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RESEARCH ARTICLE

How can social–ecological system trajectories be understood? An investigation of conceptualization through a systematic literature review

¿Cómo entender las trayectorias de los sistemas socioecológicos? Una investigación sobre su conceptualización a través de una revisión sistemática de literatura

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Abstract. This work presents a systematic literature review (SLR) on social–ecological system trajectories (SESTs) worldwide to identify the existing scientific literature focused on SEST definitions, temporal and spatial tendencies, and the theoretical and methodological approaches applied to propose a general SEST conceptualization. The sample includes 143 articles selected from the international Scopus database that were analyzed across five groups including a total of 32 variables. The results indicate that most publications originate from the Global North, whereas the study sites are predominantly located in the Global South. Few definitions of the SEST term exist. The proposed general SEST conceptualization includes multiple social–ecological dimensions and temporal (past, current and future) and spatial (territorial) dynamics. The SEST case studies focus primarily on human benefits and specific system components. Predominant analytical frameworks refer to social–ecological systems, resilience, and adaptation; are characterized by qualitative or quantitative methods; and are multidisciplinary. There are three categories of SEST studies: studies with an adaptation, development focus (for political aims) and studies with a focus on change (for research objectives). Adaptation and change studies dominate, and studies in all three categories consider pathways to sustainability goals. Key research challenges include producing cross-sectional and equitable research, integrating diverse knowledge perspectives, and adopting inter-and transdisciplinary approaches.

Keywords: transformations, social–ecological systems, temporal and spatial tendencies.

Resumen. Este trabajo presenta una revisión sistemática de la literatura (RSL) sobre las trayectorias de los sistemas socioecológicos (TSSE) en todo el mundo con el fin de identificar la literatura científica existente centrada en las definiciones de las TSSE, las tendencias temporales y espacia-

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les, y los enfoques teóricos y metodológicos aplicados para proponer una conceptualización general de las TSSE. La muestra incluye 143 artículos seleccionados de la base de datos internacional Scopus, que se analizaron en cinco grupos que incluyen un total de 32 variables. Los resultados indican que la mayoría de las publicaciones proceden del Norte Global, mientras que los sitios de estudio se encuentran predominantemente en el Sur Global. Existen pocas definiciones del término SEST. La conceptualización general de SEST propuesta incluye múltiples dimensiones socioecológicas y dinámicas temporales (pasadas, presentes y futuras) y espaciales (territoriales). Los estudios de caso de SEST se centran principalmente en los beneficios para los seres humanos y en componentes específicos del sistema. Los marcos analíticos predominantes se refieren a los sistemas socioecológicos, la resiliencia y la adaptación, se caracterizan por métodos cualitativos o cuantitativos y son multidisciplinarios. Hay tres categorías de estudios SEST: estudios con un enfoque de adaptación y desarrollo (con fines políticos) y estudios con un enfoque de cambio (con objetivos de investigación). Predominan los estudios de adaptación y cambio, y los estudios de las tres categorías consideran vías para alcanzar los objetivos de sostenibilidad. Entre los principales retos de la investigación se encuentran la realización de investigaciones transversales y equitativas, la integración de perspectivas de conocimiento diversas y la adopción de enfoques interdisciplinarios y transdisciplinarios.

Palabras clave: transformaciones, sistemas socioecológicos, tendencias temporales y espaciales.

Introduction

The term social–ecological systems (SESs) was introduced by Berkes and Folke (1998) 25 years ago. Currently, there are multiple definitions of SESs (Herrero-Jáuregui et al., 2018), which are approached using various analytical frameworks (Binder et al., 2013) and methods (Gómez-Santiz et al., 2021; Partelow, 2018; Schlüter et al., 2012; De Vos et al., 2019). However, in general, an SES is defined as a complex, evolving and adaptive system comprising heterogeneous elements that are engaged in constant interaction (Berkes et al., 2003; Ostrom, 2009). The interaction between the social and ecological subsystems through flows composed of ecosystem services (ESs) and human action (HA) within the system occurs in the context of interaction with other SESs under different internal and external drivers or pressure factors (McGinnis & Ostrom, 2014), which results in the continuous modification of outputs and sometimes complete SES transformation (Colding & Barthel, 2019). This transformation of SESs implies changes in their components and relationships at various temporal and spatial scales (Berkes et al., 2003; Cumming, 2011; Folke, 2016).

Regarding the term "transformation," Sievers-Glotzbach and Tschersich (2019, p.1) noted that there is a distinction between "transition," which is understood as an intentional reorganization of individual subsystems toward specific predefined goals, and "transformation," which refers to fundamental systemic changes encompassing

the socioeconomic, political, and cultural aspects of SES and is linked to inter- and intragenerational justice. Therefore, transformation implies a complex and profound process that challenges the existing structures of an SES and leads it along diverse, responsive, and empowering pathways (toward sustainability) that differ from the current trajectory (Scoones, 2016; Stirling, 2015).

Analytically, understanding transformations is crucial for envisioning the multitude of alternative paths or ways that an SES can take, which are linked to actors' capacities to change prevailing sociopolitical structures (Görg et al., 2017). In this process, it is necessary to consider the following aspects in an interdisciplinary and transdisciplinary manner: *i)* essential ecological functions (flows of materials and energy); *ii)* diverse spatial scales (breadth); *iii)* processes that account for complexity, uncertainty, and ignorance (time), and *iv)* power structures (Fischer-Kowalski & Rotmans, 2009; Görg et al., 2017). In the same vein, Sievers-Glotzbach and Tschersich (2019:3) proposed four dimensions for analyzing transformations: *a)* direction, which extends toward justice objectives through a variety of pathways; *b)* breadth, which focuses on social–ecological systems; *c)* temporality, which reflects continuous and long-term change; and *d)* depth, which concerns agency and structure relationships, including fundamental changes in deep leverage points (power, paradigms, and institutions).

The directional transformation of an SES, which simultaneously accounts for the plurality of visions of desirable futures (Brown, 2015; O'Brien, 2012; Sievers-Glotzbach & Tschersich, 2019), can be associated with the term 'SES trajectories' (Ávila Foucat et al., 2020; Scoones, 2016; Stirling, 2015). However, what are SES trajectories?

The Cambridge dictionary describes a trajectory (in physics) as "the curved path an object follows after it is thrown or shot into the air, or of an object that is traveling through space"; thus, it is conceptualized as a vector of changes that presents characteristics such as movement, velocity and direction (Krekelberg & Lappe, 1999). In the case of SES, the meaning of trajectory becomes more complex and integrative because of the constant nonlinear coevolution through relationships of social and ecological components in time and space under different pressure factors (Perevochtchikova et al., 2024), where the SES may or may not take a sustainable path in the transformation process (Riechers et al., 2021). There is increasing interest in SEST studies at the global scale as an effort to analyze social–ecological problems and complex territorial processes in terms of sustainability (Fischer & Riechers, 2019).

Importantly, different terms are commonly used in scientific publications to refer to SESTs, such as pathways, processes of change, changes, evolutions, transformations, and transitions; however, these terms are not necessarily defined clearly and specifically, if they are defined at all (Fischer-Kowalski & Rotmans, 2009; Cumming, 2011; Görg et al., 2017; Riechers et al., 2021; Sievers-Glotzbach & Tschersich, 2019; Stirling, 2015). It would seem that SEST is a term still under conceptual construction.

Therefore, it is interesting to investigate the state-of-the-art of SEST case studies and definitions worldwide and analyze how SEST has been studied to propose a general SEST conceptualization.

To do so, it useful to conduct a systematic literature review (SLR), which is a rigorous method that allows a comprehensive overview of a variety of topics (Grant & Booth, 2009), specifically those related to SES (Herrero-Jáuregui et al., 2018; Gómez-Santiz et al., 2021; González-Quintero & Avila-Foucat, 2019). Although several literature reviews exist on the topic of SEST (Fedele et al., 2020; Palomo et al., 2021; Riechers et al., 2021; Varis et al., 2019), this work differs in the following ways: *i)* a systematic and rigorous review method (SLR) is adopted, with a focus on SEST case studies; *ii)* an overview of the formalization (theoretical or conceptual frameworks applied) and operationalization (methodological approaches used) of such studies is provided; and *iii)* SEST term definitions and proposed general SEST conceptualizations are summarized. By clearly defining SEST in the context of political and social decisions and research, the study will prove useful for scholars and practitioners engaged in SES studies and transformation processes.

The hypotheses guiding this work suggest that *i)* there are few definitions of SEST; *ii*) in its theoretical formalization and empirical operationalization, the study of SEST is biased toward a partial understanding of some part (or component) of SES, without considering analysis of the entire system; and *iii)* as a result, multidisciplinary and interdisciplinary studies dominate.

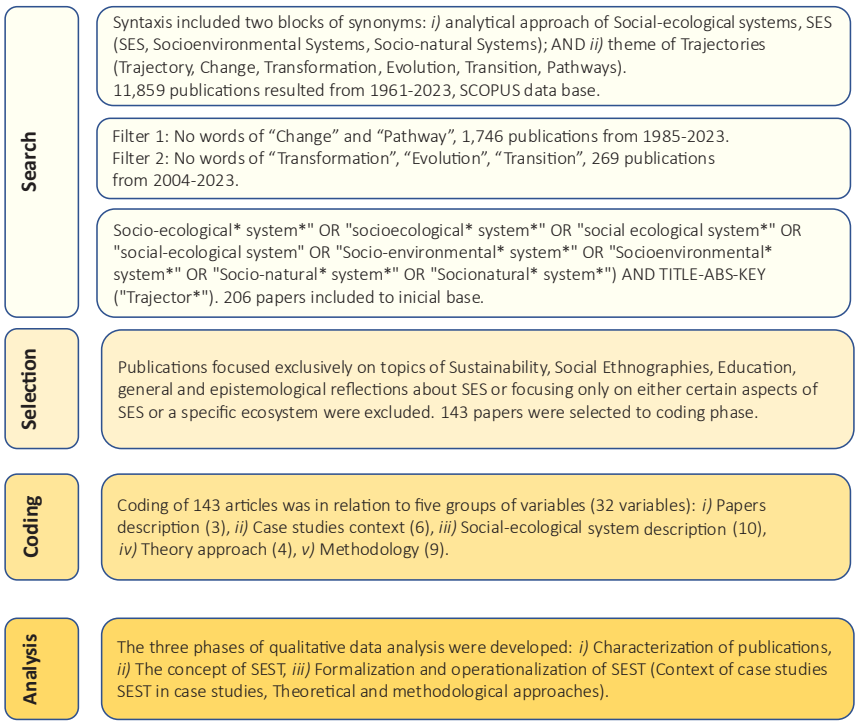
Method

The systematic literature review (SLR) method has been used for state-of-the-art analyses of various scientific topics (Moher et al., 2015; Higgins et al., 2019; Grant & Booth, 2009), specifically in relation to environmental conservation (Pullin & Stewart, 2006) and the operationalization of the SES framework (Herrero-Jáuregui et al., 2018; Gómez-Santiz et al., 2021; González-Quintero & Avila-Foucat, 2019). The main characteristics of this approach include comprehensiveness, transparency, objectivity, and reproducibility, which make it a rigorous and comprehensive method for reviewing a growing body of scientific literature (SEI-CEE, 2017). In this study, the SLR method was conducted qualitatively owing to the depth required for analyzing the case studies, according to the Cochrane Methodological Expectations for Intervention Reviews (MECIR) protocol (Higgins et al., 2019). The SLR was undertaken following the four stages described below.

