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Ecosystem accounting: past scientific developments and future challenges

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Highlights

- The SEEA is the main framework and becoming the standard for ecosystem accounting
- Research is moving towards operational issues of implementing ecosystem accounts
- Forests are the main habitats studied but the share of aquatic habitats is increasing
- Most monetary methods used are based on exchange values and accounting principles
- Europe is, to date, the most productive region for ecosystem accounts

Abstract

To better manage our environment, systematic information is needed on the state of ecosystems and their interactions with society. Efforts have been undertaken to design monitoring and recording systems, notably the United Nations System of Environmental-Economic Accounting (SEEA). However, the diverse conceptualizations and applications on ecosystem accounting found in the scientific literature have never been assessed in a systematic

way. Here, a systematic literature review on ecosystem accounting, i.e. natural capital accounting approaches that focus on ecosystems, is conducted to detail the evolving trends in concepts, methodologies, and applications, and to identify main gaps and challenges for future work. Results yielded 378 scientific articles published between 1990 and 2021. This literature is diverse in terms of frameworks developed, ecosystems studied, valuation methods used, and accounts produced. Among the eleven ecosystem accounting frameworks identified, the SEEA is the most widely used. This literature is moving from focusing on conceptual elements towards addressing implementation issues. It is primarily conducted in European countries, on forest ecosystems, using biophysical methods and monetary valuation methods consistent with exchange values to produce accounts. The gaps that should be the focus of future work include the issue of implementation: methodologies (artificial Intelligence technologies and economic valuation), data, for instance making better use of remote sensing images, collaborations, and supporting the use of ecosystem accounts in decision-making.

1. Introduction

Political decision-making at the national level is informed by macroeconomic figures (and many more factors) brought together in the national accounts. However, the conventional national accounts, that are produced in the context of the System of National Accounts (SNA) (United Nations, 2009), do not comprehensively record the state, extent and uses of ecosystems. Indeed, the core goal of the SNA is to organize macroeconomic accounts that record economic processes. International efforts have produced standards linking these national accounts to ecosystem accounts, that synthesize in a consistent and comparable way information on the status of ecosystems in every country, notably in the System of Environmental-Economic Accounting (SEEA) (Hein et al., 2020; UN, 2021). Efforts to design and implement the SEEA are led and coordinated by the UN Statistical Commission.

In the scientific literature, there have been significant research efforts on ecosystem and natural capital accounting over the past decades, including conceptual developments (e.g. Obst et al., 2016; La Notte et al., 2019b) and applications (e.g. Weber, 2007; Barbier, 2016; Caparrós et al., 2017; Schröter et al., 2014). Many conceptual frameworks and methodologies have emerged on ecosystems and natural capital accounting. Overviews on ecosystem accounting (Edens and Hein, 2013) and syntheses of particular topics of ecosystem accounting (Boyd and Banzhaf, 2007) have been produced in the literature and in the context of the United Nations with the development of the SEEA (UNSD, 2014a; UNSD, 2014b; UNSD 2017; Edens et al., 2022). In 2013 the Statistical Commission of the United Nations endorsed the SEEA Experimental Ecosystems Accounting (SEEA-EEA) as the basis for commencing testing and further development of this new field of national accounts. In 2021, the United Nations Statistical Commission has adopted chapters 1-7 of the System of Environmental-Economic Accounting—Ecosystem Accounting (SEEA EA) as an international statistical standard (Edens et al., 2022). These chapters focus on the biophysical part of ecosystem accounting, the monetary accounts were not yet considered to be developed at the level of a statistical standard (Brown et al., 2021). Note that, in the last revision, the prefix ‘Experimental’ that was previously used has

been discontinued. Furthermore, ecosystem accounting is also rising in the global environmental policies agenda. The future agreement of the Convention on Biological Diversity (CBD) on post-2020 biodiversity framework will also likely call for “integration of biodiversity and ecosystem values into national accounts” (CBD SBSTTA, 2020) and will likely follow trends in adoption of ecosystem accounts. This objective was already part of the Aichi Target, but has not been achieved yet (Secretariat of the Convention on Biological Diversity, 2020).

However, the scientific literature on this topic has never been analyzed in a systematic way. Recent reviews analyzed frameworks of ecosystem services assessments, suggesting paths for improvement (Nahlik et al., 2012; Schröter et al., 2016; Bordt and Saner, 2018). These reviews are not systematic in scope and, while they mention accounting as an important future development for the monitoring of biodiversity and ecosystem services, they deal with assessments which do not have the attributes of an accounting system. Accounting addresses issues of consistency, comparability and comprehensiveness to produce information in a structured and continuous way through time.

There is a need for analysis of the literature to understand explicitly the possible ways to fully develop ecosystem accounting and link it with national accounting and organizational accounting (Heal 2007, Feger et al., 2018; Brandon et al., 2021). One of the major constraints to developing ecosystem accounts is the feasibility of building and updating these accounts, in line with statistical standards and policy objectives. A broad range of datasets and models are needed to accurately capture the variety of interactions between people and ecosystems. Some initiatives address this challenge like the Artificial Intelligence for Environment & Sustainability (ARIES) for SEEA (<https://seea.un.org/content/aries-for-seea>) that explicitly aim to improve data/model interoperability. Policy-makers demand clarifications on experiments and resulting implication of implementing ecosystem accounting for policy use (Recuerdo-Virto et al., 2018).

The development of ecosystem accounting frameworks should rest on clear conceptual and theoretical bases and sound methodological approaches to produce ecosystem accounts that answer to statistical standards and policy objectives. To this aim, a systematic analysis of the literature on ecosystem accounting is presented here. It provides an overview on the conceptual foundations and sets of values underlying the design of ecosystem accounts, which are critical elements as the underlying theories and concepts that support the frameworks developed for the integration of ecosystems into national accounts are not often explicit. For example, applying weak or strong sustainability concepts will lead to very different outcomes when integrated in the national accounts (Dietz and Neumayer, 2007). Such choices need to be detailed to further the sound advancement of ecosystem accounting frameworks. This review also details the scope of accounts produced to date, which is essential to understand how the scientific literature contributes to the production of ecosystem accounts, to what extent it has identified gaps that need to be addressed and how this endeavor can best guide policy-making and environmental management by Nation States. Finally, this review zooms into the specific literature dedicated to advancing the SEEA framework.

2. Material and methods

This review focuses on the literature dedicated to ecosystems accounting. Abiotic resources (e.g. minerals), and biotic resources (e.g. timber) that are not approached through an ecosystem lens are excluded from this study as it is not the purpose of this study to analyze the whole literature on environmental accounting in general. Historically, “green accounting” and “environmental accounting” have mostly focused on the environment with two prisms: the environment as a source of renewable and non-renewable resources, and the environment as a sink of pollution.

Accounting for natural resources and their depletion has been the subject of extensive literature (see Edens, (2013) for a review) and is brought together in the SEEA Central Framework (SEEA CF), which has been adopted as a statistical standard by the United Nations Statistical Commission in 2012 (UNSD, 2014a). The SEEA CF allows accounting for individual natural resources, such as stocks and uses of oil and natural gas, timber and fish. However, it does not allow for a comprehensive analysis of ecosystem services or the extent, condition and monetary values of ecosystems. Therefore, we do not consider accounts that have been produced according to the SEEA CF in this paper.

We included articles that focus at different spatial scales, from local to national to international levels. These include articles that focus on environmental issues, including ecosystems “core” (e.g. extent, condition, ecosystem services, assets) and “thematic” (e.g. carbon, water, biodiversity and land) account in the SEEA EA (UNSD, 2021). Another important clarification is that the literature reviewed here focuses on the production of accounts, a parallel but different literature than the one dealing with the assessments of ecosystems and their services (e.g. publications from the Intergovernmental Panel on Biodiversity and Ecosystem Services (IPBES), The Economics of Ecosystems and Biodiversity (TEEB), The Millennium ecosystem Assessment (MA). While assessments are producing or using data to answer specific policy or research questions, accounting is dedicated to the structuring of information systems in a consistent and comparable manner. Finally, this review focuses on national accounting, and does not consider the many initiatives dedicated to the inclusion of environmental information in corporate accounting (Houdet et al. 2020). While organizational accounting is outside the scope, articles focusing on links between them, or on national accounting conducted at sub-national scale, are included (Ingram et al., 2022).

2.1 Process of selecting articles

The literature on ecosystem accounting is reviewed systematically, over the period 1990-2021, using Web of Science and Scopus as the two databases exploited. The search terms used to retrieve the literature are presented in Table 1.

