

Review Paper

Advancing the global statistical standard for urban ecosystem accounts

Javier Babí Almenar^{a,b,*}, Chiara Cortinovis^c, Sara Vallecillo^d, Davide Geneletti^c, Bálint Czúcz^e, Federica Marando^{f,g}, Grazia Zulian^h, Anna M. Addamoⁱ, Alessandra La Notte^{j,1}, Renato Casagrandi^{a,b}

^a Department of Electronics, Information and Bioengineering, Politecnico di Milano, 20133 Milano, Italy

^b NBFC, National Biodiversity Future Center, 90133 Palermo, Italy

^c Department of Civil, Environmental and Mechanical Engineering, University of Trento, 38123 Trento, Italy

^d UniSystems Luxembourg Sàrl (under contract with the European Commission's Joint Research Centre), L-8070 Bertrange, Luxembourg

^e Norwegian Institute for Nature Research, Torgarden, P.O. 5685, 7485 Trondheim, Norway

^f Climate Action, Sustainability and Science Department, European Space Agency, 00044 Frascati, Italy

^g European Commission, Joint Research Centre (JRC), 21027 Ispra, Italy

^h Institute of Earth System Sciences, Physical Geography and Landscape Ecology, Leibniz University Hannover, Schneiderberg 50, 30167 Hannover, Germany

ⁱ Faculty of Biosciences and Aquaculture, Nord University, 8049 Bodo, Norway

^j European Dynamics Luxembourg S.A. (under contract with the European Commission's Joint Research Centre), L-1466 Luxembourg, Luxembourg

A B S T R A C T

The System of Environmental-Economic Accounting-Ecosystem Accounting (SEEA-EA), adopted by the United Nations, provides a standardised global framework for measuring and monitoring the extent, condition, and services of ecosystems. However, its application to urban ecosystems faces conceptual and operational challenges. With the aim of advancing the SEEA-EA framework for thematic urban ecosystem accounting, we identify key challenges and frame potential solutions based on existing lessons and approaches. Through a review of scientific and grey literature, we identify 24 challenges, with lessons and approaches suggested for 17 of them. Many challenges are highly interconnected and shared with accounts for other ecosystem types. Still, urban ecosystems present specific challenges, such as the lack of a global classification scheme, ambiguity in defining urban ecosystems and determining which assets belong to them, and persistent gaps in fully capturing urban ecosystem degradation. To address the identified challenges, we propose solutions, such as the development of a complementary 'sister' condition table to account for socio-technological variables, the integration of scenario modelling into monetary ecosystem asset accounts to reflect future projections and uncertainties, and the definition of internationally agreed policy uses to ensure consistent implementation. We also highlight the need for a careful prioritisation of the next steps based on the interdependencies among challenges. By mapping challenges, synthesizing lessons and approaches, and framing solutions, this study contributes to moving towards a globally standardised thematic urban ecosystem accounting framework. Such standardisation will enhance the relevance of SEEA-EA thematic urban ecosystem accounts in informing urban sustainability policies.

1. Introduction

Biodiversity and healthy ecosystems are cornerstones of human health and well-being, underpinning ecosystem service supply. Yet, both continue to decline (Jaureguiberry et al., 2022; Loreau et al., 2022; Pereira et al., 2024). It is therefore crucial to track changes in the status of ecosystems and biodiversity, along with their societal and economic impacts, in a regular, consistent, and comparable manner. Ecosystem accounts provide a structured framework for measuring and monitoring the extent and condition of ecosystems, their service flows, and their

value as assets (Comte et al., 2022; Hein et al., 2015). Ecosystem accounts' implementation is expected to support policymaking across sectors and governance levels, from international to local (Edens et al., 2022; La Notte and Zulian, 2021; Nel and Driver, 2015). Recognising the value of ecosystem accounts to inform sustainable ecosystem management, countries are increasingly adopting them through legislation (Bagstad et al., 2021; European Commission, 2022).

Ecosystem accounts may be applied to any ecosystem type, including anthropogenic ones. Urban ecosystems, characterized by the presence of people and a mix of natural and artificial features (United Nations,

* Corresponding author at: Department of Electronics, Information and Bioengineering, Politecnico di Milano, 20133 Milano, Italy.

E-mail addresses: javier.babialmenar@polimi.it (J. Babí Almenar), chiara.cortinovis@unitn.it (C. Cortinovis), sara.vallecillo@ext.ec.europa.eu (S. Vallecillo), davide.geneletti@unitn.it (D. Geneletti), balint.czucz@nina.no (B. Czúcz), federica.marando@esa.int (F. Marando), anna.m.addamo@nord.no (A.M. Addamo), alelanotte.work@gmail.com (A. La Notte), Renato.casagrandi@polimi.it (R. Casagrandi).

¹ Independent Expert.

2021a), are particularly relevant from an ecosystem accounting perspective. As primary habitats for humans and hotspots of ecosystem services' demand, urban ecosystems are key drivers of global and local biodiversity changes (Brondízio et al., 2019; Elliot et al., 2022; Isbell et al., 2023; Maxwell et al., 2016). For the still-emergent urban science-policy-practice networks (Bai et al., 2019), a global framework for urban ecosystem accounts would be a valuable instrument to help translate knowledge into informed actions that address biodiversity loss and ecosystem degradation.

The System of Environmental-Economic Accounting Ecosystem-Accounting (SEEA-EA), adopted in 2021 by the UN Statistical Commission, is the globally recognised statistical standard for ecosystem accounts (United Nations, 2021a). SEEA-EA is a spatially based integrated statistical framework applicable to all ecosystem types, including urban ecosystems. It comprises five core accounting tables: 1) ecosystem extent, 2) ecosystem condition, 3) ecosystem service flows in biophysical terms, 4) ecosystem service flows in monetary terms, and 5) monetary ecosystem assets. The first three are adopted as part of the statistical standard, while the developments for the last two are currently recognised only as statistical principles and recommendations (Edens et al., 2022; United Nations, 2021a). A glossary of key SEEA-EA terms is provided in the [Supplementary Information \(SI\)1](#).

Although SEEA-EA may be applied to compile urban ecosystem accounts, some of SEEA-EA's core principles conflict with the current scientific conceptualisation of urban ecosystems. For instance, SEEA-EA requires ecosystem assets to represent ecosystems and be mutually exclusive at conceptual and geographical levels (United Nations, 2021a). However, as conceptualised by urban and landscape ecologists, urban ecosystems are heterogeneous landscape mosaics of fine-grained patches (ecosystem assets) representing multiple ecosystem types, with boundaries that are often fuzzy (Grimm et al., 2008; Wu, 2014). Additionally, as already recognised by ecosystem service scholars, ecosystem condition in urban ecosystems is shaped not only by natural abiotic and biotic components but also by social and technological factors (Cimburova and Berghauser Pont, 2021; Larson et al., 2023), which SEEA-EA does not currently account for (United Nations, 2021b). Consequently, degradation in urban ecosystems is not solely ecological but socio-ecological-technological, as also highlighted within the broader urban science and urban ecosystem service literature (Andersson et al., 2021). Failing to acknowledge these aspects when developing a global framework for urban ecosystem accounting risks creating a framework perceived as inadequate or illegitimate by key stakeholders within science-policy-practice networks, including professionals such as urban ecologists, urban planners, or ecological economists, ultimately leading to its misuse.

To overcome such inconsistencies, SEEA-EA encourages the development of thematic accounts for urban ecosystems (United Nations, 2021a). These thematic accounts offer greater flexibility than traditional SEEA-EA accounts (hereafter referred to as SEEA-EA general accounts), allowing a more comprehensive representation of the status of urban ecosystems and their societal and economic impacts. They also enable variations within specific account tables to ensure that these accounts can inform specific local, regional, or national policy priorities. However, this flexibility does not eliminate the need for standardisation. The UN Statistical Commission has not yet formally adopted thematic accounts as part of the statistical standard or recognised them as part of formal principles and recommendations (Edens et al., 2022; United Nations, 2021a). In fact, thematic urban ecosystem accounts remain underdeveloped as a standard, potentially leading to inconsistencies with SEEA-EA general accounts and the proliferation of multiple incompatible local or regional frameworks (Cryle et al., 2021). This issue threatens the ability of SEEA-EA to support sustainable urban ecosystem management in a globally coherent way.

Thus, developing a global framework for urban ecosystem accounting in the form of thematic SEEA-EA accounts is essential. This framework must integrate seamlessly with SEEA-EA general accounts and

enable a unified, systematic approach to urban ecosystem accounting. Achieving this requires identifying and addressing remaining challenges posed by SEEA-EA when applied to urban ecosystems.

This paper aims to advance the development of a global framework for urban ecosystem accounting, contributing to the standardisation of SEEA-EA thematic accounts. Specifically, it identifies:

- i. Key conceptual and operational challenges for thematic urban ecosystem accounts;
- ii. Lessons learned and approaches from past accounting studies and relevant literature on urban science in general and on urban ecosystem services in particular, which could inform potential solutions.

Conceptual challenges refer to unresolved theoretical issues, while operational challenges relate to practical issues that need to be addressed to establish standard procedures. Lessons point either to definitive solutions or to key constraints encountered when addressing specific challenges, whereas approaches represent potential alternatives, which sometimes appear contradictory in the literature.

Drawing on both types of findings, the paper discusses potential solutions and how these may lead to modifications in current SEEA-EA thematic accounts. Moreover, it identifies interconnections between the challenges and outlines a stepwise approach to address them.

2. Methods

Challenges, lessons, and approaches for urban ecosystem accounts were identified through a structured review of scientific and grey literature, following three consecutive steps. Each step is detailed below and visually summarised in [Fig. 1](#). The raw data gathered in the review can be consulted in [SI2](#).

2.1. Step 1: review of key SEEA-EA documents

The review began with the SEEA-EA Handbook (United Nations, 2021a), including its section on a research and development agenda. It then extended to pitches (presentations) from the Virtual Expert Forum of SEEA experimental ecosystem accounting (United Nations, 2020) and discussion papers of the working groups for the SEEA experimental ecosystem accounting revision, available on the SEEA website (United Nations, 2021b). Some of these discussion papers had already been published as peer-reviewed articles or technical reports. This step aimed to compile an initial list of key challenges, drawing from both the SEEA-EA Handbook and broader expert discussions in the Forum and Working Groups, capturing details that may not have been included in the Handbook ([Fig. 1](#), Step 1).

2.2. Step 2: systematic reviews of ecosystem accounting literature

The review combined an iterative systematic literature review via an online 'literature mapping tool' with a traditional systematic literature review ([Fig. 1](#), Step 2).

In the iterative systematic literature review, the key SEEA-EA documents and the references of interest cited therein were used as input data to identify other studies by making use of the online tool Connected Papers (<https://connectedpapers.com>). This tool takes an input document (e.g., a peer-reviewed paper) to build a graph of documents (e.g., papers, books, chapters) that share references and co-citations with the input (Kaur et al., 2022; Lence et al., 2023; Liu and Ali, 2022). This approach helps to overcome common issues of traditional systematic reviews (e.g., missing keywords in the search strings) that could lead to overlooking important references (Lence et al., 2023). It also helps identify relevant references in emergent areas of study where diverse keywords are still in use. For example, in the case of urban ecosystem accounts, this iterative approach captures studies that may not explicitly

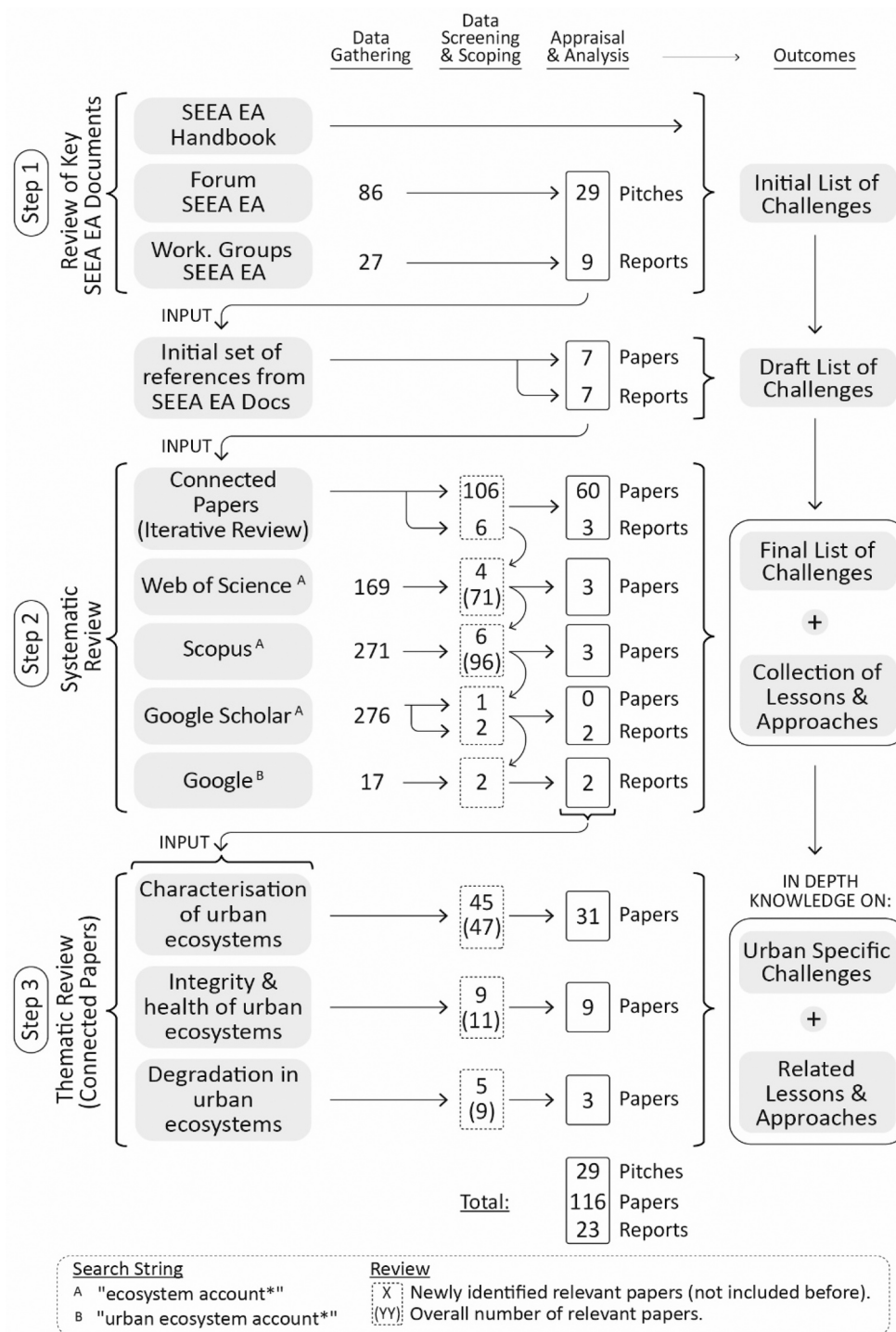


Fig. 1. Representation of the methodological workflow of the three consecutive steps of the structured literature review and number of documents gathered and retained in each part. Note: In the Figure, 'pitches' refer to the presentations in the Forum SEEA-EA, which already inform on challenges.

present themselves as formal 'urban ecosystem accounting' studies but are still relevant to the scope of the targeted review because they address related concepts, methods, or applications. In Connected Papers, once a new graph of documents was generated, prior and derived works included in the graph were screened using the criteria detailed below. Newly identified studies were then used as additional inputs. By iterating this process until no new relevant papers appeared, a comprehensive list of studies was compiled.