Publications search

To select scientific publications with rigorous academic standards and worldwide coverage, the Scopus database was used as the main source of international-level information (Visser et al., 2020). Scopus facilitates the extraction of bibliographic information through its application programming interface (API), which is constantly updated (Montoya et al., 2018) and allows the export of references in diverse formats that can be used for data coding in different programs (Gómez-Santiz et al., 2021). A search was conducted from June 7–9, 2023, using the title, abstract, and keyword fields of articles (TIT-ABS-KEY), and the final search was narrowed to scientific articles, as recommended by Booth et al. (2012), Higgins et al. (2019), and Gómez-Santiz et al. (2021). For syntax construction, two blocks of concepts and synonyms (in English) related to *i)* the SES (SES, socioenvironmental systems, or socio-natural systems); and *ii)* SEST (trajectory, change, transformation, evolution, transition, or pathways) were considered. However, during the article search process, the syntax was adjusted as indicated in Figure 1.

Figure 1
Stages of the systematic literature review process applied to the study



Source: Self-elaboration.

In the initial search, a total of 11 859 publications were found over the period of 1961–2023. However, when the titles of the publications were reviewed, many were found from other fields of study, such as medicine, biology or ecology, so several filters were used to refine the search and capture the appropriate sample. First, the words "change" and "pathway" and, second, the terms "transformation", "evolution", and "transition" were excluded. This is because studies in the field of ecology regarding, for example, socioecological niches, often use the term "evolution"; "pathways" is linked to economic capital or climate pathways; and climate "change" is similarly a common subject. Moreover, in studies of socioenvironmental problems linked to pollution and the direct effects of human activities, such as dams or agriculture, the terms "impact", "transformation" and "transition" are commonly used.

Therefore, the final syntaxis was *TITLE-ABS-KEY ("Socio-ecological* system*" OR "socioecological* system*" OR "social ecological system*" OR "social-ecological system" OR "Socio-environmental* system*" OR "Socioenvironmental* system*" OR "Socio-natural* system*" OR "Socionatural* system*") AND TITLE-ABS-KEY ("Trajector*").* As a result, 206 scientific articles focused on SEST and published from 2004–2023 were included in the database for analysis.

Publication selection

In this stage, the abstracts of the 206 preselected articles were manually reviewed, and 34 publications were excluded for not explicitly addressing the topic of trajectories or not having an SES focus. In addition, publications that focused exclusively on themes such as sustainability, social ethnographies, education, or general reflections on SESs (but not on trajectories), as well as works with a specific focus on the economy, environmental contamination, urban expansion, land use change, and ES mapping were excluded.

The full texts were subsequently read with the aim of proposing the variables to be coded. In this stage, another 29 works were excluded because they addressed topics related to general and epistemological reflections about SESs or focused only on certain aspects of SESs or a specific ecosystem. This left a final database of 143 articles (see Annex 1) related to worldwide case studies about SEST.

Coding and extraction of data

On the basis of a proof review of the full texts of the 143 selected publications and following the suggestions of Booth et al. (2016), Codina (2018), Higgins et al. (2019), and Pullin and Stewart (2006) coding of the database was proposed and carried out

using the variables listed in Annex 2. A total of 32 variables were organized into five groups: *i)* paper description (3 variables); *ii)* case study context (5 variables); *iii)* social-ecological system description (12 variables); *iv)* theory approach (3 variables); and *v)* methodology (9 variables). This categorization was based on the recommendations of Ávila Foucat et al. (2020), De Vos et al. (2019), Duval (2015), Fedele et al. (2020), Fischer-Kowalski and Rotmans (2009), Herrero-Jáuregui et al. (2018), Holzer et al. (2018), Gómez-Santiz et al. (2021), González-Quintero & Avila-Foucat (2019), Palomo et al. (2021), Perevochtchikova et al. (2022, 2024), Riechers et al. (2021), and Varis et al. (2019).

The search, selection and coding process involved several joint review sessions among the coauthors and the determination of the variables and codes to be implemented by consensus, as suggested by Perevochtchikova et al. (2019, 2021).

Analysis of data and synthesis

With the coded database, three phases of qualitative data analysis were conducted (Figure 1):

- *Characterization of publications* in the following dimensions: *i)* temporal, with the outlining of a timeline of publications and principal journals; *ii)* spatial, with the establishment of a coauthorship affiliation network by country and a map of study case sites; and *iii)* conceptual or semantic, with the development of word clouds (word frequency is given in Annex 3). To accomplish this, visual tools such as Microsoft Excel, Atlas.ti 8 software (Friese, 2019), QGIS (https://qgis.org/) and the Flourish visualizer (https://flourish.studio/) were used.
- *The concept of SEST* was developed on the basis of the sequential proposal by Perevochtchikova et al. (2022) and the definitions of SEST directly given by the authors of the reviewed articles, with the proposal of a general conceptualization, typology and graphical SEST interpretation.
- *Formalization and operationalization of SEST,* which included three aspects of analysis, and the synthesis was presented through flow (Sankey) diagrams. This method allows a graphical description of the associations between variables (Gómez-Santiz et al., 2021) through the construction of cross-tabulation tables and their projection in a Flourish visualizer.
  - *The contexts of the case studies* was considered to reveal the ecosystems, functional and thematic ecosystem services, and SESs analyzed in the case studies.

- *The SESTs in the case studies* were highlighted, with reference to the temporal and spatial scales addressed in the studies, the actors involved, the drivers of change (internal and external factors), the identified issues (Annex 4), SES components, and the type of SEST.
- *The theoretical and methodological approaches* in terms of the theories and concepts identified, the utility of the studies conducted, the methods and techniques used for data collection and analysis, and the disciplinary focus of the studies were observed (Annex 5a, b).

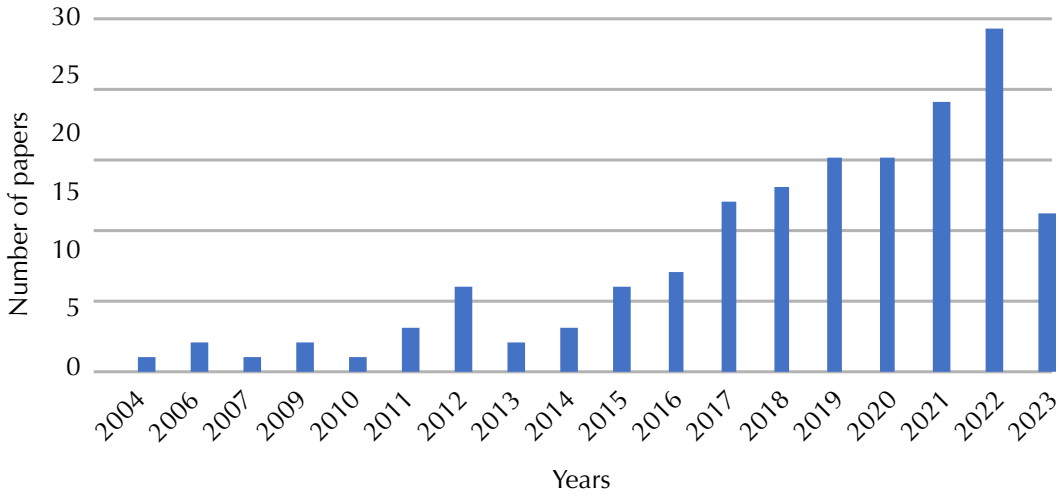
Results

Characterization of publications

The timeline of the 143 reviewed articles indicates a steady growth in publications since 2004 and reflects a progressive increase in scientific interest in SEST analysis worldwide (Figure 2).

The articles were published in 78 scientific journals, 10 of which accounted for 43.5% of the total. Notably, *Ecology and Society* (16.2%), *Sustainability* (4.9%), and *Global Environmental Change* (4.2%) stand out. This distribution highlights the journals' focus on disseminating the concept and suggests specific geographic and thematic areas where the concept of SEST has found fertile ground for exploration and discussion.

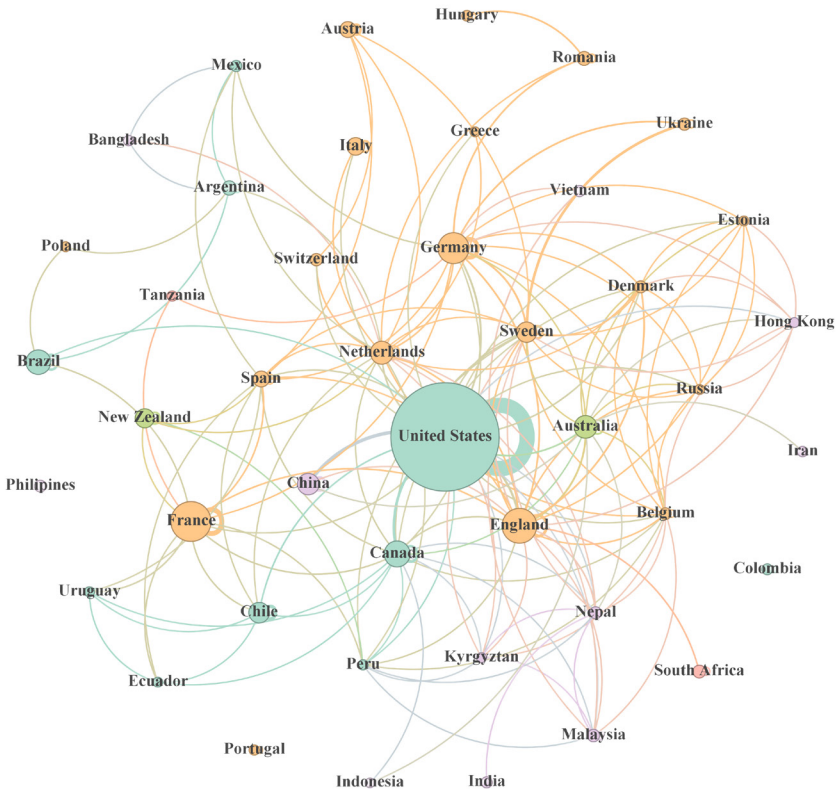
Figure 2
Timeline of articles focused on SEST studies, 2004-2023



Source: Self-elaboration.