Table 1: Terms used for the finding of articles on ecosystem accounting (TI: Title)

Search terms	Database	Timespan
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TITLE-ABS-KEY ("ecosystem accounting") OR ("natural capital accounting") OR ("ecological accounting") OR ("environmental accounting") OR ("green accounting") AND (nation* OR public) AND PUBYEAR AFT 1989 AND PUBYEAR BEF 2022	Scopus	1990-2021
TI=(ecosystem OR green OR "natural capital" OR ecological OR environmental) AND TS=(nation* OR public) AND TI=(account*)	Web of Science	1990-2021
TI=(ecosystem accounting) OR TI=(natural capital accounting) OR TI=(ecological accounting) OR TI=(environmental accounting) AND TS= (nation*)	Web of Science	1990-2021

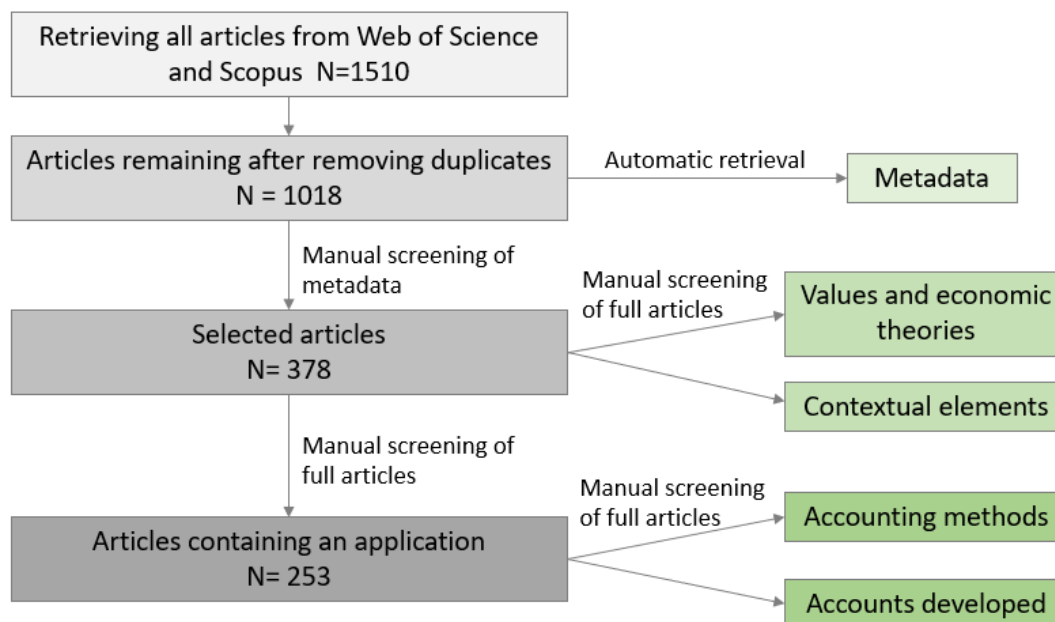


Figure 1: Process of systematically selecting and analysis the literature

After retrieving the literature from the two databases (1510 results), duplicates within databases and duplicates common to the two databases were removed, reducing the list to 1018 resulting articles (Figure 1). Missing abstracts and type of documents were then added manually to the database. Non-peer-reviewed articles were removed (e.g. book chapters, news articles, conference papers, working papers) from a screen of “type of document”. Then, articles that referred to corporate accounting (e.g. life cycle assessments or Environmental Management Accounting for example) or used the word accounting to mean “take into account” were removed, screening through paper title, journal, abstract, and keywords. Finally, articles that do not focus on ecosystems are removed. There are several of them, such as Aronson (1998) or

Aury (2007), that only include resource depletion (mostly minerals and non-renewables, energy, and air pollution) in their work and so were not considered in the review. The final list of peer-reviewed articles analyzed here contains 378 articles.

2.2 Categories of analysis of the literature

We produced a grid of themes, with detailed typologies to analyze and categorize the literature to answer our specific research objectives. These include: metadata of the articles containing general information, context information including spatial characteristics, purpose, topics addressed by the authors, then the values and theories underlying the accounts, accounting methods used to produce the accounts, and a description of the accounts produced in terms of geographic location, ecosystems and ecosystem services (see annex 1 for more details).

2.2.1 Metadata

These represent the standard way of assigning information to research articles in order to conduct a systematic literature review, including authors, title, abstract, journal, year of publication, keywords, and type of document, and were retrieved directly from Scopus and Web of Science.

2.2.2 Contextual elements

Here, information on the locations where accounts have been produced and experimented is retrieved. This information will give us clues as to which countries or territories are the most advanced in producing ecosystem accounts, as this process is in part driven by research activities. The topics identified in ecosystem accounting will be important information on future research opportunities to strengthen the development of ecosystem accounts. Accounting frameworks are the foundations on which studies build to produce or refine accounting systems.

A distinction has also been made between articles that are only theoretical in nature, and the ones that attempt to construct ecosystem accounts, which will be called “applied articles”.

2.2.3 Underlying values and economic theories mobilized

Various sets of theories have been described to characterize different types of values: intrinsic (i.e. nature, biodiversity); instrumental (i.e. nature’s contribution to people, ecosystem services); and relational values (i.e. individual, collective). Classification of values of ecosystems have been proposed over the years. IPBES has produced a classification of the different systems of values used to relate societies relationships with nature (Pascual et al., 2017). In relation to the update of the SEEA EA, a discussion paper on values proposed four categories of values, which we use here (Barton et al., 2019). It is a matrix with two dimensions: anthropocentric and non-anthropocentric for the first dimension and intrinsic, relational, or instrumental for the second dimension. The ecosystem accounting frameworks usually rely on anthropocentric instrumental values of nature, as the integration accounts into the System of National Accounts (SNA) relies on assumptions that hardly accommodate other values (e.g. the common metric is exchange values, institutional sectors are clearly identified). Other types of values (e.g. intrinsic and relational values) exist and could be used to support the creation of ecosystem accounting. While the discussion paper 5.1 of the revision of the SEEA EA suggests that biophysical

accounts relate to intrinsic values and economic accounts relate to instrumental values (Barton et al., 2019), we propose here to classify economic accounts based on the maintenance of critical natural capital as belonging to intrinsic values (Farmer and Randall, 1998).

2.2.4 Accounting methods

To produce ecosystem accounts, a diverse set of methodologies exists, which are linked to the values and conceptual frameworks mobilized by account developers (Santos-Martin et al., 2018, Obst et al., 2016, Bartelmus, 2009). These methods are categorized in two types: non-monetized (producing information with various biophysical and socio-economic units such as hectares, number of species, time traveled, employment) and monetized (producing figures in monetary terms).

2.2.5 Accounts developed

A wide variety of ecosystem accounts has been developed in the literature and are recorded here for each study. For example, there are various accounts including ecosystem extent, condition, ecosystem services, and assets proposed in the structure of the SEEA EA, as well as thematic accounts. Other accounts include ecological footprints (Wackernagel et al., 1999), emergy accounts based on thermodynamics (Campbell and Brown, 2012), or green accounts of adjusted macro-aggregates (added value, income, investment, demand). This review will not only classify and analyze all the types of ecosystem accounts produced, but also the components of environment-economy they are attempting to cover (from ecosystem functions, biodiversity to ecosystem services).

3. Results

3.1 Overview of published ecosystem accounts

These first results present an overview of the literature on ecosystem accounting: what accounting frameworks are developed, the temporal evolution of the literature, the topics these articles address, and the outlets that publishes them, to have a sense of the scientific disciplines involved.

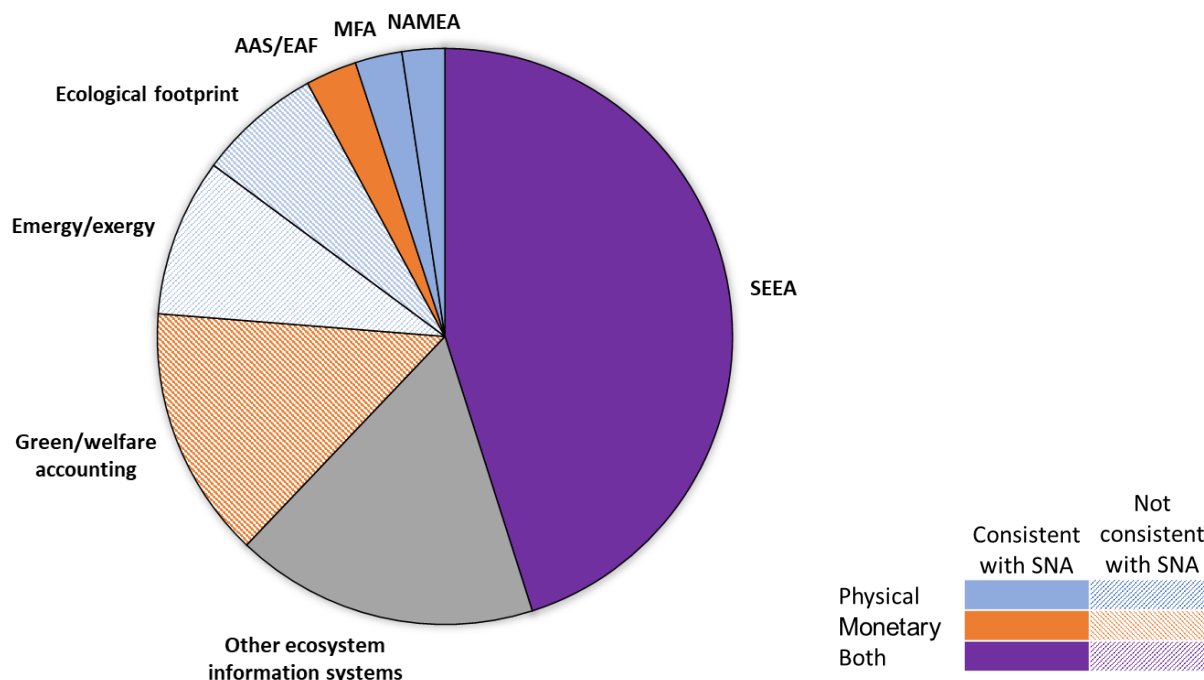


Figure 2: share of different conceptual frameworks in the literature reviewed. SEEA: System of Environmental-Economic Accounting; NAMEA: National Accounting Matrix for Environmental Accounting; MFA: Material Flow Accounting; AAS/EAF: Agroforestry Accounting System.

