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Review Article

Towards Integrated Ecosystem Assessments: A literature review on linking ecosystem condition indicators to ecosystem services

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Abstract

Ecosystem services (ES) fundamentally depend on ecosystem condition (EC), yet many ES assessments still rely on land-cover proxies, risking biased assessment results as well as weak uptake, meaning limited application of results in decision-making contexts. This review provides a comprehensive overview of how EC indicators are used in ES assessments published between 2018 and 2022.

In total, 128 publications have been included in the review, from which 929 EC indicators with a direct or implicit link to one or more ES and 707 ES indicators have been documented. The recorded EC indicators were reclassified according to the Ecosystem Condition Typology (ECT) provided by the System of Environmental-Economic Accounting - Ecosystem Accounting (SEEA EA) and supplementary classes (ECT+). Our analysis identified a focus on terrestrial ecosystems, with under-representation of marine and less intensively managed ecosystems. Within the reclassified ECT and ECT+ indicators, chemical state EC indicators were prevalent, while landscape state and functional state metrics remained under-operationalised. Besides, the share of spatially explicit indicators was limited. Moreover, we found that a significant share of indicators, labelled as EC, were not EC indicators in the strict sense, but instead related to ecosystem extent, ES or stable environmental characteristics, leading to a conceptual blurring between condition, pressure, extent and service indicators. Analysing the link between EC and ES revealed that EC indicators were: (1) primarily quantitatively compared to ES or integrated into ES assessments and (2) most frequently linked to regulating ES. The reviewed literature showed a predominance of positive EC–ES relationships, confirming that ecosystems in better condition tend to support a higher supply of ES. In summary, our review identified progress towards integrated ES assessments, highlighted persistent gaps and stressed the importance of continued efforts to achieve the widespread implementation of EC-enabled ES assessments.

Keywords

systematic review, ecosystem state, ecosystem health, integration, EC-enabled, condition-service interrelation

Introduction

The importance of ecosystem services (ES) for human well-being is widely recognised and numerous studies have assessed their supply, flow or demand (Costanza et al. 1997 , Daily 1997, Burkhard et al. 2012, Schirpke et al. 2019). ES are commonly defined as the benefits people obtain from ecosystems (Millennium Ecosystem Assessment (MA) 2005) or, more specifically, as “the contributions of ecosystem structure and function – in combination with other inputs – to human well-being” (Burkhard et al. 2012). However, the potential of ecosystems to provide such services fundamentally depends on the condition of the underlying ecosystems. In line with the System of Environmental-

Economic Accounting — Ecosystem Accounting (SEEA EA) framework, we define ecosystem condition (EC) as “the quality of an ecosystem measured in terms of its abiotic and biotic characteristics” (SEEA EA Glossary, Burkhard et al. 2023, United Nations 2025).

Despite broad recognition of the importance of EC for ES delivery, many ES assessments still rely primarily on land-use and land-cover (LULC) proxies (Maes et al. 2015, Rendon et al. 2019). While data on the EC describe the ecosystems’ quality and functioning, data on LULC show how land is physically used or covered. This provides the spatial context that often underlies variations in EC. Although LULC is a convenient and widely available dataset, using it as a proxy for ES provision can lead to substantial under- or overestimations of the actual ES supply. This mismatch between land-cover types and the EC can misinform management priorities, causing areas in need of restoration to be overlooked and overestimating the sustainable supply of ES of seemingly “intact” ecosystems. Therefore, incorporating EC into ES assessments is essential to improve ecological accuracy and enhance policy relevance.

At the same time, the demand for robust, operational and policy-relevant indicators has grown significantly. Policy-makers increasingly require clear and comparable metrics to set environmental targets and monitor progress (Geijzendorffer et al. 2016, Van Oudenhoven et al. 2018, Grizzetti et al. 2019, La Notte et al. 2022, Kokkoris et al. 2024). This need has been reinforced by recent international and regional commitments, including the adoption of the Kunming-Montreal Global Biodiversity Framework in 2022 (Convention for Biological Diversity (CBD) 2024) and the legally binding Nature Restoration Regulation of the European Union in 2024 (European Parliament, Council of the European Union 2024). Both policy frameworks call for consistent and scalable indicators capable of tracking ecosystem health, biodiversity trends and the benefits nature provides to society. Earlier efforts have already sought to establish EC indicators (Lof et al. 2019, Rendon et al. 2019, Vallecillo et al. 2022) and have explored the links between EC and ES for specific ecosystems (McLaughlin and Cohen 2013, Brockerhoff et al. 2017). However, the integration of EC in ES assessment is still lagging behind.

Quantifying EC and linking EC to ES assessments remains conceptually and technically challenging due to the complexity of ecosystems (Lavorel et al. 2017, Rieb et al. 2017, Lautenbach et al. 2019, Tanács et al. 2022). Numerous studies have demonstrated positive links between biodiversity, ecosystem functioning and ES provision (Kandziora et al. 2013, Harrison et al. 2014), yet there is still no consensus regarding the mechanisms, thresholds or specific indicators that best capture these relationships across ecosystem types. Additionally, the integration of EC into ES assessments has been highlighted as essential for over a decade (De Groot et al. 2010, Burkhard et al. 2012, Geneletti et al. 2020, Barton et al. 2024, Vári et al. 2024, Walther et al. 2025). Nevertheless, practical implementation remains limited. Only a subset of ES assessments systematically incorporate EC metrics and even fewer explicitly document how these indicators are linked to ES quantification or valuation (Ruckelshaus et al. 2015, Grizzetti et al. 2019, Rendón et al. 2020, Rendón et al. 2022). However, when EC is meaningfully embedded in ES assessment, policy uptake appears to improve (Olander et al. 2017, Barton et al. 2024), suggesting that EC-enabled ES assessments are more credible and actionable for decision-makers. Despite this growing recognition — and the inclusion of EC as one of the five core accounts in the SEEA EA framework (United Nations 2025) — there is, to our knowledge, still no comprehensive overview on the implemented link between EC and ES, nor a consolidated understanding of which EC indicators dominate across ecosystem types and ES categories. Instead, there still seems to be a prevailing confusion about the distinction of EC and ES indicators as shown by a recent review that took a questionable approach by equating the presence of ES as the sole variable for a better ecosystem health and thereby neglecting the intrinsic ecological functioning of the ecosystems (Marali et al. 2025). When analysing the Ecosystem Services Valuation Database (ESVD), an open-source tool containing > 1,300 monetary valuation studies on > 20 ES and 15 biomes (Brander et al. 2024), Hernández-Blanco et al. (2022) found that in ca. 58% of the recorded ES studies, information and data on EC were lacking.

This review addresses this gap by analysing how EC indicators have been used and integrated into ES assessments. Conducted within the framework of the SELINA Horizon Europe project (Science for Evidence-based and Sustainable Decisions about Natural Capital), this study systematically reviews how EC is incorporated into ES assessments in peer-reviewed journal articles published between 2018 and 2022. The project aims to advance knowledge of biodiversity, EC and ES and to support their integration into decision-making. In line with this mission, our review focuses on identifying the types of EC indicators used in the reviewed ES literature and analysing the links between EC and ES indicators. We synthesise research trends, classify indicator types and data sources, assess ecosystem- and ES-specific patterns and evaluate the nature of EC–ES linkages. Accordingly, we address the following research questions:

- What EC indicators are applied in ES service assessments?
- How are the linkages between EC indicators and ES assessments established and characterised?
- How is the integration of EC into ES assessments operationalised, evolving towards Integrated Ecosystem Assessments?

Material and Methods

Review Process

We conducted a systematic literature review following the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) protocol (Moher et al. 2015, Page et al. 2021). We developed a search query that was executed upon the SELINA project internal literature database to ensure SELINA internal consistency in terminology and understanding (Burkhard et al. 2023, Seguin et al. 2025). The SELINA database is derived from the Scopus and Web of Science (WoS) databases and contains 108,064 entries published from 2018 to 2022 (Seguin et al. 2025). The primary motivation for selecting this time-frame was its alignment with recent policy and research attention around ecosystem assessments, including the consolidation of MAES reporting in the EU (Maes et al. 2015, Maes et al. 2018, Maes et al. 2020c), the emergence of the IPBES methodological guidance (IPBES 2019) and increasing experimentation with EC frameworks (Czúcz et al. 2018b, Czúcz et al. 2021a, Vallecillo et al. 2022). Since the SEEA EA was only published towards the end of the review period (United Nations 2025), the review only allows for the detection of early references or methodological signals linked to its release. Furthermore, the time-frame allowed us to obtain a representative pre-SELINA baseline of the state of the art, capturing the methodological and conceptual landscape immediately preceding the project.

The relevant search query (Suppl. material 1) was structured by combining ecosystem-related terms with those referring to EC, ES and Ecosystem Accounting, as well as terms and synonyms related to indicators. Generally, an indicator is understood as being a “number or qualitative descriptor generated with a well-defined method, which reflects a phenomenon of interest (the indicandum)” (Heink and Kowarik 2010). Even though indicators are based upon variables, oftentimes, these terms are used as synonyms (Müller and Burkhard 2012, SELINA 2025). Therefore, despite recognising that, in the context of SEEA EA, EC variables and EC indicators have very distinguished definitions (United Nations 2025), we applied a broad understanding of the term indicator, encompassing “proxies”, “variables” and “metrics” (Czúcz et al. 2021a, Czúcz et al. 2021b). Moreover, in this review, terms and respective concepts, such as ecological condition, biological condition, ecosystem state, status, health, integrity, quality, functionality and capacity, are treated as conceptual equivalents to EC (see i.a. Roche and Campagne 2017, Keith et al. 2020 and references within). By using Boolean operators, establishing logical combinations of keywords and using truncations and wildcards to capture word variations in title, abstract and author keywords, we iteratively improved and refined the search logic (Suppl. material 1 and Seguin et al. 2025).

