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► **To cite this version:**

Adrien Comte, C. Sylvie Campagne, Sabine Lange, Adrián García Bruzón, Lars Hein, et al.. Ecosystem accounting: Past scientific developments and future challenges. *Ecosystem Services*, 2022, 58, pp.101486. 10.1016/j.ecoser.2022.101486 . hal-03838650

HAL Id: hal-03838650

<https://hal.science/hal-03838650>

Submitted on 3 Nov 2022

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1 Ecosystem accounting: past scientific developments and future challenges

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22 Keywords: ecosystem accounting, national accounting, SEEA, natural capital, systematic review
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27 **Highlights**

- 28
29 - The SEEA is the main framework and becoming the standard for ecosystem accounting
30 - Research is moving towards operational issues of implementing ecosystem accounts
31 - Forests are the main habitats studied but the share of aquatic habitats is increasing
32 - Most monetary methods used are based on exchange values and accounting principles
33 - Europe is, to date, the most productive region for ecosystem accounts
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36

37 **Abstract**

38
39 To better manage our environment, systematic information is needed on the state of
40 ecosystems and their interactions with society. Efforts have been undertaken to design
41 monitoring and recording systems, notably the United Nations System of Environmental-
42 Economic Accounting (SEEA). However, the diverse conceptualizations and applications on
43 ecosystem accounting found the scientific literature have never been assessed in a systematic

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

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1. Introduction

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

70
71 In the scientific literature, there have been significant research efforts on ecosystem and natural
72 capital accounting over the past decades, including conceptual developments (e.g. Obst et al.,
73 2016; La Notte et al., 2019b) and applications (e.g. Weber, 2007; Barbier, 2016; Caparrós et al.,
74 2017; Schröter et al., 2014). Many conceptual frameworks and methodologies have emerged on
75 ecosystems and natural capital accounting. Overviews on ecosystem accounting (Edens and
76 Hein, 2013) and syntheses of particular topics of ecosystem accounting (Boyd and Banzhaf,
77 2007) have been produced in the literature and in the context of the United Nations with the
78 development of the SEEA (UNSD, 2014a; UNSD, 2014b; UNSD 2017; Edens et al., 2022). In
79 2013 the Statistical Commission of the United Nations endorsed the SEEA Experimental
80 Ecosystems Accounting (SEEA-EEA) as the basis for commencing testing and further
81 development of this new field of national accounts. In 2021, the United Nations Statistical
82 Commission has adopted chapters 1-7 of the System of Environmental-Economic Accounting—
83 Ecosystem Accounting (SEEA EA) as an international statistical standard (Edens et al., 2022).
84 These chapters focus on the biophysical part of ecosystem accounting, the monetary accounts
85 were not yet considered to be developed at the level of a statistical standard (Brown et al.,
86 2021). Note that, in the last revision, the prefix 'Experimental' that was previously used has

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

93

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

102

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

113

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

129

130 2. **Material and methods**

131

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

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

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

162 **2.1 Process of selecting articles**

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

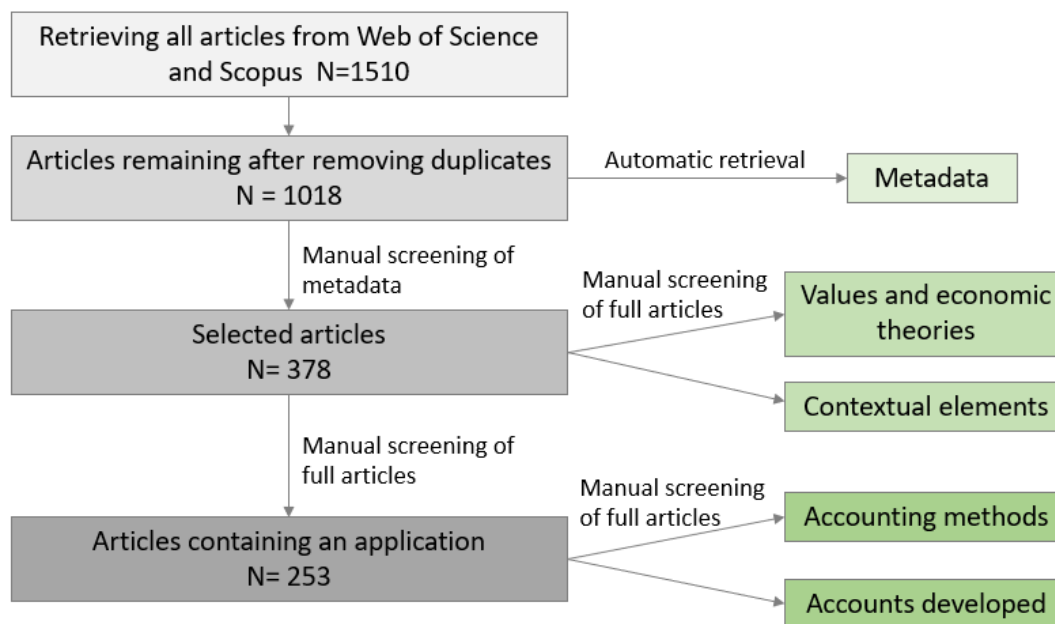
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167 Table 1: Terms used for the finding of articles on ecosystem accounting (TI: Title)