The coauthorship affiliation network, which is based on the institutional affiliation of the authors of the 143 publications by country, provides valuable information about the extent and diversity of international collaboration in the field. The network comprises a total of 44 countries (called nodes in the network), three of which (Colombia, Portugal and the Philippines) are disconnected from the main group. The node size indicates the total number of authors from a specific country, the line thickness represents the frequency of collaboration between authors, and the color of the lines indicates the connections by continent. Overall, the network metrics show moderate connectivity and collaboration between authors from different countries in the SEST articles. The clustering coefficient (0.682) and average path length (2.098) suggest that some groups of authors tend to collaborate more intensively with each other than with other groups (Figure 3).

Figure 3
Network of co-authorships in publications about SEST



Note: The nodes are countries of affiliation of the authors; the lines are collaboration relationships in articles; the colors of relationships are indicated by continent; and size of nodes indicate number of authors.

Source: Self-elaboration.

For example, the nodes with the highest levels of degree centrality (which indicates that they produce the most publications) correspond to authors' institutions located in the United States (U.S.), France, England, Germany, Sweden, Netherlands and Canada. The loop present in the U.S. shows a high level of collaboration among U.S. authors. Additionally, high coauthorship is observed among U.S. and Canadian authors with each other and with authors from Europe, as well as among authors from diverse countries inside Europe, while authors from the Global South are fewer and engage in less extensive collaboration. Specifically, from Latin America, authors from Brazil, Chile, Mexico, Argentina, Peru, Ecuador and Uruguay (with Colombia as a separate node) are present in this network, but the majority collaborate with authors from the U.S., Canada and Europe.

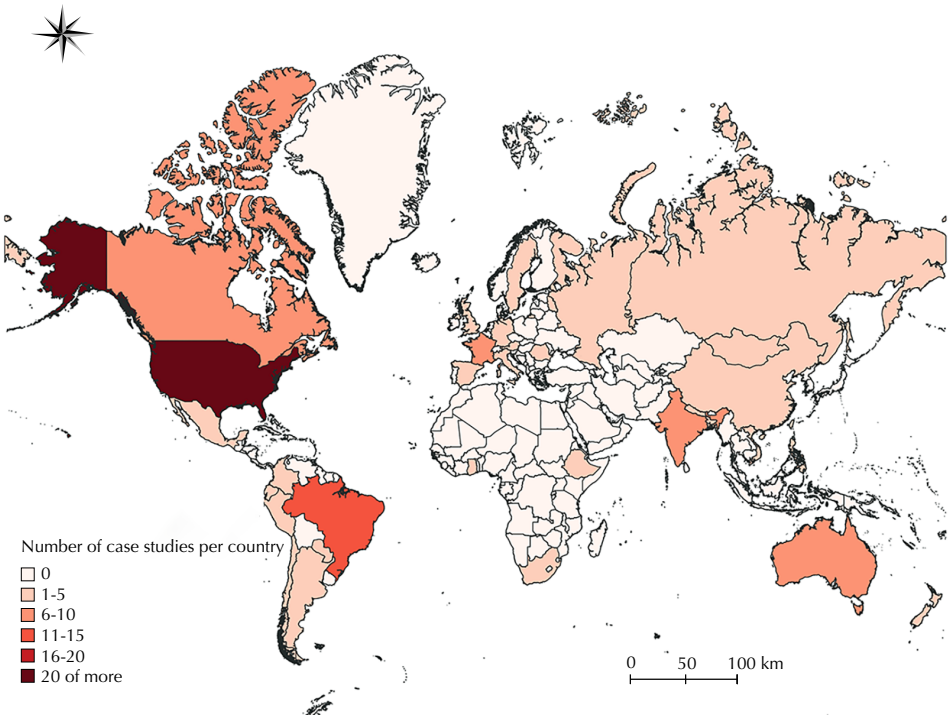
Importantly, research centers located in these countries, such as the Faculty of Sustainability at the University of Leuphana in Germany, the Laboratoire d'Ecologie Alpine at the University of Grenoble Alpes, the Stockholm Resilience Centre at Stockholm University in Sweden, and the Institute for Complex Systems Simulation and the Centre for Environmental Sciences at the University of Southampton in England, have a long tradition of studying SES topics from a systemic, integrative perspective and hold leading roles in generating and disseminating this type of knowledge. The participation of scientific research agencies in the U.S., such as the Geological Survey, the Forest Service, and the Environmental Protection Agency, as well as other research centers dedicated to sustainability, climate change, and prospective (focused on the future scenarios) studies, is also noteworthy.

Among the main authors who address the SEST topic are: S. Lavorel (4 papers), P.H. Verburg (4), J.A. Dearing (3), T. Hahn (3), N. Hanazaki (3), J. Fischer (3), K. Zhang (3), and several authors with 2 papers each, including A.J. Castro, C. Folke, L. Nahuelhual, P. Olsson, S. Zank, and others.

Among the case studies, 37% are concentrated in the Americas, 23.6% in Europe, 19.4% in Asia, 12.1% in Oceania, and 7.9% in Africa. The countries with the highest number of publications are the United States (12.1%), Brazil (7.5%), France (5.7%), India (4%), and Australia (4%) (Figure 4). All these countries, except France, are considered megadiverse by the United Nations Environment Program World Conservation Monitoring Centre (SCBD, 2016) and could be appropriate for study from the complex SES perspective.

In the semantic analysis conducted using a word cloud (Figure 5), 134 primary terms were identified on the basis of their frequency in the titles, abstracts, and keywords of the selected articles (see Annex 3). The terms "system," "social–ecological," and "change" appear frequently in the publications, referring to the most commonly used theoretical perspectives for SEST analysis. Similarly, words such as "management," "ecosystem," "landscape," "resilience," "governance," and "adaptive" are part of the conceptual and analytical frameworks employed. Other groups, such as "trajectory,"

Figure 4
Location of sites of SEST case studies



Source: Self-elaboration.

"pathway," "development," "change," "shifts," "transformation," and "transition," have lower frequencies and are related to the temporal and spatial dimensions of studies.

The words referring to specific resources (such as "fisheries, forest, water, food, livestock"), study contexts ("rural, urban, coastal, agricultural"), common techniques and methods ("modeling, scenarios, impact, assessment, interviews"), and components of SES ("social, ecological, interaction, actors, drivers, outcomes, conditions, actions") are also identified. In general, concepts from the natural and social sciences are prevalent and are articulated through multi- and interdisciplinary theoretical and methodological frameworks (Figure 5).

Conceptualization of SEST

Notably, out of the 143 articles reviewed, only 27 (19%) contained some definition of SEST (Table 1), and partial references to SEST were found in 22 papers (15%), with no definitions in the remaining papers. These publications began in 2011 and became more common since 2020.

Figure 5
Word cloud based on title, abstract and keywords of SEST studies publications

Source: Self-elaboration.

Table 1
SEST definitions in the reviewed articles

N	*Reference*	*Cited*	*SEST definition*	*SEST categories*	*Analytical approach*	*Method*	*Discipline approach*
1	Fazey et al., 2011	95	Trajectories of change are dynamic processes of individual, group and/or societal responses to change which create further change and responses, with outcomes that reflect the cumulative properties of those processes.	Chan	Adaptation, Vulnerability.	System dynamic.	Multi
2	Rueff et al., 2012	18	*"Farm trajectory"* as a succession of chronological steps in the farm development process.	Chan	Theory of change, Livelihood, Adaptative system, SES Framework.	Multivariate analysis.	Multi
3	Morzillo et al., 2015	19	*"Trajectory of change,"* defined as the cumulative and iterative process of social responses and outcomes to change.	Chan	Pathways Framework, SES Framework, Adaptation.	Comparative case studies.	Multi
4	Sinclair et al., 2017	20	Resilience thinking appears to offer a holistic approach that can be used by social researchers to interpret past and contemporary conditions and identify possible futures for social-ecological systems (SES).	Chan	Resilience, SES Framework, Adaptative cycle.	Comparative case studies.	Multi

(continued)

Table 1
(continued)

N	*Reference*	*Cited*	*SEST definition*	*SEST categories*	*Analytical approach*	*Method*	*Discipline approach*
5	Uden et al., 2018	8	The social-ecological feedbacks can lock FEWES nexuses into unsustainable trajectories characterized by short-term control, stability, and efficiency, but also the inability to withstand or adapt to novel disturbances and/or changing conditions (i.e., inflexibility, low adaptive capacity), and therefore, long-term vulnerability to large-scale collapse (i.e., undesirable, unintentional state shifts). Such phenomena are investigated as rigidity traps in the resilience literature.	Adap	Governance, Resilience, Social–ecological systems.	Tools of process-tracing, Casual loop diagramming, Scenario planning.	Inter
6	Caswell et al., 2020	26	Historical analogies exist that can provide insights for contemporary planning and implementation of blue growth (across such broad spatial and temporal scales).	Adap	Historical perspectives, Sarine socioecological systems.	Case-study approach based on expert knowledge.	Multi
7	Desjardins et al., 2020	9	Long-term culture-adaptive trajectories: Past responses to climate change for future adaptation and mitigation strategies (of past social-ecological systems intersect with modern climate adaptation).	Adap	Social-ecological systems, Resilence, Human-environment interactions.	Archaeological study, meta-analysis of multiple studies relating to theme.	Multi
8	Jiren et al., 2020	12	Four plausible future scenarios for the studied landscape, were developed (as desirable outcomes scenario).	Dev	Social-ecological systems.	Causal loop diagrams, Draft scenario narrative.	Inter
9	Karpouzoglou et al., 2020	8	Development pathways in defined as *"the particular directions in which interacting social, technological and environmental systems co-evolve over time"*.	Dev	Development pathways approach, Social-ecological systems.	Spatial analysis, Thematic analysis.	Inter
10	Riechers et al., 2020	38	As social-ecological change entails numerous inter-connected dimensions.	Chan	Landscape sustainability science, Social-ecological systems.	Narrative approach.	Multi
11	Spicer et al., 2020	2	Tangible changes in the socio-ecological system at multiscale. *"We define a landscape path as the connected transitions of a socio-ecological system over time at the catchment scale"*. Identification of a landscape pathway and transitions allow inference of possible landscape trajectories into the future.	Chan	Nested socio-ecological systems, Landscape biographies, Landscape transitions and paths.	Interpretative research.	Multi

(continued)

Table 1
(continued)