In each iteration, the titles, abstracts, and keywords of all the gathered studies were screened first, retaining only: i) urban ecosystem

accounts and related studies; ii) broad ecosystem accounts that included urban ecosystems and related studies; and iii) other thematic ecosystem accounts that discussed challenges potentially relevant for thematic urban ecosystem accounts. The same criteria were then applied to the full-text screening of retained papers. As 'related studies', were considered works not strictly focused on developing ecosystem accounts or testing pilot applications, but in which it is explicitly indicated that their methods or findings are valuable for informing or discussing conceptual aspects, methods, or operational procedures in ecosystem accounting.

When studies focused strictly on ecosystem accounting, only those

applying the SEEA-EA framework, or its previous experimental version, were retained in the review. Studies focused on the development of SEEA-Central Framework (CF) accounts or SEEA Applications and Extensions works, aimed at illustrating the potential uses of SEEA-CF accounts to compilers and users, were discarded. Similarly, studies focused on other environmental accounting frameworks, such as the Natural Capital Protocol or the Natural Capital Accounting for Organisations (ISO 14054), were excluded because they serve different purposes, have completely different systems of accounting tables, and have varying levels of standardisation, groups of interest, and institutional contexts of relevance. As an exception, studies not related to the SEEA-EA framework or its antecedents were retained if: i) they discussed general shortcomings that were also applicable to or relevant for SEEA-EA; ii) they compared advantages and disadvantages of SEEA-EA with other frameworks, provided that the challenges discussed were relevant for thematic urban ecosystem accounts. Studies that introduce concepts or methodologies related to SEEA-EA without specifically addressing conceptual or operational challenges relevant to urban ecosystems or presenting lessons were discarded.

After the iterative review, the traditional systematic review was applied to ensure completeness helping to identify additional literature. It followed a traditional systematic review approach, similar to previous studies (Babí Almenar et al., 2021; Luederitz et al., 2015) and consistent with PRISMA guidelines (Page et al., 2021a, 2021b). The literature was gathered from Web of Science, Scopus, Google Scholar, and Google. In all cases, the broad search string ‘ecosystem account*’ was used, and the studies were limited to those written in English and published from 2012. The former is the year in which the SEEA experimental ecosystem accounting framework, which led to the SEEA-EA, was developed (United Nations et al., 2014). The search string was intentionally broad to avoid missing documents of potential relevance. The keyword ‘urban’ was intentionally excluded since there might be studies that integrate accounts for more than one ecosystem type, without explicitly referring to ‘urban’ (or use a related word) in the title, abstract or keywords. There were also cases focused on other ecosystems or types of thematic ecosystem accounts, such as ocean thematic accounts, which included challenges of relevance for thematic urban ecosystem accounts. The traditional approach helped to make the systematic review more exhaustive, ensuring that relevant references were not missed. Moreover, the inclusion of Google Scholar and Google search engines was useful to identify technical grey literature of potential interest, which was not captured in Web of Science or Scopus. The same screening procedure and criteria used for the iterative approach were also used in this traditional systematic review.

The traditional systematic review and iterative literature review helped to identify challenges missed in key SEEA-EA documents as well as to further inform and better organise challenges already included in the initial draft list. After analysing all the studies, the challenges were consolidated into a final list, with each item representing an aggregation of specific problems around a common theme. Challenges were classified as conceptual or operational, following the definitions previously outlined at the end of the Introduction, and according to: i) the type of ecosystem accounting table to which they refer; and ii) their urban specificity. Based on the type of accounting table to which they referred, challenges were classified as: i) ecosystem extent, ii) ecosystem condition, iii) ecosystem services (biophysical and monetary), or iv) monetary ecosystem assets. Challenges relevant to more than one type of accounting table were classified as cross-cutting. Based on the urban specificity, challenges were classified as: i) specific to urban ecosystem accounts; ii) shared among accounts for anthropogenic ecosystems; or iii) relevant to accounts of most or all types of ecosystems, including urban ecosystems. In addition to identifying challenges, the review process also helped to identify lessons and approaches, as defined at the end of the Introduction. The aggregation and organisation of these lessons and approaches considered the specific challenge(s) to which they were related.

Besides challenges and lessons, the following data were recorded for each selected document: i) the type of document (scientific or grey literature); ii) the presence of a case study and its country; iii) the ecosystem types covered by the accounting (urban, multiple ecosystems including urban, other); iv) the focus of the ecosystem account (specific components or the entire ecosystem); and v) the type of ecosystem accounts (extent, condition, services in biophysical units [potential, actual flow – supply, actual flow – use], services in monetary units [potential, actual flow – supply, actual flow – use], and monetary ecosystem assets). These data provided contextual information about the retained ecosystem accounting studies.

2.3. Step 3: Thematic review of non-accounting literature

A thematic review of additional literature (non-accounting related) was conducted to complement the collection of lessons and approaches for certain urban-specific challenges that are relevant beyond accounting. Specifically, the thematic review focused on challenges related to: i) characterisation of urban ecosystems (i.e., conceptual definition, delineation, and classification); ii) definition of reference urban ecosystem condition or status, in terms of conceptualisation and approaches; and iii) appropriate evaluation of ecological degradation in urban ecosystems, considering relevant factors, temporal and spatial scales of interest, and both direct and indirect degradation.

These challenges, and the associated lessons and approaches, are considered “hot topics” in urban sciences, particularly in ecosystem services, land systems science, and urban ecology. For these topics, it was considered that scientific studies outside ecosystem accounting may have already advanced further, or even addressed issues still under discussion in accounting literature. The integration into this review of valuable non-urban ecosystem accounting literature was therefore deemed relevant.

This thematic review replicated the procedure of the iterative systematic literature review explained in Section 2.2. In particular, the documents used as initial inputs in Connected Papers consisted of two groups:

- i. Seed documents from the systematic review. During the systematic review screening, we retained a set of potentially relevant “seed documents” for the thematic review. This group included papers and reports that did not meet the urban ecosystem accounting criteria, as well as a few that did. The latter group included some papers that were later discarded after the full-text appraisal. Ultimately, six seed documents were confirmed as valuable (Dijkstra and Poelman, 2014; Roche and Campagne, 2017; La Notte and Marques, 2019; Keith et al., 2020; Cordella et al., 2022; Kervinio et al., 2023). Although not strictly focused on urban ecosystem accounting, they were selected as inputs because they discussed the thematic review’s focal challenges. All of the documents, including those with accounting relevance, drew extensively upon the broader literature in urban ecology, land systems science, ecosystem services, and environmental economics.
- ii. Seed documents from key urban and sustainability science literature. In addition to the seeds from the systematic review, ten seminal references from the urban ecosystem services, urban ecology, and sustainability science literature were selected based on the authors’ prior knowledge. These papers were chosen because they discuss the thematic review’s focal challenges from perspectives outside accounting literature (Schwarz, 2010; Alberti, 2010; Su et al., 2010; Su et al., 2013; Larondelle et al., 2014; Qureshi et al., 2014; Zhou et al., 2014; Zhou et al., 2017; Vallecillo et al., 2022; Rugani et al., 2023). Few of them (e.g., Qureshi et al., 2014) also draw heavily on references from land systems science, a literature considered also relevant to inform on challenges related to the characterization of urban ecosystems.

These input documents were used to generate a graph of related literature in Connected Papers. The new references are not influenced by the specific search string or the field of study, but by their similarity in shared references and co-citations with the input documents. The titles and abstracts of the prior and derived works in the graph were screened for relevance to the focal challenges of this thematic review. As in the iterative approach within the systematic review, the procedure was repeated until no new relevant papers appeared (Fig. 1, Step 3).

As a result, the thematic review helped to delve into valuable non-accounting literature in urban ecosystem service and urban ecology. However, it should not be interpreted as an exhaustive review of non-accounting literature. Connected Papers relies on co-citation networks, being effective for deep exploration within a defined conceptual domain but cannot ensure capturing entire adjacent bodies of literature, such as

green infrastructure or nature-based solutions literature. In addition, the selection of seed papers relied on the authors' perception about their relevance. Thus, our thematic review contributed to refining urban-specific challenges that are relevant beyond accounting and to enriching the set of lessons and approaches to address them, but it is not an exhaustive census.

3. Results

The review encompassed 130 documents, including 87 from the systematic review on ecosystem accounting, of which 50 were theoretical or practical case studies of ecosystem accounting. These case studies were conducted within 19 countries at local, regional, or national levels, with some in Europe developed at a transnational level. Only studies

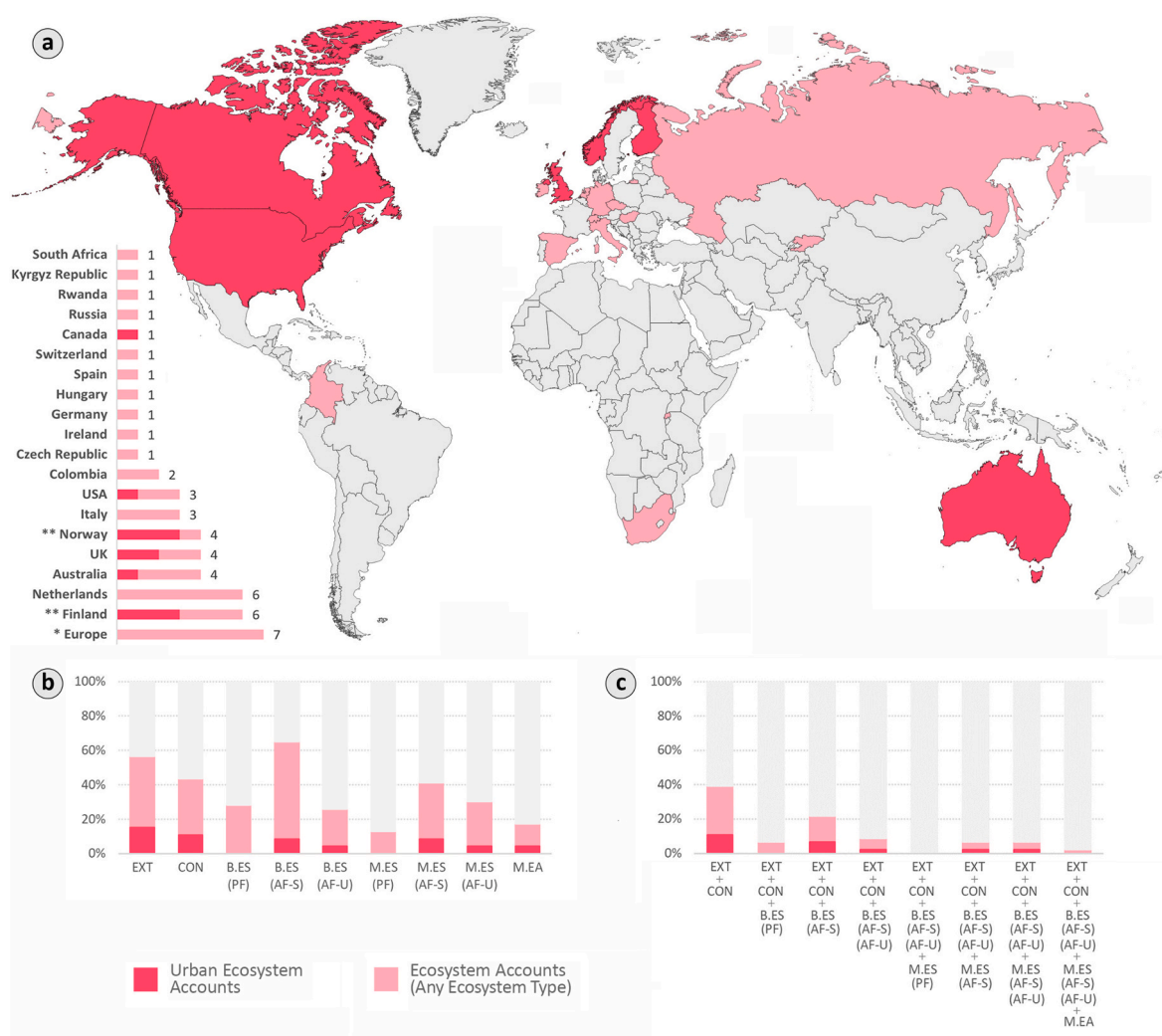


Fig. 2. Case studies of ecosystem accounts (light red), differentiating those focused exclusively on urban ecosystem accounts (red). The case studies applied SEEA-EA, its previous experimental version, or, in a few cases, very similar ad-hoc frameworks that referred to SEEA-EA. a) World map showing countries where ecosystem accounts were tested in the literature reviewed. The bar chart displays the number of case studies per country. *Refer to case studies of ecosystem accounting developed at European level, including 25 or more countries. **Indicates that one document included three case studies from Finland and one from Norway, which are reported as individual case studies. b) Share of documents, within ecosystem accounting exercises, that included specific types of accounts. List of acronyms: EXT = Ecosystem Extent Account; CON = Ecosystem Condition Account; B.ES (PF) = Biophysical Ecosystem Services Account (Potential Flow); B.ES (AF-S) = Biophysical Ecosystem Services Account (Actual Flow – Supply); B.ES (AF-U) = Biophysical Ecosystem Services Account (Actual Flow – Use); M.ES (PF) = Monetary Ecosystem Services Account (Potential Flow); M.ES (AF-S) = Monetary Ecosystem Services Account (Actual Flow – Supply); M.ES (AF-U) = Monetary Ecosystem Services Account (Actual Flow – Use); M.EA = Monetary Ecosystem Assets Account. **Note:** Both *Actual Flow – Supply* and *Actual Flow – Use* tables refer to actual flows. However, the first table presents the amount of an ecosystem service provided by different ecosystem types, while the second table shows which economic unit(s) use the service and how much they use. This information can be presented in both biophysical and monetary terms for each service. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

from six countries focused exclusively on some kind of thematic urban ecosystem accounts (Fig. 2a). The rest of the exercises included built areas, settlements, or similar categories among several ecosystem types for which accounts were developed. Within the case studies, there was at least one example of each type of accounting table (e.g., extent, condition). However, exercises focused exclusively on urban ecosystem accounts collectively cover seven out of the nine accounting tables (Fig. 2b) and there was no single case study that included all types of accounting tables (Fig. 2c). In terms of specific accounting tables, ecosystem services potential flow accounts (biophysical and monetary) and monetary ecosystem asset accounts were among the least common within the exercises, urban-specific or not.

