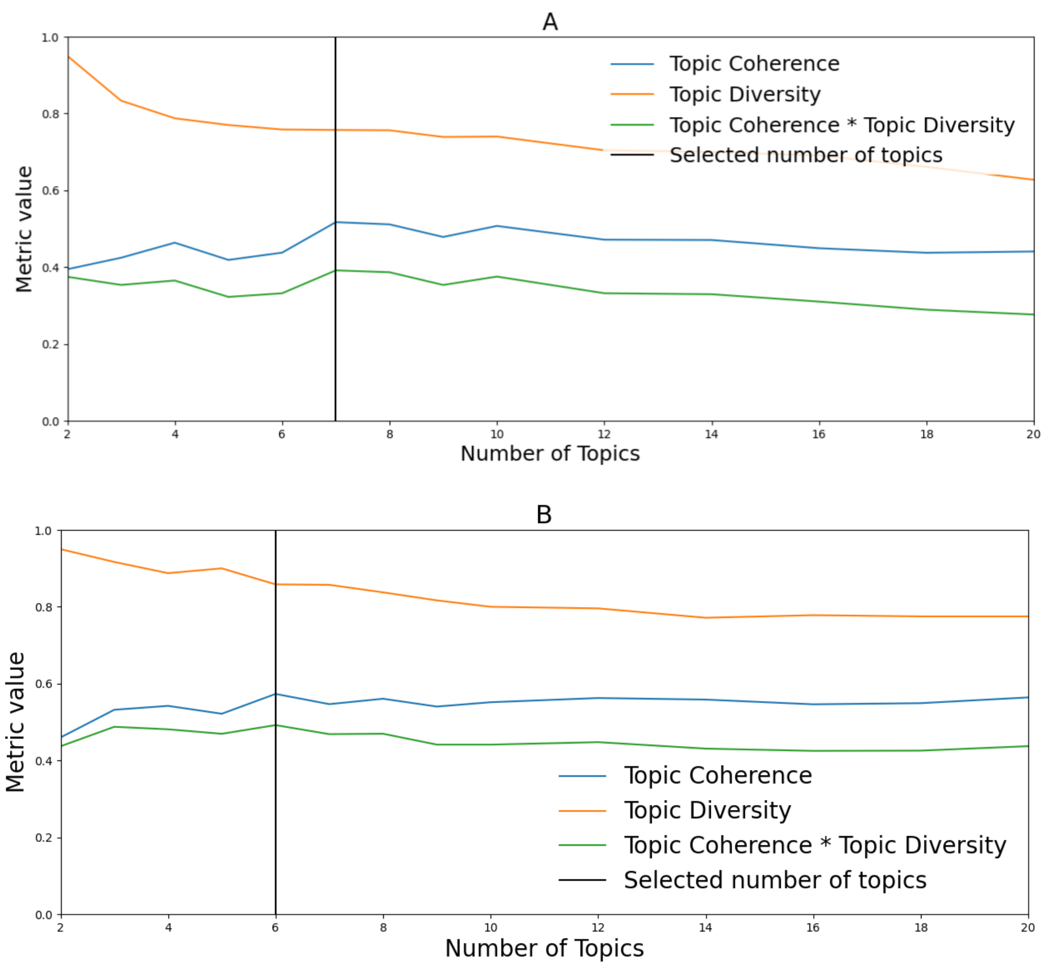


Figure S2: Topic quality metrics per number of topics for the meta-review (a) and modelling review (b).

Table S1: Topic modelling main words per topic for the meta-review and modelling review. We show the 7 top words by topic and their probabilities.