In total, 3,430 studies were initially found. The database was cleaned to remove duplicates and filtered to include only English-language scientific peer-reviewed publications (n_p = 2,720 papers). In the first screening phase, 23 reviewers checked publications by all reviewed documents title, abstract and author keywords on seven inclusion criteria (n_p = 664 papers; Fig. 1). For the second screening phase, based on the full text of the articles, we refined the inclusion criteria to only include studies addressing a link between EC and ES. This means that the study had to quantitatively or qualitatively connect the assessment of EC (or related concepts) with an assessment of ES or Nature’s Contributions to People (NCP; Díaz et al. 2018). This includes, for example, the comparison of the results from both assessments, indicators, direct input-output relations by integrating EC results into the ES assessment and the integration of EC and ES results for a third purpose.

Five articles were excluded because their full texts were not accessible (n_p = 659 papers). Ultimately, 128 publications were included in the full review (see list of included publications in Suppl. material 2) from which data were extracted, based on specific questions.

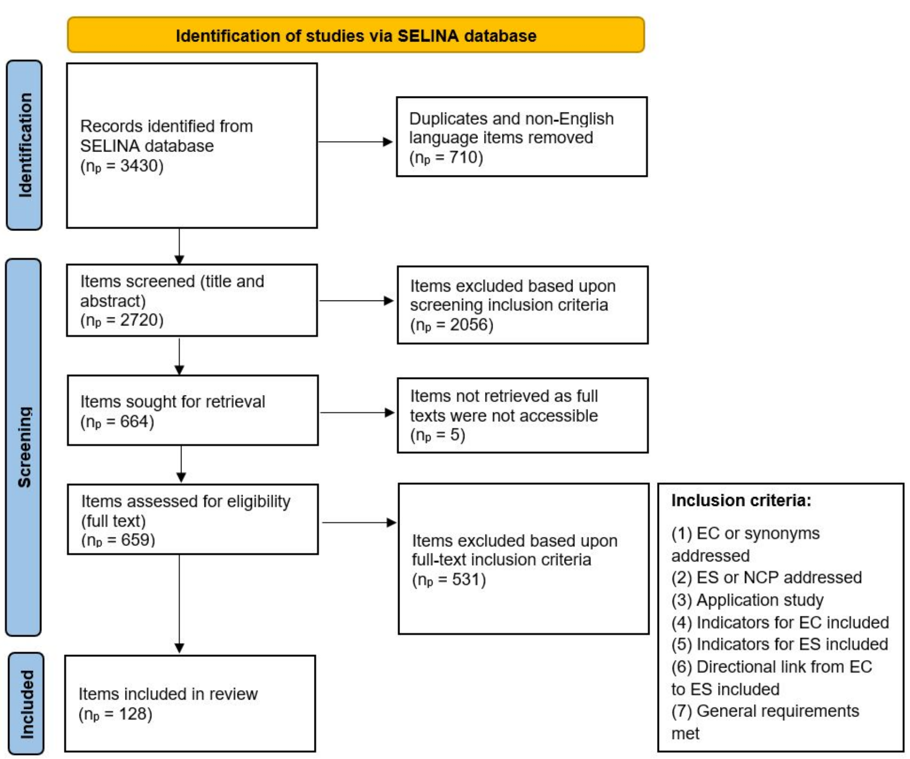


Figure 1.

PRISMA Scheme (adapted after Page et al. (2021), CC BY 4.0). The seven inclusion criteria are listed in the box on the right.

Data extraction and processing

To collect, systematise and analyse the content of the reviewed literature items, we developed a structured coding template (Suppl. material 3) of several tabular sheets within Microsoft Excel 2019 (Version: 1808), that incorporated various functionalities to ensure a user-friendly, consistent and comparable review and evaluation process. Only a few entries allowed free text to ensure high inter-reviewer consistency and standardisation of entries. Throughout the fields and predefined response options, we prioritised and built upon standardised methodologies, common classifications and definitions, amongst which the SEEA EA Ecosystem Condition Typology (ECT; United Nations et al. 2021, Czúcz et al. 2021a), which was used to reclassify EC indicators (for further information see Section “Reclassification of ecosystem condition indicators”), the Common International Classification of Ecosystem Services (CICES v.5.1; Haines-Young and Potschin 2018), which was applied to reclassify recorded ES and the ES method type according to the ESMERALDA MAES Method Explorer (ESMERALDA 2018) and the SELINA Ecosystem Assessment Explorer (EASE; Brander et al. 2024a).

The review template consisted of four tabs:

1. The first tab included bibliographical details and a final set of inclusion criteria that had to be answered by each reviewer after a study was assigned to be included or excluded;

2. In the second tab, the reviewers recorded general information for each study on EC (e.g. number of EC indicators), ES (e.g. concept of ES and number of ES) and location (e.g. spatial scale);

3. The third tab focused on the specifics of individual EC indicators, referring to type and units of the described indicators, reference levels, spatial scale and type of ecosystem assessed. The latter followed the MAES level 2 ecosystem type classification (Maes et al. 2020b) with the only modification being for the marine category “coastal, shelf and open ocean”, which was further divided into (1) “coastal” and (2) “marine (shelf and open ocean)”. To account for the characteristics of EC indicators, each reported indicator was categorised according to its degree of independence, either: (1) independent; (2) composite indicators or (3) components of composite indicators. In cases where two or more EC indicators were combined into a single aggregated metric (e.g. in the form of an index), each contributing indicator was recorded individually and coded as “part of a composite indicator”. The resulting index itself was additionally coded as a “composite indicator”. This procedure, adapted from the SEEA EA classification logic (United Nations et al. 2021, United Nations 2025), ensured that the coding template captured both the component-level detail and the level of aggregation used in the assessment. In this tab, we also recorded the essential information on the connection between EC and ES: (1) if the specific EC indicator were linked to ES; (2) to which ES class; (3) how it was linked (the slection options were qualitative comparison, quantitative comparison, integration of EC into ES assessment and integration of EC and ES for a third purpose; Suppl. material 3) and (4) what the nature of the relation was (the selection option included positive relation, negative relation, no relation, unclear/ not specified). A positive relation suggests that improvements in EC are associated with enhanced provision of ES. Conversely, a negative relation indicates that an increase in EC is linked to a reduction in ES, without implying a linear correlation. "No relation" signifies the absence of a recognisable connection between EC and ES;

4. The fourth tab referred to individual ES, recording respective methods, spatial resolution, input data used, ES class recorded and ES class following CICES v. 5.1 (Haines-Young and Potschin 2018). Hence, the information gathered in the third and fourth tab was completed per indicator. Based on the ES classification of CICES v.5.1, our assessment primarily focuses on services within the biotic categories, which align most closely with the objectives of this study. Nevertheless, CICES v.5.1 recognises that abiotic (geophysical) outputs may also be considered when they represent important contributions to human well-being and, thus, they were retained. This is particularly relevant for water-related ES,

> which, although categorised as abiotic in CICES v.5.1, play a central role in ES frameworks and in the context of our study. Accordingly, we use the term ES throughout the manuscript in a broad sense, encompassing both the biotic services that dominate our analysis and this minor, but relevant subset of abiotic services.

During the review, each contributor was asked to follow the original statements as made in the papers to minimise interpretation bias. For example, the position of the publication on whether an indicator represented EC or ES was followed, regardless of the reviewer's interpretation. If five or more ecosystems were assessed in a study, the reviewers were asked to state "various" ecosystem types, based on the hypothesis that indicators that were applied to assess five or more ecosystems may be regarded as giving an broader integral or holistic understanding of the landscape interactions emphasising its multifunctionality.

Quality check

Several quality checks were implemented to design the review process as transparently, consistently and objectively as possible. Most reviewers were involved in co-creation when developing the search objectives, inclusion criteria and review template. Every reviewer received training before starting and each screening phase included a pilot run, during which the task and material were tested and adjusted if necessary. For the choice of the ES method according to the list defined in the MAES Method Explorer (Burkhard et al. 2018a), reviewers indicated their uncertainty; during the post-review cleaning phase "highly uncertain" and "very highly uncertain" results were double-checked and corrected if necessary.

Moreover, after completion, each phase of the review underwent manual inspection by a dedicated team of experts to validate that the entries meet the requirements. Semi-automated processes in R (4.3.2 (2023-10-31 ucrt); R Core Team (2023)) streamlined the validation process of the data entries. Furthermore, a Fleiss-Kappa consistency test was applied to evaluate the literature review's quality and assess the reviewers' inter-rater reliability (Fleiss 1971, Fleiss et al. 2003, McHugh 2012, Kassambara 2019). It was calculated, based upon the reviewer's answers on inclusion criteria for two randomly selected publications that were screened by all reviewers (κ: 0.706, $p < 0.0005^*$). A second Fleiss-Kappa coefficient was calculated, based on one publication that had garnered a consensus for inclusion in the review amongst a large majority of 21 out of 23 reviewers (κ: 0.856, $p < 0.0005^*$). By examining these two groups separately, the aim was to gain insights into the consistency of reviewer assessments, with a particular emphasis on understanding the reliability and agreement in the screening and inclusion decisions. The Kappa values indicate a substantial to strong level of agreement reinforcing the robustness and validity of the screening process.

Reclassification of ecosystem condition indicators

The ecosystem characteristic represented by EC indicators, following the SEEA EA Ecosystem Condition Typology (ECT) described in Czúcz et al. (2021a), was recorded during the review when specified in the publication. Additionally, all EC indicators were reclassified to match the SEEA EA ECT by trained review team members following data extraction to aid in aggregating the data. Indicators that did not represent any of the main ecosystem characteristics described in the ECT were assigned to additional classes (ECT+), largely based on the different types of ancillary data sources detailed in Czúcz et al. (2021a) (Suppl. material 4). In case an indicator could not be assigned to any ECT or ECT+ class, it was classified as ‘Other’. Two review team members reclassified each indicator independently, with conflicting classifications discussed and resolved within pairs.