3.1. Overview of challenges, lessons, and approaches for urban thematic ecosystem accounting

Across the documents reviewed, 24 challenges were identified (Table 1), 13 of which are conceptual. Lessons and approaches were identified for 18 challenges (Table 2). As indicated in Table 1, challenges specific to urban and anthropogenic ecosystems were identified only for ecosystem extent accounts, ecosystem condition accounts, and cross-

cutting categories. Notably, in the case of ecosystem extent, all the challenges are conceptual and specific to urban ecosystems. In contrast, all the operational challenges, except for one cross-cutting challenge, are shared among most or all ecosystem types. Further details on the data gathered, as well as descriptions of all identified challenges, approaches, and lessons, are provided in SI2–4.

The following sections focus greatly on urban-specific challenges as well as challenges shared with other anthropogenic ecosystems. They present challenges, along with related lessons and approaches, clustered into three main topics that broadly correspond to different accounting tables. Section 3.2 addresses challenges related to the characterisation and classification of urban ecosystems and their fine-scale patches, all linked to the accounting of ecosystem extent. Section 3.3 examines challenges associated with the tracking of socio-ecological degradation, impacts, and dependencies, linked to the accounting of ecosystem condition, ecosystem services, and monetary ecosystem assets. Finally, Section 3.4 outlines the cross-cutting challenge of defining policy uses as a prerequisite for the development of a coherent ecosystem accounting framework.

Table 1

Challenges of thematic urban ecosystem accounting, grouped by SEEA-EA accounting table, relevant ecosystem types (classified as U: urban; AE: anthropogenic ecosystems, including urban ecosystems; MAE: Most or All Ecosystems), and challenge types (C: Conceptual; O: Operational). Supplementary Information (SI3) provides a detailed description of each challenge and includes an extended version of this table with the sources that informed on each challenge.

Accounting Table	Ecosystem Types	Challenge Type	Id	Short description
Extent	U	C	1	A univocal distinction between urban ecosystem assets and artificial surfaces is still missing.
	U	C	2	A univocal procedure for the spatial delineation of urban ecosystems and their accounting areas is still missing.
	U	C	3	At the global level, urban ecosystems still lack an ecologically sound, agreed-upon classification of homogeneous ecosystem areas, along with guiding principles to develop it.
	U	C	4	Urban ecosystems still lack a shared, ecologically sound classification of the fine-scale patches (assets) that compose them.
Condition	AE	C	5	Ecosystem condition variables only partially represent the socio-ecological-technological characteristics that drive urban ecosystems' functioning and quality.
	AE	C	6	A clear conceptualization of reference conditions in anthropogenic ecosystems is still missing, since 'ecological integrity' is inadequate as a default concept in these ecosystems.
	AE	C	7	Ecosystem condition accounts cannot fully capture socio-ecological degradation or indirect degradation in urban ecosystems.
	MAE	O	8	Boundaries between ecosystem condition and ecosystem extent accounts may be difficult to establish, particularly at fine levels of ecosystem classification.
	MAE	O	9	No consensus exists yet on a common minimum set of ecosystem condition variables and on their reference levels.
	MAE	O	10	Insufficient evidence and consensus on the appropriate procedure(s) to aggregate ecosystem condition indicators into indices.
Services	MAE	C	11	No consensus about the concept of ecosystem capacity, and its connection to extent and condition and to other related concepts (e.g., degradation, sustainability, and resilience).
	MAE	C	12	Ecosystem service accounts fall short in informing whether there are mismatches in service flows that represent sustainability issues (e.g., degradation), unmet societal needs, and/or missed flows.
	MAE	C	13	A complementary pluralistic valuation of ecosystem services (and assets) that represents multiple systems of values is still missing.
	MAE	O	14	Intermediate ecosystem services require explicit consideration, along with clear rules for allocating inter- and intra-ecosystem service flows and avoiding double counting.
Monetary Assets	MAE	C	15	Modelling future ecosystem service flows involves complex, interrelated difficult-to-make assumptions and inherits uncertainties from other accounting tables, which are not yet reflected in monetary ecosystem asset accounts or their methodological framework.
	MAE	C	16	Robust agreed-upon principles for estimating and allocating value loss due to ecosystem degradation are still lacking in monetary ecosystem asset accounts and their methodological framework.
	MAE	O	17	Insufficient evidence and consensus on the appropriate 'asset life' value(s) to use in monetary ecosystem asset accounts.
	MAE	O	18	Insufficient evidence and consensus on the most appropriate discount rate(s) to apply to future ES flows.
Cross-cutting	U	C	19	Varied and unclear policy uses of urban ecosystem accounts across multiple spatial levels (national, regional, local) create diverse requirements that risk undermining coherent framing.
	MAE	O	20	Complete and consistent examples of ecosystem accounts that can serve as practical guidance are still missing.
	MAE	O	21	Ecosystem accounts still lack explicit assessment and reporting of uncertainties, along with agreed-upon procedures.
	MAE	O	22	The implementation of ecosystem accounts faces practical barriers due to demands of expertise, time and resources.
	MAE	O	23	Gaps and lack of consensus persist regarding suitable input data, data quality frameworks, and generalizable models for use in ecosystem accounting.
	MAE	O	24	Need to establish shared principles and practices for developing data infrastructures for ecosystem accounting, ensuring interoperability and data sharing among stakeholders.

3.2. Characterisation and classification of urban ecosystems and their fine-scale patches

The literature reviewed highlights a lack of consensus on the definition and characterisation of urban ecosystems (Bruzón et al., 2022; De Fioravante et al., 2023; EFTEC-DEFRA, 2017; Gomez Cardona et al., 2023; Grenier et al., 2020; Petersen et al., 2022). Specifically, the distinction between artificial surfaces and urban ecosystem assets remains ambiguous (Table 1 – Challenge [Ch.1]), with accounting exercises not always classifying the same set of features as urban ecosystem assets (Grenier et al., 2020; Petersen et al., 2022). This variability partly arises from how the boundaries of urban ecosystem accounts are defined (Ch.2). While several approaches have been proposed to determine which artificial surfaces qualify as urban ecosystem assets, no consensus has been reached (de Jong et al., 2016; La Notte and Zulian, 2021; Vallecillo et al., 2022). A key suggested criterion is that, to qualify as an urban ecosystem asset, artificial surfaces must be related to built-up areas where humans reside (de Jong et al., 2016; Vallecillo et al., 2022). This criterion seeks to exclude isolated infrastructures (e.g., mining sites, energy-related facilities) that are not physically or functionally tied to specific human settlements.

There is also no agreed-upon ecologically sound classification system to divide urban ecosystems into groups of homogeneous ecosystem areas (Ch.3) (Lemoine-Rodríguez et al., 2020; Mahtta et al., 2019; Taubenböck et al., 2020; Vallecillo et al., 2022). Globally, urban ecosystems are often treated as a single homogeneous group (Keith et al., 2020). However, they span multiple regions, biomes, and climates, exhibiting different urban forms shaped by surrounding environments, historical legacies, and variations in socio-demographic, ecological, and technological characteristics (Fig. 3). Scholars are exploring potential classification approaches, such as those based on urban ecoregions, growth patterns, and morphology, that can be adopted to categorise urban ecosystems into multiple coherent groups of homogeneous ecosystem areas (Demuzere et al., 2022; Dong et al., 2019; Esch et al., 2014; Heris et al., 2021; Huang et al., 2007; Lemoine-Rodríguez et al., 2020; Mahtta et al., 2019; Reis et al., 2016; Stathakis and Tsilimigkas, 2015; Taubenböck et al., 2020, 2019; Vallecillo et al., 2022).

Similarly, there is no consensus on an ecologically sound classification for the fine-scale patches (assets) that compose urban ecosystems (Ch.4) (Grenier et al., 2020; Grunewald et al., 2020; Kremer et al., 2018; Larondelle and Haase, 2013; Zhao and Sander, 2018; Zhou et al., 2014). Traditionally, these assets are classified based on integrated land cover and land use classes (Cadenasso et al., 2007; Vallecillo et al., 2022; Zhou et al., 2017), but alternatives, such as local climate zones (Grenier et al., 2020), have been applied in a few urban ecosystem accounting studies. Additionally, several scholars advocate for the use of asset classifications, such as HERCULES (Cadenasso et al., 2007) or STURLA (Hamstead et al., 2016), that (i) avoid mixing land cover and land use, (ii) incorporate the third dimension (height), and (iii) treat interconnected artificial, natural, and semi-natural features as unified patches, preventing classification artefacts (Cadenasso et al., 2007; Hamstead et al., 2016; Larondelle et al., 2014; Zhou et al., 2017). STURLA, in particular, has already been applied in an ES study in Oslo related to urban ecosystem accounting (Venter et al., 2020). Cadenasso et al. (2007) argue that traditional classifications hinder a robust ecological understanding of how the composition and configuration of urban ecosystem assets influence ecological functions, and therefore, also condition, service supply and demand, and asset values.

Both classification issues (Ch.3–4), stem from a lack of scientific consensus, as evidenced by ongoing debates within urban ecology and related fields (Cadenasso et al., 2007; McDonnell and Hahs, 2008; Zhou et al., 2017). This partly explains why only approaches and lessons highlighting key considerations were identified for these challenges. A similar absence of scientific consensus also affects challenges that are not urban-specific, such as estimating and allocating value loss due to ecosystem degradation (Ch.16), where fundamental issues remain

debated within environmental and ecological economics (Hein et al., 2020; La Notte et al., 2019; Ogilvy et al., 2018).

3.3. Tracking socio-ecological degradation, impacts and dependencies

Several limitations in condition accounts, and shortcomings in services and monetary ecosystem asset accounts, hinder the comprehensive tracking of urban socio-ecological degradation, impacts, and dependencies.

For condition accounts, scholars point out that there are limitations in capturing: i) local degradation that is not strictly ecological, but which also refers to the human component (Larson et al., 2023; Wang et al., 2019); and ii) how urban ecosystems influence the degradation of nearby and far-away assets on which they depend (Wang et al., 2019), which may indirectly lead to urban degradation (Ch.7).

Regarding local degradation, limitations partly arise from excluding social and technological characteristics, leading to a partial representation of urban ecosystems (Ch.5). For example, Cimburova and Berghauser Pont (2021) point out that mediating mechanisms such as human management, mobilisation, and allocation-appropriation influence the potential of urban ecosystems to provide services, the actual flow of those services, and their perceived value. Then, by disregarding social and technological characteristics, the role of human management in urban ecosystem condition, services, and value might not be captured. Additionally, Alberti (2010) highlights that continuous interactions between humans and ecological processes influence urban ecosystem conditions and result in emergent phenomena that cannot be understood by studying social, economic, or ecological factors in isolation. This latter statement is also stressed by other urban science scholars (McPhearson et al., 2022). Thus, leaving out social and technological factors may overlook certain types of socio-ecological degradation, such as a decline in public health due to environmental factors or inequalities in the distribution of ecosystem assets and services. Shortcomings in capturing local degradation may partly stem from relying on the concept of ecological integrity to define reference conditions in urban ecosystems (Ch.6). Karr, a proponent of the concept of ecological integrity referenced in the SEEA-EA, and colleagues (Karr et al., 2022) note that ecological integrity – which excludes humans by definition – may not provide appropriate reference conditions (called ‘endpoints’) for ecosystems under intensive human use, such as agroecosystems or urban ecosystems. Instead, they advocate for using ecological health as a more suitable concept (Karr et al., 2022). Similar alternatives, such as urban ecosystem health, have been proposed by other authors (Lu et al., 2015; Su et al., 2013, 2010). All these alternatives acknowledge humans as intrinsic components of the system, allowing characteristics of human populations and built infrastructure to be considered as condition variables (Karr et al., 2022; Su et al., 2013, 2010).

A few documents also indicate that defining reference condition in urban ecosystems may be as much a policy issue as a scientific one. In practice, urban condition variables can be used to track whether conditions are improving or deteriorating in relation to a policy target, without necessarily requiring the definition of an objective reference level based on a purely ecological rationale (United Nations, 2020). For instance, variables applied in performance-based planning approaches (Cortinovis and Geneletti, 2020; Stange et al., 2022) could be adapted to fit within condition accounts. Nevertheless, even when reference levels are not strictly ecological, as a good practice the establishment of policy targets should remain informed by current scientific and ecological knowledge. In this regard, scholars such as Keith et al. (2019) suggest that assessing conditions in anthropogenic ecosystems may be better achieved through the use of target levels, grounded in ecological and scientific rationale, with quality inferred from the distance between condition indicators and those targets. Such an approach could benefit policy applications, but it also requires careful consideration regarding its scientific objectivity (Keith et al., 2019).

In addition, some approaches indicate that assessments against a

Table 2

Lessons (L) and approaches (A) for thematic urban ecosystem accounting organised by accounting table and challenge type (challenge Ids as in Table 1). Additional details for each L and A included in [Supplementary Information \(S14\)](#).