Eleven accounting frameworks dealing with ecosystems have been identified. The main one is the System of Environmental-Economic Accounting (SEEA), with 45% of the articles reviewed here using this framework to discuss or produce ecosystem accounts (Figure 2). There are several iterations of the SEEA. The first one was first published in the 1990s under the name Integrated Environmental and Economic Accounting (Bartelmus et al., 1991; United Nations, 1993). It was first revised in 2003 (United Nations et al., 2003). A second revision, in 2012, gave rise to a volume solely dedicated to ecosystems accounting, the SEEA Experimental Ecosystem Accounting (SEEA-EEA) (UNSD, 2014b). A third revision has just been adopted as a statistical standard in its chapters 1-7 on the biophysical accounts of ecosystem extent, condition, and ecosystem services. Research articles throughout the period studied have been discussing ecosystems in the context of these different versions of the SEEA. The SEEA is currently the only accounting framework that contains both biophysical and economic accounts consistent with the System of National Accounts (SNA) (Figure 2).

The second most used framework is green accounting (14% of articles), also referred to as welfare accounting, that encompasses research conducted mostly by economists, with theoretical developments on welfare (El Serafy, 1998; Cairns, 2000; Dasgupta, 2009; Arrow et al., 2012; Mäler, 1991) and practical applications that have produced for example the Genuine Savings, which extends a nation's capital stock to include natural capital, implemented in most countries of the world (e.g. Hassan and Ngwenya, 2006 in Swaziland, or Lange et al., 2018 for a global picture). The main difference between the green accounting literature and the SEEA is

their approach to monetary valuation. Under the SEEA, monetary valuation of ecosystem goods and services is using exchange values to be consistent with SNA, thus neglecting consumer surpluses, while the green accounting literature specifically aims at assessing welfare values that are not consistent with the SNA (Caparrós et al., 2017; Hein et al., 2016).

Many articles are also written about biophysical approaches to the environment economy relationship. The emergy/exergy framework (9% of articles), which is very different from the SEEA and Green accounting conceptually, is using principles of thermodynamics and uses solar energy as a single unit to describe interactions between the economy and the environment (Odum, 1996; Ugliati and Brown, 1998), and it has been used in the Asia and Pacific region (Chen and Chen, 2007). Also converting human-environment interactions into a single unit is the ecological footprint framework (7% of articles) (and sometimes discussed in relation with emergy (Shao et al., 2013)), which converts human appropriation of natural capital into a metric of sustainable use of biologically productive areas (Wackernagel et al., 1999). A third framework of this “reductionist” nature is the Material Flow Accounting (MFA; Radermacher, 1999) (3% of articles), which is now one of the accounts of the SEEA CF and includes flows of emissions and waste (UNSD, 2014a). Since the goal of ecosystem accounts is to go beyond the construction of accounts of material flows (Weber, 2007), we find very little literature on MFA in this review. These frameworks target ecological processes but do not differentiate specific ecosystems. They can however differentiate between economic sectors. Similarly, the National Accounting Matrix for Environmental Accounting (NAMEA) (2% of articles), is producing accounts at the sectoral level on environmental impacts and can be linked to the SEEA (Dalmazzone and La Notte, 2013).

All the other frameworks have been developed by specific research programs. The Agroforestry Accounting System (AAS) framework (3% of articles) has been developed in Spain (Campos et al., 2008) over the past decade. This framework is consistent with the exchange value criteria of national accounts and that propose a full set of economic accounts with a headline indicator, Environmental Income (Campos et al., 2019). All other frameworks represent less than 2% of the articles included here. The Ecosystem Natural Capital Accounting (ENCA) framework developed by the Convention on Biological Diversity (CBD) (Weber, 2014), has similar aspects as the SEEA, including a geospatial biophysical basis, and differences as it describes the integration of indicators into an index, the Ecosystem Capability Unit (ECU). The Environmental Sustainability Gap (ESGAP) framework operationalizes indices of strong sustainability (Ekins et al., 2003) that stems from the notion of critical natural capital as a minimum level of natural capital that is not substitutable (Ekins & Simons, 1999). China’s Gross Ecosystem Product is a more recent endeavor, valuing in monetary terms ecological degradation to produce macro-economic indicators (Ma et al., 2020; Yang et al., 2021). Other frameworks discuss forms of structuring environmental information, such as the FDES of the United Nations (Bartelmus, 2015) and the evaluative information systems for conservation (EISC) (Feger et al., 2017).

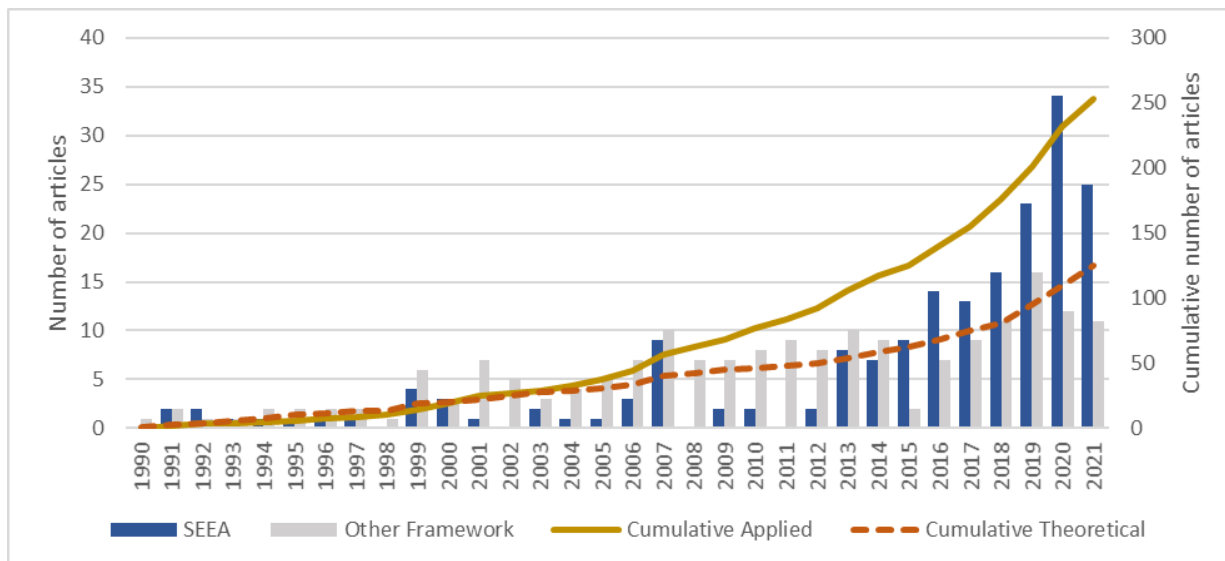


Figure 3: Evolution of the number of articles published over the years. Distinction has been made between articles following the SEEA or other frameworks, and articles with or without application (“applied” or “theoretical”)

From 2015 to 2021, more articles have been published using the SEEA than all the other conceptual frameworks combined (Figure 3). This shows a commitment from the scientific community to build on this framework for developing ecosystem accounting, and which is fed by concepts and methodologies from the other frameworks. For example, researchers on the AAS framework are now comparing their findings with the SEEA EA framework (Campos et al., 2019). 253 out of the 378 (67%) articles reviewed are applied. These applications can be found as tables, graphs or maps, and be very focused or very broad in scope. The number of articles containing an application is growing faster than conceptual articles, which indicates that ecosystem accounting is becoming operational and work is now moving towards case studies and implementation in different settings (Figure 3).

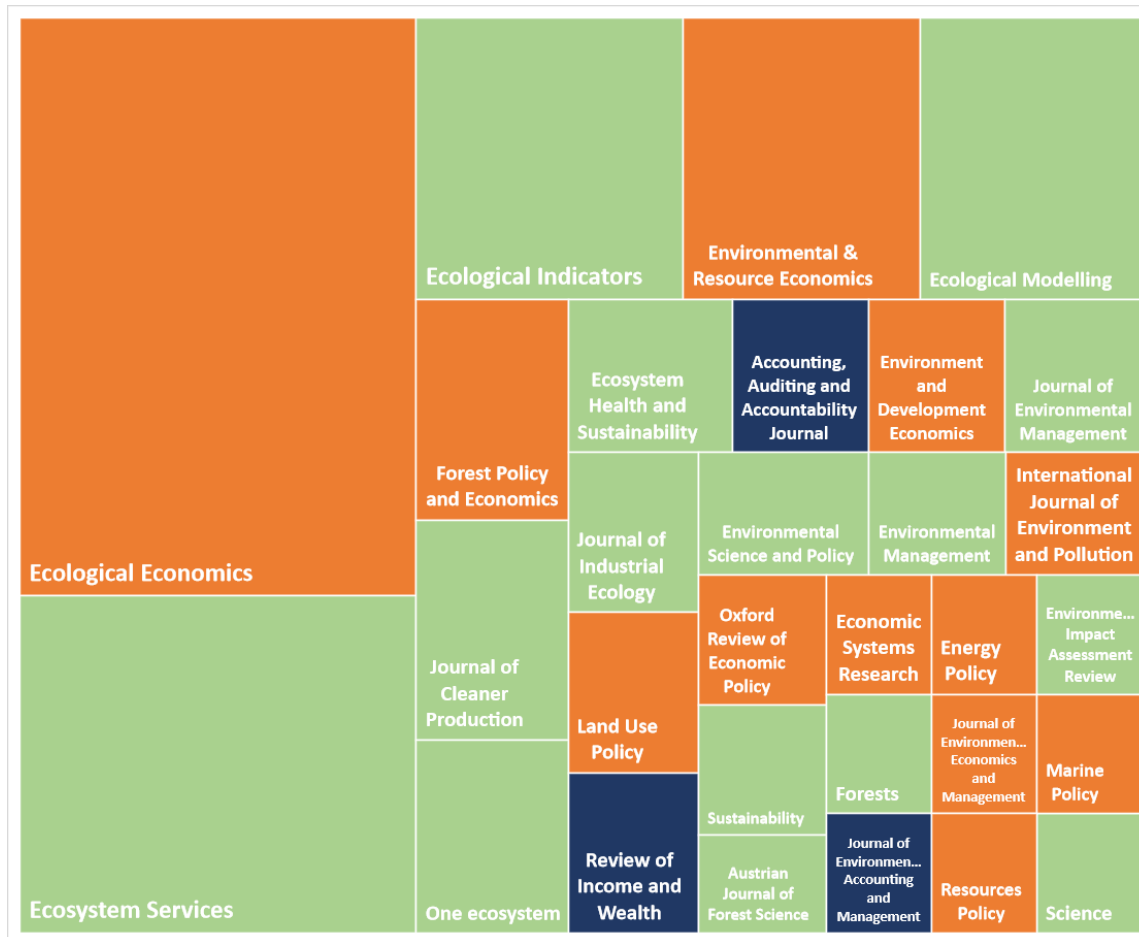


Figure 4: Journals publishing three or more of the articles reviewed here. Size represents the relative share of articles published, color represents main topic of the journal (Orange=economics, Light Green=ecology, Dark Blue=accounting).