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

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171
172 Figure 1: Process of systematically selecting and analysis the literature
173

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

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

186

187 2.2 Categories of analysis of the literature

188

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

195 2.2.1 Metadata

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

200

201 2.2.2 Contextual elements

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

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

210 2.2.3 Underlying values and economic theories mobilized

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

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

228 2.2.4 Accounting methods

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

235

236 2.2.5 Accounts developed

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

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248 **3. Results**

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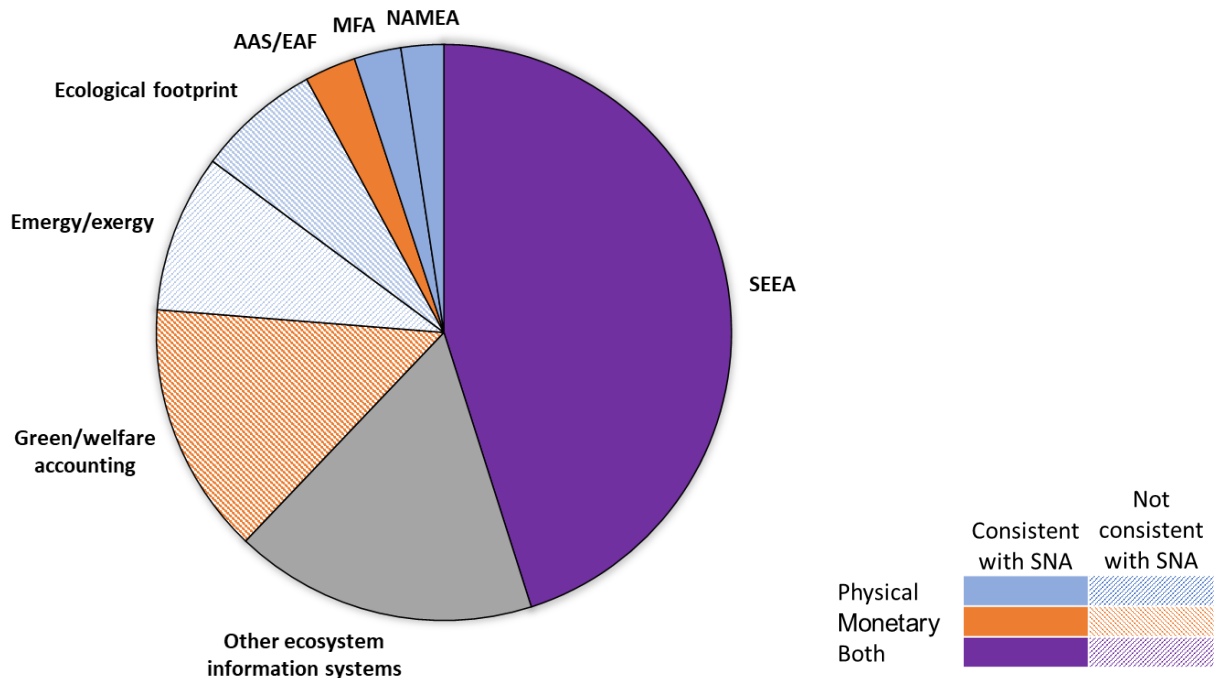
250 3.1 Overview of published ecosystem accounts