Accounting Table	Id	L/A	Short Description
Extent	1	A	A dominant approach in Europe defines urban ecosystem assets as built-up land where people live and its surrounding areas, which may include semi-natural and natural patches.
	2	A	Several alternatives already exist for delineating urban ecosystems (e.g., administrative boundaries, degree of urbanization, urban gradient).
		L	The delineation of urban ecosystems influences how transboundary effects, both impact and dependencies, are considered in ecosystem accounts.
		L	The factors influencing the delineation of urban ecosystem boundaries may not be entirely objective.
	3	A	There are already several alternatives (e.g., urban ecoregions, growth patterns, morphology) for dividing urban ecosystems into homogeneous groups.
		L	Common metrics are often used when grouping urban ecosystems based on morphology and spatial composition and configuration.
	4	A	There are already several alternatives for classifying the fine-scale assets that compose urban ecosystems.
Condition	5	L	Considering socio-technological variables, and their interactions with ecological processes, can provide a more comprehensive assessment of urban ecosystem condition.
	6	A	There are alternatives to ecological integrity for defining reference conditions in urban ecosystems (e.g., urban ecosystem health, long-term socio-ecological resilience, ecological health).
	7	L	Integrating ecosystem accounting with other natural capital assessment frameworks, such as life cycle assessment, may help to capture degradation more comprehensively.
	8	–	<No lesson or approach was identified>
	9	L	Consensus requires collaborative systematic approaches that involve a broad range of experts and stakeholders.
		L	The set of condition variables and related reference levels should be partially differentiated across regions.
		L	The set of ecosystem condition variables should reflect a diversity of value rationales.
Services	10	–	<No lesson or approach was identified>
	11	L	Key aspects, such as resilience, should be considered when conceptualising ecosystem capacity.
	12	L	Explicitly reporting both ecosystem service potential and ecosystem service demand in accounting tables would help to inform on mismatches in ecosystem services flows.
	13	L	For some purposes, local ecosystem accounts should consider existing alternatives to using exchange values.
	14	–	<No lesson or approach was identified>
Monetary Assets	15	L	Integrating other impact assessment methods, such as scenario modelling, could enhance accounting and reporting in monetary ecosystem asset accounts.
	16	A	In monetary ecosystem asset accounts, a few approaches exist for valuing loss due to ecosystem degradation (e.g., value loss by limited use), but they cannot coexist, and no preferred approach has been agreed upon.
		L	Agreeing on principles for the monetary valuation of ecosystem degradation could help to discern between changes in demand and changes in ecosystem condition.
	17	–	<No lesson or approach was identified>
	18	–	<No lesson or approach was identified>
Cross-cutting	19	L	Urban ecosystem accounts have proved valuable for policy making (including planning) at national, regional, and local level, but they are not suited for all policy purposes.
		L	Key stakeholders should be involved to define clear uses of urban ecosystem accounts in policy making.
	20	–	<No lesson or approach was identified>
	21	L	Different types of ecosystem accounts have different levels of uncertainty, and their acceptability ultimately depends on the policies they aim to inform.
		L	There are multiple types of uncertainty in ecosystem accounts.
		L	It is possible to assess and report uncertainty in ecosystem accounts making use of simple methods.
	22	L	The development of ready-to-use tools and training material can help reduce practical barriers for practitioners.
		L	Broad representation of expertise and improved communication between producers and end users is needed to raise awareness on potentialities and limitations of ecosystem accounts and to reduce practical barriers.
		L	A tiered approach to implementing ecosystem accounts may gradually overcome barriers, demonstrating the added value of these accounts to stakeholders and policy makers.
		L	Regional networks and communities of practice support capacity building for the development of ecosystem accounts.
		L	Institutionalising ecosystem accounts requires allocating additional budget to the producer agencies.
		L	Strengthening governance and coordination mechanisms can support a shared vision and a more efficient development of ecosystem accounting.
	23	A	A few approaches are already available to reduce data gaps in ecosystem accounting by combining multiple types of input data (e.g., earth observation with in-situ observation data or social data with land cover data).
	24	L	Regional networks and communities of practice also contribute to establishing shared principles and practices for ecosystem accounting.

reference urban ecosystem condition should account not only for local socio-ecological degradation but also for how urban characteristics influence service demand both locally and remotely (Su et al., 2013, 2010; Vallecillo et al., 2022). This would inform not only how urban ecosystems drive (impact) the degradation of nearby or far-away ecosystem assets but also about their dependencies. These suggestions extend beyond standard SEEA-EA rules, which typically define ecosystem condition based on the overall ecological quality of a given ecosystem in terms of its local biotic and abiotic characteristics. In effect, these approaches highlight the strong telecoupling relationships between urban ecosystems and other ecosystems (Cordella et al., 2022; VanderWilde and Newell, 2021), driven by social, economic, and technological factors. They emphasize the importance of incorporating these connections when assessing urban ecosystem condition and its changes, particularly

if condition accounts are intended to inform urban sustainability analyses. Some scholars have suggested using complementary natural capital assessment frameworks, such as life cycle assessment, to characterize telecoupling relations by tracking supply-chain connections (Cordella et al., 2022; Oginah et al., 2023; Rugani et al., 2023).

To better track socio-ecological degradation, impacts, and dependencies of urban ecosystems, the literature also stresses the need for agreed-upon principles to estimate and allocate value loss from ecosystem degradation in monetary ecosystem asset accounts (Ch.16). However, estimation of value loss due to degradation is complex since it may involve changes in the net present value or in the sustainable capacity of an ecosystem asset (Obst et al., 2016). Degradation cannot be assumed solely on the basis of a change in the net present value, since its total change results from changes in price variability (revaluation),

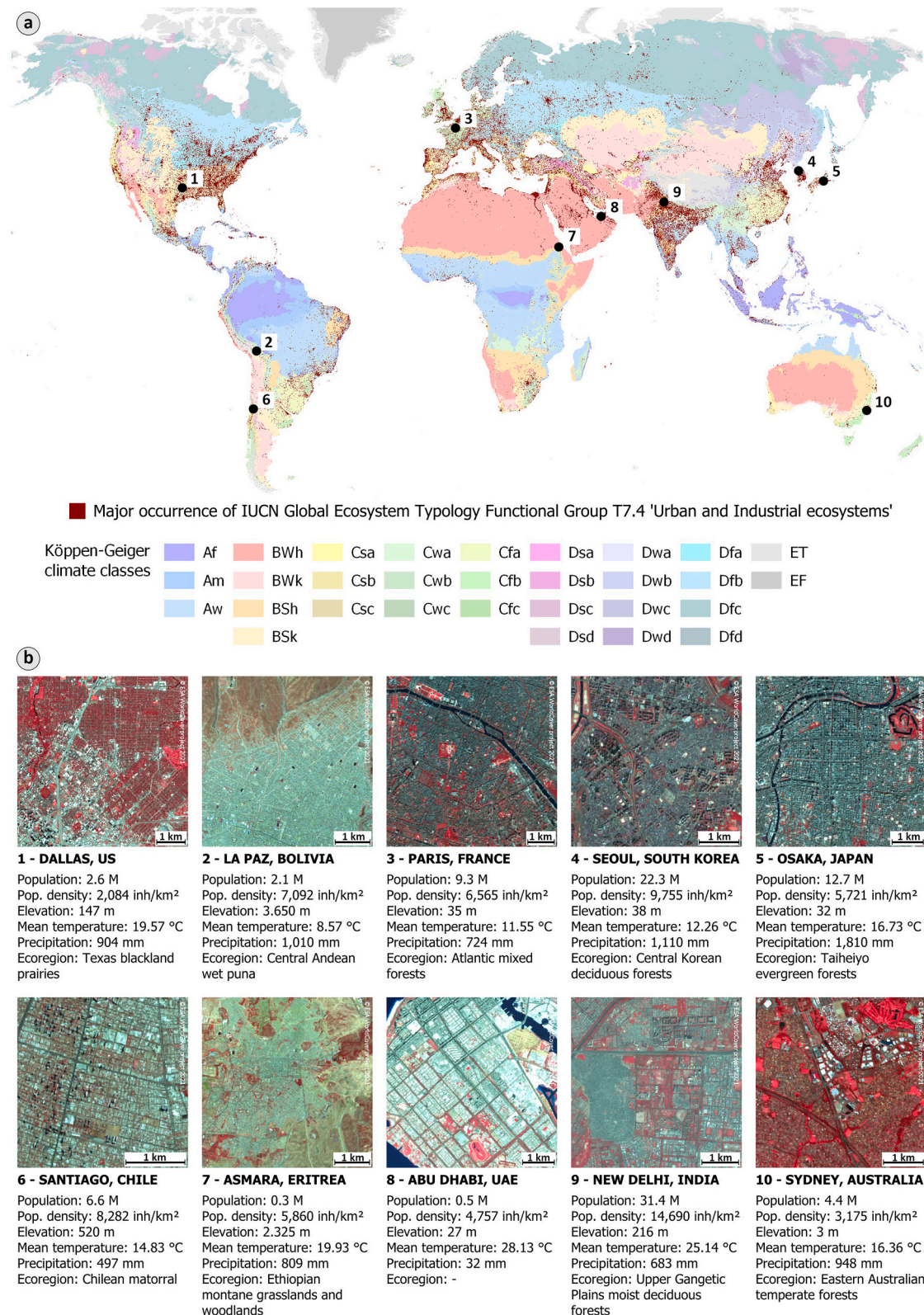


Fig. 3. Visualisation of the diverse climates, (eco)regions, and environmental and socio-demographic characteristics across which urban ecosystems extend worldwide, underscoring the relevance of classifying these systems into multiple groups of homogeneous ecosystem areas. a) Global distribution of urban and industrial ecosystems, as defined in the IUCN Global Ecosystem Typology (Keith et al., 2022, 2020), overlaid on a global map of Köppen-Geiger climate classes (Beck et al., 2018), illustrating the range of climates on which urban ecosystems are present. b) Aerial imagery snapshots (Sentinel-2 False Colour Composite, 2021) of 10 urban ecosystems worldwide. In these illustrative snapshots, vegetation appears in red, while annotations highlight key factors such as population, environmental conditions, and ecoregion—underscoring the global diversity of urban ecosystems. The data for these factors come from the GHS Urban Centre Database R2024 of the Joint Research Centre, which delineates individual urban ecosystems based on the Degree of Urbanisation approach. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

human activity, or natural processes and events; and only the last two include degradation (Hein et al., 2016). From an accounting perspective, the allocation of ecosystem degradation also poses significant challenges, primarily in determining whether to attribute the degradation to the economic and human activities that cause it, i.e., activity-based allocation, or to those incurring the costs of degradation, i.e., receiver-based allocation (La Notte et al., 2019). Partially as a result of this complexity, estimations often assume constant flows, even when there is degradation, overlooking the dynamic nature of ecosystem service supply (Hein et al., 2020). Besides ecosystem degradation, past studies have often overlooked an explicit consideration of the applied assumptions and existing uncertainties when modelling future ecosystem service flows (Ch.15) and quantifying changes in asset values (Barton, 2023; Schenau et al., 2022). To partially minimise this limitation, one paper suggests the use of scenario modelling (Mokany et al., 2019), and thus the consideration of more than one future state when estimating monetary ecosystem asset values.

3.4. The relevance of policy uses for a coherent framework

The ability to track socio-ecological impacts and dependencies through thematic urban ecosystem accounts is also influenced by how urban ecosystems are delineated (Ch.2). Different approaches, such as using municipal boundaries or buffers around built-up areas, affect the inclusion or exclusion of specific ecosystem assets, thereby influencing the consideration of transboundary effects, i.e., impacts and dependencies (Cryle et al., 2021). Some scholars note that delineating these boundaries is not entirely objective (Cryle et al., 2021; Taubenböck et al., 2022), as it partly depends on the policy uses of the accounts.

The lack of clear policy uses is highlighted as a cross-cutting challenge (Ch.19), alongside a weak policy pull, an issue also faced by SEEA-EA general accounts (Bagstad et al., 2021). For thematic urban ecosystem accounts, both policy uses, and spatial levels of interest (e.g., national, regional, local) can vary significantly, potentially leading to misalignments among expected policy uses at different scales. In fact, a challenge for municipalities in adopting SEEA-EA at the local level is that policy priorities, their geographical scale, and the required resolution are different from national accounts (La Notte et al., 2019). In this sense, there is a partial disconnection between the ecosystem accounting needs of local governments and those at the national level as policy issues differ across scales, and even regionally within the local scale (United Nations, 2020). This disconnection simply reflects the differing priorities that exist across scales and geographical contexts, which in turn shape ecosystem accounting implementations and their specific framing. Indeed, pioneer practitioners in Australia (Cryle et al., 2021) highlight that the framing of urban ecosystem accounts is heavily influenced by the initial local policy purposes, and the spatial level at which they are developed, both of which vary between implementations. As a result, the initial purpose and scales of interest strongly influence how an accounting implementation is designed, potentially affecting its future development, alignment with evolving needs, and interoperability with other accounting systems. Consequently, coherence in a global framework for thematic urban ecosystem accounting may partly depend on reaching an early agreement on common rules or policy uses across regions and scales of interest. This does not mean that the policy priorities of specific scales or contexts should be ignored or prioritised over others, but rather that they should be carefully considered when developing common rules and identifying the overall set of policy uses that urban ecosystem accounts are best suited to inform.

4. Discussion

Our work highlights a global shortage of consistent pilots on urban ecosystem accounting, which partly explains the lack of lessons and approaches (Table 2) for several of the challenges identified (Table 1).

As illustrated in Fig. 2, large regions, including most of Latin America, Asia, and Africa, appear to have neither tested SEEA-EA general accounts nor developed specific urban ecosystem accounts. This finding aligns with the gaps in SEEA-EA implementation identified in the UN's 2023 Global Benchmark (United Nations, 2024) and more recently by Inácio et al (2025). In Europe, Lange et al. (2022) observed that only a few countries have tested all five SEEA-EA general accounting tables, and thematic urban ecosystem accounts remain rarely explored. Furthermore, as shown by Fig. 2, case studies do not include the full set of accounting tables, with some, such as monetary ecosystem asset accounts, being particularly underrepresented. This scarcity of pilots, incomplete in terms of the set of ecosystem accounting tables, partially explains the absence of complete, consistent examples that could provide practical guidance for ecosystem accounting implementations (Ch.20).

Developing such examples for thematic urban ecosystem accounts, or creating concrete guidelines for them, first requires defining and implementing solutions to the identified challenges in a logically prioritised way. Yet it is unrealistic to expect that guidelines can only emerge once all challenges are fully resolved. A pragmatic alternative may be to design pilot studies aimed at advancing the development of a global standard for thematic urban ecosystem accounts. These pilots would provide valuable opportunities to test different methodological approaches to specific challenges and to compare their practical implications. To ensure that the resulting guidelines capture the full range of lessons learned, pilot outcomes should be carefully documented and made openly accessible. This includes explicitly reporting the solutions adopted for critical issues, so that ad-hoc decisions are transparent, comparable, and open to corroboration, or rejection, in other pilots. It is also essential that pilots consider the relative priority of challenges and their logical interconnections, as outlined below in Section 4.2. While pilots cannot replace expert studies on specific challenges or broader discussions among ecosystem accounting specialists and stakeholders, they can meaningfully inform such debates with evidence from real-world applications.

4.1. From approaches and lessons learned towards specific solutions

For the challenges related to the characterisation and classification of urban ecosystems, we identified approaches or lessons focused on specific aspects rather than comprehensive solutions.

Despite the lack of scientific consensus on which assets belong to urban ecosystems (Ch.1), it is increasingly clear to scholars that not all artificial surfaces should be considered urban. This perspective is also gaining recognition among policymakers, as illustrated by a recent amendment to the regulation on environmental accounts in the European Union (European Parliament and Council of the European Union, 2024a). As required by SEEA-EA general accounts, the amendment differentiates a broad set of mutually exclusive ecosystem types, including 'Settlements and Other Artificial Areas', which represent artificial surfaces. The amendment also refers to urban ecosystems, named 'cities and their adjacent towns and suburbs', explicitly recognising that urban ecosystems comprise multiple types of ecosystem assets, not just artificial surfaces. This growing differentiation between urban ecosystems and artificial surfaces, reinforced by the EU policy-making example, points to two partial solutions (as illustrated at the top of Fig. 4 – Solution [Sol.] 1): i) using a term other than 'urban ecosystems' when referring solely to artificial surfaces, as not all of them belong to urban ecosystems; and ii) compiling urban ecosystem accounts exclusively through SEEA-EA thematic accounts to avoid creating confusion, breaking mutual exclusivity, and reporting incomplete representations of urban ecosystems.