The articles reviewed are published in 141 different journals. Thirty journals published three or more of the reviewed articles (Figure 4). While it is not possible to reduce all of these journals to single scientific disciplines, they revolve around three fields, from most to least invested in publications of ecosystem accounting studies: economics, ecology, and accounting. Most of the studies are published in journals at the interface of ecology and economics, with 'Ecological Economics' standing out (55 articles published in this journal). There are relatively few papers published in accounting journals, which may reflect that ecosystem accounting is not yet considered mainstream in accounting, and that ecosystem accounting builds on an interdisciplinary approach requiring spatial modelling and ecological skills that may be somewhat scarcer in the accounting community. Economists are bigger contributors to the literature than accountants, which may have implications in terms of constructing ecosystem accounts as some concepts do not have the same meaning in economics and in accounting sciences. For instance, the role of modelling and of accounting prices are not used necessarily in the same way in these two fields (Mäler et al., 2008), as the default rule is to use historical

exchange prices in accounting as a measure of value, whereas most economists are concerned with welfare measures of value.

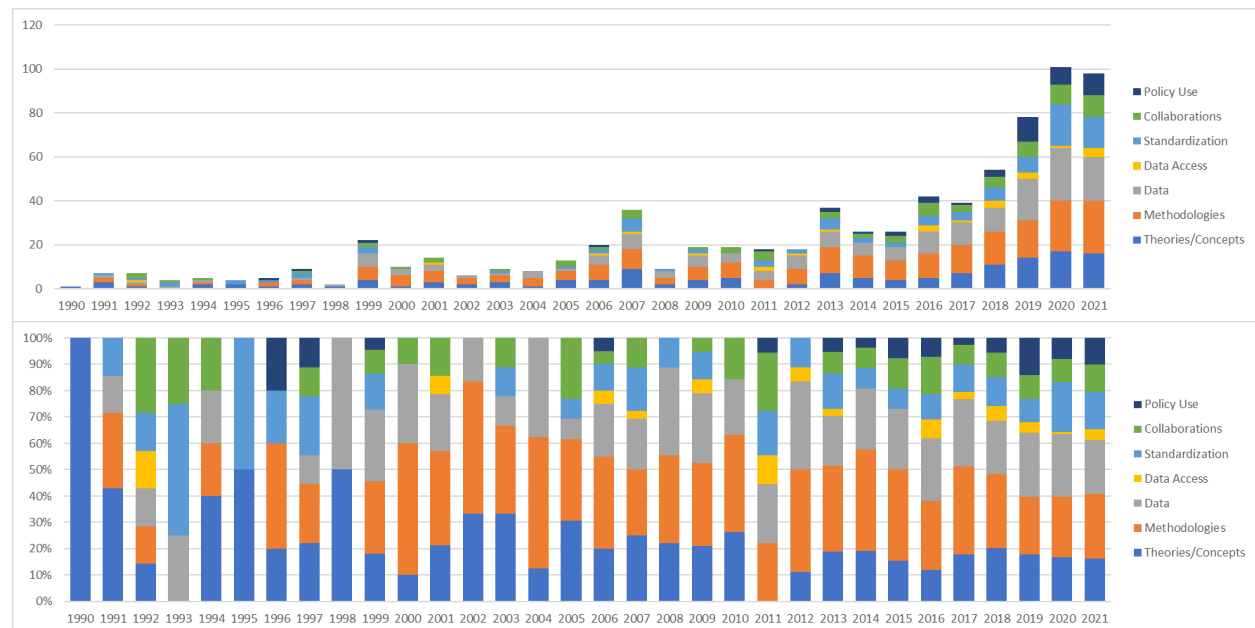


Figure 5: Evolution of the topics addressed by the scientific literature, in number of articles per year (top) and distribution of articles by types per year (bottom).

The topics identified in the literature on constructing ecosystem accounts are important elements to guide future research. Part of the literature focuses on concepts to construct ecosystem accounting frameworks. For instance, a clear definition of ecosystem services (ES) is a prerequisite to the accounting of ES flows and their inclusion in adjusted-macro-aggregates (Boyd, 2007). Concepts and methodologies represent more than 50% of the topics that the literature addresses (Figure 5). The number of articles focusing on conceptual topics is still increasing, but its relative share in the topics covered in the literature is decreasing. Methodological issues pertaining to ecosystem accounting are now the main topic that the literature is attempting to address. Still a minority, an increasing number of articles over the recent years addresses issues of data access, standardization, and collaborations. Collaborations between different disciplines (ecology, economics, and accounting) and between different stakeholders (public and private sectors) are now seen as crucial for the establishment of natural capital accounts (Boyd et al., 2018; Hein et al., 2020).

A relatively recent topic identified in the literature is the need for policy relevance of ecosystem accounting. Given that the overarching goal of ecosystem accounting is to guide public policies, it is surprising to find that this issue is only recently starting to be addressed. There are recent calls from the global community, for instance from the Rio+20 Conference, for producing ecosystem accounts, that respond to policy demands (Bagstad et al., 2021). Most of the studies

that include a discussion on policy describe in a general way how correcting national accounts would give a more accurate picture of economic activity and therefore help decisions which are based on the use of these figures (e.g. Ochuodho, & Alavalapati, 2016). Some articles are looking at the use of accounting to respond to specific policy agendas such as the Sustainable Development Goals, or to identify policy barriers to implementation of ecosystem accounting (Terema et al., 2016). One paper discusses how ecosystem accounts have been used in support of policy making (Shvidenko et al., 2010). Overall, it seems that more in-depth collaboration between scientists and stakeholders outside of academia is needed to improve policy uptake of ecosystem accounts (Bagstad et al., 2021).

Differentiating the topics that are the most addressed across the main conceptual frameworks of ecosystem accounting shows that methodological gaps are the main focus across the main frameworks. The frequency of the other topics varies greatly between the different conceptual frameworks. One clear result is the focus of green accounting on conceptual issues, with less emphasis on issues related to constructing accounts empirically (data, data access, standardization issues). Indeed, economic theory on the value of natural capital and its implication for wellbeing has emerged within the green accounting field (Arrow et al., 2012; Dasgupta, 2009; Cairns, 2000). On the contrary, the SEEA framework has been the focus of both theoretical but also empirical research articles. Collaboration is the subject of 30% of articles within the NAMEA framework, while only 3% of the investigations of emergy/exergy identify this topic. The ecological footprint is still being pursued, including by studies commissioned by the World Wildlife Fund, and this remains a policy relevant indicator. Potentially, in the future data from the SEEA ecosystem accounts could be used in support of assessing national or even global ecological footprints.

3.2 The scope of applications

Here are presented details on which ecosystems are studied in applications, what are the underlying values behind these accounts, what kind of methods are used to produce accounts, and the links between ecosystem accounts and national accounts.

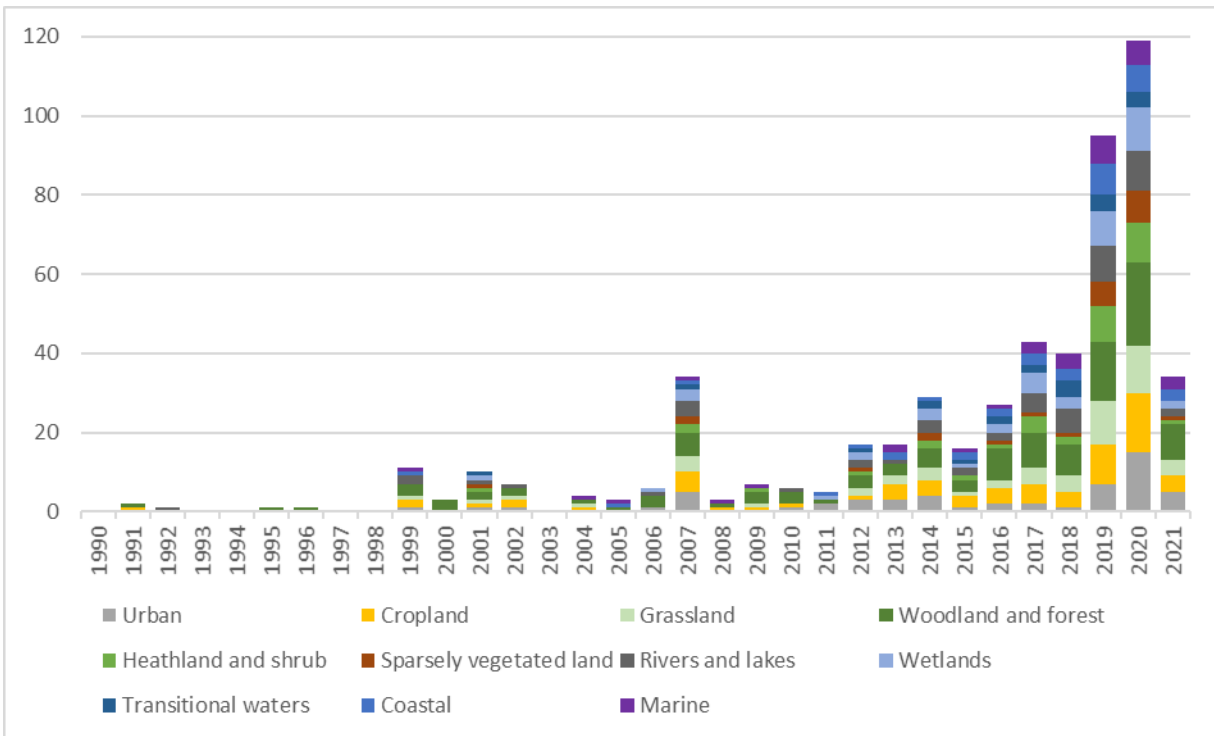


Figure 6: Number of articles focusing on each ecosystem per year. NB: palm oil plantations are part of cropland, not forest ecosystems. Fisheries are part of marine ecosystems.