Meta-review							
Topic	**Word 1 (prob.)**	**Word 2 (prob.)**	**Word 3 (prob.)**	**Word 4 (prob.)**	**Word 5 (prob.)**	**Word 6 (prob.)**	**Word 7 (prob.)**
Environmental science and food	change (0.025)	system (0.024)	climate (0.021)	community (0.017)	food (0.017)	climate_change (0.017)	sustainability (0.014)
Ecological, soil and animal	change (0.022)	ecosystem (0.022)	stress (0.016)	climate (0.016)	response (0.13)	environmental (0.013)	Specie (0.012)
Urban, community and disaster	urban (0.022)	community (0.021)	disaster (0.021)	risk (0.019)	assessment (0.015)	study (0.014)	management (0.014)
Health and psychology	study (0.043)	intervention (0.023)	systematic (0.018)	health (0.012)	result (0.011)	outcome (0.010)	included (0.010)
Health and psychology 2	health (0.032)	factor (0.28)	mental (0.021)	mental_health (0.017)	child (0.015)	study (0.014)	family (0.014)
Supply-chain	supply (0.038)	chain (0.035)	supply_chain (0.034)	concept (0.017)	disruption (0.015)	study (0.014)	paper (0.014)
Energy and Power-grid	system (0.117)	power (0.026)	energy (0.017)	health (0.016)	power_system (0.016)	resiliency (0.015)	network (0.014)
Modelling review							
Ecological, soil and animal	specie (0.014)	community (0.008)	effect (0.008)	ecosystem (0.007)	population (0.007)	change (0.007)	coral (0.007)
Urban, community and disaster	risk (0.013)	system (0.009)	community (0.008)	supply (0.008)	management (0.007)	disaster (0.007)	urban (0.007)
Energy and Power-grid	network (0.024)	system (0.024)	proposed (0.009)	performance (0.008)	energy (0.007)	method (0.007)	power (0.007)
Environmental science and food	climate (0.023)	change (0.019)	water (0.017)	climate_change (0.012)	forest (0.011)	ecosystem (0.009)	area (0.009)

Health and psychology	factor (0.010)	psychological (0.010)	support (0.009)	relationship (0.009)	family (0.009)	social (0.009)	student (0.009)
Health and psychology 2	health (0.016)	stress (0.013)	symptom (0.009)	associated (0.007)	risk (0.008)	depression (0.007)	factor (0.007)

4. Determination of frequency of diversity and agency inclusion in the meta-review

To simplify the paper narrative, we used a categorical classification for both diversity and agency. However, we performed a metric-by-metric classification of diversity inclusion in the meta-review (Figure S3). We did this because assessing the inclusion of diversity is less context-specific, i.e. usually, metrics that include diversity do it on the metric definition. On the other hand, determining whether metrics include agency is difficult without a clear context of where these metrics are applied. For example, in the performance under disruption category, a performance loss metric includes agency by our criterion if the performance indicator is the community capacity to provide houses for residents and does not include agency if the indicator is the number of goods produced by a company. Therefore, the same metric can include agency or not, depending on its usage context. Given this complication, and because we do not have the usage context in reviews, rather than classifying each metric, we defined more broadly how frequently applications of metrics in the category take agency into account, based on our understanding of the literature and discussions with co-authors.