N	*Reference*	*Cited*	*SEST definition*	*SEST categories*	*Analytical approach*	*Method*	*Discipline approach*
12	Dinis and Simões, 2021	1	The trajectory of this (productive) system up to present, its adaptation to internal and external changes and evolution trends.	Adap	Resilience, Theory of the adaptive cycle, Socio–ecological system.	Participatory approach, Social perception.	Multi
13	Epstein et al., 2021	6	The social-ecological system dynamics/transitions and potential future trajectories.	Chan	Resilience assessment approach, Social-ecological systems.	Meta-analysis literature review, Structured narrative literature review.	Multi
14	Angelstam et al., 2022	3	Cultural trajectories, where wood production and biodiversity conservation encompass different portfolios of ecosystem aspects and spatio-temporal scales.	Chan	Social-ecological systems.	Narrative approach, Exploratory review, Longitudinal case studies.	Multi
15	Aslan et al., 2022	1	Feedbacks between the social and ecological systems pathways (as model context).	Chan	Social-ecological systems, Coupled natural–human systems.	Multi-response permutation procedure, Spatial autocorrelation.	Inter
16	Carrie et al., 2022	3	Ecosystem Services change, adaptation and current adaptive capacities.	Adap	Adaptive capacity, Resilience, Socialecological system.	Spatial analysis, Thematic analysis.	Inter
17	Debonne et al., 2022	9	Transformations (social-ecological) are the consequence of or response to shocks and long-term pressure buildup. Megatrends are long-term driving forces that are observable now and likely have transformational potential in the future.	Adap	Geography of megatrends, Social-ecological systems, STEEP (Social, Technological, Economic, Environmental, Political) framework.	Foresight approach, Quantify and map megatrends.	Inter
18	Elleaume et al., 2022	2	Response capacity (understood as *"adaptation"* in this manuscript) of a specifc and local SES to environmental, economic, social and political per-turbations during the last four centuries. reconstrtuting a comprehensive mountain SES trajectory by exploring past changes and adaptation pathways. A way to study the past trajectory of a SES is through the analysis of past land use and land cover changes.	Adap	Social-ecological systems, Paleoenvironmental approach.	Historical archives analysis, Paleoenvironmental analysis.	Inter

(continued)

Table 1
(continued)

N	*Reference*	*Cited*	*SEST definition*	*SEST categories*	*Analytical approach*	*Method*	*Discipline approach*
19	Feiner et al., 2022	13	Consider the transformation in terms of (1) resisting trajectories of change by acting to maintain a contemporary state or restore prior ecological conditions, (2) accepting trajectories of change without interventions, (3) directing changes through interventions intended to shape ecological conditions toward new desired conditions or states.	Chan	Resist-Accept-Direct (RAD) framework, Ecological transformation.	Mental model (deterministic, stage-based matrix model).	Inter
20	Imbrenda et al., 2022	3	Development trajectory of socio-ecological systems towards land degradation on a regional or local scale.	Dev	Sustainable land management, Desertification risk.	Geographically weighted regression, Environmental Sensitive Area.	Inter
21	Quintas-Soriano et al., 2022	7	Coupling trajectory: Transition process by which the feedbacks within the SES increase the adaptive capacity of the SES through time and thereby lead to a more coupled SES. De-coupling trajectory: Transition process by which the feedbacks within the SES lead to less adaptive capacity of the SES through time and thereby to a more de-coupled SES.	Adap	Social-ecological systems, Human–environment systems (HES), Coupled human–nature systems (CHANS).	Comparative case study, Indicators.	Inter
22	Tàbara et al., 2022	9	In a given social-ecological system, three key moments need to be considered to study transformation: (1) The building of transformative conditions and capacities for systemic change, (2) A tipping event or intervention shifting the system towards a diferent trajectory or systems' confguration, and (3) the structural efects derived from such transformation.	Dev	Social-ecological tipping points (SETPs), Systems transformations, sustainability science.	Relational methodology, Narrative interpretation..	Inter
23	Villasante et al., 2022	12	As analyzing the interactions between drivers, potential trajectories (shifts, traps, and collapses), and the influence of enabling and inhibiting conditions in determining possible outcomes, including the opportunity to navigate sustainable transformations in SSF. Also, as how SSF can follow different pathways and how transformative changes are catalyzed over time.	Dev	Pathways of change, Resilience, Social-ecological systems, Sustainability transformations.	Heuristic model, Conceptual model.	Multi

(continued)

Table 1
(concluded)

N	*Reference*	*Cited*	*SEST definition*	*SEST categories*	*Analytical approach*	*Method*	*Discipline approach*
24	Zank et al., 2022	1	Ethnomedical systems are complex social-ecological structures and processes affected by drivers that may lead to changes in the trajectories of these systems, or even to collapse, according to their resilience and adaptation capacity.	Adap	Biocultural systems, Ethnomedical systems, Resilience, Adaptation capacity.	Discourse analysis, Virtual ethnography, Multilevel logistic regression.	Multi
25	Derolez et al., 2023	0	As dynamics of coevolution of the social and ecological components of a complex coastal system along with regime shifts (in hisoric perspective).	Adap	Social-ecological systems, Resilience, Drivers-Pressures-State-Impacts-Responses framework.	Chronosystemic timeline approach, Time series analyses based on indicators.	Inter
26	Lazurko et al., 2023	0	Big-picture scenarios of a river basin under climate change by characterizing future change as emergent from interactions between diverse eforts to build resilience and a complex, cross-scale SES.	Adap	Social–ecological systems, Water governance, Resilience.	Cross-impact balances method, Narrative scenarios, Participative modeling.	Trans
27	Walsh et al., 2023	0	Human decision-making trajectories, with continued and prescient impacts in the rapidly changing Arctic.	Chan	Cultural evolutionary framework.	Cultural evolution method, Ethnographic analysis, Literature review.	Multi

Note: Adap = adaptation; Chan = change; Dev = development; Multi = multidiscipline; Inter = interdiscipline; Trans = Transdiscipline.
Source: Self-elaboration.

As shown in Table 1, three principal characteristics of SEST can be detected: *i)* multiple components and interactions inside and outside the SES (systems, interconnected dimensions, interactions between diverse efforts, etc.); *ii)* temporal dynamics of SES transformations (dynamic processes, chronological steps, short- or long-term processes, historical perspectives, past, contemporary, evolution trends, etc.); and *iii)* spatial scales (large-scale collapse, cross-scale SES, regional or local scales, etc.). Different analytical and methodological frameworks are used for the study of SESTs, depending on the objectives of each particular study.

However, the SEST studies clearly focus on examining the change processes within the entire SES under various external and internal pressures and analyze its past and present conditions to project possible or plausible future scenarios toward sustainability.

Therefore, depending on the concepts applied for the SEST analysis and the study purposes, three categories (or typologies) of SEST can be observed: *i) adaptation*,

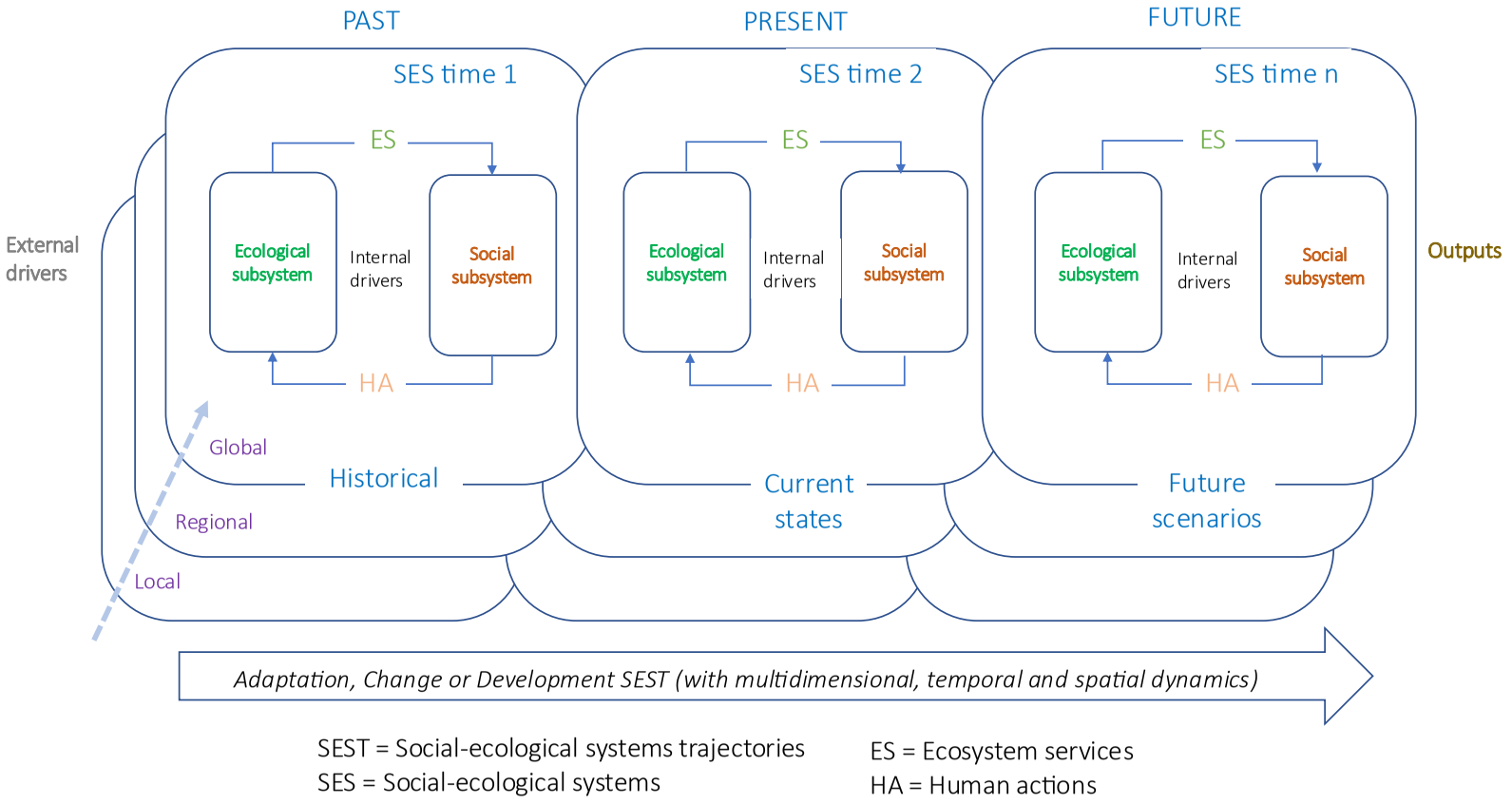
referring to SES transition, evolution, and adaptation processes (studies of global drivers, such as climate change, and the mitigation or adaptation processes of SESs); *ii) change*, related to SES transformations *per se*, processes of changes, coevolution, interactions, and settings studies (studies of total SES dynamics or their components and interconnecting changes); and *iii) development*, referring to development processes, dynamic processes, pathways to sustainability (or not), mega tendencies, and regional or global trends (studies of the projected effects of political policies or economic instruments). The adaptation and development types frequently focus on political aims and changes to research proposals.