A large portion of articles containing applications does not specifically define ecosystems. This is explained by many articles designed around sectors instead of ecosystems (e.g. agriculture, industry) or because articles discuss specific issues not tied to particular ecosystems (e.g. valuing ecosystem services). For the ecosystems that are explicitly mentioned, forests and woodlands are the most studied, and one of the few ecosystems studied since the beginning of the study period (Figure 6). The least studied is sparsely vegetated land. An increasing attention is dedicated to marine and coastal ecosystems (Buonocore et al., 2020; Cavalletti et al., 2020; Dvaskas, 2019; Fenichel et al., 2020; Lai et al., 2018), supported by the Global Ocean Accounts Partnership (<https://www.oceanaccounts.org/>).

While some studies are broad scale and cover a large array of ecosystems (dark shade, Figure SM1), other studies focus on one or two ecosystems, and particularly on forests. It may be the case because forests are important functionally, provide many ecosystem services, have been a subject of accounting for a longer time, and are easier to study compared to more remote ecosystems such as marine and coastal ecosystems. This however could bias the design of ecosystem accounting that should be applicable to all ecosystems, for example as the use of remote sensing to map ecosystem extent is harder for marine ecosystems.

	Anthropocentric Instrumental	Anthropocentric Relational	Non-anthropocentric instrumental	Non-anthropocentric Intrinsic
Theoretical	64%	26%	36%	5%
Applied	77%	15%	40%	3%
All articles	74%	17%	42%	4%

Table 2: Percentages of articles belonging to four dimensions of values. As multiple values are possible, the sum of percentage across the four categories of values is higher than 100%.

The majority of articles reviewed (68%) here can be classified as using an instrumental approach (Table 2). This is intuitive as one of the objectives of ecosystem accounting is to relate the status and uses of ecosystems to the economy (the national accounts). There is also an important proportion of articles that are classified as non-anthropogenic instrumental (29%). A recent focus of the literature has been to experiment biophysical accounts of ecosystem extent and condition of the SEEA (and species accounts, e.g., Weir (2018)), which falls in this category of values (Maes et al., 2020; Czúcz et al., 2021; Keith et al., 2021). Some articles also develop economic accounts focused on the maintenance and restoration of critical natural capital (Ekins et al., 2003; Levrel et al., 2014). A non-negligible percentage of articles also belong to the relational category of values towards nature. Relational values include cultural, social, emotional and physical relationships with nature. Articles on ecosystem accounting discussing non-anthropocentric values are marginal but not totally absent. These discussions revolve around the implications of accounting on ethical choices (Gamborg, 2002), for instance on the design of information systems to manage uses of multiple actors including world views or ceremonial uses of indigenous peoples (Feger et al., 2017; Normyle et al., 2022;).

While there is ongoing research on eliciting different definitions and measurements of these different values (Arias-Arévalo et al., 2017; Jacobs et al., 2018), our crude approach can be used to analyze the differences between what values are discussed in theory vs. in practice. The applied articles are more inclined to use instrumental as opposed to relational and intrinsic values (70%, Table 2), which is associated with the fact that instrumental values are more easily quantifiable, and a large amount of methods has been developed to quantify instrumental relationships between ecosystems and the economy. There is a spike in instrumental values in 2007 linked to the special issue on accounting in the journal Ecological Economics that introduced advances in the 2003 version of the SEEA (Lange, 2007). Relational values are more difficult to quantify and indeed we find more theoretical than applied articles discussing this type of value. For example, Sullivan & Hannis (2017) criticize economic quantification of nature in environmental accounting, which (according to them) misses the point of "value" of nature and is set in a specific political setting where natural capital is a rent that rewards private ownership of nature.

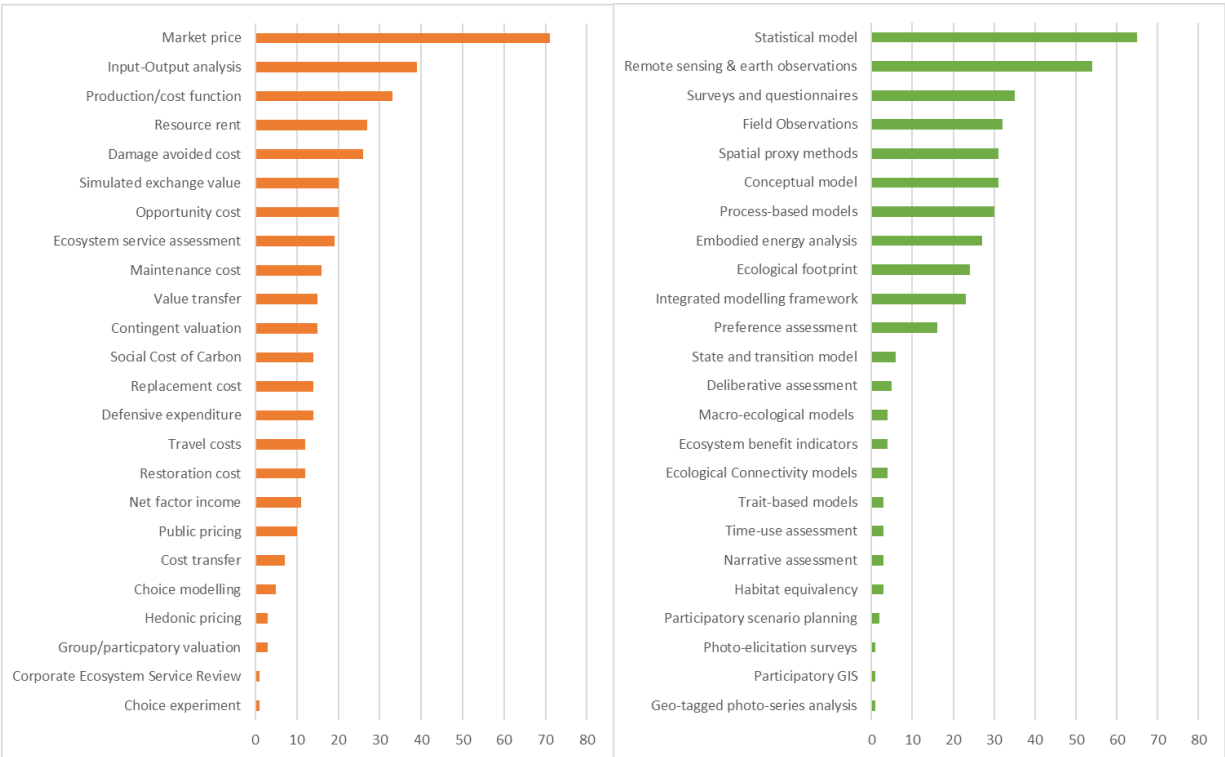


Figure 7: Number of applied articles using monetized methods (left, orange) and non-monetized methods (right, green) to construct accounts

There are mainly two types of methods to produce ecosystem accounts: monetized methods and non-monetized (i.e. biophysical and socio-cultural) valuation methods (Santos-Martin et al., 2018; Schröter et al., 2016). These are not mutually exclusive, as producing monetary values of ecosystem services often relies on surveys, questionnaires, and other types of assessments. A large variety of methods are used in the literature to produce accounts, which we classified in 24 non-monetized methods and 24 monetized valuation methods (Figure 7). This result parallels the predominant use of instrumental and to a lesser extent intrinsic values above relational value.

Looking specifically at the monetized valuation methods, market prices are the most used methodology, which is consistent with the use of exchange values recommended in the SNA (SNA, 2008). Many articles use preference-based methods to conduct economic valuation of ecosystem accounts since 2000 (Figure 7). For instance, articles developing the AAS framework use preference-based methods to estimate simulated exchange value and not the consumer surplus or other welfare measure (Campos et al., 2021). Several propositions on the measurement of the cost of degradation are starting to offer consistent complementary accounts to the current structure developed in the SEEA Ecosystem Accounts (Ogilvy et al., 2018; Comte et al., 2020).

Biophysical quantification and representation on maps is fundamental for ecosystem accounting. The UN is working on updated valuation guidelines for SEEA EA that will parallel

their guidelines for biophysical modeling (United Nations, 2022). Monetary accounts can't be compiled without precise biophysical quantification, because biophysical data on ecosystem services is required as input into their monetary valuation (UN et al., 2021). However reliable biophysical data is required for sustainable use and management of ecosystems, ecosystem services and natural capital accounting at local, country, and regional levels. Biophysical data can be gathered either by direct observations and measurements, by indirect methods such as proxies or spatial extrapolation, or by modelling. In practice, multiple different methods are often used together, e.g. via integrated modelling platforms such as InVEST or ARIES, or through purpose-fitted selection of appropriate data and methods.