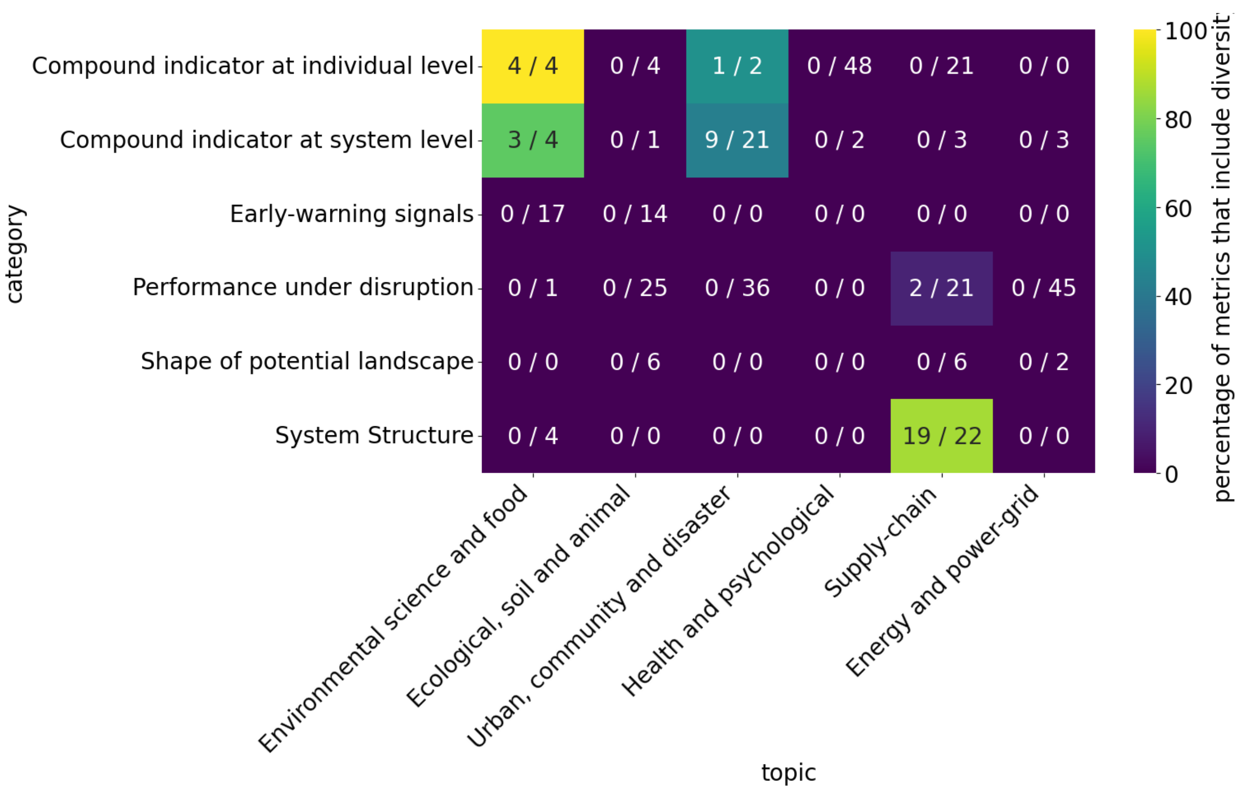


Figure S3: Heat map of the percentage of resilience metrics that include diversity per category and topic in the meta-review corpus. In the text inside each cell, the numerator is the number of metrics that include diversity, and the denominator is the total number of metrics in the cell.

5. Agency codebook

We chose a set of seven illustrative examples to show how we applied the agency criteria. For each example, we describe how resilience is measured, our reasoning for applying the agency criteria, and a few other documents showing a similar metric type.

5.1 Shape of potential landscape metric, with agent directly affecting the system state, and metric measure at the system level

Reference: Anthony et al., 2011

Description of metric: the measure is which set of parameters increases the probability of collapse. Collapse is measured by coral cover being close to zero. The herbivory grazing rate is caused by the amount of overfishing and is one of the main parameters analysed in the paper.

Application of the criteria: the agent is the local human population living in the study area. Agents influence coral cover by altering overfishing, which directly impacts herbivory grazing rate, a key model variable. So, the system incorporates agents capable of taking actions and changing the system state. However, despite agents' influence on resilience, no human property is directly included in the resilience metric. So, the metric did not satisfy the agency criteria: the metric does not include a measure of agents' capability to act.

Other documents in the same category:

- Boulton et al., 2017
- Llope et al., 2011

5.2 Early-warning signal or performance under disruption metric, without a clear influence of agents in the state of the system

Reference: De Keersmaecker et al., 2014

Description of the metric: the model analyse time series of normalised difference vegetation index (NDVI) for different land covers. The document presents three metrics. We describe the first metric presented. The metric is one minus the lag one autocorrelation. Higher lag one autocorrelation "relates to more similar subsequent anomalies and thus slower return to equilibrium".

Application of the criteria: agents living in each region can influence remote sense results, but the model and analysis do not focus on specifying the role of humans or how they can alter the system state. So, the metric did not satisfy the agency criteria: the metric does not include a measure of agents' capability to act.