Data analysis

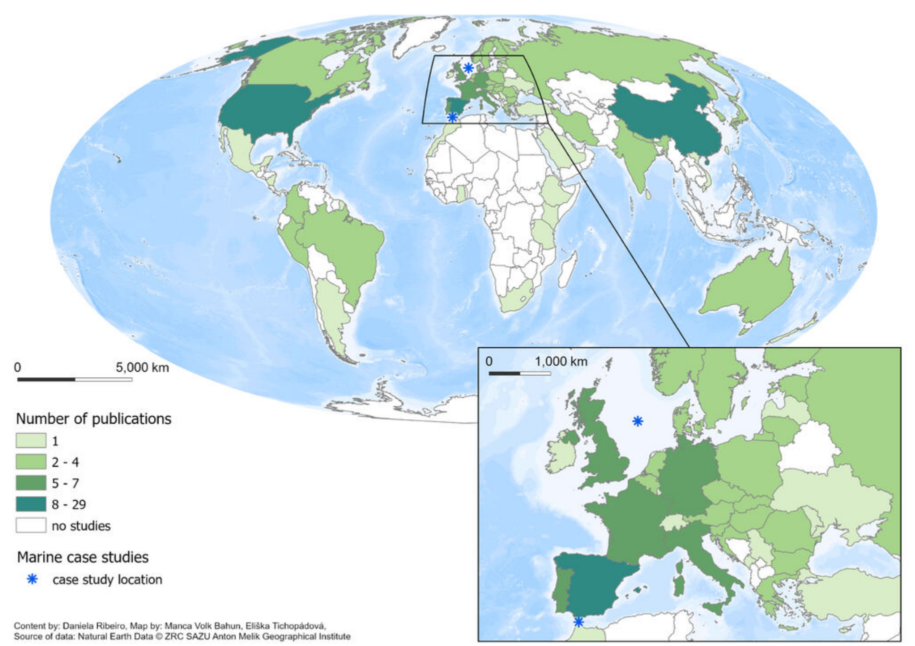
The data processing, as well as analysis, was fully conducted in the R environment using various packages like “tidyverse” (Wickham et al. 2019), “revtools” (Westgate 2019a, Westgate 2019b), “readxl” (Wickham and Bryan 2023), "writexl” (Ooms 2023), “ggsankey” (Sjoberg 2024), “extrafont” (Chang and Bertrand 2023) and “cowplot” (Wilke 2024).

The collected data were compiled into one database. All EC indicators that did not have a link to a specific ES – either directly or implicitly as part of a composite indicator – were removed from the database (n_i = 82). Subsequently, the database was analysed using descriptive statistics, based on the number of papers (n_p) or the number of indicators (n_i) and their relative frequencies. Additional evaluation for specific parts of the dataset, such as a spatial assessment and a Sankey diagram, were added to visualise and better understand the connections between EC indicators and ES classes. The spatial analysis was conducted to detect asymmetries in the global distribution of studies. We firstly examined their distribution at the country level using ArcGIS Pro (version 3.5). For this, publication counts were assigned per country: if a publication included multiple case studies within the same country, it was counted once, whereas publications covering multi-national assessments or multiple case studies in different countries contributed to the count of each country assessed. Publications that presented an assessment conducted only at the continental level, without precise details of the countries included in the study, were excluded from this spatial analysis (n_p = 5).

Results

General study characteristics

In the following, we provide insights into the general publication characteristics and focus, amongst others, on the spatio-temporal distribution of the researched studies. Out of the 128 reviewed publications, 119 dealt explicitly with the ES concept, while in nine publications, the conceptual frame was not mentioned. In the majority of cases, the ES potential was assessed ($n_p = 74$), followed by the ES flow ($n_p = 52$); ES demand was addressed far less frequently ($n_p = 7$). Four publications applied the Ecosystem Accounting approach, thus compiling accounts for ES ($n_p = 3$) or for EC and ES ($n_p = 1$). In terms of temporal distribution, we observed a continuous increase in the number of publications over the years, with a dip in 2020 and a more prominent increase in 2022. The spatial scale applied in the publications shows a clear focus on smaller scales with regional to local assessments (Fig. 2). Five publications focused on a continental scale (including Europe $n_p = 2$; Africa $n_p = 1$; Africa, Asia and America $n_p = 2$). In total, 64 countries were recorded, while marine ecosystems were addressed in two publications (Fig. 2). No publications addressed Antarctica and only a few included assessments located in Africa, Central America and Oceania. In contrast, the majority of publications included assessments in North America, Europe and Asia. More precisely, most publications included assessments located in China ($n_p = 30$), followed by the USA ($n_p = 15$). Most Chinese assessments were conducted on the regional scale, while US assessments were predominantly local. In Europe, Spain was the most studied country.



Content by: Daniela Ribeiro, Map by: Manca Volk Bahun, Eliška Tichopádová,
Source of data: Natural Earth Data © ZRC SAZU Anton Melik Geographical Institute

Figure 2.

Spatial distribution of the case studies included in the selected papers. The marine case studies have been localised using an asterisk. Note: 3.9% ($n_p = 5$) of papers are continental studies that are not presented on the map.

The focus of the EC assessments were diverse and often overlapping. Most frequently, they related to the mapping and/or assessment of ES ($n_p = 89$), followed by mapping or assessment of EC ($n_p = 50$), while nearly 20 publications were associated with the planning or evaluation of restoration actions. Most publications included the same number or more EC indicators than ES, typically ranging from two to five. An exception are publications addressing marine ecosystem types, where the total number of ES was on average more than double the number of EC indicators.

General indicator characteristics

In this section, details are given on the EC and ES indicators identified across the reviewed studies. In total, 1636 indicators were identified. Hereof, 929 have been identified as EC indicators with a direct (n_i = 744) or implicit (n_i = 185) link to one or more ES and 707 have been identified as ES indicators. In the following, we present the specifics of the EC indicators, notably focusing on the distributions according to the extended ECT classification (including both ECT and ECT+ classes) and the ecosystem types. Thereafter, the specifics of the recorded ES indicators are shown.

Even though the majority of EC indicators (n_i = 700; 75.3%) were not classified according to the SEEA EA ECT by the respective publication authors, most recorded indicators could, nonetheless, be matched to the extended ECT classification. In total, 895 indicators (96.3%) were successfully assigned, with 74.1% classified as ECT (n_i = 688) and 22.3% as ECT+ (n_i = 207); the remaining 3.7% (n_i = 34) were classified as “other”, which included, for example, Terrain Location, Snow Gliding Distance, Average Mutual Information and System Entropy (Fig. 3). The predominance of ECT over ECT+ classes was consistent across all ecosystem types, with the exception of the “various” category, where the distribution between ECT and ECT+ indicators was more balanced.

EC indicators were identified for each ECT class. Within the **ECT classes**, chemical state characteristics (n_i = 168), such as carbon, nutrients and heavy metal concentrations, as well as pH measurements, were most frequently used, whereas functional state characteristics, for example, indicators related to leaf traits, were least represented (n_i = 69, Fig. 3). The distribution of indicator types varied according to the ecosystem type. For woodland and forest ecosystems, structural state indicators, for example, indicators related to vegetation cover, were most common (n_i = 51), while grasslands were predominantly assessed using compositional state indicators (n_i = 28), i.e. indicators related to specific species composition, diversity, richness and abundance. Cropland ecosystems were primarily assessed using chemical state indicators (n_i = 104), followed by physical state (n_i = 66) indicators, for example, those related to soil texture, composition and structure, whereas indicators recorded for the “various” ecosystem type most frequently referred to landscape characteristics (n_i = 57), such as landscape connectivity or complexity, as well as patch density and size. Within the **ECT+ classes**, pre-aggregated indicators were most common (n_i = 57, Fig. 3), mainly related to “various” ecosystem types. Additionally, 34 indicators represented pressures acting on ecosystems, for example, indicators related to pollution, contamination and land use and another 34 referred to stable environmental characteristics, such as topography and climatic conditions (Fig. 3).

Generally, EC indicators were identified for all ecosystem types, but they were unevenly distributed (Fig. 4, Table 1). The majority of EC indicators were used for one specific ecosystem type (n_i = 504), while 20.1% (n_i = 187) were applied for 'various' ecosystem types. The highest number was used to quantify the condition of cropland ecosystems (n_i = 331), followed by woodland and forests (n_i = 212) and “various” ecosystem types (n_i = 187, Fig. 4). Few EC indicators were applied to describe heathland and shrub, sparsely vegetated land, wetlands and marine and coastal ecosystems.

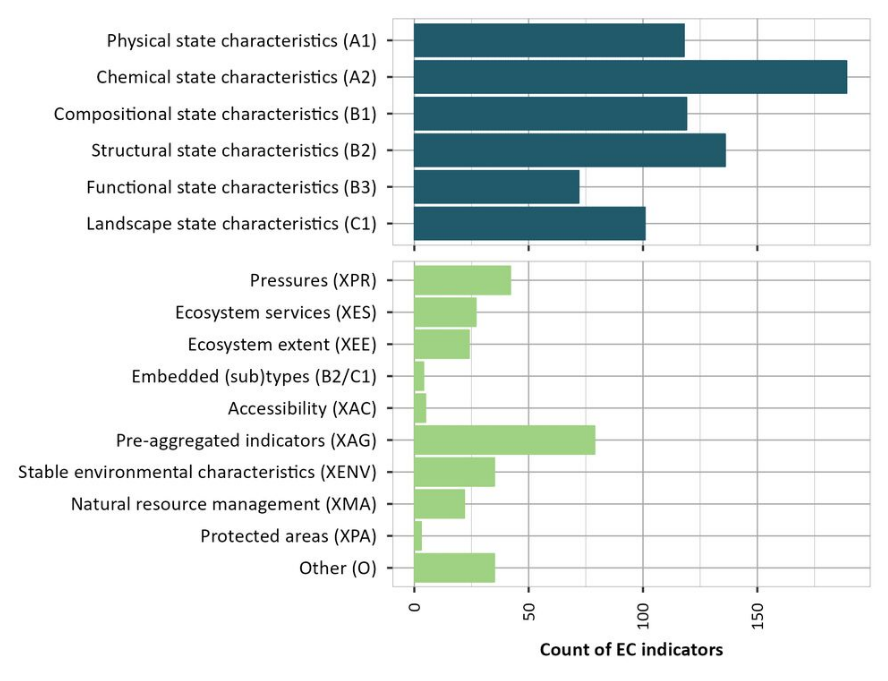


Figure 3.