It is becoming increasingly clear that Artificial Intelligence (AI) and Machine Learning (ML) will greatly enhance our capacity to model and understand ecosystem services, in particular regulating and cultural services that require modelling of complex, spatially variable processes involving large amounts of data. For example, Duku and Hein (2021) analyze the rainfall maintenance service in Africa using ML, Araza et al. (2021) produce an above ground biomass map of the Philippines that can be extended to map carbon sequestration and Havinga et al. (2021) analyse landscape aesthetic quality with ML. The results obtained in these models could not have been achieved with traditional, e.g. process-based, modelling approaches. It is clear that, with large datasets increasingly available and the new generation of students increasingly schooled in ML this type of analysis will soon dominate the field of ES modelling.

In the context of ecosystem accounting, it is important to highlight ARIES, developed by researchers at the Basque Centre for Climate Change. This tool is an integrated, open-source modelling platform for environmental sustainability, where researchers from across the globe can add their own data and models to web-based repositories. In particular, the ARIES for SEEA Explorer application allows users anywhere in the world to produce rapid, standardized, scalable and customizable ecosystem accounts for their area of interest that are consistent with the SEEA Ecosystem Accounting framework.

In the ecosystem service supply and use account, most studies focus on provisioning and regulation services (both discussed by 32% of the articles reviewed), as opposed to cultural services (22% of articles). The tendency to discuss or even assess more provisioning and regulation services has also been highlighted in other papers containing ecosystem service assessments like in Campagne et al. (2020) which show that in 108 papers using the matrix approach (Burkhard et al. 2014) to assess ecosystem services, 94% assessed regulation services, 87% assessed provisioning services and 83% assessed cultural services. Similar tendency with more assessments of regulation services has been highlighted also in Egoh et al. (2012); Crossman et al (2013); Haase et al. (2014); Malinga et al. (2015); Englund et al. (2017) and Hölting et al. (2019).

Our literature review shows that an impressive number of accounts has been published. We count more than 25 unique types of accounts produced by the 253 applied articles reviewed here, among which the 6 core accounts and 5 thematic accounts proposed in the SEEA EA, but also ecological footprint accounts such as the embodied ecological overshoot account in China

between 1981 and 2001 (Chen & Chen, 2007), or green accounts such as the wealth account for storm protection benefits from marsh creation in Louisiana (Barbier, 2016). Within these categories, 614 individual accounts have been reported in the literature, presented as tables, maps, or graphs in the publications. The vast majority of research papers focus on one or two ecosystem accounts. The exceptions are seminal papers, either applied or conceptual, including Bartelmus et al. (1991) that first built the conceptual frameworks to link environmental and economic accounting and builds the accounts for one selected country and Dubé et al. (2006) that synthesises forestry and forestry-related accounts in a selected number of countries. Also, Edens and Hein (2013) propose a consistent way of including ecosystem services and ecosystem assets into ecosystem accounting.

3.3 Zooming into applications of the SEEA EA

After the adoption the SEEA EA framework as a global statistical standard (UN et al., 2021), several guidelines and technical reports are being developed to support the implementation strategy of ecosystem accounts: Guidelines on Biophysical Modelling (UN 2022); a Technical report on Monetary Valuation of Ecosystem Services and Assets (Interim version); as well as tools to support compilation such as ARIES for SEEA.

Here are provided results specifically linked to the implementation of the SEEA EA framework and concern the types of accounts produced and their geographic scope.

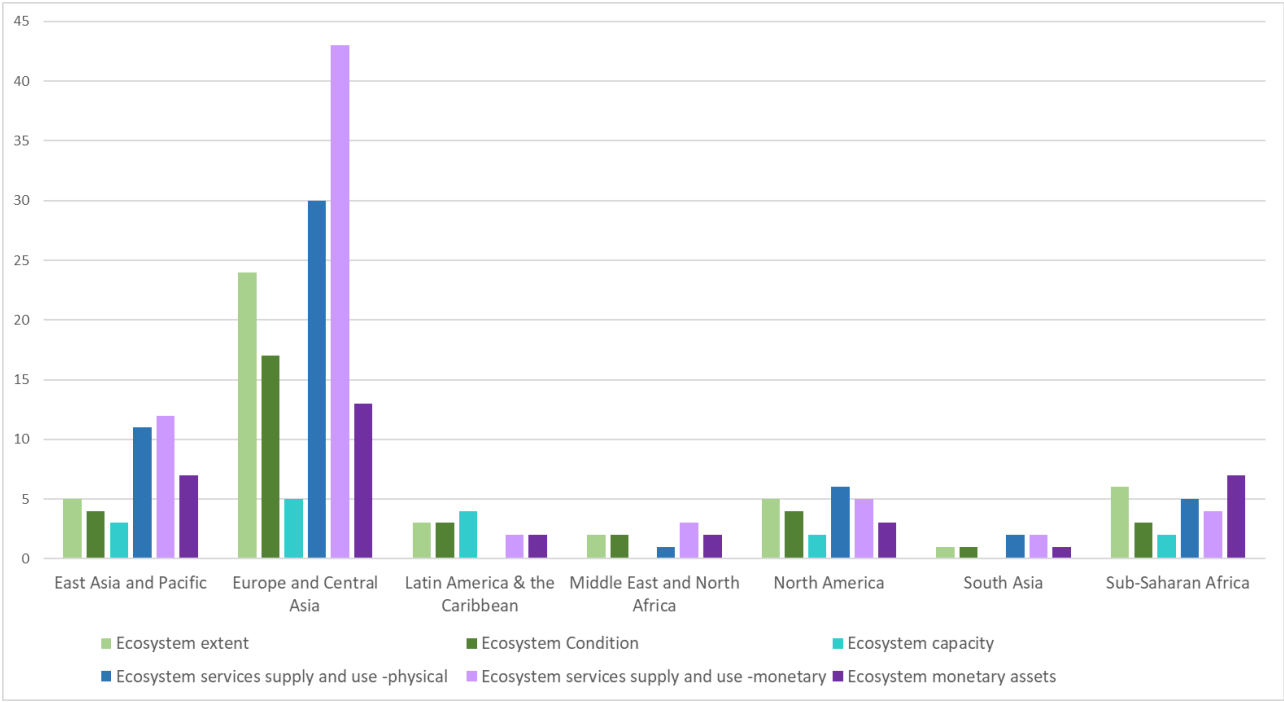


Figure 8: Number of applied articles that have produced accounts within the SEEA EA core accounts, per region of the world

The main accounts discussed in the literature on the SEEA are the ecosystem services flows accounts, both in biophysical and monetary terms (Figure 7; e.g. Schröter et al., 2016; Lai et al., 2018; Remme et al., 2015). The least discussed accounts are the condition account and the capacity account. Even though some interesting developments have attempted to operationalize ecosystem capacity account as a measure of sustainability (Schröter et al., 2014; La Notte et al., 2019a; Hein et al., 2016), this account does not appear in the last version of the SEEA EA (UNSD, 2020), but could be integrated in the condition account (Comte et al., 2020).

Geographical disparities exist in the production of ecosystem accounts. Europe is the region of the world that has produced the most extensive literature on EA (Figure 8). West-European countries and Australia (part of the East Asia and Pacific region) are the main contributors. Zooming into the ecosystem core accounts proposed in the SEEA EA, a slightly different picture emerges. While Europe is still leading the scientific production, followed by East Asia and Pacific, North America contributes a lot less, and Africa a bit more. North America only contributed to monetary accounts until recently, but biophysical accounts have been produced at the sub-national level in the United States (Warnell et al., 2020). However, SEEA accounts compilation in the US could speed up rapidly now that the White House has communicated an intention to start compiling SEEA EA accounts as of 2023 (<https://www.whitehouse.gov/ostp/news-updates/2022/04/24/accounting-for-nature-on-earth-day-2022/>).

4. Discussion

4.1 Frameworks and topics

Eleven different conceptual frameworks to produce ecosystem accounts have been highlighted in this review (Figure 2). These frameworks are not completely independent from each other, and overlaps or cross-breeding have occurred. Comparisons and integrations of different frameworks have been discussed, notably to fill conceptual gaps on the many compartments of ecosystem accounting. Lawn (2007), in his review of green accounting, argues for the necessity of using a broad variety of indicators, including economic indicators using the “green accounting” framework and biophysical indicators using the “ecological footprint” approach. Bartelmus (2003) compares material flow analysis and SEEA. Ultimately, MFA and NAMEA were included in the Central Framework of the SEEA. Vargas et al. (2018) also compares the SEEA, but with the more recent framework of planetary boundaries. The ENCA framework developed for the CBD and work on land accounts have participated in the definition of biophysical accounts in the SEEA (Weber, 2007). Research on green accounting was also used as foundations for the SEEA (Mäler et al., 2008). The increase in papers is related to the publication of the SEEA-EEA in 2012. Despite the evolution of topics that are the focus of the literature, conceptual issues are still discussed because of the complexity of accounting for

ecosystem and ecosystem services, and because of the conceptual and methodological difficulties to integrate ecosystem accounts with the SNA (La Notte et al., 2020).