According to the timeline of included studies, interest in the SEST topic initially began with a focus on the change category and underwent a transition toward adaptation and the eventual dominance of adaptation and development in recent years. Similarly, the SES analytical framework was predominant at the beginning of the timeline, whereas the social–ecological systems, governance, resilience, and human–environment interaction frameworks are currently more prevalent. Multidisciplinary methodological approaches were developed ten years ago, and interdisciplinary and even transdisciplinary studies emerged beginning in 2020. The methodological approach of coupling human–ecosystem models allows the analysis of not only one or several components of an SES but also comprehensive studies of an SES as a whole, considering the interactions between the social and ecological subsystems. The usefulness of SEST studies is evidenced in the interest in early studies for academic and public policy purposes and the current move toward contributions to society and local communities.

On the basis of this review, a generalized conceptualization of an SEST could be formulated as follows: "the continuous change process of understanding the present state of an SES as a result of past transformations and seeking to project possible future scenarios and determine the human actions or complex interventions required to achieve desirable (usually called sustainable) conditions"; this conceptualization is visualized in a framework (Figure 6). This definition is more comprehensive than the definition of a transformation process because it considers temporal–spatial scales of changes and projects different future paths for SESs.

Figure 6 shows that SESTs are characterized by multiple SES dimensions that include drivers (external and internal pressure factors), social and ecological subsystems, feedback or interaction through flows of ecosystem services and human actions, and outputs, which can lead to shifts, traps or system collapse. The SEST is dynamic at two scales: *i)* the temporal scale, which includes the past through historical tendencies, current states, and future scenarios (including desirable, plausible, anticipatory, resilient or sustainable conditions); and *ii)* the spatial (or territorial) scale, which includes the local, regional, and global scales. The SEST includes *adaptation, change and development* categories.

Figure 6
General SEST conceptualization proposal, with multidimensions, temporal and spatial scales dynamics



Note: Colors define the temporal (blue), spatial (purple) and multidimensional dynamics (dark and light green = ecological; dark and light coffee = social; grey = external drivers; black = internal drivers; and swamp = outputs).

Source: Self-elaboration, based on the publications review.

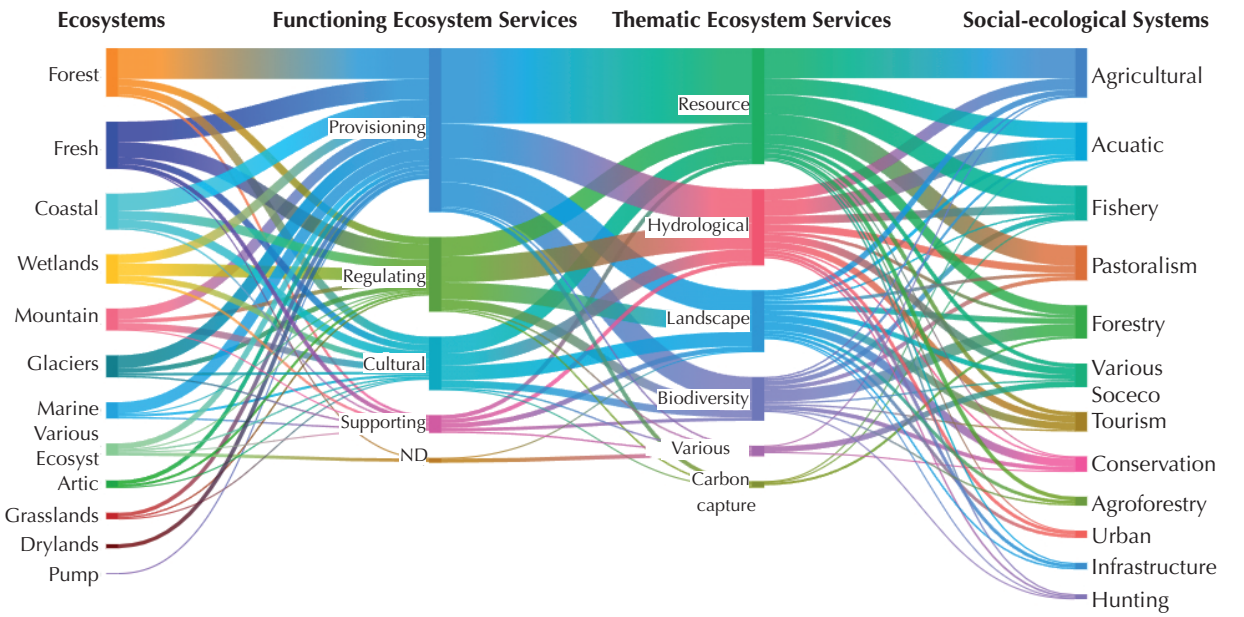
Formalization and operationalization of the SEST

Contexts of the case studies

The case studies identified in the 143 articles covers diverse ecosystems. Forests (19.5%), coastal (15.2%), and freshwater ecosystems (15%) are predominant, whereas grasslands (13.4%), mountains (9%), wetlands (9%), marine ecosystems (7.9%), arctic ecosystems (3%), and pampas ecosystems (0.6%) are less represented. In terms of ecosystem services (ESs), provisioning services (56%), which refer to the production of tangible resources, such as food, water, raw materials, and energy, are dominant. They are followed by regulating services (22%), cultural services (16%) and supporting services (5%), which are less prevalent. Additionally, ESs include resource provision (43%), followed by hydrological (21%), landscape (17%), biodiversity (14%), and carbon capture (2%).

Eleven types of SESs are identified in the analyzed articles. Agricultural (20.6%), pastoral (14%), and fisheries SESs (14.1%), which are characterized by economic activities, predominate. These are followed by forest (11%), aquatic (11%), tourist (6%), conservation (5%), agroforestry (3%), infrastructure (3%), urban (2%), and hunting SESs (1%), which are less common. When analyzing ecosystems, ESs and SESs as a whole, there is a clear bias toward valuing and considering human benefits, mainly in terms of resource extraction or good production (food, wood, energy, etc.) (Figure 7).

Figure 7
Flow diagram of the relationship between ecosystems, functional and thematic ES, and social-ecological systems



Source: Self-elaboration.

SESTs in the case studies

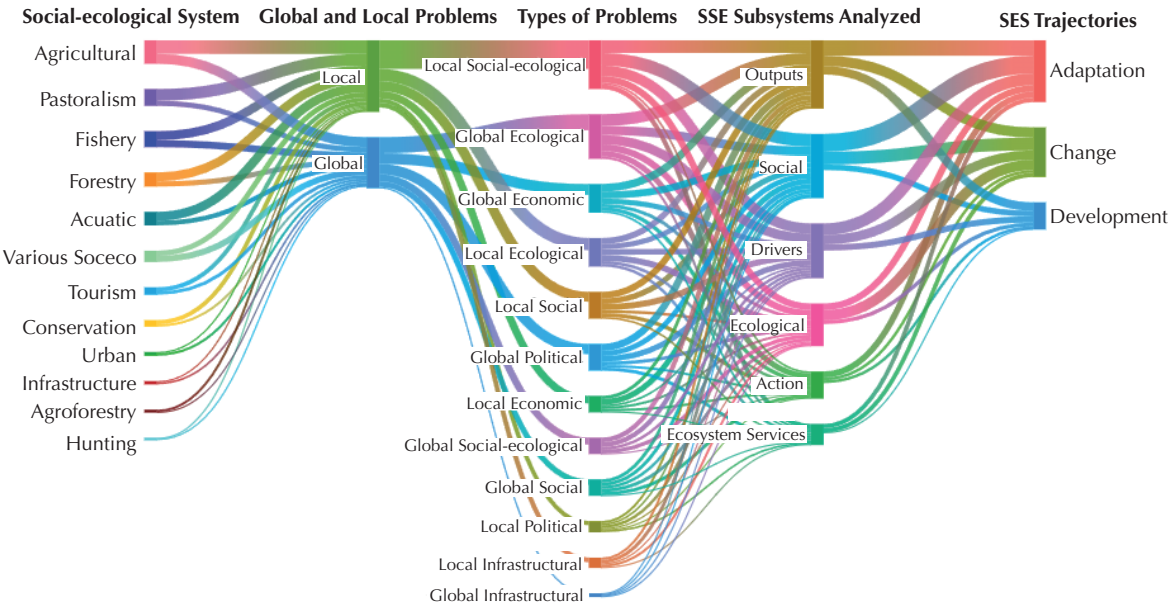
Among the identified problems for SESs (see Annex 4) are social–ecological (30.8%), ecological (23.9%), economic (14.2%), social (13.4%), political (12.6%) and infrastructure challenges (5.3%). In 57.9% of the cases, the acknowledged problems have a local territorial scale (as reflected in land use change, the loss of community knowledge, the weakening of governance systems, and the presence of illicit activities), whereas the remaining cases focused on global issues (climate change, economic crises, demographic changes, urbanization, and international politics). Listed from the most to the least represented, the actors involved in SES functioning include communities residing in the study areas that directly use and benefit from different ESs (39%), public entities that regulate ES access and exploitation (28%), and, to a lesser extent, private companies (18%), academia (9%), and nongovernmental organizations (7%).

Among the drivers that influence SES changes, 32.9% of the external drivers are economic, 25.2% environmental, 23.4% political, 11.7% social, and 6.8% are technological. In terms of the sources of internal drivers, 46.9% are social, 19.6% environmental, 17.2% economic, 12.9% political, and 3.3% are technological. Interestingly, some global phenomena, mainly economic phenomena (such as economic regulation, financial crises, and the international market), drive processes that are typically of a social nature and thereby affect the dynamics and functioning of SESs at the local level. This trend is also evident in the analysis of the SES components considered in the studies. Therefore, most of the articles (26%) analyze social subsystems, with 25% analyzing outputs, 20% analyzing drivers, 15% analyzing ecological subsystems, 8% analyzing actions, and 6% analyzing ESs (Figure 8).

The majority of the studies were conducted in rural settings (89.5%), with a minority concentrated in urban (4.9%) and periurban (1.4%) contexts. The remaining 4.2% of studies correspond to cases that, owing to their scope, encompass all three contexts. The spatial scale is regional (including watersheds, deltas, and bioregions) in 69% of the studies, local (villages, settlements, cities, and protected natural areas) in 15.5%, international (involving multiple countries) in 13.4%, and national (country-level studies) in 4.2%. Only 1.4% of the articles adopt a multiscale perspective.