Reclassification of EC indicators into ECT (blue) and ECT+ classes (green) (according to Czúcz et al. (2021)).

In most cases, input data were used to directly quantify the respective EC indicator (n_i = 433; 46.6%, Table 1). For one third of the EC indicators (n_i = 293; 31.5%), the input data were used for an index calculation. Further data processing or modelling was required for 17.5% (n_i = 163). However, this general pattern did not apply to marine, river and lake ecosystems and various ecosystem types, where input data were most commonly used for index calculation. The assessment of EC indicators relied predominantly on field data (n_i = 517, Table 1). Additional data sources included remote sensing (n_i = 150), other processed spatial data (n_i = 137) and statistical data (n_i = 135). Across ECT classes, landscape state characteristics were the only exception here, as their EC indicators were primarily derived from remote sensing and other processed spatial sources. This specific pattern was also observed for indicators assigned to “various” ecosystem types. Almost one third of the EC indicators were not spatially explicit (Table 1). The remaining two thirds were distributed fairly evenly across fully spatially explicit indicators and those aggregated either at the ecological or administrative scale. Only in very few publications

(n_p = 20; n_i = 90), reference conditions or levels were applied to the EC indicators. In cases where they were used, this was most commonly done following a fixed-year approach (n_i = 25), using reference levels defined by a policy target (n_i = 21) or a natural reference condition (n_i = 12). Reference levels and conditions were most frequently used in the calculation of indicators in freshwater ecosystems (n_i = 33). The majority of collected indicators were individual metrics (n_i = 647; 69.6%), while 24.4% (n_i = 227) of the collected metrics were part of a composite indicator (n_i = 40; 4.3%). Relatively, EC indicators applied to “various” ecosystem types (n_i = 187) had the highest share of composite indicators (n_i = 28) and part of composite indicators (n_i = 127).

Table 1.

Overview of EC indicator characteristics per ecosystem type (expressed in absolute numbers). Note: U = Urban; CL = Cropland; GL = Grassland; WF = Woodland and forest; HS = Heathland and Shrubs; SVL = Sparsely vegetated land; W = Wetlands; RL = Rivers and lakes; C = Coastal; MT = Marine inlets and transitional waters; M = Marine (including shelf and open ocean); V = Various. Note: Several EC indicators (n_i = 242) were applied across multiple ecosystem type categories; therefore, the summed n_i over the ecosystem types exceeds the total n_i. The fields “Applied methodology” and “Input data type” allowed for multiple responses. In addition, all response options such as “unclear/not specified” and “other(s)” were removed from this table overview.

	Total	U	CL	GL	WF	HS	SVL	W	RL	C	MT	M	V
n_i	**929**	85	331	141	212	32	18	32	143	48	11	16	187
Applied Methodology													
Input data used for direct quantification	**433**	56	244	117	135	18	15	10	13	35	5	7	34
Input data used for index calculation	**293**	22	42	5	13	11	3	3	88	10	1	9	108
Input data further processed by a model or algorithm	**163**	7	45	19	31	3	0	19	9	3	0	0	43
Input Data Type													
Remote sensing data	**150**	15	17	10	19	2	0	5	13	0	0	0	89
Statistical data	**135**	18	35	9	40	2	0	5	15	0	3	0	26
Other processed spatial data	**137**	19	26	17	23	0	0	0	1	0	0	0	78
Expert opinion	**13**	3	2	2	5	2	0	0	0	0	0	0	7
Field data	**517**	47	251	110	160	31	18	23	97	38	2	11	8
Literature	**94**	7	16	5	19	1	0	0	19	0	0	11	17
Reference Level													
Yes	**90**	4	15	3	10	0	0	1	33	0	6	0	14
No	**839**	81	316	138	202	32	18	31	110	48	5	16	173
Spatial Resolution													
Fully spatially explicit	**197**	8	21	12	30	4	0	3	32	0	0	0	108
Aggregated at ecological scale	**171**	9	43	45	47	0	0	8	56	0	6	8	14

	Total	U	CL	GL	WF	HS	SVL	W	RL	C	MT	M	V
Aggregated at administrative scale	**157**	9	58	7	23	0	0	2	3	0	0	3	55
Not spatially explicit	**289**	55	120	76	90	2	0	19	48	48	0	5	10

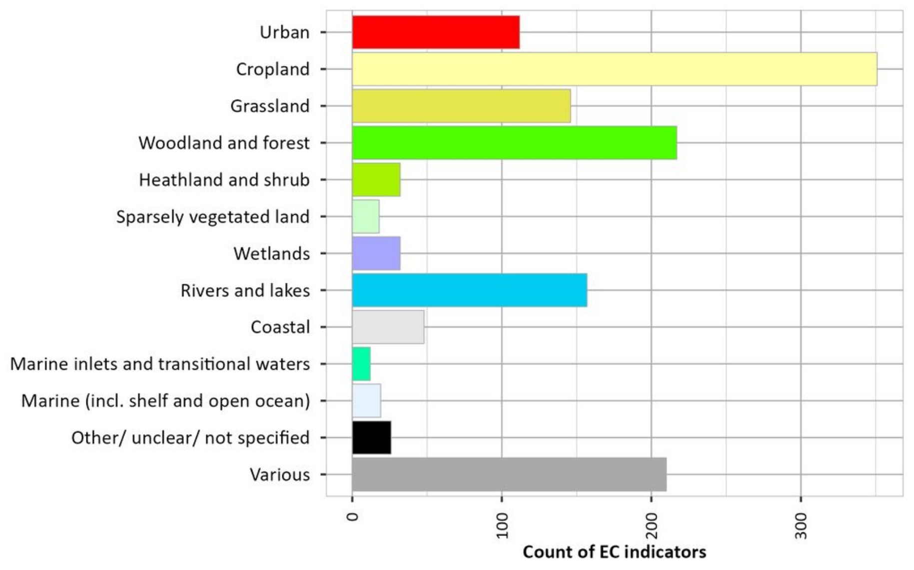


Figure 4.

Identified EC indicators per ecosystem type. Note: Some EC indicators were assessed in multiple ecosystem types.

Specifics of ecosystem services indicators

Out of the total 707 ES recorded, 25 could not be directly linked to a specific CICES v.5.1 class. Of these, four were assigned to CICES v.5.1 only at the “section” level, while 15 were categorised more broadly under “Ecosystem Services” without further specification. In the publications, these cases were labelled using generic descriptors such as “(Total) Ecosystem Service Value” (e.g. Cui et al. 2019, Shi et al. 2020), “Ecosystem Service Index” (Kesgin Atak and Ersoy Tonyaloğlu 2020) or “Ecosystem Service Supply Score” (Teixeira et al. 2019). In six instances, no meaningful link to CICES v.5.1 could be established (e.g. cargo turnover value, Zhao and Wang 2021). More than half of all recorded ES (n_i = 464) belonged to the Regulation & Maintenance section (Fig. 5).

Approximately one quarter of all ES was evaluated in assessments of “various” ecosystem types (n_i = 171). These were followed in frequency by assessments conducted for cropland, woodland and forest and grasslands. In over 40% of the cases, ES assessments were not spatially explicit (n_i = 310). Where spatial explicitness was given, results were most commonly aggregated at the ecological scale (n_i = 191). For marine ecosystems, aggregation at the ecological scale was generally predominant (n_i = 68). When it came to the applied methodology, more than 80% of the ES were assessed using biophysical approaches (n_i = 598), with field observations and spatial proxy methods being the most frequently applied techniques. However, this trend was less pronounced for ES assessed across marine and “various” ecosystem types, where the distribution between biophysical and economic approaches was more balanced. For “various” ecosystem types, value transfer was, alongside spatial proxy methods, the most commonly applied approach. Generally, the most common input data sources for the ES assessments were field data (n_i = 253), statistical data, literature and expert opinion, each of which was used in at least 20% of all ES assessments. Cropland, grassland and woodland and forest ecosystems showed a clear predominance of field data as input, whereas ES assessments relating to marine or “various” ecosystem types most frequently relied on literature sources.

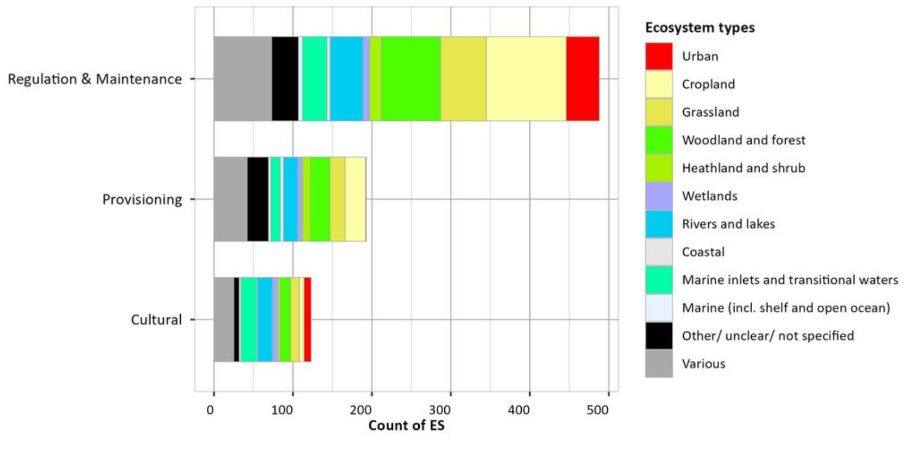


Figure 5.

Distribution of ES according to CICES v.5.1 section and ecosystem types. Note: A few ES were classified as corresponding to CICES v.5.1 classes from multiple CICES v.5.1 sections (n_i = 13). In addition, many ES (n_i = 113) were applied across multiple ecosystem type categories; therefore, the total n_i in this figure exceeds the actual number of recorded ES.