While these discussions have helped to map the different possibilities to build ecosystem accounts, there is limited success in their integration. One stream of ecosystem accounting is green accounting and modifications of NNP to provide welfare aggregates (Mäler, 1991). While it has been argued early on that theoretical advances have been made and that empirical applications should now be undertaken in various countries (Vincent, 2000), this has not turned into reality for the study of ecosystems. Two products, the ISEW and the Genuine Savings, are the empirical applications of these theoretical advances, but have been criticized as inappropriate measure of sustainability (Hueting and Reijnders, 2004). While the World Bank is implementing Genuine Savings in many countries (Lange et al., 2018) and regularly updates its findings (World Bank, 2021), we have not found much of this literature in our review. It appears that this stream of literature has mainly stayed theoretical or focused on the issues of natural resources and pollution, but has not moved to focus on ecosystems and ecosystem services, mainly due to data constraints. However, this body of work has also influenced the initial development of the SEEA (Mäler et al., 2008).

The sequence of scientific inquiries through time also merits discussion. It appears that the literature began by formulating concepts and methodologies before clarifying the purpose that these accounts could serve in decision-making. Very few have questioned the use of ecosystem accounting in decision-making explicitly (Recuerdo-Virto et al., 2018). This is one of the major gaps identified in this paper, and that was already revealed for the literature on ecosystem services assessments (Laurans et al., 2015). The value of producing ecosystem accounts is broadly recognized, but their actual use for policy-making is still unknown. Few countries have yet produced these sets of accounts or provided access to underlying spatial data. Capacity building to produce complex ecosystem accounts is still necessary. As macro-economic aggregates, including GDP, are widely used, developing such an aggregate indicator using ecosystem accounts could lead to effective use by decision-makers. Another approach to their use is through a dashboard of indicators (Stiglitz, Sen, Fitoussi, 2009). These visions invariably lead to engage in the discussion of defining sustainability.

4.2 Sustainability

One major conceptual issue to be resolved is the measurement of sustainability (Dietz and Neumayer, 2007; Hamilton, 2016). Sustainability has to be conceptualized with respect to the relationship between ecosystem condition, capacity, and flow of services (La Notte et al., 2019a, with the use of monetary valuation methods, and), with the formulation of critical natural capital (Bordt and Saner, 2018; Fairbrass et al., 2020).

Ecosystem accounting goes beyond other approaches to ecosystem analysis through its explicit linking of ecosystems to economic and other human activity. The links are forged through the services provided by ecosystems and the impacts that economic and other human activity may

have on ecosystems and their future capacity. While ecosystem accounting does consider ecosystems and the economy to be different systems, they are analyzed jointly to reflect the fundamental connections between them. The use of an accounting framework enables the stock of ecosystems and flows from ecosystems to be defined in relation to each other and to a range of other sustainability information. Through the adoption of a systems perspective on environmental assets, information organized within the context of SEEA EA is able to provide an indication of impacts (both positive and negative) of economic and other human activity on the environment and can highlight the potential trade-offs among the different combinations of ecosystem services.

Monetary valuation of ecosystems can be done based on a valuation of the ecosystem services provided by the ecosystem (as in SEEA EA and in Wealth accounting) or based upon alternative approaches such as the restoration cost approach. Antagonist approaches to sustainability are mostly found in the monetary valuation of ecosystems (Dietz and Neumayer, 2007). A distinction exists between preference-based valuation and cost-based valuation methods as they represent different kinds of values and are associated with weak and strong approaches to sustainability respectively (Pearce et al., 2001; Levrel et al., 2014; Dietz and Neumayer, 2009). Ecosystem accounting does not imply a choice for a specific sustainability paradigm. The information in the accounts can be used to measure sustainability, as far as the use of ecosystems is concerned, in terms of both a weak (allowing conversion of natural to other types of capital) or a strong (allowing no such conversion) sustainability approach. The ecosystem extent and condition accounts show the area covered by different ecosystem types and their condition or state. A strong sustainability paradigm requires these areas and their condition to remain intact, or potentially to allow conversion of one ecosystem type to another, or a decrease in ecosystem quality in one ecosystem if compensated by an increase in quality of another ecosystem. This is measured in the ecosystem accounts. In case a weak sustainability approach is followed, some trade-off between ecosystem and other capital is allowed. In this case, it is useful to have information on the monetary value of ecosystems and the services they supply.

Hence, ecosystem accounting can support both (very) weak and (very) strong sustainability assessments. Depending upon the sustainability paradigm followed, either each individual type of ecosystem or the total amount of ecosystem assets needs to be at least stable (i.e. not be depleted or degraded). In both cases, some type of aggregation is necessary in order to compare trends in different types of ecosystem, or to analyze changes within ecosystem types. Aggregation is likely to require monetary valuation – since individual biophysical indicators (e.g. tons of standing biomass and soil organic matter content) cannot be summed.

Given the importance of measuring the sustainability of ecosystem use, the monetary valuation of ecosystems is also for this reason (in addition to monetary indicators being easier to communicate to policy makers) likely to become more important in the future. This echoes the scientific efforts on the developments of the economic accounts of the SEEA EA, focused on valuing benefits of ecosystem services in economic terms (Hein et al., 2016), which itself is supported by the rapidly growing literature on valuing ecosystem services (Laurans et al., 2015),

but the attempt to link measures of inclusive wealth (weak sustainability) with critical natural capital resilience is under early development (Walker and Pearson, 2007; Vargas et al., 2018).

This result suggests a gap in scientific efforts towards cost-based methods to produce economic accounts for maintaining critical natural capital (Vanoli, 1995; Bartelmus, 2009). These different points of view have practical implications for ecosystem accounting (Brouwer and Leipert, 1999). A welfare approach would include ecosystem services flows in calculation of final output as they represent changes in well-being (Mäler et al., 2008), which would lead to comparability and consistency issues (notably with SNA figures), according to many (Carpenter et al., 2009; Ludwig, 2000; Toman, 1998; Spash and Vatn, 2006). New techniques are allowing the valuation of simulated exchange values that do not include consumer surplus and therefore is not considered a welfare valuation of ecosystems (Caparrós et al., 2017). These monetary valuations are anchored in the weak sustainability paradigm when used to correct macro-aggregate figures. The critical natural capital approach in monetary terms emphasize the state of the environment as a reference and maintenance costs as a mean to attain it. It could produce a stand-alone figure of an “ecological debt” in monetary terms, or be included in the national accounts (Vanoli, 1995).

Another limitation in ecosystem accounts linked to sustainability is that, to date, there has been relatively little attention for ecosystem regime shifts, resilience and thresholds in ecosystem dynamics (e.g. Folke et al., 2004). These thresholds are critical to the safe operating space and resilience concepts (Steffen et al., 2015; Vargas et al., 2018). Biophysical indicators of critical natural capital need normative targets, using precautionary approaches (Farmer and Randall, 1998), operationalized notably through the environmental sustainability gap framework (Ekins & Simon, 1999; Usubiaga-Liaño & Ekins, 2021; Comte et al., 2021). These fields still need to be connected somehow. One possibility is to have reference conditions that describe the boundaries of critical natural capital (Comte et al., 2020).

4.3 Applications and the SEEA

The adoption of SEE-EA as global statistical standard, and rolling out this system among countries would greatly enhance the availability of data for ecosystem assessments as well as support a systematic monitoring of ecosystem state and the supply of ecosystem services. Implementing the SEEA EA requires biophysical modelling of ecosystem services. These models should be robust and accurate, have a high spatial resolution and be applicable at local to national scale. In the past decade, several approaches and lines of thinking have been developed on how to model ecosystem services for accounting. In the coming years, one of the main research topic will be how to apply this model for decision making and discuss complementarity and synergies between approaches. For instance in Europe, the MAIA (Mapping and Assessment for Integrated ecosystem Accounting) projects (<https://maiaportal.eu/>) aims to promote the mainstreaming of natural capital accounting in EU Member States and Norway.

Western European countries, Australia and North American countries account for a disproportionate share of scientific articles. The Netherlands and the United Kingdom seem to be the most advanced in producing SEEA ecosystem accounts (Hein et al., 2020). This could be explained by cultural differences, as ecosystem accounts are produced to inform national accounts and guide public policies in a top-down manner, whereas liberal democracies may be more interested in economic evaluations to inform cost-benefit analyses for public and private decision-making. The Integrated Natural Capital Accounting (INCA) initiative (<https://ecosystem-accounts.jrc.ec.europa.eu/>) is also an important building block that steered the process of ecosystem accounting in Europe. Eurostat, the statistical office of the European Union, is the first to enforce legislation on the mandatory production of ecosystem accounts following the SEEA guidelines (European Commission, 2022). In the emerging world, Mexico, Brazil, China, India and South Africa have been producing ecosystem accounts outside of the peer-reviewed literature, partly thanks to international programs such as Wealth Accounting and the Valuation of Ecosystem Services (WAVES) and Natural Capital Accounting and Valuation of Ecosystem Services (NCAVES) (Hein et al., 2020). So far, there seems to have been relatively little consideration of SEEA accounts in IPBES, which may be related to ecosystem accounts being published only recently in many countries, and to the different perspective on valuation taken in IPBES. Nevertheless, the biophysical information in the SEEA accounts, and parts of the monetary valuation (although narrower in scope than the value concept of IPBES) could support IPBES by providing comprehensive data on ecosystems that is both consistent in time and between countries. At the same time, IPBES yields valuable insights in human-ecosystem interactions that are relevant for SEEA ecosystem accounts. Hence, further collaboration would likely be mutually beneficial.