Unlike the previous challenge, the delineation of urban ecosystems (Ch.2) lacks an established clear approach from both scholarly and policymaking perspectives. This is illustrated in the EU Nature Restoration Regulation (European Parliament and Council of the European

Union, 2024b), where three interrelated approaches for delineating urban ecosystem areas are proposed: i) selecting entire (urban) municipalities based on the degree of urbanization; ii) restricting the boundaries only to highly populated zones within urban municipalities; and iii) expanding the restricted boundaries to also include a *peri*-urban buffer around the highly populated zones. While delineating ecosystem accounting areas is difficult also in other mosaic-like ecosystems, such as wetlands, and in ecosystems with highly variable ecotones, like coastal ecosystems, this challenge partly differs for urban ecosystems. In other ecosystems, asset characterisation and boundary delineation are typically conducted by experts and generally accepted by other stakeholders. In contrast, characterizing (Ch.1) and delineating (Ch.2) urban ecosystems must be perceived as credible and legitimate not only by scientists but also by other stakeholders, including policymakers, which adds constraints to the development of a coherent framework for

thematic urban ecosystem accounts (Fig. 4 – Sol. 2). Local authorities, regions, or even countries, can certainly come up with individual ways of delineating urban ecosystems in their urban ecosystem accounting pilots. However, in the absence of standardisation, individual approaches risk defining the boundaries of urban ecosystems and what is represented as an urban ecosystem in different ways. Thus, this variability may hinder information exchange and comparability, which are particularly important when accounts should respond to binding obligations, as is currently the case in EU and EEA countries.

While our review identified several approaches for classifying fine-scale urban assets (Ch.4), as outlined in Section 3.2, these were partly drawn from literature gathered in the thematic review rooted mostly in land systems science and urban ecology, notably, from the 'ecology in cities' and 'ecology of cities' paradigms. However, a large and parallel body of literature exists on 'green infrastructure' and 'nature-based

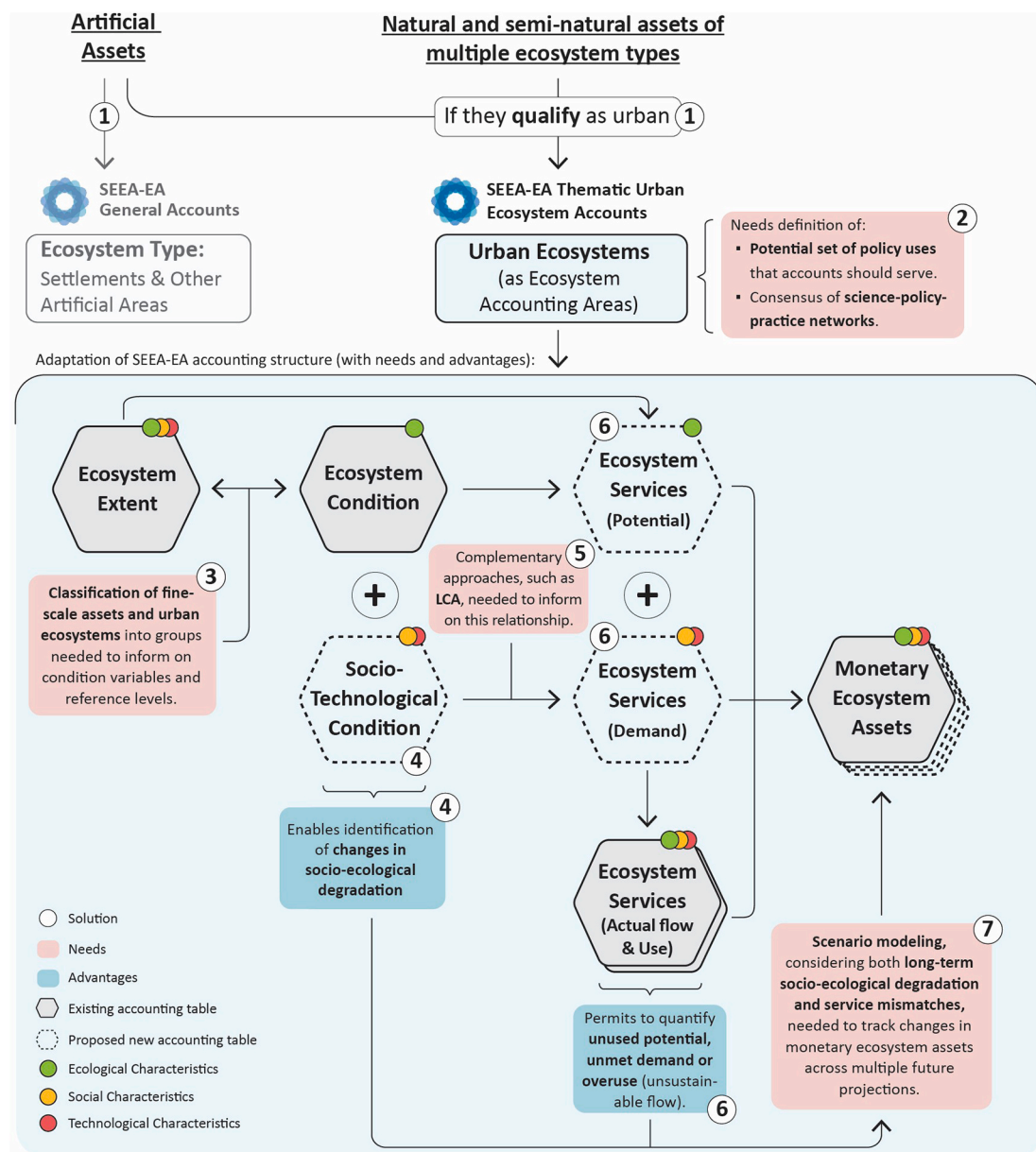


Fig. 4. Visual summary of key solutions based on existing lessons and approaches. The figure presents solutions in the form of: decisions, actions to be implemented at specific steps (needs), and new accounting tables to be integrated into the SEEA-EA structure for thematic urban ecosystem accounting. For each proposed accounting table, the visual summary highlights its advantages, as challenges it may help to address, arising from the combined use of existing and newly proposed accounting tables. Additionally, the figure indicates whether ecological, social, and technological characteristics are relevant for defining each accounting table or estimating their values.

solutions' that goes beyond urban ecology and extends into spatial planning literature, which offers alternative classifications for natural and semi-natural elements in cities (e.g., [Morpurgo et al., 2023](#)). Integrating the ecologically grounded classifications from our review with the planning- and urban function-oriented typologies from the green infrastructure and nature-based solutions literature could provide a larger, more diverse pool of classifications from which to build a comprehensive and unified system for fine-scale urban assets. Although complex, such a synthesis would make urban ecosystem accounts more immediately legible and actionable for practitioners like urban and landscape planners.

For challenges related to tracking socio-ecological degradation, impacts, and dependencies of urban ecosystems, approaches and univocal lessons point towards clear solutions.

Integrating social and technological variables into condition accounts would enable a more comprehensive assessment of urban degradation (Ch.5). However, this may conflict with the rules of SEEA-EA general accounts, where ecosystem condition focuses on abiotic and biotic characteristics, strict ecological degradation, and where there is a widely agreed-upon typology of condition variables. Directly modifying condition accounts in thematic urban ecosystem accounts could impact interoperability with SEEA-EA general accounts. As a potential solution, we propose creating a 'sister' condition table, specific to thematic accounts, in which only socio-technological characteristics are represented (Fig. 4 – Sol.4). This new table, whose structure must be agreed upon, combined with the traditional condition table, could help capture socio-ecological degradation in urban ecosystems more comprehensively. Likewise, adopting ecological health or urban ecosystem health, instead of ecological integrity, as the conceptual basis for defining reference conditions in urban ecosystems (Ch.6) may help better capture changes in socio-ecological-technological conditions, although these concepts still require refinement and testing for use in ecosystem accounting. Implementing this solution would not only inform on changes in the ecological quality of ecosystem assets, but also in their social quality in terms of potential accessibility, equity in the distribution of ecosystem assets across space and social groups, and potential public health impacts. The latter requires a combined consideration of social and ecological factors (e.g., the share of highly allergenic plant species together with the share of population allergic to pollen). It would also help inform reference levels for technology and management factors (technological quality), focusing on tools and management practices that influence resource use and waste generation. Nevertheless, capturing urban degradation more comprehensively requires tailoring condition variables and reference conditions to specific groups of urban ecosystems (Fig. 4 – Sol. 3), which in turn requires classifying urban ecosystems, and their fine-scale assets, into coherent groups.

In addition to the above solutions, integrating complementary natural capital approaches with a strong focus on the technosphere, such as life-cycle assessment, would help capture how social and technological characteristics shape services demand (Fig. 4 – Sol.5), and would also partially aid in informing about indirect degradation. This integration would contribute to identifying mismatches in ecosystem service flows (Ch.12), i.e., unused potential, unmet demand, and overuse (unsustainable service flow), thus capturing the socio-ecological impacts and dependencies of urban ecosystems more accurately. As stressed in the literature ([La Notte et al., 2019](#); [Vallecillo et al., 2019](#)), addressing Ch.12 first requires explicitly reporting ecosystem service potential and ecosystem service demand as individual mandatory accounting tables (Fig. 4 – Sol.6). This is not a current requisite under SEEA-EA general ecosystem accounts, where these accounting tables are auxiliary.

The integration of scenario modelling into monetary ecosystem asset accounts would also enable tracking impacts on assets' value across different future projections while making explicit the assumptions (Ch.15) used in each scenario (Fig. 4 – Sol.7). Ideally, these scenarios should consider the effects of socio-ecological degradation and long-term service mismatches, leveraging the solutions proposed for

condition and service accounts. Additionally, scenarios should integrate social and technological variables alongside climatic and environmental factors to provide more realistic projections. Scenario modelling further underscores the need to explicitly account for uncertainty (Ch.21), including propagated uncertainty. The SEEA-EA does not yet include guidelines or standardisation for auditing uncertainty ([Venter et al., 2024](#)). As suggested in the literature, simple techniques can be applied initially ([Cryle et al., 2021](#)).

While the proposed scheme may help address some of the open issues, solutions for others remain problematic. For certain challenges, such as defining a clear set of policy issues (Ch.19), no single correct solution exists. Their resolution depends not only on scientific consensus but also on broad agreements across science-policy-practice networks. Lessons proposed for Ch.19, 22 and 24 lead to key recommendations for achieving these broad agreements: i) engage key stakeholders early in the process, ensuring representation from both producers and end users with diverse expertise; ii) foster regional networks and communities of practice to help identify policy needs across different spatial levels and regional contexts; iii) focus on a limited set of policy purposes, to avoid positioning ecosystem accounting as a 'one-size-fits-all' tool, which could diminish its effectiveness.

Engaging a broad list of stakeholders and experts with clearly defined roles can increase awareness of the expertise, time, and resource demands required to develop urban ecosystem accounts. It could also enhance inclusivity and legitimacy and foster collaboration between producers and users at an early stage, avoiding future impasses. The range of expertise should go beyond that of traditional statistical offices, including among other professionals, environmental economists, ecologists, and geoinformaticians ([Cryle et al., 2021](#); [United Nations Statistics Division, 2021](#)). Representatives of diverse types of end users such as local governments, environmental agencies, built environment professionals, or citizen groups, should either participate in working groups or be kept informed ([Cryle et al., 2021](#); [Mattsson et al., 2022](#); [United Nations Statistics Division, 2021](#)). Strengthening communication and engagement among diverse stakeholders will help raise public awareness of the value of ecosystems in policy and sustainability reporting ([Mattsson et al., 2022](#)).

Additionally, the establishment of regional or sub-regional networks and communities of practice, supported by international institutions such as regional development banks, can facilitate knowledge exchange, build capacity, and raise awareness about the importance of ecosystem accounting ([Department of Economic and Social Affairs, 2021](#)). Within these communities of practice, the broad ecosystem service community of practitioners and scholars that exists beyond ecosystem accounting could play a key role. As illustrated in this review, some challenges have already been discussed in this community, in the broader urban science community, and in parallel bodies of literature (e.g., nature-based solutions) before they became relevant to urban ecosystem accounting. For example, the need of a pluralistic valuation of services (Ch.13), brought forward in a first instance by IPBES related literature ([Pascual et al., 2017](#)), it is also being discussed within the nature-based solutions literature ([Tallent and Zabala, 2024](#); [Wijsman et al., 2025](#)). Building on the discussions of the broad ecosystem service and urban science communities, and their parallel bodies of literature, could enrich the conversation, by facilitating exchange beyond strict accounting interests, and indirectly benefit progress in thematic urban ecosystem accounts by attracting an even wider range of experts and knowledge. In terms of more concrete actions, organising workshops for communities of practice within thematic urban ecosystem accounting can support capacity building among local and regional public authorities, endorse specific approaches to solving operational issues, and help identify relevant policy questions that thematic urban ecosystem accounts should address ([Cryle et al., 2021](#)).

This last point is particularly important because, before individual urban ecosystem accounting systems are implemented, the main reasons for their development should be defined to ensure that accounts align

with their intended purposes (Cryle et al., 2021). This includes deciding on the policy and planning themes the accounts are meant to inform. Consequently, establishing a global agreement on key common policy questions or themes that urban ecosystem accounts should inform would enhance coherence across outputs, facilitate comparative analysis, and improve the transferability of lessons learned across different urban ecosystem accounting implementations.

4.2. Interrelations of challenges and priorities for actions

As illustrated in previous sections, and explicitly visualised in Fig. 5, the challenges are closely interconnected. These connections can either be bottlenecks, where one challenge hinders the resolution of another, or influences, shaping how issues are addressed or determining the most suitable approaches when no single solution exists. Therefore, it is important not only to derive solutions to individual challenges but also to consider their interconnections to establish a logical prioritisation for resolution.

As indicated in Fig. 5, some challenges depend on resolving multiple

levels of interrelated dependencies. This is particularly true for challenges related to ecosystem service and monetary ecosystem asset accounts. For example, several interconnected challenges must be addressed before resolving shortcomings in ecosystem service accounts for capturing mismatches in service flows (Ch.12). Among other aspects, this requires consensus on what constitutes ecosystem capacity, how it should be assessed (e.g., service-by-service or systemically), and when it is exceeded (Ch.11). Without these steps, it is impossible to capture overuse (unsustainable service flows), as this requires an unequivocal definition of ecosystem capacity. In turn, Ch.11 itself depends on resolving bottlenecks related to ecosystem extent and condition (Fig. 5). Thus, challenges must be tackled with a logical prioritisation, avoiding premature attempts to address those constrained by multiple bottlenecks, which would be counterproductive and may raise the need for repeated revisions.