At the temporal scale, the periods under analysis are diverse. For example, 18.9% of the studies analyze periods of less than 10 years, 64.3% cover periods of 10 to 99 years, and 16.8% cover periods of more than 100 years. Some archaeological and paleontological studies even analyze periods longer than 1000 years. Thus, the majority of studies (72.8%) are retrospective and analyze past events to determine how they have influenced the historical SES trajectory of a region. These studies are followed by cross-sectional studies (11.2%) that assess the current state of SESs, including their development

Figure 8
Flow diagram of the relationship between social-ecological systems, type of problems, components of the analyzed SES and tendencies of trajectories



Source: Self-elaboration.

and evolution. Finally, prospective (11.9%) and retrospective studies (4.2%) predict and analyze future scenarios and past or present tendencies.

Among the three identified categories or types of SESTs, *adaptation* trajectories are found in 45.8% of the articles; these studies analyze the directions or SES paths followed in response to specific drivers or disturbances. These indices are often used to assess the capacity of an SES to adapt to changing conditions (usually climate) while maintaining relatively stable properties, functioning, and equilibrium. *Change* trajectories are identified in 38% of the studies, which explore SES transformations due to exposure to disruptive events or stress factors that modify SES properties, structure, and functioning. This trajectory is adopted in the study of thresholds, transitions, and regime shifts in SESs. *Development* trajectories focus on SES evolution toward more sustainable, equitable, and desirable states, and they are present in 16.2% of the articles. This perspective is used to describe the changes that SESs undergo, especially in the long term.

Theoretical and methodological approaches

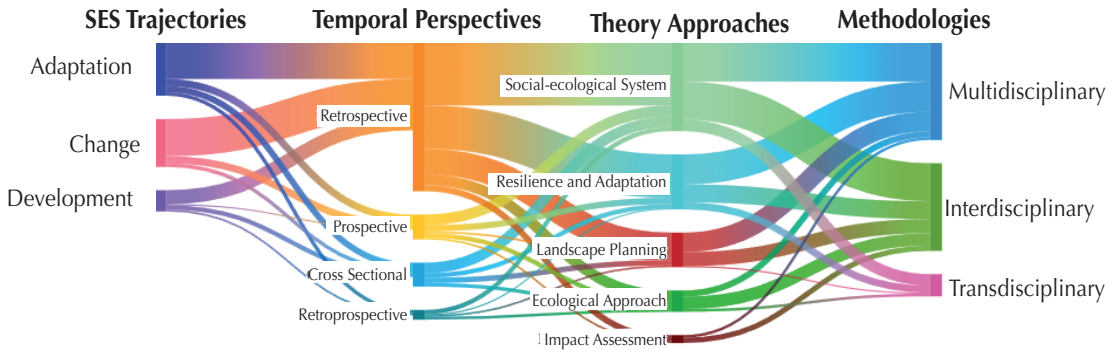
Based on the review of the theoretical approaches applied in SEST studies (see Annex 5a), five major groups that are used for the construction, description, and analysis of trajectories are identified:

- Social–ecological system and human ecology approaches are the most commonly adopted (44%); these incorporate analytical frameworks that consider both social and ecological dynamics and their interactions with human activities.
- The second-most common approaches are the resilience and adaptation approaches (26%), which include frameworks that assess levels of risk and vulnerability and determine the capacity of SESs to absorb disturbances and adapt to changes.
- Landscape, planning, management, and land use change approaches (16%) involve theories and concepts used to examine land use changes at various territorial scales and analyze the implementation effects of public policy instruments.
- Ecological approaches (10%) are undertaken in efforts to understand ecosystem interactions and dynamics.
- Finally, impact assessment approaches (4%) include the use of frameworks and tools to determine the effects of human activities on SESs and SESTs. Interestingly, given the complex and interdisciplinary nature of SESs, most articles (55%) combine theories, frameworks, and concepts from different approaches, with the SES framework interacting with or combining most of them.

There is a clear correlation between the SEST categories and the theoretical approaches used for their analysis. For example, *adaptation* trajectories are explored primarily through resilience and adaptation approaches, as well as impact assessment approaches. *Change* trajectories tend to involve ecological approaches and theories related to the landscape, planning, management, and land use change assessment approaches. Finally, *development* trajectories are often examined using SES and human ecology approaches (Figure 9).

Methodologically, qualitative methods and related tools are used in 48.3% of the articles, which focus mainly on the social subsystem or the action situation and describe components, dynamics, issues, and trajectories. Quantitative methods, present in 35% of the papers, are applied mostly to analyze ecological subsystems and outputs and examine SES relationships, patterns, effects, tendencies, and impacts. Mixed-methods studies, which combine and analyze qualitative and quantitative data for a more comprehensive and in-depth understanding of SESTs, constitute only 16.7% of the total.

Figure 9
Flow diagram of the relationship between tendencies in social-ecological trajectories, temporal perspective, theoretical and methodological approach



Source: Self-elaboration.

In terms of data collection forms and special techniques, the following are predominant: historical analysis and scientific document reviews (46%); interviews with communities, organizations, decision-makers, and other stakeholders (20%); focus groups (13%); surveys (10%); geostatistical data systematization (5%); field sampling (3%); monitoring (2%); and role-playing (1%). The following data analysis methods (see Annex 5b) stand out: perception-based, narrative, and discourse analyses (28%); scenario modeling and simulations (17%); documentary analyses (13%); statistical analyses (11%); indicator generation and analyses (9%); development of conceptual models (6%); remote sensing and spatial analyses (6%); participatory and interactive methods (4%); laboratory measurements (4%); and ethnographic methods (2%).

Multidisciplinary approaches are found in 51% of the articles regarding knowledge integration in SESTs. Interdisciplinary approaches, which aim for a systemic understanding, are present in 38.5% of the publications. Finally, transdisciplinary approaches, which aim to integrate the perspectives of scientists and other involved actors, are present in only 10.5% of the publications.

With respect to the methodologies applied by SEST category, the studies from the *adaptation* perspective adopt the qualitative (22%), mixed (24%) and quantitative (13%) methodologies. The applied techniques include documentary analysis, narrative analysis, spatial analysis, thematic analysis, conceptual modeling, archaeological studies, meta-analysis, and case-study approaches. Among the methodological approaches, 22% of studies adopt a multidisciplinary approach, 15% an interdisciplinary approach, and 8% a transdisciplinary perspective. Among the *change* studies, 17% are qualitative, 16% are quantitative, and 4% have a mixed focus; and techniques such as scenario analysis, landscape modeling, social perception, spatial and statistical analysis, conceptual modeling, literature reviews, and network analysis are used. Among

these studies, 21% adopt a multidisciplinary approach, 15% an interdisciplinary approach, and 1% a transdisciplinary approach. Finally, for studies in the *development* category, 10% present a qualitative focus, 6% a quantitative focus, and 1% a mixed focus, and the technical methods adopted include documentary review, system dynamics modeling, interpretative research, meta-analysis literature review, statistical analysis, system dynamics, and spatial analysis. Moreover, 8% of these studies adopt an interdisciplinary approach, 7% a multidisciplinary approach and 1% a mixed methodological approach.

With respect to the usefulness of the generated knowledge, given the scientific nature of the articles, academic use (100%) is dominant. However, a significant percentage of the papers have results that are useful for informing and enriching public policies (54.5%), as well as inspiring social actions and empowering communities in different areas (50.3%), especially in recent years.

Discussion

Characterization of publications

The results of the SLR show a steady growth in SEST studies since 2004, which indicates an increased interest in and understanding of this topic. However, up to this point, such publications have been led by authors from countries in the Global North, particularly from institutions in the United States, France, England, Germany and Sweden. In contrast, the majority of the studied sites are in countries in the Global South. The same tendency has been identified with regard to other environmental issues, such as state-of-the-art of ES studies, ES payment thematic studies (Perevochtchikova et al., 2019, 2021) and operationalization of the SES framework (Gómez-Santiz et al., 2021). According to Hazlett et al. (2020) and Maas et al. (2019) this geographical and cultural bias among authors has repercussions for the selection of case studies, the issues analyzed, the theoretical approaches used, and the analytical perspectives adopted. It also highlights financial inequalities among countries in terms of the resources invested in scientific research (Balvanera et al., 2020).

In this context, the lack of representation of authors from countries and institutions from the Global South in SEST publications can lead to "parachute science," in which scientists and communities in the study areas are either not incorporated into the research processes or excluded from the publication (Haelewaters et al., 2021; Odeny & Borsugi, 2022; Stefanoudis et al., 2021). The significant risk here is that research led by scholars from a limited group of countries may lack the richness of perspectives provided by different cultures, knowledge systems, and local experiences; furthermore, they may result in the absence of a transdisciplinary view. To mitigate

this issue, it is essential to promote equal international collaboration and include diverse perspectives, contexts and voices. Research on SEST must be truly global and open to the participation and contributions of authors worldwide (Asase et al., 2021; Ocampo-Ariza, 2023).

Conceptualization of SEST

The conceptual definition of SEST in this work provides an integrated proposal for studying SESTs in various dimensions and at the temporal and spatial scales. This is essential for addressing the complexity and dynamics of SES transformations and facilitating the development of theoretical and empirical studies that model SES development and evolution in different contexts and with different drivers (Perevochtchikova et al., 2024). Such a definition is necessary for practices and studies on social–ecological dynamics, for example, for territorial planning and local decisions.

Furthermore, the framework is useful for visualizing multiactor participation in social–ecological research for political ends and generating useful information for decision-making at different levels (Leenhardt et al., 2015). In this regard, it is encouraging that a significant percentage of the reviewed studies can provide inputs for public policy design and local community empowerment (Perevochtchikova et al., 2024).

An interesting example is the work of Ford et al. (2013), which was developed with a community-based participatory research approach for vulnerability and adaptation to climate change analysis. Similarly, Nayak (2014) analyzed the impact of changes in the ecological subsystem on small-scale fisheries; Gaube et al. (2009) simulated land use change scenarios on the basis of a locally developed model; and Lamarque et al. (2013) modeled land management trajectories on the basis of social participation. Therefore, the understanding of potential SESTs and related effects can help raise awareness in society and support appropriate changes in human activities.

SESTs in the case studies

An important tendency observed in the SLR is that the studied ecosystems, ES and SES, are oriented toward the attainment of human benefits. The emphasis on the anthropocentric dimension, which is evident in the types of issues, drivers, and components of the analyzed SES, raises interesting questions about how ecological aspects and SES are considered in general (Binder et al., 2013). Given the complexity and uncertainty surrounding the behavior and dynamics of SESs under stressed conditions (due to internal and external drivers), it is necessary to promote research that examines resilience and adaptation issues (Folke, 2016) and recognizes the intrinsic value

of ESs and their capacity to maintain essential ecological processes as a foundation for society (Arias-Arevalo et al., 2017). In this sense, the conceptual tensions of resilience must be considered, and its definition must be reviewed (Meerow et al., 2016).