Linkages between ecosystem condition and ecosystem services

In the following, we focus on the assessment of those EC indicators that have been directly linked to one or more ES (n_i = 744; 80%). Overall, their distribution largely mirrors the general pattern described above with a few differences. There are relatively few landscape characteristic indicators, particularly those derived from remote sensing or other processed spatial data. Furthermore, relatively few EC indicators applied to various ecosystem types were directly linked to ES and they exhibited an even stronger predominance of field data as input.

The EC indicators were most frequently linked to ES from the Regulation & Maintenance section (n_i = 291) and multiple ES classes (n_i = 222), followed by Provisioning (n_i = 158) and then Cultural ES (n_i = 72). EC indicators applied in croplands were predominantly linked to Provisioning ES, whereas those used in wetlands, rivers and lakes were more frequently associated with Cultural ES. For composite indicators, 68.9% (n_i = 40) were explicitly linked to ES, while, for the parts of the composite indicator, only 18.4% (n_i = 42) were recorded showing this direct connection. The majority of these indicators (n_i = 341) were quantitatively compared to ES, for example, through statistical analysis, while 73 were qualitatively compared (Fig. 6a). In other cases, EC indicators were directly integrated into the ES assessment (n_i = 256). Here, we found the largest share of ECT+ indicators (Fig. 6a). Finally, in 90 cases, the EC and ES results were assessed individually and afterwards combined for a third purpose, such as conservation or restoration measures, for example. However, when differentiated by ecosystem type, the pattern deviated from this overall trend. In cropland, grassland as well as woodland and forest ecosystems, EC indicators were most frequently integrated directly into the ES assessments, whereas in heathland and shrub, sparsely vegetated lands, wetlands and "various" ecosystem types, EC indicators were predominantly combined with ES assessments for a third purpose. In 14 cases, EC indicators could only be linked to general ES rather than to specific CICES v.5.1 classes or sections. In most of these instances (n_i = 11), the EC indicator and ES were combined for a third purpose, for example, a Life Cycle Impact Assessment (Chen et al. 2021).

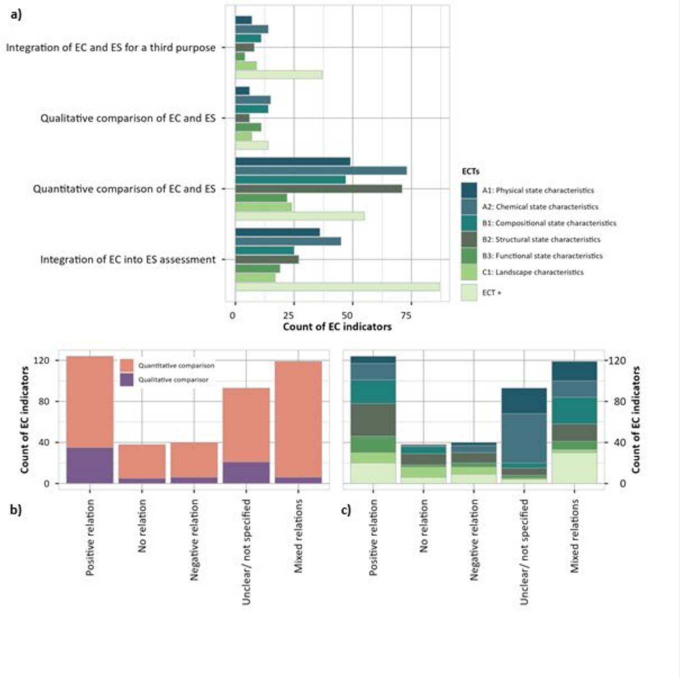


Figure 6.

Distribution of: a) type of link between EC indicators and ES per ECT/ ECT+ class; b) direction of relation between EC indicators and ES per type of comparison; and c) direction of relation between EC indicators and ES per ECT/ ECT+class. Note: In a) and c), the EC indicators classified as ECT+ are displayed as a merged class.

For EC indicators compared to ES (Fig. 6b), either quantitatively or qualitatively, the majority of relationships were positive (n_i = 124), followed by mixed (n_i = 119), referring to cases that showed positive and negative relations and unclear/not specified relationships (n_i = 93). In contrast, no relation (n_i = 38) and negative relationships (n_i = 40) were comparatively rare. This overall pattern holds when distinguishing between quantitative and qualitative comparisons; however, in the qualitative comparisons, only a small number of mixed relationships were addressed (Fig. 6b).

When the assessed **directionality of links is differentiated by ECT class**, several patterns become apparent (Fig. 6c). For EC indicators related to physical and chemical state characteristics, most relationships were reported as unclear/not specified or mixed. EC indicators, for which solely negative or negative and no relation was found, were mostly reported as chemical state characteristics. Indicators linked to compositional state were most frequently associated with mixed and positive relationships. In contrast, indicators related to structural and functional state characteristics predominantly showed positive relationships. For landscape-related indicators, no dominant trend emerged; instead, positive, negative and no relationships were more evenly distributed. Negative relationships to ES were primarily found for landscape indicators related to (mean) patch size, length, cohesion or aggregation. By contrast, landscape indicators showing positive relationships to ES were more diverse and related to aspects, such as connectivity, complexity, density and continuity.

When **differentiating the directionality of EC–ES links by ecosystem type**, further patterns can be observed. Woodland and forest ecosystems, wetlands, coastal and marine ecosystems were clearly dominated by positive relationships. In croplands, positive relationships predominated, with negative and no relations occurring at lower, but comparable frequencies. In urban ecosystems, links were most frequently reported as unclear/not specified, followed by positive relations. Grassland, as well as heath and shrubland ecosystems, showed a more even distribution across positive, mixed and no-relation outcomes. The pattern for rivers and lakes was more balanced than in other ecosystem types.

To gain deeper insights into the role of EC indicators in ES assessments, we examine different aspects of these indicators and their **links to specific ES** (i.e. CICES v.5.1 classes). We differentiate their distributions according to the CICES v.5.1 sections that they are linked to – namely, Provisioning, Regulation & Maintenance and Cultural ES (Fig. 7). We focus on trends and distributions that depart from the general patterns described above and draw attention to particularly noteworthy findings. It is important to note that a single EC indicator may be associated with multiple ES and, thus, with multiple CICES v.5.1 classes across different sections. Therefore, in the following paragraph, the assessment differentiates between EC indicators linked to Provisioning, Regulation & Maintenance and Cultural ES, as well as those linked to ES from multiple CICES v.5.1 sections. The latter includes those EC indicators that were linked to "Ecosystem Services" in general (Fig. 7). Generally, links were identified from EC indicators from each ECT class to all CICES v.5.1 sections.

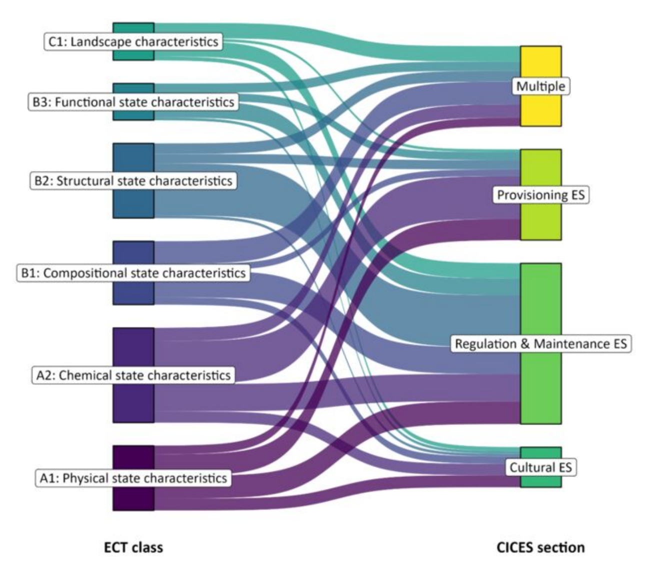


Figure 7.

Sankey diagram showing the link between EC indicators per ECT class and EC according to the CICES v.5.1 section. The width of each flow represents the number of EC indicators. Node sizes are proportional to the total number of indicators within each category.

EC indicators that were only linked to **Provisioning ES** (n_i = 158) mainly related to chemical and physical state characteristics (n_i = 64 and 32, respectively; Fig. 7). Within this group of EC indicators, the most frequently linked ES classes were “cultivated terrestrial plants (including fungi, algae) grown for nutritional purposes” (CICES v.5.1 code: 1.1.1.1; n_i = 79), “wild animals (terrestrial and aquatic) used for nutritional purposes” (CICES v.5.1 code: 1.1.6.1; n_i = 28) and “wild plants (terrestrial and aquatic, including fungi, algae) used for nutrition” (CICES v.5.1 code: 1.1.5.1; n_i = 20). Additionally, the spatial scale of these EC indicators was mostly unclear/not specified (n_i = 82), followed by “not spatially explicit” (n_i = 42). In many cases, the direction of the relationship (in both quantitative and qualitative comparisons) was reported as unclear or not specified (n_i = 72), while positive relations were the next most frequently noted pattern (n_i = 21).

EC indicators that were only linked to **Regulation & Maintenance ES** (n_i = 291) mainly related to structural state characteristics (n_i = 77), followed by chemical state and compositional state characteristics (Fig. 7). Comparatively high was also the relation to landscape characteristics (n_i = 23). Within this group of EC indicators, the most frequently linked ES classes were “maintaining nursery populations and habitats (including gene pool protection)” (CICES v.5.1 code: 2.2.2.3; n_i = 116), “decomposition and fixing processes and their effect on soil quality” (CICES v.5.1 code: 2.2.4.2; n_i = 80) and “regulation of chemical composition of atmosphere and oceans” (CICES v.5.1 code: 2.2.6.1; n_i = 77). The EC indicators were predominantly not spatially explicit (n_i = 111) or aggregated at the ecological scale (n_i = 98). Naturally, most of the linked EC indicators were not (part of) a composite indicator (n_i = 274). However, the share of EC indicators reported as "composite indicator" (n_i = 13) outnumbered the share of "part of composite indicators" (n_i = 2). Across both quantitative and qualitative comparisons, positive relationships were detected most frequently (n_i = 71).