Instead, certain challenges related to extent (Ch.1–4), cross-cutting (Ch.19,21,23,24), and condition (Ch.5,6) are primary bottlenecks, being minimally or not constrained by other challenges. Prioritising their resolution will unlock progress for other challenges. For instance,

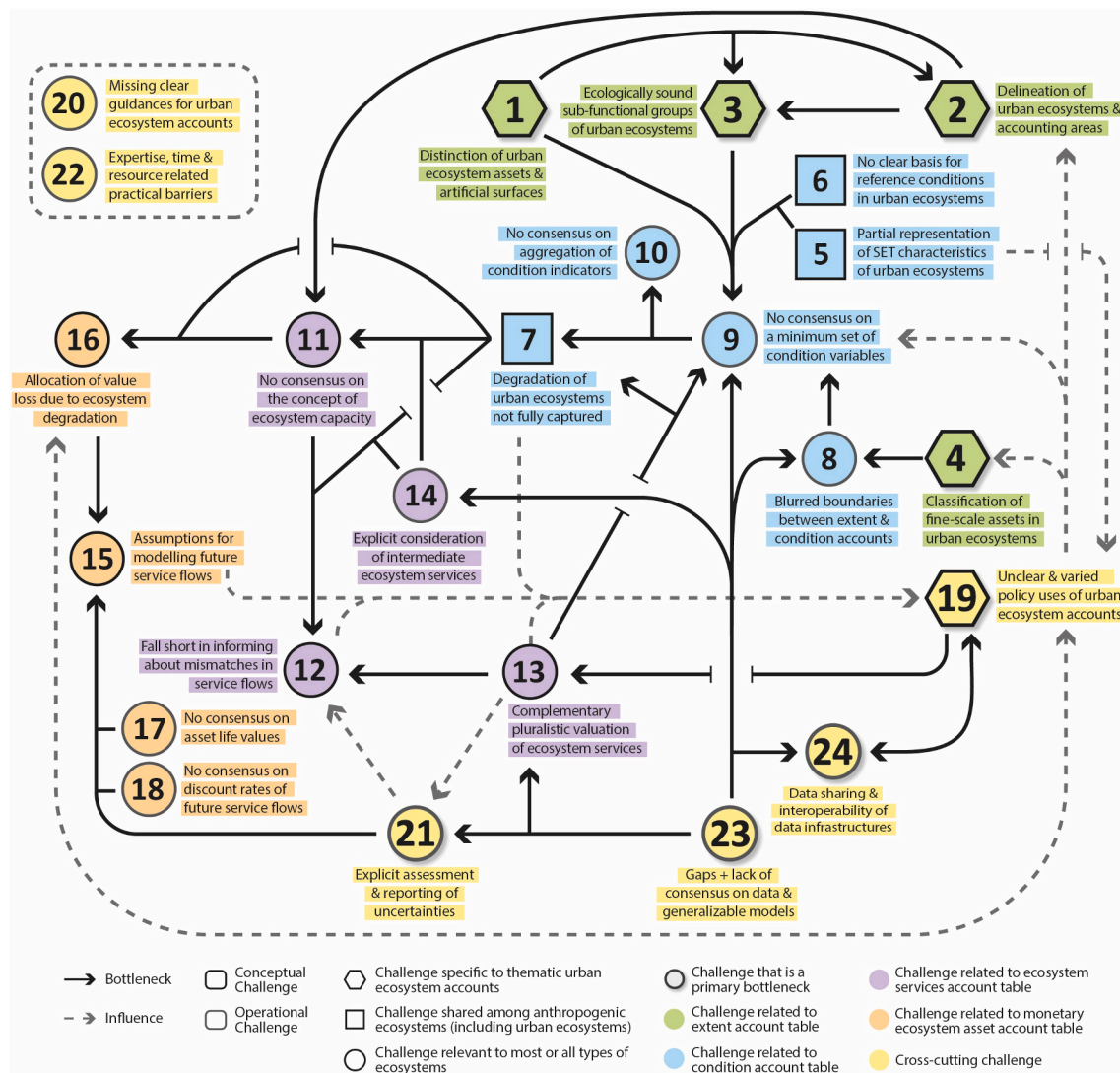


Fig. 5. Interrelations among the identified challenges. Challenges are represented by their IDs (as used in Table 1), along with brief descriptive labels. The colours indicate the type of ecosystem account each challenge pertains to. Black arrows denote challenges (arrowheads) that are constrained by specific bottlenecks (end of arrow), while grey dashed arrows indicate challenges (arrowheads) that are influenced by others (end of arrow) but do not act as strict bottlenecks. The two operational challenges inside the dashed rectangle are indirectly influenced by how the remaining challenges are resolved. This network of interrelations helps determine which challenges need to be addressed first, as well as those that should be tackled simultaneously and in a coordinated manner. Further details on specific interrelations are provided in the [Supplementary Information \(S15\)](#).

defining the policy uses that accounts should serve (Ch.19) strongly influences the development of a consistent framework for thematic urban ecosystem accounts, as policy needs strongly shape implementation (Cryle et al., 2021) and influence how multiple other challenges are addressed. Thus, to achieve a coherent global framework for thematic urban ecosystem accounting, it is a top priority to define early on a clear and consistent set of potential policy uses, agreed at the international level. Similarly, the absence of a robust ecological classification of urban ecosystems and their individual assets may hinder comparability and limit the transferability of lessons across studies. Without such consistency, urban ecosystem accounts may fall short in enhancing our understanding of urban ecosystem structure and function, as well as their influence on condition and the supply and demand of services.

Addressing primary bottlenecks that are not urban-specific will also benefit SEEA-EA general accounts and thematic accounts for other ecosystems. However, resolving these challenges cannot emerge solely from within the urban ecosystem accounting community, requiring broader consensus to ensure interoperability with SEEA-EA general accounts. Consequently, experts in thematic urban ecosystem accounting should first focus on primary bottlenecks specific to urban or anthropogenic ecosystems (Ch.1–6,19), as these require less coordination. Meanwhile, cross-cutting and condition challenges relevant to most ecosystem types and similarly unconstrained (Ch.8,20–24) should be addressed in collaboration with experts in SEEA-EA general accounts and in ecosystems other than urban. Thus, addressing the identified challenges through a stepwise approach, building on existing lessons and approaches, will accelerate the advancement of standardised thematic urban ecosystem accounts. SI-5 offers further details on specific interrelations, including those not discussed here.

5. Conclusions

This study contributes to advancing a globally coherent framework for thematic urban ecosystem accounting by identifying key remaining challenges and proposing solutions building on learned lessons and approaches from existing studies.

Challenges of thematic urban ecosystem accounts span all core SEEA-EA accounting tables, but those specific to urban ecosystems and other anthropogenic ecosystems are concentrated within ecosystem extent, condition, and cross-cutting categories. Among these categories, we identified key bottlenecks such as the lack of a robust classification for urban ecosystems and their assets, the insufficient representation of socio-technological dimensions in condition accounts, and the absence of agreed-upon policy uses across scales. Prioritising the resolution of these issues will be critical to unlocking progress on other interdependent challenges. We suggest concrete solutions, including the establishment of a complementary ‘sister’ condition table to capture social and technological variables, or the early definition of internationally agreed policy uses on which thematic urban ecosystem accounts should inform. This research also underscores the need for broader stakeholder engagement, which will help to legitimise the framework and ensure its practical applicability, and for fostering communities of practices, which can also leverage the ecosystem service community and its multiple bodies of knowledge. These actions will not only enhance inclusivity but also build capacity and improve the transferability and relevance of thematic urban ecosystem accounts globally.

In the long term, thematic urban ecosystem accounts may play a pivotal role in enhancing our understanding of urban ecosystems and supporting their sustainable management in a globally coherent manner, guiding evidence-based urban policy. Future efforts should focus on operationalising the proposed solutions through pilot studies and collaborative international initiatives that bridge the gap between theory and implementation. Nevertheless, beyond the identified challenges, ecosystem accounting, like any framework, still has inherent limitations. While it can serve as a valuable tool for informing policies that promote urban sustainability, it should not be regarded as the sole

tool.

CRediT authorship contribution statement

Javier Babí Almenar: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Chiara Cortinovis:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis. **Sara Vallecillo:** Writing – review & editing, Writing – original draft, Formal analysis. **Davide Geneletti:** Writing – review & editing, Writing – original draft. **Bálint Czúcz:** Writing – review & editing, Writing – original draft. **Federica Marando:** Writing – review & editing, Writing – original draft. **Grazia Zulian:** Writing – review & editing. **Anna M. Addamo:** Writing – review & editing, Writing – original draft. **Alessandra La Notte:** Writing – review & editing, Writing – original draft. **Renato Casagrandi:** Writing – review & editing, Writing – original draft, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

We are thankful to Maria Luisa Paracchini and Davide Stucchi for their input and feedback during the development of this work. We are also grateful to Daniele Cerva for his suggestions, which helped improve the graphical material. Our appreciation extends to the participants of the workshop on ecosystem condition accounting at the European Ecosystem Services Partnership Conference 2022, with whom we discussed our ideas and confirmed the need for this research at its very early inception.

This work was supported by the National Biodiversity Future Centre (NBFC) project, funded by the European Union’s NextGenerationEU, National Recovery and Resilience Plan (NRRP), CN00000033, Concession Decree No. 1034 of 17 June 2022 adopted by the Italian Ministry of University and Research (MIUR), D43C22001250001. It was also supported by the SELINA project funded by the European Union’s Horizon Europe Research and Innovation Programme under grant agreement No 101060415. Views and opinions expressed are those of the authors only and do not necessarily reflect those of the European Union, the European Research Executive Agency or MIUR. Neither the European Union nor the granting authorities can be held responsible for them.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ecoser.2025.101804>.

Data availability

The data is included as part of the [Supplementary Information](#) (e-component)

References

- Alberti, M., 2010. Maintaining ecological integrity and sustaining ecosystem function in urban areas. *Curr. Opin. Environ. Sustain.* <https://doi.org/10.1016/j.cosust.2010.07.002>.
- Andersson, E., Borgström, S., Haase, D., Langemeyer, J., Mascarenhas, A., McPhearson, T., Wolff, M., Łaszkiwicz, E., Kronenberg, J., Barton, D.N., Herreros-Cantis, P., 2021. A context-sensitive systems approach for understanding and enabling ecosystem service realization in cities. *Ecol. Soc.* 26. <https://doi.org/10.5751/ES-12411-260235>.
- Babí Almenar, J., Elliot, T., Rugani, B., Philippe, B., Navarrete Gutierrez, T., Sonnemann, G., Geneletti, D., 2021. Nexus between nature-based solutions,