Through the SLR, three categories of SEST are identified, with a dominance of *adaptation*, followed by the *change* and *development* trajectories. The predominance of adaptation trajectories can be explained by the need to understand how SESs maintain stability and functionality in changing environments (Júnior et al., 2015). The emphasis on adaptation is closely related to the significant scientific interest generated by global climate change, as well as the political failure of mitigation agendas (Schipper, 2006; Bassett & Fogelman, 2013). Considering that publications on SESTs began eight years after the adaptation term was included in the international policy agenda, this approach, along with related notions of risk, vulnerability, and resilience, clearly carries weight in the scientific literature.

On the other hand, SEST studies related to change and development emphasize the evolutionary dynamics and transformations that SESs undergo. These studies of the change in SESTs focus on determining critical thresholds and transitions to other states of equilibrium (Arlinghaus et al., 2022; Debonne et al., 2022). In contrast, studies of the change in SESs focus on determining pathways (Cradock-Henry et al., 2021; De Herde et al., 2022; Karpouzoglou et al., 2020), levers, and leverage points (Fischer & Riechers 2019; Gómez-Santiz et al., 2021). Developmental trajectories refer to SES evolution toward more desirable, sustainable, and prosperous futures with respect to sustainability (Abson et al., 2016; Ávila Foucat et al., 2020; Chan et al., 2020; Fischer & Riechers, 2019; Riechers et al., 2021).

Theoretical and methodological approaches

The three categories of SESTs identified in the SLR (*adaptation, change,* and *development*) include a variety of approaches and are clearly associated with specific analytical and methodological approaches. The prevalence of SES and human ecology frameworks suggests that a significant portion of studies focus on understanding the complex interactions between ecological subsystems and human activities (Virapongse et al., 2016). Nevertheless, there is an evident interest in exploring SES resilience, planning, governance, landscape-level changes, and certain types of strictly ecological processes from alternative theoretical perspectives.

Notably, regardless of the categories of trajectories, theoretical approaches, and analytical frameworks applied, the sustainability discourse dominates in almost all the reviewed studies. Sustainability is considered a guiding principle, goal, and desirable future in projected SES trajectories, with various nuances and meanings often left unquestioned (Kuhlman & Farrington, 2010). In this context, several studies (Ciegis et

al., 2009; Toman, 2010) have noted that sustainability is an ambiguous and politically charged term that is susceptible to varied interpretations and raises questions about who defines what is sustainable and under what conditions. Bostrom (2013) proposed understanding sustainability in dynamic terms rather than as a sustainable state, especially in the face of existential risk.

The theoretical approaches, coupled with the methodological strategies applied in the case studies, support the examination of SEST temporality in a prospective, retrospective, retroprospective, and cross-sectional manner. Such analysis is conducted primarily using qualitative methods aimed at constructing narratives, historical analyses, or symbolic explanations for social subsystems, followed by quantitative methods that employ modeling and other statistical techniques to provide quantified representations of the transformations experienced by ecological subsystems and complete SESs (Jahel et al., 2023). To date, a low proportion of studies adopt mixed methods, the prospective and retrospective perspectives, and multiple spatial scales, which reflects the challenges involved in employing these approaches (Schlüter et al., 2012). However, the combination of these methods can offer a more comprehensive understanding of the analyzed SES trajectories in a cross-sectional manner (Ávila Foucat et al., 2020; Perevochtchikova et al., 2024).

In the same vein, there is a prevalence of multidisciplinary and interdisciplinary approaches, with limited studies from a transdisciplinary perspective, despite the importance of such a perspective for understanding complex SES dynamics (Folke, 2016; Merçon et al., 2018), where the incorporation of nonscientific actors into the research process is a fundamental requirement (Lang et al., 2012). However, infrequent use of the transdisciplinary approach, adopted in approximately 10% of the articles, suggests a low level of stakeholder involvement in the scientific research process and related decision-making.

The transition from additive perspectives, which are typical of multidisciplinary approaches, to the integrative and interdisciplinary perspectives involves the use of common theoretical approaches that facilitate the transfer of assumptions, concepts, and methods across different disciplinary fields (Duval, 2015). In this SLR, theoretical approaches were identified that allow for the examination of interactions between ecological and social subsystems (such as social metabolism, social–ecological tipping points, and coupled human and natural systems). These approaches incorporate various dimensions of processes or phenomena under study (social, technological, economic, environmental, and political frameworks; sustainable livelihoods; multicriteria assessment framework; etc.) and establish causal relationships while explaining SES changes over time and space (cascading impacts; drivers–pressures–state–impacts–responses framework; pathways; etc.).

However, the applied methodologies do not always aim for integration but often focus on the analysis of one or several SES components. A similar pattern can be

observed in the methods used for the operationalization of SESs (Gómez-Santiz et al., 2021).

Study contributions and limitations

The main limitation of the study is that only scientific publications (articles) were considered, whereas the world of literature on SEST is broad and potentially includes books, chapters, reports, and theses, among other sources. On the other hand, to represent SEST studies worldwide, the decisions to use only English in the syntaxis search and only the Scopus database limit the regional representation, as mentioned by Gómez-Santiz et al. (2021) and Perevochtchikova et al. (2021, 2022).

However, this study offers the following contributions: *i)* a rigorous review of worldwide SEST case studies; *ii)* an analysis of SEST term definitions and proposal for general SEST conceptualization; and *iii)* a presentation of the formalization and operationalization tendencies of SESTs in reviewed case studies. Additionally, in the present work, three categories of SESTs are identified (*adaptation, change* and *development*). This typology can be useful for scholars and practitioners interested in the study of SESs and their trajectories, especially in search of sustainable future scenarios, and can be applied in tasks such as territorial planning (Chen et al., 2023; Karpouzoglou et al., 2020), environmental and local governance and decisions (Fischer-Kowalski & Rotmans, 2009; Görg et al., 2017; Perevochtchikova et al., 2024), the development of public policy instruments (Toman, 2010) and the implementation of adaptation measures (Bassett & Fogelman, 2013; Cradock-Henry et al., 2021; Fedele et al., 2020).

This SLR on SEST studies identifies the following challenges and needs: *a)* expanding research to urban and peri-urban contexts, where SES dynamics may present different but reflect equally important issues (Chen et al., 2023); *b)* including multiscale and multidimensional perspectives in the analysis, especially through the complementary use of qualitative and quantitative methods to enhance the understanding and anticipation of long-term SES dynamics (Jahel et al., 2023); *c)* developing and applying analytical frameworks and methodological tools that consider issues related to the complexity, discontinuity, and uncertainty of SES (Elsawah et al., 2020; Jahel et al., 2023; Mallampalli et al., 2016); *d)* extending the scope of generated knowledge by conducting new studies in countries and regions that have not been previously analyzed (McGinnis & Ostrom, 2014); *e)* fostering international collaboration and the involvement of diverse stakeholders to more effectively address global social–ecological challenges (Holzer et al., 2018); *f)* adopting the inter- and transdisciplinary perspectives to incorporate the knowledge of different involved actors (Folke, 2016; Merçon et al., 2018); and *g)* encouraging critical reflection and in-depth exploration of the socioeconomic

and political implications, regulations within the sustainability discourse, and their influence on SES trajectories (Ávila Foucat et al., 2020; Newton & Freyfogle, 2005).

Conclusions

This work offers an SLR on SESTs through worldwide case studies. All of the following hypotheses are confirmed: *i)* few definitions of the term SEST exist; *ii)* studies of the formalization and operationalization of the term are biased toward a partial understanding of SES; and *iii)* multidisciplinary and interdisciplinary studies dominate. In this context, the main contribution of this work is in its review of the existing definitions and studies of SEST conceptualization, along with the temporal and spatial tendencies and theoretical and methodological approaches applied in related research. Additionally, the adaptation, change and development SEST categories are identified.

This study highlights significant research challenges, such as the development and application of comprehensive and mixed methods that reflect both the interdisciplinary and transdisciplinary focuses and the adoption of the multiscale, multitemporal, and multiactor perspectives. Improved understanding of the complex dynamics of SESTs represents a crucial step in enriching territorial planning and decision-making processes and expanding the capacity to address essential challenges along the path toward territorial resilience, sustainability, and socioecological equity.

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Annexes

Annex 1

List of 143 papers included in the final database for systematic literature review

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Annex 2
List of variables and codes implemented for systematic literature review

Groups of variables	*Variables*	*Codes*
Papers description	Year of publication	Year.
	Source title	Name of journal.
	Affiliations	Country of authors affiliation.
Case studies context	Sites of study	Author determination.
	Country of study case	Country name.
	Spatial scale unity	Admin=Administration boundary (municipality, city, country), Bioregion=Bioregion, Region=Region with specific problematic, Basin=Basins (including rivers, lakes, delta, coast).
	Spatial scale classification	Loc=Local, Reg=Regional, Nat=National, Sev=Several countries, Glob=Global, Multi=Multiscale.
	Temporal scale of study	Period, year-year.
Social-ecological system description	Ecosystems	Art=Artico, Coast=Coastal, Dry=Drylands, Glac=Graciaries, Gras=Grasslands, For=Forest, Fresh=Freshwater (river, lagoon, lake), Mar=Marine, Mon=Mountain, Pamp=Pampa, Wet=Wetlands (including Mang=Mangrove), Var= Various.
	Functioning Ecosystem Services	Pro=Provisioning, Reg=Regulating, Sop=Soporting, Cult=Cultural.
	Thematic Ecosystem Services	Carb=Carbon (including Carbon capture and charcoal), Bio=Biodiversity (including forest biodiversity), Hydro=Hydrological (including water supply, flood), Resource= Resources (including food, energy, timber), Land=Landscape (including soil, ski, recreation), Var=Various.
	Types of involved actors	Acad=Academic, Pub=Public policy, Priv=Private, Com=Communities (including local population, local people), Org=Organizations (including civil societies, NGO, etc.).
	Social-ecological System	Acua=Aquatic (including Aquaculture, irrigation, portuary, shipping), Agr=Agricultural, Af=Agroforestal, Fore=Forestry, Fish=Fishery, Hunt=Hunting (including recollection), Infra=Infrastructure, Past=Pastoral (including livestock, rangelands), Tour=Tourism, Urb=Urban, Var=Various, Cons=Conservation, Natural Protected Areas.
	Urban context	Urb=Urban, Periurb=Periurban, Rur=Rural, Terr=Urban, Periurban, Rural.
	Problems identificated	Autor determination, 5 words, coded in relation to categories found (Annex 3).
	Internal drivers	Env=Environmental, Soc= Social, Econ=Economic, Pol=Politic, Tech=Technology.