EC indicators exclusively linked to **Cultural ES** (n_i = 72) commonly related to chemical and physical state characteristics (n_i = 15 and 13, respectively), followed by compositional state characteristics (Fig. 7). Within this group of EC indicators, the most frequently linked ES classes were "characteristics of living systems that enable activities promoting health, recuperation or enjoyment through active or immersive interactions" (CICES v.5.1 code: 3.1.1.1; n_i = 66) and those enabling such activities through passive or observational interactions (CICES v.5.1 code: 3.1.1.2; n_i = 21), as well as "characteristics of living systems that enable aesthetic experiences" (CICES v.5.1 code: 3.1.2.4; n_i = 5). For the EC indicators linked to Cultural ES, diverse spatial scales were reported. They were all not (part of) a composite indicator. Regarding the comparison between EC indicators and ES, mixed relationships were observed most frequently (n_i = 46).

EC indicators linked to ES from **multiple** CICES v.5.1 sections (n_i = 222), show a less pronounced trend when it comes to related ECT classes (Fig. 7). A slight peak in compositional state characteristics can be identified (n_i = 38), followed by landscape characteristics (n_i = 28) and the ECT+ class "Pre-aggregated indicators" (n_i = 24). Furthermore, the distribution of the nature of the relation between the EC indicators and the ES showed an emphasis on the integration of EC indicators into ES assessments (n_i = 92).

Ecosystem condition-enabled ecosystem services assessments

Of the 744 EC indicators linked to ES, 256 were integrated into ES assessments. Within this subset, several distinct patterns emerged compared to the general pool of EC indicators with any link to ES presented above. The predominance of EC indicators linked to Regulation & Maintenance ES, as well as to multiple CICES v.5.1 sections, was even more pronounced. In terms of ecosystem types, EC indicators were most frequently applied in croplands (n_i = 167), followed by grasslands (n_i = 125) and woodland and forests (n_i = 90). Notably, the relative share of indicators applied in rivers and lakes was considerably lower (n_i = 16). The share of EC indicators with unclear or unspecified spatial resolution dropped substantially compared to all linked EC indicators. Fully spatially-explicit indicators were slightly less common (n_i = 25), while indicators aggregated at the administrative scale became more prevalent (n_i = 59). EC indicators integrated into assessments of Cultural or Provisioning ES were largely not spatially explicit. Regarding ECT classes, chemical state characteristics remained dominant (n_i = 45), but physical state characteristics were also well represented in this subset (n_i = 36). A relatively higher proportion of indicators were classified as ECT+ (n_i = 87), particularly those related to stable environmental characteristics, ecosystem services and ecosystem extent (whereas pre-aggregated indicators were less prominent). Overall, fewer types of

input data were used, mainly for index calculations. When reference levels were applied, simple
data-driven approaches became less common, while policy-orientated and safety/health-related approaches relatively increased – especially amongst EC indicators integrated into Cultural ES assessments. No “part of composite” indicators were integrated into ES assessments; instead, either stand-alone metrics or a few composite indicators were used. Examples of those composite indicators were “Forest structure” aggregating “Stand density” and “Mean tree size” (González-Díaz et al. 2019) and “Ecological environmental quality index” aggregating information on the “Normalised difference vegetation index”, “Leaf area index” and “Net primary productivity” (Zhou et al. 2021). These composite indicators were mainly applied in assessments involving multiple CICES v.5.1 sections and, to a lesser extent, in assessments of Regulation & Maintenance ES. Finally, seven EC indicators were not only integrated, but also directly compared to a specific ES. Of these, six showed a positive relationship; amongst those six, there were multiple EC indicators related to soil nutrient concentrations and microbial biomass carbon with an identified positive relation to the ES “Regulation of soil quality” (CICES v.5.1 codes 2.2.4.1 and 2.2.4.2).

Discussion

Spatio-temporal distribution of studies and general insights

With regard to the temporal distribution, a noticeable increase in publications was observed in 2022. However, given the short review period, it is not possible to determine whether this rise reflects a coincidence, a delayed publication effect from the COVID-19 pandemic or a response to major policy developments, such as the release of the SEEA EA framework (United Nations 2025), the EU Biodiversity Strategy for 2030 or advances under MAES/KIP INCA initiatives (La Notte et al. 2022, Inácio et al. 2025b). Since the SEEA EA ECT was only published towards the end of the review period, it was not surprising that the majority of papers did not apply this typology.

A spatial asymmetry was evident in the literature, with most studies being conducted in the United States, China and Europe – a pattern also found in previous reviews (Runting et al. 2017, Pinto et al. 2022). Additionally, differences could be detected with regard to the applied methodological approaches between regions. For example, several studies from China employed total ES value approaches and composite Ecosystem Health Index models, based on the Vigour–Organisation–Resilience framework (e.g. Ma et al. 2022, Xu et al. 2022).

Only a small number of publications identified in this review dealt explicitly with ecosystem accounting. Most operational ecosystem accounting applications – particularly those aligned with the SEEA EA framework (United Nations 2025) – are implemented by national or regional statistical offices and other public authorities, who typically disseminate results through official reports rather than peer-reviewed scientific publications (Comte et al. 2022, Lange et al. 2022). Second, the temporal window covered (2018–2022) largely precedes or overlaps only partially with the formal release of SEEA EA (United Nations 2025), meaning that many accounting initiatives may still be in early development or not yet published.

Insights into indicator characteristics

The EC and ES indicators, discussed in this review, represent a specific subset where EC is explicitly linked to ES. Thus, we only focused on indicators that directly or implicitly connect the two concepts, so the patterns we observed are influenced by this research scope and might not mirror the broader methodological landscape assessed in other studies (e.g. Nicholson Thomas et al. 2025).

We observed a clear imbalance in ecosystem type representation, with cropland and “various” ecosystems being most frequently assessed, followed by woodland and forest, grassland and river and lake ecosystems. In contrast, exclusively marine ecosystems were substantially under-represented, indicating a strong bias towards terrestrial assessments, in particular for EC indicators. This trend is in line with Maes et al. (2016), Vári et al. (2024), Zhou et al. (2024) and also shows similar patterns to the EC consideration in ES valuation studies from the ESVD (Hernández-Blanco et al. 2022). Assessments covering “various” ecosystem types differed from ecosystem type-specific assessments. Whereas the latter often aim to understand ecological functioning or rather specific management needs, multi-ecosystem assessments tend to pursue broader comparative, prioritisation or policy-support objectives, such as spatial conservation planning or land-use optimisation (e.g. Maes et al. 2020b). Following the EU-wide MAES assessment (Maes et al. 2020b), these indicators are referred to as cross-cutting and, for EC, they include “landscape fragmentation, water quality related indicators and the share of the ecosystem that is managed as a protected area”. Indicators related to “various” ecosystem types often rely more heavily on generalised or transferable indicators, which can be consistently applied across heterogeneous landscapes. In this context, Nicholson Thomas et al. (2025) highlight that, while standardisation supports alignment across studies, excessive uniformity can neglect ecosystem-specific realities and undermine stakeholder legitimacy. Within the ECT classes, EC indicators applied in “various” ecosystem types were mostly related to landscape characteristics and, within ECT+, pre-aggregated indicators were most common. The dominance of remote sensing and other processed spatial data for this share of EC indicators reflects the need for wall-to-wall, spatially standardised inputs (Turner et al. 2015, Nicholson Thomas et al. 2025), while the frequent use of value transfer methods in ES assessments aligns with literature that highlight the importance of respective scalable approaches (Johnston et al. 2021, Grammatikopoulou et al. 2023, Brander et al. 2024). In contrast, the more ecosystem type-specific assessments, such as those focusing on croplands or forests, are more likely to use field-based or functional data and methods, reflecting domain expertise (Binder 2017, Burkhard et al. 2018a, Bank et al. 2025, Nicholson Thomas et al. 2025).

We identified a general predominance of chemical state indicators, while process-orientated indicators, for example, those describing functional state characteristics, remain less operationalised. This pattern is consistent with the broader challenge of translating ecosystem functioning into standardised indicators with relevance, for example,, for decision-making and policy (Smit et al. 2021, Nicholson Thomas et al. 2025). The comparatively high use of reference conditions in freshwater ecosystems likely reflects the strong regulatory and monitoring frameworks that exist for rivers and lakes already since the turn of the millennium. Instruments, such as the EU Water Framework Directive (WFD; European Commission 2000) and comparable national policies mandate the definition of ecological status classes and require assessments against established reference conditions or policy-defined targets (Solimini et al. 2009, Maes et al. 2012, Reyjol et al. 2014, Lyche Solheim et al. 2025). This has led to the widespread development of standardised water quality indices and long-term monitoring datasets, facilitating diverse reference level approaches. For example, Apostolaki et al. (2019) provide a conceptual approach how to combine the EU WFD requirements with the ES approach and EC assessment, although not explicitly considering reference conditions. In contrast, structured reference frameworks are less consistently available for other ecosystem types, which may explain the more limited use of reference levels in those systems.

More generally, this review confirms that EC is not used in a consistent or conceptually disciplined way across scientific literature, particularly when implemented through indicators. As also reported by Bank et al. (2025) and Nicholson Thomas et al. (2025), EC is applied across a broad spectrum of interpretations, ranging from ecosystem properties or environmental characteristics (slope, relief, climatic variables) to direct biophysical state metrics, composite indices, pressure proxies and even outcome-based measures that quantify ES supply rather than EC. To bring structure to this heterogeneity, we classified all EC indicators recorded in this review according to the SEEA EA ECT and assigned remaining indicators to an extended classification (ECT+), following Czúcz et al. (2021b). Around one fourth of the reviewed EC indicators were not linkable to the original ECT classes recognised by SEEA EA. In contrast to this diverse and sometimes ambiguous usage found in the reviewed literature and also identified by recent studies (Bank et al. 2025, Nicholson Thomas et al. 2025), both SEEA EA (United Nations 2025) and the EU-wide methodology for EC assessment (Vallecillo et al. 2022) define EC more narrowly. Under these frameworks, EC refers to the quality of an ecosystem measured in terms of its abiotic and biotic characteristics and ES are the contributions of ecosystems to the benefits that are used in economic and other human activity. Therefore, we recommend that indicators labelled as EC in literature, but in fact describing pressures or ES (thus having been reclassified as respective ECT+ class) should not be treated as condition metrics in a strict sense (United Nations 2025). Their inclusion in EC assessments may be practical in applied contexts, but, for analytical clarity, condition, pressure and service roles, should be clearly distinguished.