- ecosystem services and urban challenges. *Land Use Policy* 100, 104898. <https://doi.org/10.1016/j.landusepol.2020.104898>.
- Bagstad, K.J., Ingram, J.C., Shapiro, C.D., La Notte, A., Maes, J., Vallecillo, S., Casey, C. F., Glynn, P.D., Heris, M.P., Johnson, J.A., Lauer, C., Matuszak, J., Oleson, K.L.L., Posner, S.M., Rhodes, C., Voigt, B., 2021. Lessons learned from development of natural capital accounts in the United States and European Union. *Ecosyst. Serv.* 52, 101359. <https://doi.org/10.1016/j.ecoser.2021.101359>.
- Bai, X., Colbert, M.L., McPhearson, T., Roberts, D., Siri, J., Walsh, B., Webb, B., 2019. Networking urban science, policy and practice for sustainability. *Curr. Opin. Environ. Sustain.* <https://doi.org/10.1016/j.cosust.2019.08.002>.
- Barton, D.N., 2023. Value 'generalisation' in ecosystem accounting-using Bayesian networks to infer the asset value of regulating services for urban trees in Oslo. *One Ecosyst.* 8. <https://doi.org/10.3897/oneeco.8.e85021>.
- Beck, H.E., Zimmermann, N.E., McVicar, T.R., Vergopolan, N., Berg, A., Wood, E.F., 2018. Present and future köppen-geiger climate classification maps at 1-km resolution. *Sci. Data* 5. <https://doi.org/10.1038/sdata.2018.214>.
- Brondizio, E.S., Settele, J., Diaz, S., Ngo, H.T., 2019. The global assessment report of the intergovernmental science-policy platform on biodiversity and ecosystem services. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). <https://doi.org/10.5281/zenodo.3831673>.
- Bruzón, A.G., Arrogante-Funes, P., Martínez de Anguita, P., Novillo, C.J., Santos-Martín, F., 2022. How the ecosystem extent is changing: a national-level accounting approach and application. *Sci. Total Environ.* 815. <https://doi.org/10.1016/j.scitotenv.2021.152903>.
- Cadenasso, M.L., Pickett, S.T.A., Schwarz, K., 2007. Spatial heterogeneity in urban ecosystems: Reconceptualizing land cover and a framework for classification. *Front. Ecol. Environ.* [https://doi.org/10.1890/1540-9295\(2007\)5\[80:SHUER\]2.0.CO;2](https://doi.org/10.1890/1540-9295(2007)5[80:SHUER]2.0.CO;2).
- Cimburowa, Z., Berghauer Pont, M., 2021. Location matters: a systematic review of spatial contextual factors mediating ecosystem services of urban trees. *Ecosyst. Serv.* <https://doi.org/10.1016/j.ecoser.2021.101296>.
- Comte, A., Sylvie Campagne, C., Lange, S., Bruzón, A.G., Hein, L., Santos-Martín, F., Levrel, H., 2022. Ecosystem accounting: past scientific developments and future challenges. *Ecosyst. Serv.* <https://doi.org/10.1016/j.ecoser.2022.101486>.
- Cordella, M., Gonzalez-Redin, J., Lodeiro, R.U., Garcia, D.A., 2022. Assessing impacts to biodiversity and ecosystems: Understanding and exploiting synergies between Life Cycle Assessment and Natural Capital Accounting, in: *Procedia CIRP*. Elsevier B.V., pp. 134–139. <https://doi.org/10.1016/j.procir.2022.02.023>.
- Cortinovis, C., Geneletti, D., 2020. A performance-based planning approach integrating supply and demand of urban ecosystem services. *Landsc. Urban Plan.* 201. <https://doi.org/10.1016/j.landurbplan.2020.103842>.
- Cryle, P., Pelletier, M., McInnes, C., Hills, T., Gunawardana, D., Cherian, M., Cowood, A., Romanovska, L., 2021. Practical Guidance Notes for Urban Ecosystem Accounting. A draft report by Working Group on Urban Ecosystem Accounting in Australia.
- De Fioravante, P., Strollo, A., Cavalli, A., Cimini, A., Smiraglia, D., Assennato, F., Munafo, M., 2023. Ecosystem mapping and accounting in Italy based on Copernicus and national data through integration of EAGLE and SEEA-EA frameworks. *Land (Basel)* 12. <https://doi.org/10.3390/land12020286>.
- de Jong, R., Edens, B., van Leeuwen, N., Schenau, S., Remme, R., Hein, L., 2016. Ecosystem accounting Limburg province, the Netherlands. Part I: Physical supply and condition accounts. <https://doi.org/10.13140/RG.2.1.3422.9520>.
- Demuzere, M., Kittner, J., Martilli, A., Mills, G., Moede, C., Stewart, I.D., Van Vliet, J., Bechtel, B., 2022. A global map of local climate zones to support earth system modelling and urban-scale environmental science. *Earth Syst. Sci. Data* 14, 3835–3873. <https://doi.org/10.5194/essd-14-3835-2022>.
- Department of Economic and Social Affairs, S.D.U.N., 2021. Implementation strategy for the SEEA Ecosystem Accounting.
- Dijkstra, L., Poelman, H., 2014. A harmonised definition of cities and rural areas: the new degree of urbanisation. Working Paper 01/2014. DG Regional & Urban Policy, European Commission.
- Dong, T., Jiao, L., Xu, G., Yang, L., Liu, J., 2019. Towards sustainability? Analyzing changing urban form patterns in the United States, Europe, and China. *Sci. Total Environ.* 671, 632–643. <https://doi.org/10.1016/j.scitotenv.2019.03.269>.
- Edens, B., Maes, J., Hein, L., Obst, C., Siikamäki, J., Schenau, S., Javorsek, M., Chow, J., Chan, J.Y., Steurer, A., Alfieri, A., 2022. Establishing the SEEA Ecosystem Accounting as a global standard. *Ecosyst. Serv.* 54, 101413. <https://doi.org/10.1016/j.ecoser.2022.101413>.
- EFTEC-DEFRA, 2017. A study to scope and develop urban natural capital accounts for the UK.
- Elliot, T., Torres-Matallana, J.A., Goldstein, B., Babí Almenar, J., Gómez-Baggethun, E., Proença, V., Rugani, B., 2022. An expanded framing of ecosystem services is needed for a sustainable urban future. *Renew. Sustain. Energy Rev.* 162. <https://doi.org/10.1016/j.rser.2022.112418>.
- Esch, T., Marconcini, M., Marmanis, D., Zeidler, J., Elsayed, S., Metz, A., Müller, A., Dech, S., 2014. Dimensioning urbanization – an advanced procedure for characterizing human settlement properties and patterns using spatial network analysis. *Appl. Geogr.* <https://doi.org/10.1016/j.apgeog.2014.09.009>.
- European Commission, 2022. Proposal for a Regulation of the European Parliament and of the Council amending Regulation (EU) No 691/2011 as regards introducing new environmental economic accounts modules.
- European Parliament, Council of the European Union, 2024a. REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Regulation (EU) No 691/2011 as regards introducing new environmental economic accounts modules.
- European Parliament, Council of the European Union, 2024b. REGULATION (EU) 2024/1991 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 24 June 2024 on nature restoration and amending Regulation (EU) 2022/869 (Text with EEA relevance), Official Journal of the European Union.
- Gomez Cardona, C.J., Yesid Moreno, J., Contreras, A., Sanchez-Núñez, D.A., Arciniegas Moreno, N., Guerrero, D., Vilorio Maestre, E.A., Lopez Navarro, J., 2023. Accounting of marine and coastal ecosystems at the Ramsar Site, Estuarine Delta System of the Magdalena River, Ciénaga Grande de Santa Marta, Colombia. *One Ecosystem* 8. <https://doi.org/10.3897/oneeco.8.e98852>.
- Grenier, M., Lantz, N., Soulard, F., Wang, J., 2020. The use of combined Landsat and Radarsat data for urban ecosystem accounting in Canada. *Stat. J. IAOS* 36, 797–806. <https://doi.org/10.3233/SJ-200663>.
- Grimm, N.B., Faeth, S.H., Golubiewski, N.E., Redman, C.L., Wu, J., Bai, X., Briggs, J.M., 2008. Global change and the ecology of cities. *Science* 319, 756–760. <https://doi.org/10.1126/science.1150195>.
- Grunewald, K., Schwappe-Kraft, B., Syrbe, R.U., Meier, S., Krüger, T., Schorcht, M., Walz, U., 2020. Hierarchical classification system of germany's ecosystems as basis for an ecosystem accounting – methods and first results. *One Ecosyst.* 5. <https://doi.org/10.3897/oneeco.5.e50648>.
- Hamstead, Z.A., Kremer, P., Larondelle, N., McPhearson, T., Haase, D., 2016. Classification of the heterogeneous structure of urban landscapes (STURLA) as an indicator of landscape function applied to surface temperature in New York City. *Ecol. Ind.* 70, 574–585. <https://doi.org/10.1016/j.ecolind.2015.10.014>.
- Hein, L., Bagstad, K., Edens, B., Obst, C., De Jong, R., Lesschen, J.P., 2016. Defining ecosystem assets for natural capital accounting. *PLoS One* 11. <https://doi.org/10.1371/journal.pone.0164460>.
- Hein, L., Obst, C., Edens, B., Remme, R.P., 2015. Progress and challenges in the development of ecosystem accounting as a tool to analyse ecosystem capital. *Curr. Opin. Environ. Sustain.* <https://doi.org/10.1016/j.cosust.2015.04.002>.
- Hein, L., Remme, R.P., Schenau, S., Bogaart, P.W., Lof, M.E., Horlings, E., 2020. Ecosystem accounting in the Netherlands. *Ecosyst. Serv.* 44. <https://doi.org/10.1016/j.ecoser.2020.101118>.
- Heris, M., Bagstad, K.J., Rhodes, C., Troy, A., Middel, A., Hopkins, K.G., Matuszak, J., 2021. Piloting urban ecosystem accounting for the United States. *Ecosyst. Serv.* 48. <https://doi.org/10.1016/j.ecoser.2020.101226>.
- Huang, J., Lu, X.X., Sellers, J.M., 2007. A global comparative analysis of urban form: applying spatial metrics and remote sensing. *Landsc. Urban Plan.* 82, 184–197. <https://doi.org/10.1016/j.landurbplan.2007.02.010>.
- Inácio, M., Baltranaitė, E., Pinto, L.V., Meisutovic-Akhtarieva, M., Barceló, D., Pereira, P., 2025. A systematic literature review on the implementation of the System of Environmental-Economic Accounting-Ecosystem accounting in forests, cities and marine areas. *Ecosyst. Serv.* 74. <https://doi.org/10.1016/j.ecoser.2025.101752>.
- Isbell, F., Balvanera, P., Mori, A.S., He, J., Bullock, J.M., Regmi, G.R., Seabloom, E.W., Ferrier, S., Sala, O.E., Guerrero-Ramírez, N.R., Tavella, J., Larkin, D.J., Schmid, B., Outhwaite, C.L., Pramual, P., Borer, E.T., Loreau, M., Omotoriogun, T.C., Obura, D. O., Anderson, M., Portales-Reyes, C., Kirkman, K., Vergara, P.M., Clark, A.T., Komatsu, K.J., Petchey, O.L., Weiskopf, S.R., Williams, L.J., Collins, S.L., Eisenhauer, N., Trisos, C.H., Renard, D., Wright, A.J., Tripathi, P., Cowles, J., Byrnes, J.E., Reich, P.B., Purvis, A., Sharip, Z., O'Connor, M.I., Kazanski, C.E., Haddad, N.M., Soto, E.H., Dee, L.E., Diaz, S., Zirkel, C.R., Avolio, M.L., Wang, S., Ma, Z., Liang, J., Farah, H.C., Johnson, J.A., Miller, B.W., Hautier, Y., Smith, M.D., Knops, J.M., Myers, B.J., Harmáková, Z.V., Cortés, J., Harfoot, M.B., Gonzalez, A., Newbold, T., Oehri, J., Mazón, M., Dobbs, C., Palmer, S.M., 2023. Expert perspectives on global biodiversity loss and its drivers and impacts on people. *Front. Ecol. Environ.* 21, 94–103. <https://doi.org/10.1002/fee.2536>.
- Jaureguiberry, P., Titeux, N., Wiemers, M., Bowler, D.E., Coscieme, L., Golden, A.S., Guerra, C.A., Jacob, U., Takahashi, Y., Settele, J., Díaz, S., Molnár, Z., Purvis, A., 2022. The direct drivers of recent global anthropogenic biodiversity loss. *Sci. Adv.* 8, 9982. <https://doi.org/10.1126/sciadv.abm9982>.
- Karr, J.R., Larson, E.R., Chu, E.W., 2022. Ecological integrity is both real and valuable. *Conserv. Sci. Pract.* <https://doi.org/10.1111/csp2.583>.
- Kaur, A., Sharma, R., Mishra, P., Sinhababu, A., Chakravarty, R., 2022. Visual research discovery using connected papers: a use case of blockchain in libraries. *Ser. Libr.* 83, 186–196. <https://doi.org/10.1080/0361526X.2022.2142722>.
- Keith, D.A., Ferrer-Paris, J.R., Nicholson, E., Bishop, M.J., Polidoro, B.A., Ramirez-Llodra, E., Tozer, M.G., Nel, J.L., Mac Nally, R., Gregr, E.J., Watermeyer, K.E., Essl, F., Faber-Langendoen, D., Franklin, J., Lehmann, C.E.R., Etter, A., Roux, D.J., Stark, J.S., Rowland, J.A., Brummitt, N.A., Fernandez-Arcaya, U.C., Suthers, I.M., Wiser, S.K., Donohue, I., Jackson, L.J., Pennington, R.T., Iliffe, T.M., Gerovasileiou, V., Giller, P., Robson, B.J., Pettorelli, N., Andrade, A., Lindgaard, A., Tahvanainen, T., Terauds, A., Chadwick, M.A., Murray, N.J., Moat, J., Plischoff, P., Zager, I., Kingsford, R.T., 2022. A function-based typology for Earth's ecosystems. *Nature* 610, 513–518. <https://doi.org/10.1038/s41586-022-05318-4>.
- Keith, D.A., Ferrer-Paris, J.R., Nicholson, E., Kingsford, R.T., 2020. IUCN Global Ecosystem Typology 2.0: descriptive profiles for biomes and ecosystem functional groups, IUCN Global Ecosystem Typology 2.0: descriptive profiles for biomes and ecosystem functional groups. <https://doi.org/10.2305/iucn.ch.2020.13.en>.
- Keith, H., Maes, J., Czúcz, B., Jackson, B., Driver, A., Bland, L., Nicholson, E., 2019. Discussion paper 2.1: Purpose and role of ecosystem condition accounts. Paper submitted to the SEEA EEA Technical Committee as input to the revision of the technical recommendations in support of the System on Environmental-Economic Accounting.
- Keith, H., Czúcz, B., Jackson, B., Driver, A., Nicholson, E., & Maes, J., 2020. A conceptual framework and practical structure for implementing ecosystem condition accounts.
- Kervinio, Y., Surun, C., Comte, A., Levrel, H., 2023. Defining ecological liabilities and structuring ecosystem accounts to support the transition to sustainable societies. *One Ecosyst.* 8, e98100.
- Kremer, P., Larondelle, N., Zhang, Y., Pasles, E., Haase, D., 2018. Within-class and neighborhood effects on the relationship between composite urban classes and