Other documents in the same category:

- McManus et al., 2020

- Sarremejane et al., 2021

5.3 Performance under disruption metric, with agent directly affecting the system state, metric including measure at the agent level, but not measure of capability to act

Reference: Qin et al., 2022

Description of the metric: the agent is a company that owns a supply chain. The document presents four metrics. We consider here the first metric presented. The state is the number of production goods in a supply chain. The metric is performance loss, the number of goods not produced during a machine breakdown. The metric is measured by computing the integral of the performance during the disruption period.

Application of the criteria: the agent can influence the system state, and the resilience metric is defined at the agent level. The number of goods produced is a property defined at the agent level. However, this measure does not assess or consider what factors influence the agent's capability to act. So, the metric did not satisfy the agency criteria: the metric does not include a measure of agents' capability to act.

Other documents in the same category:

- Cardoni et al., 2022
- Das and Lashkari, 2015

5.4 Compound indicator at the system level, where properties of a group of humans are assessed and with a measure of agents' capability

Reference: Pagano et al. 2017

Description of the metric: the agents are the population of the city. The resilience index is computed based on indexes from four dimensions: Technical, Organizational, Social and Economic. All these indicators are grouped to compute water deficit, "the relation between the total volume of available water (deriving from the infrastructure and from emergency sources) and the water demand for the population to be served".

Application of the criteria: the resilience metric includes multiple properties of the agents in the city. The water deficit depends on measures of agent capability, mainly organisational dimensions, such as level of knowledge, human resources in an emergency, and available economic resources. They later analyse how these factors related to agent capability alter the system resilience. So, the metric satisfies the agency criteria: the metric includes a measure of agents' capability to act.

Other documents in the same category:

- Rezvani et al., 2022
- Mohammed et al., 2023

5.5 Performance under disruption metric, with state computed at the agent level and with a measure of agents’ capability to act

Reference: Rose, 2007

Description of the metric: the agent is a company that produces some good or economic output. Resilience is how much recovery actions avoid performance loss compared to business-as-usual. This metric is applied to the level of economic activity against power and water outrage but is applicable in disasters in general.

Application of the criteria: the agent clearly influences the system state and the measure of resilience by taking different recovery actions. The resilience metric also considers the agent's capability to act. For example, agents with more resources might use more expensive recovery actions and have higher resilience. So, the metric satisfies the agency criteria: the metric includes a measure of agents' capability to act.

Other documents in the same category:

- De Sanctis et al., 2018

5.6 System structure metric, with an agent that influences system state and state computed at the system level
Reference: Pagano et al., 2022

Description of the metric: the agent is the water management company or the manager responsible for the company's decision-making. The document presents four metrics. Here, we consider the metric 'average path length.' This metric is the average distance along the shortest paths between any two pairs of nodes compared to all possible pairs of network nodes, where the network is the water supply and distribution network.

Application of the criteria: the agent can influence the system's resilience by deploying new infrastructure and changing the design of the network. However, the resilience metric does not include a measure defined at the agent level and does not include a measure of the agents' capability. So, the metric did not satisfy the agency criteria: the metric does not include a measure of agents' capability to act.

Other documents in the same category:

- Baños et al., 2011
- Tanyimboh et al., 2016

5.7 Compound indicator at the individual level, with a measure of agent capability
Reference: Connor and Davidson, 2003

Description of the metric: measures resilience by applying a Likert-based questionnaire to a human being. The metric evaluates elements such as personal competence and tolerance of negative effects.

Application of the criteria: the resilience measure is defined at the agent level. The resilience measure assesses individual characteristics such as personal competence, positive acceptance of change and secure relationships to understand how the individual might respond to future stressful events. So, the metric satisfies the agency criteria: the metric includes a measure of agents' capability to act.

Other documents in the same category:

- Friborg et al., 2003
- Wagnild and Young, 1993

6. Diversity codebook

We chose a set of five illustrative examples to show how we applied the diversity criteria. Because this criterion is easier to apply, we restrict our examples to metrics that include diversity. For each example, we describe how resilience is measured, our reasoning for applying the agency criteria, and a few other documents showing a similar metric type.