Analysing the linkages between ecosystem condition and ecosystem services indicators

As outlined in the Introduction, the relationship between EC and the supply of ES remains conceptually established, but empirically unresolved. While numerous studies report positive associations between EC or related concepts (such as ecological integrity) and ES, agreement is still lacking on the specifics or contexts in which these links hold (Strong et al. 2015, Roche and Campagne 2017, Townsend et al. 2018, Smit et al. 2021). Against this backdrop, we here provide a synthesis of how EC–ES connections are currently implemented through indicators across ecosystem types, ECT classes and CICES v.5.1 sections.

Implementation across ecosystem types

The observed pattern of EC indicators being most frequently linked to Regulation & Maintenance ES likely reflects both ecological dependencies and long-lasting research efforts (Müller 2005, Quijas et al. 2010, Rendón et al. 2022). Regulation & Maintenance ES build upon crucial processes for the ecosystems' long-term functioning and maintenance and are often closely tied to measurable biophysical functions, which makes them more amenable to indicator-based linkage from EC (Müller and Burkhard 2007, Harrison et al. 2014, Martínez Pastur et al. 2017, Sutherland et al. 2018). Furthermore, ecosystem type-specific patterns emerged. EC indicators in croplands were predominantly linked to Provisioning ES, reflecting the production-orientated framing of agricultural landscapes (Power 2010, Wiggering et al. 2016, Inácio et al. 2025a). Conversely, in wetlands, rivers and lakes, EC indicators were more commonly associated with Cultural ES, consistent with the recreational, aesthetic and identity-based values, emphasised in the Ramsar Convention (Carpenter et al. 2006, Lankia et al. 2023). These findings suggest that EC–ES linkages, reported in literature, are not only neutral reflections of ecological interdependencies, but are also shaped by disciplinary norms, policy priorities and the availability of operational indicators across ecosystem types, as well as CICES v.5.1 classes and sections.

Implementation across CICES v.5.1 sections

Across CICES v.5.1 sections, the EC indicators linked to ES revealed differences in how they are implemented depending on the ES context. When EC indicators were linked to Provisioning ES, they were predominantly chemical and physical state characteristics, based on field measurements. This mirrors long-established practices in agroecosystem monitoring (OECD 2001, Bank et al. 2025, Nicholson Thomas et al. 2025). Most EC–ES relationships were reported as unspecified or positive, echoing a general dependence of Provisioning ES on EC (Harrison et al. 2014). When EC indicators were linked to Regulation & Maintenance ES, a broader spectrum of EC types was involved — structural, chemical, compositional and landscape characteristics. This reflects the inherently multi-dimensional nature of Regulating ES, which depend on system organisation rather than single-state variables (Müller and Burkhard 2007, Kandziora et al. 2013). Most EC-ES relationships were positive, aligning with the theory that higher ecological integrity underpins stronger supply of Regulating ES (Kandziora et al. 2013, Harrison et al. 2014). EC indicators linked to Cultural ES again drew mostly on chemical and physical state characteristics, but these were more frequently transformed into composite indices and benchmarked against policy or safety standards. This may reflect the need for methodological plurality, as well as the need to aggregate biophysical metrics into socially interpretable values for culture, recreation or aesthetics (Fish et al. 2016). Reported EC-ES relations were most frequently mixed, consistent with evidence that cultural appreciation can peak at intermediate landscape openness or heterogeneity (e.g. Kandziora et al. 2013, Dronova 2017). Kandziora et al. (2013) also found that Cultural ES are condition-dependent, but socially mediated, while Graves et al. (2017) highlighted that the use of species richness as a single proxy for landscape aesthetics and the assumption that more species confer greater Cultural ES value are insufficient. Finally, EC indicators that were linked to ES across multiple CICES v.5.1 sections did not cluster around a specific EC type and were more frequently integrated directly into ES assessments (e.g. Laporta et al. 2021, Marull et al. 2021). This is consistent with observations from broader literature, where aggregated indicators are often used when assessments aim to capture multifunctionality rather than a single service pathway (Andreasen et al. 2001, Rowland et al. 2020).

Implementation of directionality by ECT class and ecosystem types

Healthy ecosystems are recognised as fundamental providers of ES, contributing to human well-being (Kandziora et al. 2013, Burkhard et al. 2018b, Haines-Young and Potschin 2018, Grizzetti et al. 2019, Hatziiordanou et al. 2019, Martini et al. 2024, United Nations 2025). In this perspective, the enhancement or degradation of EC influences ES supply. Ideal EC variables offer a univocal, clear and broadly accepted "directional interpretation" (Heink and Kowarik 2010, Czúcz et al. 2021a, La Notte et al. 2022). Our research revealed that EC–ES relations are complex and can have different directions. This is in line with findings from a review on various linkages between Biodiversity and ES (Harrison et al. 2014).

While structural and functional EC indicators more consistently exhibited positive relations to ES, physical and chemical indicators showed more context-dependent or even contrasting relationships. This finding mirrors earlier observations that functional and structural metrics capture ecological capacity more directly, while some chemical or physical indicators tend to reflect stress gradients whose relationship to service delivery may be non-linear or even inverted (Keith et al. 2020). Additionally, some chemical state characteristics relate to pollutant concentration in ecosystems, for example, high sulphate or heavy metal concentrations in rivers and lakes (López Sardi and Larroudé 2020, Lomnicky et al. 2021). For landscape characteristics diverse relations were identified. This variability can be partly attributed to the interdependence of landscape metrics themselves. Many commonly used indicators describe opposite aspects of spatial structure – for example, fragmentation versus cohesion or patch size versus density. As a result, positive relations of certain metrics with ES may mirror negative relations of their counterparts.

EC indicators should be interpreted in light of their ecological pathways rather than assumed to correlate uniformly with ES. Additionally, these findings support the need for a balanced EC indicator set covering all ECT classes (Czúcz et al. 2021a, Bank et al. 2025, United Nations 2025). For croplands, woodland and forest ecosystems, wetlands, coastal and marine ecosystems, we found dominantly positive relationships between EC indicators and ES, which is in line with earlier findings. For croplands and grasslands, high biodiversity or soil condition have been linked to increased pollination, erosion control and carbon storage (Egoh et al. 2009, Bai et al. 2011, Maes et al. 2012, Rendón et al. 2020, Rendón et al. 2022). For woodland and forest, EC indicators, such as species richness and tree cover density, have been positively linked to ES, such as nursery population and habitat maintenance services, recreation, wood provisioning and global climate regulation (Albrich et al. 2018, Martini et al. 2024). Intact wetlands, having a better EC condition than those intensively used, are found to provide more ES (De Groot et al. 2010, Bonn et al. 2016). For freshwater, coastal and marine ecosystems, a positive relationship between EC and the supply of regulating and cultural ES, such as coastal protection and nursery population and habitat maintenance services, is described (Liquete et al. 2016, Grizzetti et al. 2019). Urban ecosystems represent a special case within EC and ES assessments. Within our review, EC indicators applied in urban systems mainly related to structural state and landscape characteristics. Unlike predominantly natural ecosystem types, they function as socio–ecological–technological systems (McPhearson et al. 2016, Pickett et al. 2016, Babí Almenar et al. 2023, Babí Almenar et al. In press). As shown in the European pilot on urban ecosystem accounting (Babí Almenar et al. 2023), applying condition indicators in cities often requires adjusted metrics and reference logics. This might explain why EC–ES relationships in urban systems are reported more frequently as unclear/not specified in our study.

Integrative analysis: Paving the way towards ecosystem condition-enabled ecosystem services assessments

Scientific consensus increasingly holds that EC must form the basis for ES assessment and accounting efforts (Burkhard et al. 2018b, Hein et al. 2020, Rendón et al. 2022, Kokkoris et al. 2024, Martini et al. 2024, Hinsch et al. 2024). In recent years, great progress has been made in the development and use of EC indicators, for example, in relation to the SEEA EA framework (Czúcz et al. 2021a, La Notte et al. 2022, La Notte et al. 2022, Nicholson Thomas et al. 2025, United Nations 2025), helping to move the field from theoretical proposals towards operational, evidence-based applications. In particular,Nicholson Thomas et al. (2025) provide a comprehensive review of over 300 studies to derive a harmonised typology of condition indicators per ecosystem types. Meanwhile, Bank et al. (2025) apply SEEA EA selection criteria, followingCzúcz et al. (2021a), to select the most meaningful and applicable EC indicators for agroecosystem in a case study area in Lower Saxony, Germany. Their methodology underscores the trade-offs between ecological significance and data practicality in indicator selection. Together, these studies illustrate how the indicator selection process is maturing — moving beyond ad hoc choices towards evidence-based, transparent criteria applied across ecosystem types. These advancements can be taken up in future integrated ecosystem assessments (Lange In press), that build upon EC-enabled ES assessment approaches.

Our results indicate that the implementation of EC-enabled ES assessment approaches up to 2022 is most advanced in cropland, grassland and woodland/forest ecosystems. This likely reflects the management- and production-orientation of these ecosystems (Graves et al. 2017, Maes et al. 2018, Bethwell et al. 2021, Bruzón et al. 2023), while our findings suggest that other ecosystem types remain comparatively under-represented in EC-enabled ES assessments. This imbalance suggests that methodological development should prioritise expanding EC-enabled ES assessments beyond the traditionally well-instrumented boundaries.