(continued)

Annex 2
(concluded)

Groups of variables	***Variables***	***Codes***
	Which are?	Autor determination, 5 words.
	External drivers	Env=Environmental, Soc= Social, Econ=Economic, Pol=Politic, Tech=Technology.
	Which are?	Autor determination, 5 words.
	Trends of SSE trajectories	Adap=Adaptation trajectory, Chan=trajectory of Change, Dev=Development trajectory, etc.
Theory approach	Concept definition of "SES trajectory"	Author definition, 10 words.
	Implemented theories, concepts	Author determination, 5 words, coded in relation to categories found (Annex 4a).
	Utility of study	Acad=Academic, Soc=Social action (including community), PP=Public Policy, etc.
Methodology	SES subsystems analyzed	Act=Action, Ecol=Ecological, Drive=Drivers, ES=Ecosystem services, Out=Outputs, Soc=Social.
	Trajectory temporal perspective	Retro=Retrospective; Pros=Prospective; Cross=Cross sectional; Retropros=Retro-prospective.
	Methodological focus	Quan=Quantitative, Qual=Qualitative, Mix=Mixed.
	Data collection methods or techniques	Doc=Documental, Excav=Excavation, Field=Field data (including transect walks), Focal=Focal groups (including workshops), Game=Game, Interv=Interviews (including oral history), Map=Maps, Monit=Monitoring, Surv=Surveys.
	What is monitoring?	Bird=Birds, Clim=Climate, Crab=Crabs, Fish=Fishes, Plant=Plants, Sed=Sediment, Water=Water, Moll= Mollusks, Soil=Soil.
	¿Monitoring is participative?	Yes/No.
	Data analysis methods	Author determination, 5 words, coded in relation to categories found (Annex 4b).
	Data analysis methods or techniques	Spat=Spatial analysis (including remote sensing, GIS), Disc=Discourse analysis, Text=Text analysis (including Atlas. ti, narrative analysis, etc.), Model=Modeling (including system dynamic, etc.), Stat=Statistical analysis (including probabilistic analysis), Agent=Agent based, Net=Network analysis), Arch= Archeological.
	Methodological approach	Multi=Multidisciplinary, Inter=Interdisciplinary, Trans=Transdisciplinary.

Source: Self-elaboration, based on:

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Annex 3

Word frequencies in reviewed publications for word cloud diagram construction

Word	*Total*	*Other*		*Other*		*Other*		*Other*		*Other*
system	487	systems	278	system	209					
change	346	change	236	changes	101	changed	9			
socialecological	237		237							
trajectory	217	trajectories	145	trajectory	72					
management	199	mangement	199							
ecosystem	186	ecosystem	142	ecosystems	44					
use	166	use	75	used	36	using	55			
landscape	161	landscape	120	landscapes	41					
social	145	social	145							
development	138	development	95	developments	2	develop	13	developed	28	
resilience	137	resilience	137							
approach	128	approach	87	approaching	2	approaches	39			
sustainability	126	sustainability	69	sustainable	57					
forest	125	forest	102	forests	20	forestry	3			
adaptive	122	adaptation	12	adaptability	12	adaptive	86	adapt	12	
governance	122	governance	122							
study	121	study	85	studies	36					
ecological	116	ecological	116							
region	116	region	45	regions	28	regional	43			
future	109	future	92	futures	17					
services	107	services	92	service	15					
fisheries	99	fisheries	63	fishery	36					
environment	99	environment	28	environmental	71					
dynamic	98	dynamics	70	dynamic	24	dynamical	4			
analysis	98	analysis	62	analyzed	14	analyze	11	analyzing	11	
community	97	communities	55	community	42					
climate	90	climate	88	climates	2					
resource	90	resource	56	resources	34					
human	89	human	83	humans	5	humanity	1			
scenarios	86	scenarios	54	scenario	32					
different	82	different	82							
policy	80	policy	54	policies	26					
agricultural	79	agriculture	18	agricultural	61					
process	77	processes	41	process	36					
model	77	model	57	models	20					
driver	76	driver	8	drivers	68					
natural	74	natural	74							
rural	72	rural	72							
impacts	71	impacts	37	impact	34					
level	69	levels	30	level	39					
complex	67	complex	48	complexity	19					
social-ecological	65	social-ecological	65							
provide	65	provide	25	provides	15	providing	12	provided	13	
scale	63	scale	63							
water	61	water	60	waters	1					
new	61	new	61							
livelihood	61	livelihood	33	livelihoods	28					
cultural	59	cultural	54	culture	5					
framework	57	framework	50	frameworks	7					
areas	57	areas	37	area	20					
knowledge	56	knowledge	56							
outcomes	56	outcomes	49	outcome	7					

(*continued*)

Annex 3

(continued)

Word	*Total*	*Other*		*Other*		*Other*		*Other*		*Other*
research	55	research	55							
potential	53	potential	53							
spatial	52	spatial	52							
transformation	52	transformation	39	transformations	13					
strategy	52	strategies	42	strategy	10					
shifts	52	shifts	34	shift	18					
conservation	51	conservation	51							
key	50	key	50							
modeling	50	modeling	27	modelling	23					
results	49	results	49							
interaction	49	interactions	42	interaction	7					
decision	49	decision	32	decisions	17					
traditional	49	traditional	43	traditions	5	tradition	1			
explore	47	explore	31	explores	3	explored	7	exploring	6	
method	47	methods	33	method	14					
historical	46	historical	46							
challenges	46	challenges	33	challenge	9	challenged	4			
economic	45	economic	44	economics	1					
transition	45	transition	32	transitions	13					
context	45	context	32	contexts	13					
urban	44	urban	44							
coastal	44	coast	5	coastal	39					
institutional	43	institutional	43							
influence	43	influence	21	influenced	10	influences	10	influencing	2	
biodiversity	42	biodiversity	42							
vulnerability	42	vulnerability	42							
regime	42	regime	33	regime	9					
conditions	41	conditions	41							
identify	41	identify	41							
relationships	41	relationships	31	relationship	10					
stakeholders	41	stakeholders	27	stakeholders	14					
farming	40	farming	40							
practice	40	practices	30	practices	10					
farmers	39	farmers	39							
multiple	39	multiple	39							
pathway	39	pathways	31	pathway	8					
support	39	support	27	supports	3	supported	5	supporting	4	
actions	38	actions	22	action	16					
effects	37	effects	31	effect	6					
organization	39	organization	19	organizations	11	organized	5	organize	2	organizing
participatory	36	participatory	27	participation	6	participate	2	participating	1	
integrated	36	integrated	25	integrates	4	integrate	2	integrating	5	
food	35	food	35							
associated	35	associated	35							
production	35	production	35							
actors	35	actors	32	actor	3					
years	35	years	27	years	8					
risk	35	risk	24	risks	11					
values	35	values	24	value	11					
perspective	35	perspectives	20	perspective	15					
people	34	people	34							

(*continued*)

Annex 3
(concluded)

Word	*Total*	*Other*		*Other*		*Other*		*Other*	
marine	34	marine	34						
assessment	32	assessment	23	assessments	9				
activities	31	activities	22	activity	9				
quality	30	quality	30						
components	30	components	25	component	5				
intervention	30	interventions	20	intervention	10				
government	30	government	18	governmental	7	governments	5		
significant	29	significant	29						
fire	29	fire	26	fires	3				
factors	28	factors	25	factor	3				
socioeconomic	27	socioeconomic	27						
history	27	history	17	histories	10				
growth	27	growth	27						
cover	26	cover	26						
information	26	information	26						
population	26	population	26						
diversity	26	diversity	26						
nature	25	nature	25						
recovery	24	recovery	24						
indigenous	24	indigenous	24						
biophysical	22	biophysical	22						
interviews	22	interviews	20	interviews	2				
resilient	21	resilient	21						
alternative	21	alternative	21						
intensification	20	intensification	20						
livestock	20	livestock	20						
flow	19	flows	9	flow	10				
deforestation	18	deforestation	18						
degradation	17	degradation	17						
political	13	political	13						
agroecological	6	agroecological	6						

Source: Self-elaboration.

Annex 4

List of categories applied to determine the problems identified by the authors in 143 reviewed publications

Scale/ thematic	***Economic***	***Ecological***	***Social-ecological***	***Political***	***Infraestructure***
Global	Economic crisis, neoliberal economy, international market, industrialization, food security, international tourism, etc.	Climate change, extreme hydroclimatological events, global ecological crisis, global biophysical changes, disasters, such as volcanic eruptions, tsunami, etc.	Pollution, change in hydroclimatological regimes, etc.	International public policy, conservation and restoration instruments, conservation incentives, institutions, etc.	Hydraulic technology, technology for generation and transmission of knowledge
Local	Change in livelihoods, illegal market and illicit activities, local tourism, food security, abandonment of traditional practices, eg. agricultural, etc.	Climate variability, changes in landscape, changes in species regimes, species change, etc.	Change in land use, such as deforestation, over-exploitation of species, introduction of species, health disasters, contamination, erosion, habitat destruction, ecosystem degradation, loss of biodiversity, hydroclimatological events, such as floods, etc.	National and local public policy, national and local management and planning strategies and programs, conservation incentives, counterproductive programs, local and community decisions, capacities, weaknesses and institutional changes, etc.	Technology for protection against disasters, technology for monitoring, technology for generation and transmission of knowledge, etc.

Source: Self-elaboration.

Annex 5

List of categories applied to determine in reviewed publications: *a)* theoretical and *b)* methodological approaches

a) Implemented theories, frameworks or concepts

1. Resilience and Adaptation Approach
- *1.1.* Resilience Assessment
- *1.2.* Vulnerability and Risk
- *1.3.* Adaptation and Governance

2. Ecological Approach
- *2.1. Ecological Systems*
- *2.2.* Ecological Interactions

3. Social-Ecological Systems Approach and Human Ecology
- *3.1.* Social-ecological Systems
- *3.2.* Behavior, Power and Decision-making
- *3.3.* Livelihood and Strategies
- *3.4.* Governance and Participation

4. Landscape, Planning, Management and Territorial Change
- *4.1.* Territory management and planning
- *4.2.* Landscape and Land Use
- *4.3.* Changes and transformations

5. Impact Assessment Approach
- *5.1.* Impact assessment approaches

b) Data analysis methods or techniques

1. Quantitative
- *1.1.* Remote Sensing and Spatial Analysis
- *1.2.* Statistical Analysis
- *1.3.* Modeling and Simulation
- *1.4.* Indicator-based Analysis
- *1.5.* Laboratory and Field Measurements

2. Qualitative
- *2.1.* Ethnographic Method
- *2.2.* Perceptions, Narrative and Discourse Analysis
- *2.3.* Documentary Analysis
- *2.4.* Participatory and Interaction Methods
- *2.5.* Conceptual Models

3. Mix
- *3.1.* Combination of quantitative and qualitative methods

Source: Self-elaboration.