6.1 Early-warning signal metric that includes diversity measure

Reference: De Keersmaecker et al., 2014

Description of metric: this document presents three metrics. Here, we consider the 'normalised spectral entropy' metric. This metric computes the variance of the frequency spectrum of the anomaly time series. "The normalised spectral entropy expresses the evenness of the distribution of variance, where higher entropies indicate more resilient ecosystems".

Application of the criteria: the metric assesses the structural complexity of an ecological time series, and there are some proposed links between the complexity and diversity of the system and the presence of more frequencies in the spectrum of the time series. So, the metric satisfies the diversity criteria: the metric includes a measure of the variety, balance, or disparity of a specific element within the system.

Other documents in the same category: no other examples were found.

6.2 Performance under disruption metric that includes diversity measure

Reference: De Sanctis et al., 2018

Description of the metric: the document describes two metrics, but one metric is a modification of the original one. Here, we consider the original metric. The resilience index is related to the capacity of the system to overcome failures while still satisfying demands and pressures in nodes. "The resilience index is a measure of the available surplus power that, potentially, could be further dissipated by the flow through network in the event that extra stresses arise (e.g. due to an increase in demand)".

Application of the criteria: The metric considers networks with higher redundancy (higher diversity of pipelines) better at overcoming failures. The metric is proposed as a measure of energy redundancy. So, the metric satisfies the diversity criteria: the metric includes a measure of the variety, balance, or disparity of a specific element within the system

Other documents in the same category:

- Review that has metrics of this type: Zhou et al., 2019

6.3 System structure metric that includes diversity measure

Reference: Tanyimboh et al., 2016

Description of the metric: the document describes two metrics, but one metric is a modification of the original one, here we discuss the original metric. The resilience index is related to the capacity of the system to overcome failures while still satisfying demands and pressures in nodes. “The resilience index is a measure of the available surplus power that, potentially, could be further dissipated by the flow through network in the event that extra stresses arise (e.g. due to an increase in demand)”.

Application of the criteria: The metric considers networks with higher redundancy, where there is a higher diversity of pipelines, are better at overcoming failures. The metric is proposed as a measure of energy redundancy. So, the metric satisfies the diversity criteria: the metric includes a measure of the variety, balance, or disparity of a specific element within the system

Other documents in the same category:

- Review that has metrics of this type: Zhou et al., 2019

6.4 Compound indicator at system level that includes diversity measure

Reference: Pagano et al. 2017

Description of the metric: The resilience index is computed based on indexes from four dimensions: Technical, Organizational, Social and Economic. All these indicators are grouped to compute water deficit, "the relation between the total volume of available water (deriving from the infrastructure and from emergency sources) and the water demand for the population to be served".

Application of the criteria: Water deficit depends on variables such as having alternative water supplies available and the volume of these alternative supplies. So, the metric satisfies the diversity criteria: the metric includes a measure of the variety, balance, or disparity of a specific element within the system.

Other documents in the same category:

- Rezvani et al., 2022
- Namdar et al., 2021

6.5 Compound indicator at individual level metric that includes diversity measure

Reference: FAO, 2016

Description of the metric: Resilience Index Measurement and Analysis II estimates household resilience to food insecurity with a comprehensive pack that includes direct and indirect measures.

Application of the criteria: the compound indicator metrics include a measure of dietary diversity computed using the Simpson index. So, the metric satisfies the diversity criteria: the metric includes a measure of the variety, balance, or disparity of a specific element within the system.

Other documents in the same category:

- Review that has metrics of this type: Ansah et al., 2019

7. Metric category mention per discipline

To validate that our result on the distribution of metric category per topic is robust against different divisions, we made a complementary analysis using the discipline of the paper instead of the topic. Based on our understanding, we classified each paper into three disciplines: environmental science, engineering, and psychology. The classifications considered our knowledge of the fields, reading of the paper and the journal where it was published. Then, we assign each metric to one discipline based on the paper where the metric is mentioned. Analysing the distribution of metric category per discipline, we obtained similar results as Figure 2. Performance under disruption was dominant in engineering reviews (62%), while compound indicators were predominant in psychology reviews (96%) (Figure S3). In environmental science reviews, there was no dominant metric category, as performance under disruption (30%), early-warning signals (30%), and compound indicators (26%) were all widely mentioned (Figure S4).