The types of EC indicators that are directly integrated into ES assessments reveal a strong dominance of chemical and physical state characteristics, suggesting that practitioners in these cases gravitate towards those components of EC that are relatively easy to quantify and to monitor through established environmental reporting frameworks (Grizzetti et al. 2019, Maes et al. 2020b, Vallecillo et al. 2022). We also observed a comparatively high representation of EC indicators integrated into ES assessments, that related to ecosystem extent, ES outputs themselves or stable environmental characteristics. Following the SEEA EA guidance (United Nations et al. 2021) and the conceptual clarifications by Czúcz et al. (2021a) and La Notte et al. (2022), such indicators should be treated with caution when used as proxies for EC. Extent and service-based metrics do not capture the underlying ecological functions or resilience of ecosystems and stable environmental characteristics are not sensitive to change (Czúcz et al. 2021a, Czúcz et al. 2021b). This suggests that a substantial fraction of current EC-enabled ES assessments may still rely on indicators of limited diagnostic value for the actual assessment of EC. A striking pattern is the prevalence of positive relationships between EC indicators (that are related to ECT classes) and ES whenever these relations were explicitly tested. This generally supports the prevailing notion that ecosystems in a better condition provide more ES (Haines-Young and Potschin 2010, Kandziora et al. 2013, Burkhard et al. 2018b, Hatziiordanou et al. 2019, Martini et al. 2024). Despite the progress in EC assessments described above, many EC indicators identified here remain spatially non-explicit, which constrains their utility for fine-scale assessment and limits their integration into spatial planning. These findings indicate that the field continues to face critical gaps related to, for example, ecosystem type coverage, EC indicator diversity and spatial explicitness. Addressing these limitations will be essential for advancing robust, integrated assessments capable of supporting ecosystem-based management and decision-making processes, as well as for a meaningful and fit-for-purpose national and European implementations of SEEA EA.

Interpretative boundaries and methodological limitations

This section provides insights into the strengths and limitations of this review and suggests areas for further study. This review specifically focuses on the applied links between EC and ES as reported in the assessed literature published in 2018-2022. Our focus has been on documenting how researchers have implemented this linkage in practice — that is, which EC indicators have been connected to which ES and what the nature of that link was. Importantly, we did not evaluate whether these linkages represent the most meaningful, scientifically robust or societally relevant relationships between nature and human well-being. Rather, the links reported here reflect the choices made by researchers, potentially shaped by disciplinary traditions, data availability, methodological feasibility and policy or funding priorities. Consequently, the absence or under-representation of certain EC–ES relationships in literature should not be interpreted as a lack of relevance in ecological or socio-economic terms. Instead, it may point to limitations in available indicators, gaps in understanding, challenges in quantification or mismatches between observation scales. Emerging developments in the direction of integrated ecosystem assessments (Lange In press) – such as guiding frameworks, improved functional indicators, long-term monitoring data or advances in social-ecological modelling – may enable additional EC–ES links to be assessed in future research.

An additional limitation is given by the selected time frame, 2018-2022. Consequently, some more recent developments in the integration of EC indicators into ES assessments have not been captured in our analysis. Recognising this gap, an updated review is currently underway to incorporate the latest data and insights, ensuring that our findings remain relevant and reflect the most recent advancements in the field.

The literature review faced common challenges, such as potential omissions due to limiting the search to English-language scientific publications. The use of diverse terminology and synonyms, particularly for ecosystem concepts, may have impacted the review's comprehensiveness and may have introduced selection bias. The review's reliance on scientific literature excluded potentially valuable grey literature (Yoshida et al. 2024). While precise inclusion criteria enhanced the review's reliability and rigour, bias persisted due to subjective judgement and interpretation. Fleiss’ Kappa results indicated robustness in the screening process, though sample size limitations and team-based reviewing may have affected the analysis. The varied quality of publications, with incomplete reporting and selective data, affected synthesis and conclusions. The review’s indicator-based approach risked over-representing methodological procedures in studies assessing multiple indicators.

Conclusions and Outlook

This review provides a comprehensive overview of how EC indicators are used in ES assessments, offering critical insights for scientists and policy-makers to design robust ecosystem assessment strategies. The conclusion follows the structure of the three research questions outlined in the Introduction. Related to the types and characteristics of the EC indicators used in ES assessments, this review identified that EC indicators focused on terrestrial ecosystems, with a strong emphasis on cropland and multi-ecosystem assessments, whereas marine ecosystems are notably under-represented. Chemical state indicators are prevalent, while landscape state, process-orientated and functional state metrics remain under-implemented. It was observed that a significant share of indicators labelled as EC are not EC indicators in the strict sense, but instead relate to, for example, ecosystem extent, ES or stable environmental characteristics. These have little diagnostic value for condition, blurring the boundary between pressure-condition-service. To maintain the integrity of EC indicator sets, we recommend excluding ES or extent variables and ensuring that each indicator's directionality and sensitivity to change are documented. The incomplete integration of EC indicators into the SEEA EA typologies highlights the need for more systematic classification and respective applications in the future.

The analysis of the EC and ES linkages reveals that two predominant methods emerged: quantitative comparison between EC indicators and ES, followed by direct integration of EC data into ES assessments. These approaches facilitate different analyses of EC-ES integration. Quantitative comparison, often involving empirical data, is primarily used to test hypotheses and explore cause-effect relationships between EC and ES. This method enhances transparency and supports rigorous hypothesis testing, making it suitable, inter alia, for exploring heterogeneity amongst ecosystems and ES. In contrast, direct integration of EC indicators into ES assessments typically involves modelling to evaluate the impacts of measures or policy scenarios, such as nature restoration or resource management, on ES supply. Here, EC-ES linkages are assumed to be established and are embedded within the analysis, allowing researchers to forecast the outcomes of various interventions. Literature shows a predominance of positive EC–ES relationships, reinforcing the expectation that ecosystems in better condition tend to support a higher supply of ES. EC indicators are most frequently associated with Regulation & Maintenance ES due to their foundation in ecosystem functioning. However, the observed linkages appear influenced by policy priorities and data availability rather than purely reflecting ecological relationships, suggesting a potential bias in their empirical representation.

The actual integration of EC indicators into ES assessments supports the road towards integrated ecosystem assessments and enables evidence-based support for decision-making. Our findings indicate an uneven implementation of EC-enabled ES assessments with a concentration on cropland, grassland and forest ecosystems, while aquatic and less intensively managed systems remain under-represented. This skews generalisability and risks biasing well-instrumented systems over ecosystems with equally pressing policy needs. It is, therefore, crucial to broaden ecosystem type coverage and raise spatial resolution to improve assessment accuracy and transferability, while reducing the bias in cross-ecosystem inference. The predominance of chemical and physical state indicators, as well as the focus on ecosystem extent or ES rather than actual condition metrics, hinders deeper understanding and diagnostic capabilities, necessitating progress in applying more functional and structural state characteristics. Moreover, spatial explicitness remains a significant limitation, restricting the utility of assessments for planning and restoration efforts, as well as accounting. Overall, gaps persist regarding ecosystem type coverage, indicator diversity and spatial resolution.

Progress in this domain requires the clear recognition of the gaps and constraints identified in this review. A refined conceptualisation of EC, in alignment with ongoing efforts in ECT (e.g.Bank et al. (2025) for agroecosystems), is critical. Future research should also strive for a balanced selection of EC indicators across ecosystem types and enhance spatial explicitness, utilising emerging methodologies and data collection strategies to embrace a broader array of EC-ES linkages enhancing the accuracy and applicability of integrated ecosystem assessments and ultimately supporting more sustainable ecosystem management and policy decisions. From an accounting perspective, significant progress is expected, for example, aligning the input data used by ES models with EC variables and advancing the 'capacity account', which would further strengthen the linkage between EC and ES (Maes et al. 2020a, La Notte et al. 2022, Maes et al. 2023, United Nations 2025). Ongoing and future efforts will be directed towards assessing the impact and usefulness of implemented EC-ES linkages, identifying best practices in EC integration into ES assessments and capturing new advancements, inter alia, through a systematic follow-up review. A follow-up systematic review will examine literature after 2022 to track latest methodological and conceptual evolutions. This synthesis aids in prioritising conservation efforts, guiding restoration and promoting sustainable management practices by enhancing the accuracy and applicability of ecosystem assessments, ultimately supporting more informed policy decisions.

Authors' Contributions

JS and SL designed the study and were responsible for planning and coordinating the research activity, as well as for designing the methodology and creating the review template (Conceptualisation, Project administration, Methodology). SL, INT, PR, CC and HD were responsible for data cleaning and Validation. SL, JS, CC, JKH, MDCM, DR, MSH, ET and JV analysed the data and prepared the figures and tables (Formal analysis, Visualisation). JS, INT, PR, CC, IA, HD, DG, NG, VGG, MI, JKH, IPK, SLC, PL, MDCM, PP, DR, MSH, MS, ET, VVH, JV, IZ and SL collected data by reviewing articles for the systematic literature review (Data curation). JS, SL, INT, PR, CC, BC, DR, MSH and MS contributed to Writing – original draft. All authors contributed to Writing – review and editing and have read and approved the final version of the manuscript.

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Conflicts of interest

The authors have declared that no competing interests exist.
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Supplementary materials

Suppl. material 1: R code showing the original search query used to retrieve the potentially relevant publications for the literature review. doi

Authors: Seguin et al.
Data type: R code
Brief description: This is the R code that was used to retrieve the literature items relevant for this review study from the SELINA Super-Query (Seguin et al. 2025).
Download file (89.81 kb)

Suppl. material 2: List of included literature items doi

Authors: Seguin et al.
Data type: literature references
Brief description: These are the references of the literature items that have been included in the full review.
Download file (305.26 kb)

Suppl. material 3: Review Template doi

Authors: Lange et al.
Data type: Excel .xlsm
Brief description: This is the Excel review template using macros.
Download file (557.05 kb)

Suppl. material 4: Overview of ECT and ECT+ classes based upon Czúcz et al. (2021) doi

Authors: Czúcz et al.
Data type: Text
Brief description: This table shows the overview of ECT and ECT+ classes, based upon Czúcz et al. (2021). Ecosystem type is abbreviated as ET in the table.
Download file (155.18 kb)