A large portion of the literature from 1990 to 2021 focuses on more than one ecosystem, focuses on more than one account, and uses more than one type of methodology to populate these accounts. However, there is no evidence that the number of methods or accounts in a single article is increasing over the years. There is however an upward trend in the number of ecosystems included since 2008. The evidence is therefore not clear that more extensive sets of ecosystem accounts are created over time in the peer-reviewed literature. This may not be the case for several reasons: either the amount of work and the diversity of methods that have to be used to produce an extensive set of ecosystem accounts is a barrier for the scientific community, or the format of journal articles is not appropriate or use to report on a wide variety of ecosystems and accounts in a single paper. Nevertheless, recent examples show that scientific papers can assemble a wide variety of ecosystems and accounts (e.g. Hein et al. 2020 and Vallecillo et al., 2019). It is likely that the scientific community focuses on developing and testing ecosystem accounts on specific issues, with standardization and comprehensive applications being conducted outside of the academic literature by statistic offices and other organizations.

4.4 Limits

The scope of this review, while designed to be exhaustive, only focuses on the English-written peer-reviewed literature. While this is an important corpus of information, the “grey literature” and the literature published in other languages is at least as valuable, particularly as ecosystem

accounting is an applied issue involving many stakeholders, some of which publish grey literature. Many accounts are published by statistical agencies outside peer-reviewed journals and in their native language. Other important sources of knowledge outside the scope concerns London Group papers and reports from international programs such as WAVES (<https://www.wavespartnership.org/>). Considering the narrow scope of this present review, it was not possible to assess to which extent the literature on ecosystem accounting was used to guide decision making and production of accounts by different actors outside of academia (and particularly statistical offices). We acknowledge that the exclusion of gray literature and the non-English language accounts are the major and critical limit of our study, and suggest careful interpretation of the figures presented (particularly Figure 8).

The list of articles reviewed here does not include much of the literature on environmentally-adjusted macro-aggregates such as the concepts of inclusive wealth or genuine savings (World Bank, 2006). These papers, while very important to further the development of new indicators of wealth, mostly consider natural resources (renewables or not) but not ecosystems per se. This review also misses all the “inventories” produced in the literature, including for example greenhouse gas inventories that are reported under the United Nations Framework Convention on Climate Change. Inventories could be associated to satellite accounts (outside of the core set of accounts described in the SNA) for the environment and aim at responding to specific policy objectives, whereas ecosystem accounts should be able to give a broader overview of ecosystem assets (Azqueta and Sotelsek, 2007).

The uptake of the literature in policy documents is outside the scope of this paper because we do not focus on the grey literature but would be an important avenue for future work. Moving forward, it is recommended to include decision-makers, and not limited to statistical offices but also other departments and ministries at every level of decision, in order to assess the possible use and demands for building ecosystem accounting systems (Vardon et al., 2016; Hein et al., 2020). This dialogue could potentially lead to reappraising the sets of accounts to be developed, which may not be aligned with current scientific proposals (Bartelmus, 2015; Comte et al., 2020). For instance, van den Bergh & Grazi (2014), argue that while the ecological footprint framework has gained attention in science and the general public, it is not useful for policy-making. Because a diverse set of indicators should be developed to produce useful information for policy-making (Lintott, 1996), we hope that the description of the scientific efforts’ breadths towards ecosystem accounting presented here will promote its implementation and development across geographies.

5. Conclusion

Ecosystem accounting has grown to become an important theme of research, with increasing number of articles and depth of scope. It first started as an emerging field with theoretical and methodological developments going in different directions. A second phase of structuring and refinement of the concepts and methods, aligned with the principles of accounting, ecology, and economy emerged, around the SEEA. The next phase that is just starting now revolves around testing, engagement, and adoption of ecosystem accounting. More applications are coming out,

on specific settings and policy-oriented questions, that engage the broader community beyond academia, including policy makers, managers, private sector, and NGOs.

It is also paramount to better connect SEEA ecosystem accounting efforts to IPBES, that could benefit from the comprehensive data in the ecosystem accounts in the countries where they are produced. However, the main next step in ecosystem accounting needs to be to connect ecosystem accounts to the user, including national and local policy makers, civil servants informing policy makers, research bodies and environmental assessment agencies informing civil servants informing policy makers, etc. Compiling ecosystem accounts requires substantial investments in data, capacity and forging institutional set-up for data sharing etc. and this will only be sustained if the policy makers and the ministries deciding upon budgets are convinced of the added value of ecosystem accounts. Amongst others, this requires providing easy access to users to all data in accounts, developing the guidance that users need to interpret the data in ecosystem accounts, and showcasing policy applications of accounts. In addition to further enhancing the quality of the accounts, these should be priorities for the accounting community in the coming years.

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1196 **Annex 1: supplementary information**

1197

Summary statistics
Authors
Title
Keywords
Abstract
Nb Citations
Affiliation
Country affiliation
doi
Type of document
Sources of funding

1198

Context	Justification
Scale of analysis	Statement
Location (regions of the world)	World Bank classification
Location (country)	country or countries where accounts are developed
Topics identified	Seven possible topics are used to categorize the focus and gaps discussed in the literature: Theories/concepts, Methodologies, Data, Data access, Standardization, Collaborations, and Policy use. These categories partly come from Ekstrom et al., 2015 (itself based on Zins 2007), with addition of standardization as a potential issue for statistics and indicators development. Data = artifacts/raw information: information = structured data; knowledge = subjective construct of information. Data gaps include geographic or sectoral data to complete accounts (for example lacking data on ecosystem de-services to produce ecosystem accounts (Shapiro et al., 2014), updating of the accounts. Collaborations include pluri-disciplinary work and resources to produce accounts. Policy-oriented gaps include lack of political will to sustain accounts, and inappropriateness of accounts to answer policy needs.
Conceptual framework	Several concepts have emerged in the literature on ecosystem accounting, including the UN's SEEA (UNSD, 2014a,b), the CBD's ENCA (Wever, 2014), ecological footprints (Wackernagel et al., 1997), thermodynamics accounting (emergy), green

	accounting (Arrow,...), Ekin's SGAP (Ekins et al., 2003), and the evaluative information systems for conservation (EISC) (Feger et al., 2017)
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Theory/economics	Justification
Values	We chose a typology that is relevant specifically for ecosystem accounting, from the discussion paper 5.1 of the SEEA EEA revision process (Barton et al., 2019).

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Methods	Justification
Non-monetized methods	Santos-Martin et al 2018; EPA 2009, Vaissière et al., 2013
Monetized valuation methods	Obst et al., 2016, Santos-Martin et al., 2018, Levrel et al., 2014

1201

Accounts	Justification
Core accounts (SEEA EEA)	Following the SEEA-EEA
Thematic accounts (SEEA EEA)	Following the SEEA-EEA
Accounts (non-SEEA)	From the literature
Categories of ecosystem services	Based on the CICES classification (Haines-Young and Potschin (2010))
Units used	from literature; access can be public or private access, or distance to access a natural amenity
Ecosystems	From the literature
Input data	From the literature

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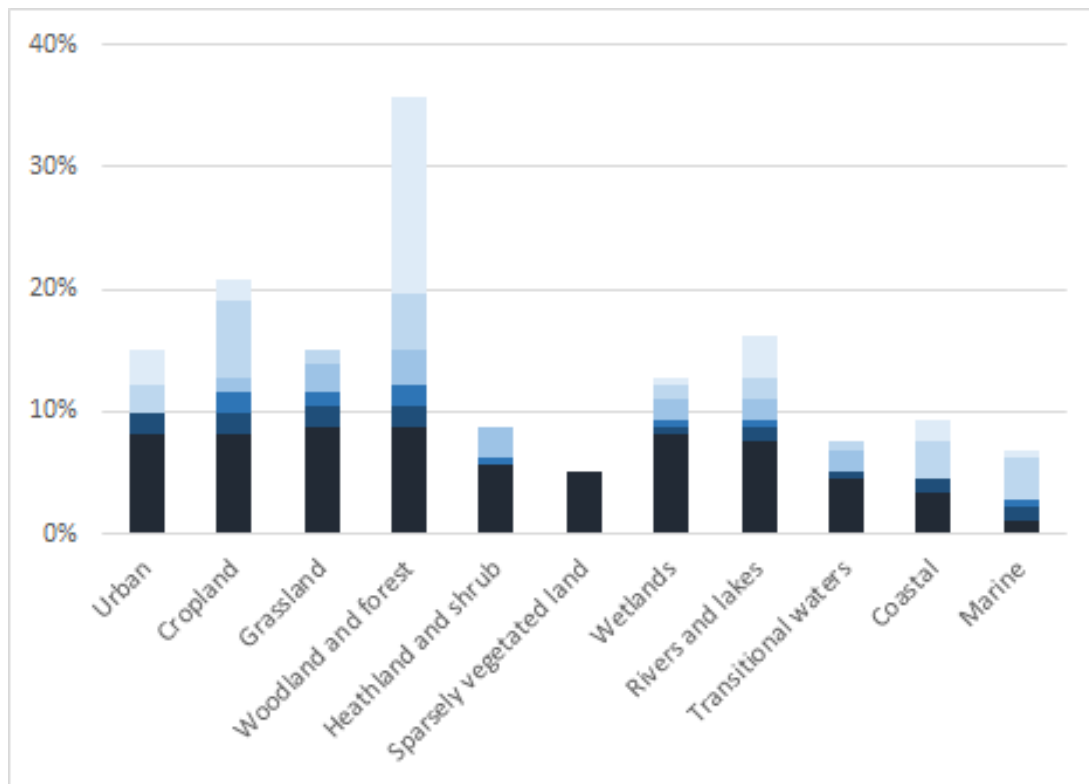


Figure SM1: Number of ecosystems studied, in percent of applied articles. Black: article considers this ecosystem in addition to at least 5 other ecosystems, shades of blue: this ecosystem and a total of 4 to 1 ecosystems per article were studied in the papers. Light blue: only this ecosystem is studied in a single article. NB: palm oil plantations are part of cropland, not forest. Fisheries are part of marine ecosystems.