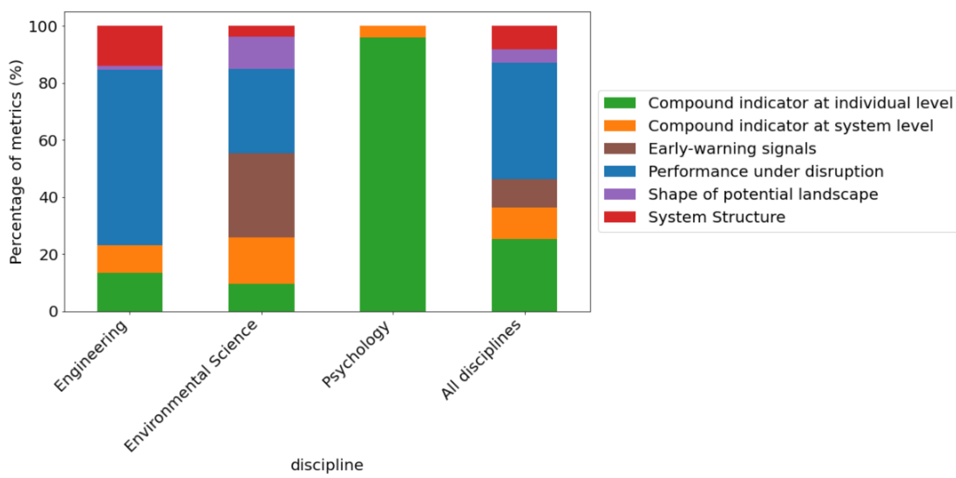


Figure S4: Percentage of metrics category mention in meta-review corpus per discipline (N= 312 metrics).

8. Modelling review validation using selected journals

To validate that the modelling review results are robust, we made an alternative analysis using selected journals. The selected journals cover all topics, and we added one extra journal to better represent the social-ecological systems field. The journals are: Global Change Biology (ecological topic), Sustainable Cities and Society (urban, community and disaster topic), Water Resources Management (environmental science topic), IEEE Transactions on Smart Grid (Energy and power-grid topic) and Ecology and Society (shared between ecological; urban, community and disaster and environmental science topics).

The results are similar to the main modelling review methodology. The performance under disruption category is predominant, with 69% of all the metrics (Figure S5). Performance under disruption metrics was the most used across all journals except for Ecology and Society, where metrics related to the shape of potential landscapes and early-warning signals — categories more directly associated with social-ecological resilience — predominated (69%).