- surface temperature. Sustainability (Switzerland) 10. <https://doi.org/10.3390/su10030645>.
- La Notte, A., Marques, A., 2019. Adjusted macroeconomic indicators to account for ecosystem degradation: an illustrative example. *Ecosyst. Health Sustainability* 5 (1), 133–143.
- La Notte, A., Vallecillo, S., Marques, A., Maes, J., 2019. Beyond the economic boundaries to account for ecosystem services. *Ecosyst. Serv.* 35, 116–129. <https://doi.org/10.1016/j.ecoser.2018.12.007>.
- La Notte, A., Zulian, G., 2021. An Ecosystem Services-Based Approach to Frame NBS in Urban Context, in: *Nature-Based Solutions for More Sustainable Cities – A Framework Approach for Planning and Evaluation*. Emerald Publishing Limited, pp. 47–65. <https://doi.org/10.1108/978-1-80043-636-720211005>.
- Lange, S., Campagne, C.S., Comte, A., Bank, E., Santos-Martín, F., Maes, J., Burkhard, B., 2022. Progress on ecosystem accounting in Europe. *Ecosyst. Serv.* 57. <https://doi.org/10.1016/j.ecoser.2022.101473>.
- Larondelle, N., Haase, D., 2013. Urban ecosystem services assessment along a rural-urban gradient: a cross-analysis of European cities. *Ecol. Ind.* 29, 179–190. <https://doi.org/10.1016/j.ecolind.2012.12.022>.
- Larondelle, N., Hamstead, Z.A., Kremer, P., Haase, D., McPhearson, T., 2014. Applying a novel urban structure classification to compare the relationships of urban structure and surface temperature in Berlin and New York City. *Appl. Geogr.* 53, 427–437. <https://doi.org/10.1016/j.apgeog.2014.07.004>.
- Larson, S., Jarvis, D., Stoeckl, N., Barrowei, R., Coleman, B., Groves, D., Hunter, J., Lee, M., Markham, M., Larson, A., Finau, G., Douglas, M., 2023. Piecemeal stewardship activities miss numerous social and environmental benefits associated with culturally appropriate ways of caring for country. *J. Environ. Manage.* 326. <https://doi.org/10.1016/j.jenvman.2022.116750>.
- Lemoine-Rodríguez, R., Inostroza, L., Zepp, H., 2020. The global homogenization of urban form: an assessment of 194 cities across time. *Landsc. Urban Plan.* 204. <https://doi.org/10.1016/j.landurbplan.2020.103949>.
- Lence, A., Extramiana, F., Fall, A., Salem, J.E., Zucker, J.D., Prifti, E., 2023. Automatic digitization of paper electrocardiograms – a systematic review. *J. Electrocardiol.* <https://doi.org/10.1016/j.jelectrocard.2023.05.009>.
- Liu, C., Ali, N.L., 2022. Co-citation and bibliographic coupling based on connected papers: review of public opinion research in a broad sense in the West. *Asian Soc. Sci.* 18, 29. <https://doi.org/10.5539/ass.v18n7p29>.
- Loreau, M., Cardinale, B.J., Isbell, F., Newbold, T., O'Connor, M.I., de Mazancourt, C., 2022. Do not downplay biodiversity loss. *Nature* 601, E27–E28. <https://doi.org/10.1038/s41586-021-04179-7>.
- Lu, Y., Wang, R., Zhang, Y., Su, A., Wang, P., Jenkins, A., Ferrier, R.C., Bailey, M., Squire, G., 2015. Ecosystem health towards sustainability. *Ecosyst. Health Sustainability* 1, 1–15. <https://doi.org/10.1890/EHS14-0013.1>.
- Luederitz, C., Brink, E., Gralla, F., Hermelingmeier, V., Meyer, M., Niven, L., Panzer, L., Partelow, S., Rau, A.L., Sasaki, R., Abson, D.J., Lang, D.J., Wamsler, C., von Wehrden, H., 2015. A review of urban ecosystem services: six key challenges for future research. *Ecosyst. Serv.* 14, 98–112. <https://doi.org/10.1016/j.ecoser.2015.05.001>.
- Mahtta, R., Mahendra, A., Seto, K.C., 2019. Building up or spreading out? typologies of urban growth across 478 cities of 1 million+. *Environ. Res. Lett.* 14. <https://doi.org/10.1088/1748-9326/ab59bf>.
- Mattsson, E., Eriksson, F.A., Malmgren, M., Anctuary, M.S., 2022. Ecosystem accounting in the Nordic countries, TemaNord. Nordisk Ministerråd. <https://doi.org/10.6027/temanord2022-554>.
- Maxwell, S.L., Fuller, R.A., Brooks, T.M., Watson, J.E.M., 2016. Biodiversity: the ravages of guns, nets and bulldozers. *Nature* 536, 143–145. <https://doi.org/10.1038/536143a>.
- McDonnell, M.J., Hahs, A.K., 2008. The use of gradient analysis studies in advancing our understanding of the ecology of urbanizing landscapes: current status and future directions. *Landsc. Ecol.* <https://doi.org/10.1007/s10980-008-9253-4>.
- McPhearson, T., Cook, E.M., Berbes-Blázquez, M., Cheng, C., Grimm, N.B., Andersson, E., Barbosa, O., Chandler, D.G., Chang, H., Chester, M.V., Childers, D.L., Elser, S.R., Frantzeskaki, N., Grabowski, Z., Groffman, P., Hale, R.L., Iwaniec, D.M., Kabisch, N., Kennedy, C., Markolf, S.A., Matsler, A.M., McPhillips, L.E., Miller, T.R., Muñoz-Erickson, T.A., Rosi, E., Troxler, T.G., 2022. A social-ecological-technological systems framework for urban ecosystem services. *One Earth* 5, 505–518. <https://doi.org/10.1016/j.oneear.2022.04.007>.
- Mokany, K., Harwood, T.D., Ferrier, S., 2019. Improving links between environmental accounting and scenario-based cumulative impact assessment for better-informed biodiversity decisions. *J. Appl. Ecol.* 56, 2732–2741. <https://doi.org/10.1111/1365-2664.13506>.
- Morpurgo, J., Remme, R.P., Van Bodegom, P.M., 2023. CUGIC: the Consolidated Urban Green Infrastructure Classification for assessing ecosystem services and biodiversity. *Landsc. Urban Plan.* 234, 104726.
- Nel, J.L., Driver, A., 2015. National River Ecosystem Accounts for South Africa. Discussion document for Advancing SEEA Experimental Ecosystem Accounting Project. Pretoria.
- Obst, C., Hein, L., Edens, B., 2016. National accounting and the valuation of ecosystem assets and their services. *Environ. Resour. Econ. (Dordr)* 64, 1–23. <https://doi.org/10.1007/s10640-015-9921-1>.
- Ogilvy, S., Burritt, R., Walsh, D., Obst, C., Meadows, P., Muradzika, P., Eigenraam, M., 2018. Accounting for liabilities related to ecosystem degradation. *Ecosyst. Health Sustainability* 4, 261–276. <https://doi.org/10.1080/20964129.2018.1544837>.
- Oginah, S.A., Posthuma, L., Maltby, L., Hauschild, M., Fantke, P., 2023. Linking freshwater ecotoxicity to damage on ecosystem services in life cycle assessment. *Environ. Int.* <https://doi.org/10.1016/j.envint.2022.107705>.
- Page, M.J., McKenzie, J.E., Bossuyt, P.M., Boutron, I., Hoffmann, T.C., Mulrow, C.D., Shamseer, L., Tetzlaff, J.M., Akl, E.A., Brennan, S.E., Chou, R., Glanville, J., Grimshaw, J.M., Hróbjartsson, A., Lalu, M.M., Li, T., Loder, E.W., Mayo-Wilson, E., McDonald, S., McGuinness, L.A., Stewart, L.A., Thomas, J., Tricco, A.C., Welch, V.A., Whiting, P., Moher, D., 2021a. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *The BMJ* 372. <https://doi.org/10.1136/bmj.n71>.
- Page, M.J., Moher, D., Bossuyt, P.M., Boutron, I., Hoffmann, T.C., Mulrow, C.D., Shamseer, L., Tetzlaff, J.M., Akl, E.A., Brennan, S.E., Chou, R., Glanville, J., Grimshaw, J.M., Hróbjartsson, A., Lalu, M.M., Li, T., Loder, E.W., Mayo-Wilson, E., McDonald, S., McGuinness, L.A., Stewart, L.A., Thomas, J., Tricco, A.C., Welch, V.A., Whiting, P., McKenzie, J.E., 2021b. PRISMA 2020 explanation and elaboration: Updated guidance and exemplars for reporting systematic reviews. *The BMJ* 372. <https://doi.org/10.1136/bmj.n160>.
- Pascual, U., Balvanera, P., Díaz, S., Pataki, G., Roth, E., Stenseke, M., Watson, R.T., Dessane, E.B., Islar, M., Kelemen, E., Maris, V., 2017. Valuing nature's contributions to people: the IPBES approach. *Curr. Opin. Environ. Sustain.* 26, 7–16.
- Pereira, H.M., Martins, I.S., Rosa, I.M.D., Kim, H., Leadley, P., Popp, A., van Vuuren, D. P., Hurtt, G., Quoss, L., Arneth, A., Baisero, D., Bakkenes, M., Chaplin-Kramer, R., Chini, L., Di Marco, M., Ferrier, S., Fujimori, S., Guerra, C.A., Harfoot, M., Harwood, T.D., Hasegawa, T., Havard, V., Havlik, P., Hellweg, S., Hillbers, J.P., Hill, S.L.L., Hirata, A., Hoskins, A.J., Humpenöder, F., Janse, J.H., Jetz, W., Johnson, J.A., Krause, A., Leclère, D., Matsui, T., Meijer, J.R., Merow, C., Obersteiner, M., Ohashi, H., De Palma, A., Poulter, B., Purvis, A., Quesada, B., Rondinini, C., Schipper, A.M., Settele, J., Sharp, R., Stehfest, E., Strassburg, B.B.N., Takahashi, K., Talluto, M.V., Thuijter, W., Titeux, N., Visconti, P., Ware, C., Wolf, F., Alkemade, R., 2024. Global trends and scenarios for terrestrial biodiversity and ecosystem services from 1900 to 2050. *Science* 379 (384), 458–465. <https://doi.org/10.1126/science.adn3441>.
- Petersen, J.E., Mancosu, E., King, S., 2022. Ecosystem extent accounts for Europe. *Ecosyst. Serv.* 57. <https://doi.org/10.1016/j.ecoser.2022.101457>.
- Qureshi, S., Haase, D., Coles, R., 2014. The theorized urban gradient (TUG) method—a conceptual framework for socio-ecological sampling in complex urban agglomerations. *Ecol. Ind.* 36, 100–110.
- Reis, J.P., Silva, E.A., Pinho, P., 2016. Spatial metrics to study urban patterns in growing and shrinking cities. *Urban Geogr.* 37, 246–271. <https://doi.org/10.1080/02723638.2015.1096118>.
- Roche, P.K., Campagne, C.S., 2017. From ecosystem integrity to ecosystem condition: a continuity of concepts supporting different aspects of ecosystem sustainability. *Curr. Opin. Environ. Sustain.* 29, 63–68.
- Rugani, B., Osset, P., Blanc, O., Benetto, E., 2023. Environmental footprint neutrality using methods and tools for natural capital accounting in life cycle assessment. *Land (Basel)*. <https://doi.org/10.3390/land12061171>.
- Schenau, S., van Berkel, J., Bogaart, P., Blom, C., Driessen, C., de Jongh, L., de Jong, R., Horlings, E., Mosterd, R., Hein, L., Lof, M., 2022. Valuing ecosystem services and ecosystem assets for the Netherlands. *One Ecosyst.* 7. <https://doi.org/10.3897/ONEECO.7.E84624>.
- Schwarz, N., 2010. Urban form revisited—Selecting indicators for characterising European cities. *Landsc. Urban Plan.* 96 (1), 29–47.
- Stange, E.E., Barton, D.N., Andersson, E., Haase, D., 2022. Comparing the implicit valuation of ecosystem services from nature-based solutions in performance-based green area indicators across three European cities. *Landsc. Urban Plan.* 219. <https://doi.org/10.1016/j.landurbplan.2021.104310>.
- Stathakis, D., Tsilimigkas, G., 2015. Measuring the compactness of European medium-sized cities by spatial metrics based on fused data sets. *Int. J. Image Data Fusion* 6, 42–64. <https://doi.org/10.1080/19479832.2014.941018>.
- Su, M., Fath, B.D., Yang, Z., 2010. Urban ecosystem health assessment: a review. *Sci. Total Environ.* <https://doi.org/10.1016/j.scitotenv.2010.03.009>.
- Su, M., Zhang, Y., Liu, G., Xu, L., Zhang, L., Yang, Z., 2013. Urban ecosystem health assessment: perspectives and Chinese practice. *Int. J. Environ. Res. Public Health* 10, 5874–5885. <https://doi.org/10.3390/ijerph10115874>.
- Tallent, T., Zabala, A., 2024. Social equity and pluralism in Nature-based Solutions: Practitioners' perspectives on implementation. *Environ. Sci. Policy* 151, 103624.
- Taubenböck, H., Debray, H., Qiu, C., Schmitt, M., Wang, Y., Zhu, X.X., 2020. Seven city types representing morphologic configurations of cities across the globe. *Cities* 105. <https://doi.org/10.1016/j.cities.2020.102814>.
- Taubenböck, H., Droin, A., Standfuß, I., Dosch, F., Sander, N., Milbert, A., Eichfuss, S., Wurm, M., 2022. To be, or not to be 'urban'? A multi-modal method for the differentiated measurement of the degree of urbanization. *Comput. Environ. Urban Syst.* 95. <https://doi.org/10.1016/j.compenurbysys.2022.101830>.
- Taubenböck, H., Wurm, M., Geiß, C., Dech, S., Siedentop, S., 2019. Urbanization between compactness and dispersion: designing a spatial model for measuring 2D binary settlement landscape configurations. *Int. J. Digit. Earth* 12, 679–698. <https://doi.org/10.1080/17538947.2018.1474957>.
- United Nations, 2024. Global Assessment of Environmental-Economic Accounting and Supporting Statistics 2023.
- United Nations, 2021a. System of Environmental-Economic Accounting—Ecosystem Accounting (SEEA-EA). White cover publication, pre-edited text subject to official editing.
- United Nations, 2021b. SEEA Experimental Ecosystem Accounting Revision. <https://seea.un.org/content/seea-experimental-ecosystem-accounting-revision> (accessed 3.6.24).
- United Nations, 2020. Virtual Expert Forum on SEEA Experimental Ecosystem Accounting 2020. <https://seea.un.org/events/virtual-expert-forum-seea-experimental-ecosystem-accounting-2020> (accessed 3.6.24).
- United Nations, European Commission, Food and Agriculture Organization of the United Nations, Organisation for Economic Co-operation Development, World Bank Group,

2014. System of Environmental-Economic Accounting 2012 : experimental ecosystem accounting. New York.
- United Nations Statistics Division, 2021. Implementation strategy for the SEEA Ecosystem Accounting.
- Vallecillo, S., La Notte, A., Ferrini, S., Maes, J., 2019. How ecosystem services are changing: an accounting application at the EU level. *Ecosyst. Serv.* 40. <https://doi.org/10.1016/j.ecoser.2019.101044>.
- Vallecillo, S., Maes, J., Teller, A., Babí Almenar, J., Barredo, J.I., Trombetti, M., Malak, Abdul., Paracchini, M.L., Carré, A., Addamo, A.M., Czucz, B., Zulian, G., Marando, F., Erhard, M., Liqueste, C., Romao, C., Polce, C., Pardo Valle, A., Jones, A., Zurbaran-Nucci, M., Nocita, M., Vysna, V., Cardoso, A.C., Gervasini, E., Magliozzi, C., Baritz, R., Barbero, M., Andre, V., Kokkoris, I.P., Dimopoulos, P., Kovacevic, V., Gumbert, A., 2022. EU-wide methodology to map and assess ecosystem condition towards a common approach consistent with a global statistical standard. <https://doi.org/10.2760/13048>.
- VanderWilde, C.P., Newell, J.P., 2021. Ecosystem services and life cycle assessment: a bibliometric review. *Resour. Conserv. Recycl.* <https://doi.org/10.1016/j.resconrec.2021.105461>.
- Venter, Z.S., Czucz, B., Stange, E., Nowell, M.S., Simensen, T., Immerzeel, B., Barton, D. N., 2024. 'Uncertainty audit' for ecosystem accounting: Satellite-based ecosystem extent is biased without design-based area estimation and accuracy assessment. *Ecosyst. Serv.* 66. <https://doi.org/10.1016/j.ecoser.2024.101599>.
- Venter, Z.S., Krog, N.H., Barton, D.N., 2020. Linking green infrastructure to urban heat and human health risk mitigation in Oslo, Norway. *Sci. Total Environ.* 709. <https://doi.org/10.1016/j.scitotenv.2019.136193>.
- Wang, J., Soulard, F., Henry, M., Grenier, M., Schenau, S., Barton, D., Harris, R., Chan, J. Y., Keith, D., Obst, C., 2019. Discussion paper 1.2: Treatment of ecosystems assets in urban areas. Paper submitted to the SEEA EEA Technical Committee as input to the revision of the technical recommendations in support of the System on Environmental-Economic Accounting.
- Wijsman, K., Pineda-Pinto, M., Sarkki, S., Stijnen, C., den Dekker-Arlain, J., Raymond, C. M., 2025. Rethinking trade-offs in nature-based solutions from a multispecies justice perspective. *Npj Urban Sustain.* 5 (1), 67.
- Wu, J., 2014. Urban ecology and sustainability: the state-of-the-science and future directions. *Landsc. Urban Plan.* 125, 209–221. <https://doi.org/10.1016/j.landurbplan.2014.01.018>.
- Zhao, C., Sander, H.A., 2018. Assessing the sensitivity of urban ecosystem service maps to input spatial data resolution and method choice. *Landsc. Urban Plan.* 175, 11–22. <https://doi.org/10.1016/j.landurbplan.2018.03.007>.
- Zhou, W., Cadenasso, M.L., Schwarz, K., Pickett, S.T.A., 2014. Quantifying spatial heterogeneity in urban landscapes: integrating visual interpretation and object-based classification. *Remote Sens. (Basel)* 6, 3369–3386. <https://doi.org/10.3390/rs6043369>.
- Zhou, W., Pickett, S.T.A., Cadenasso, M.L., 2017. Shifting concepts of urban spatial heterogeneity and their implications for sustainability. *Landsc. Ecol.* 32, 15–30. <https://doi.org/10.1007/s10980-016-0432-4>.