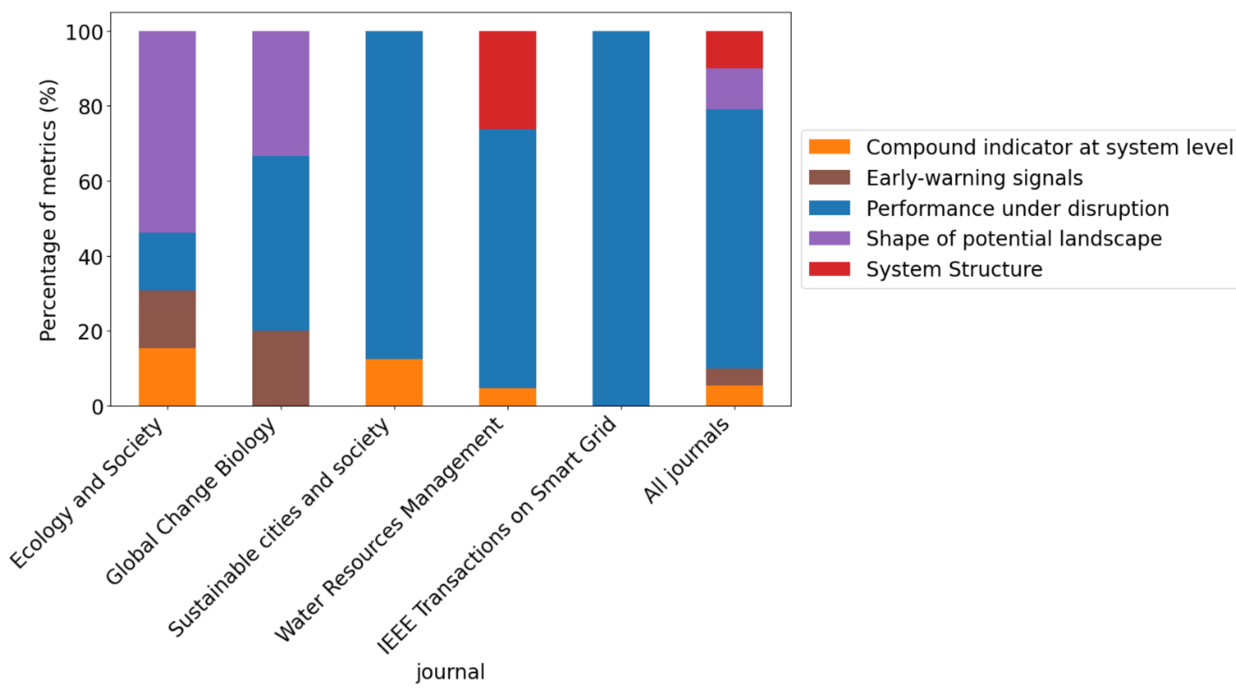
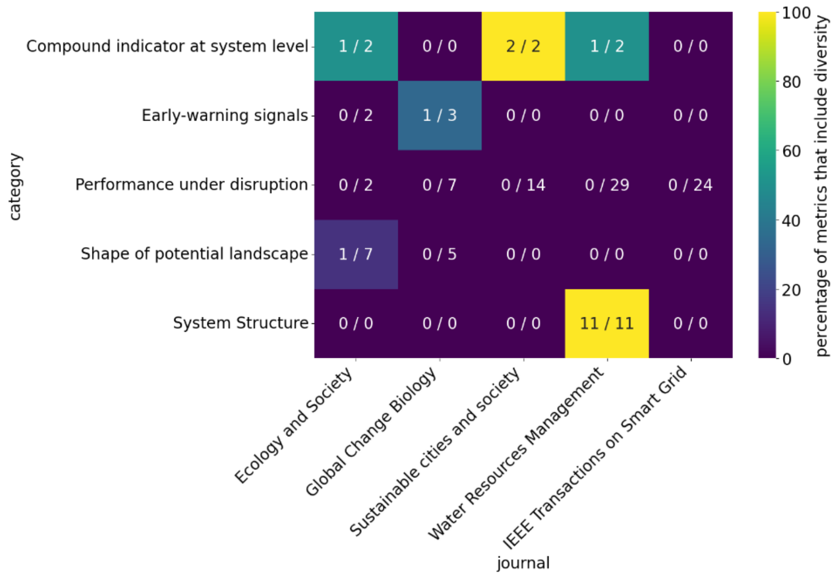
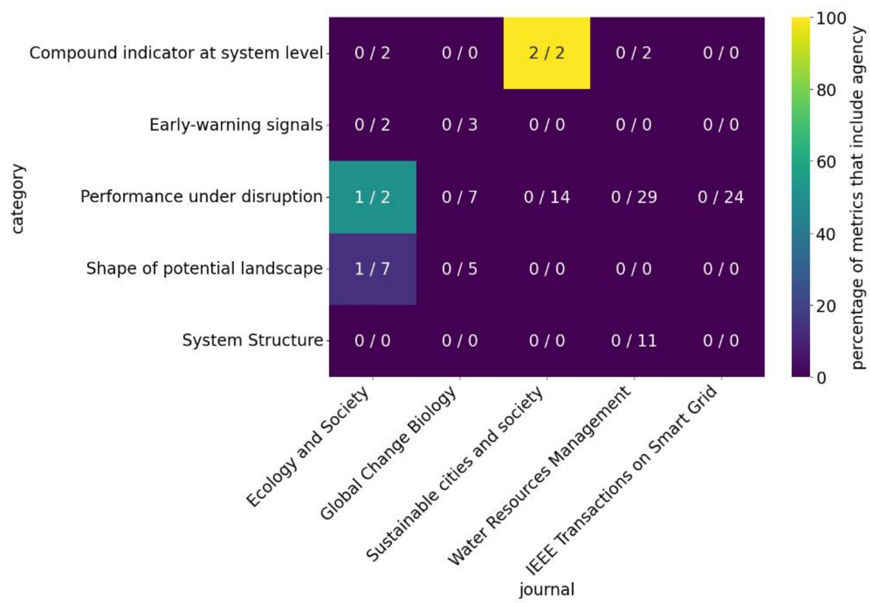


Figure S5: Percentage of metrics category mentioned in the modelling review corpus per journal (N= 110 metrics). Based on the classification of all resilience metrics from the modelling review, we show the most common metrics category per topic. The category compound indicator at the individual level was not found in this corpus. Journals closer to the social-ecological fields are on the left.

Few resilience metrics in the selected journals include diversity measures (15% of all metrics) and agency metrics (3% of all metrics) (Figure S6), showing a similar result to the main modelling review methodology. Most metrics that include diversity are in the system structure and compound indicator at the system level categories (Figure S6). The Water Resources Management journal includes a great proportion of such metrics, mainly measuring network-based metrics on water distribution networks. Most metrics that include agency are in the compound indicator at the system level category (Figure S6). Organisational elements emerge as a recurrent theme in these metrics, encompassing facets like the availability of human resources and knowledge during disasters (Pagano et al., 2017) and the learning curve of workers within a company (De Sanctis et al., 2018).



A



B

Figure S6: Heat map of (A) the percentage of resilience metrics that include diversity (B) the percentage of resilience metrics that include agency, per category and journal in the modelling review corpus (N= 110 metrics). In the text inside each cell, the numerator is the number of metrics that include diversity (A), or agency (B) and the denominator is the total number of metrics in the cell. Journals closer to the social-ecological fields are on the left.

9. Determination of summary figure scores

To determine the score of Figure 5, we used the results from Table 3 (meta-review) and Figure 4 (modelling review). We attribute a score ranging from zero to three for the percentages of agency and diversity inclusion (Tables S2 and S3). The thresholds we used to map the percentages to scores are: [0, 1] -> score 0, [1, 35] -> score 1, [35, 65] -> score 2, [65, 100] -> score 3. For the meta-review classification of agency there is a direct map to the scores. Then, we choose the final score by comparing the meta-review and modelling review scores for agency and diversity inclusion, opting for the score we judge to be more relevant. In most cases, both scores are the same.

Table S2: Determination of the summary score for diversity per category.

Category	Meta-review frequency	Meta-review score	Modelling review (%)	Modelling score	Final score	Justification
Shape of potential landscape	0.0	0	0.0	0	0	Consensus between reviews
Early-warning signals	0.0	0	0.0	0	0	Consensus between reviews
Performance under disruption	1.6	1	4.1	1	1	Consensus between reviews
System Structure	73.1	3	75.0	3	3	Consensus between reviews
Compound indicator at the system level	35.3	2	50.0	2	2	Consensus between reviews
Compound indicator at the individual level	6.3	1	---	---	1	Chose meta-review because is the only result

Table S3: Determination of the summary score for agency per category.

Category	Meta-review frequency	Meta-review score	Modelling review (%)	Modelling score	Final score	Justification
Shape of potential landscape	Very low	0	0.0	0	0	Consensus between reviews
Early-warning signals	Very low	0	0.0	0	0	Consensus between reviews
Performance under disruption	Low	1	6.25	1	1	Consensus between reviews
System Structure	Very low	0	0.0	0	0	Consensus between reviews
Compound indicator at the system level	High	2	25.0	1	2	Chose meta-review due to bigger sample size
Compound indicator at the individual level	Very high	3	---	---	3	Chose meta-review because is the only result

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