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

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

263

264 Eleven accounting frameworks dealing with ecosystems have been identified. The main one is
265 the System of Environmental-Economic Accounting (SEEA), with 45% of the articles reviewed
266 here using this framework to discuss or produce ecosystem accounts (Figure 2). There are
267 several iterations of the SEEA. The first one was first published in the 1990s under the name
268 Integrated Environmental and Economic Accounting (Bartelmus et al., 1991; United Nations,
269 1993). It was first revised in 2003 (United Nations et al., 2003). A second revision, in 2012, gave
270 rise to a volume solely dedicated to ecosystems accounting, the SEEA Experimental Ecosystem
271 Accounting (SEEA-EEA) (UNSD, 2014b). A third revision has just been adopted as a statistical
272 standard in its chapters 1-7 on the biophysical accounts of ecosystem extent, condition, and
273 ecosystem services. Research articles throughout the period studied have been discussing
274 ecosystems in the context of these different versions of the SEEA. The SEEA is currently the
275 only accounting framework that contains both biophysical and economic accounts consistent
276 with the System of National Accounts (SNA) (Figure 2).

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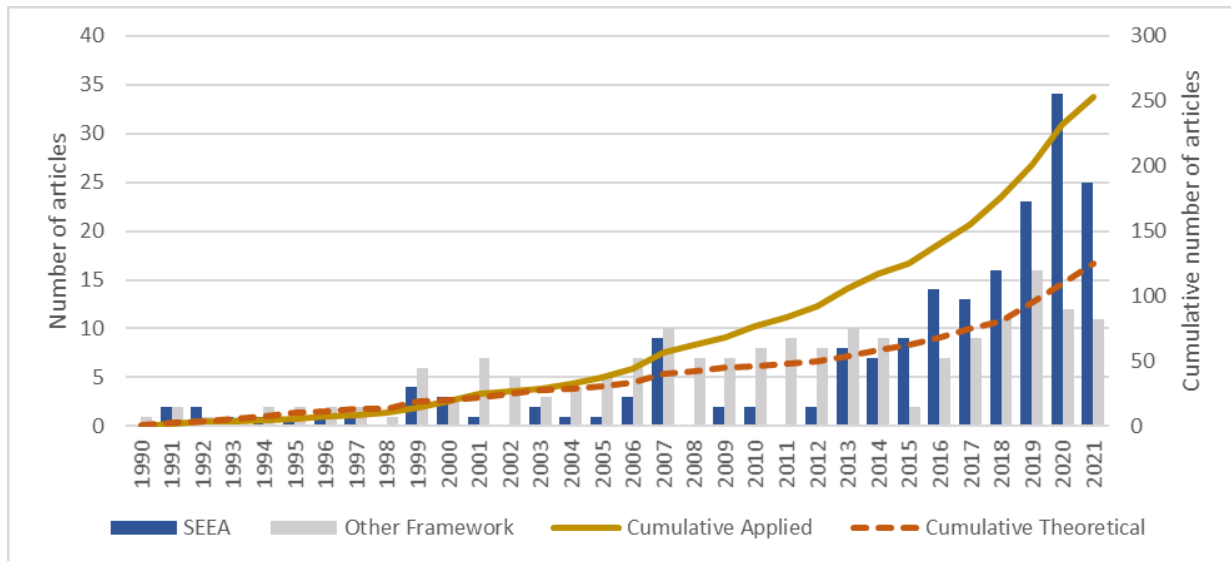
278 The second most used framework is green accounting (14% of articles), also referred to as
279 welfare accounting, that encompasses research conducted mostly by economists, with
280 theoretical developments on welfare (El Serafy, 1998; Cairns, 2000; Dasgupta, 2009; Arrow et
281 al., 2012; Mäler, 1991)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

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

289
290 Many articles are also written about biophysical approaches to the environment economy
291 relationship. The emergy/exergy framework (9% of articles), which is very different from the
292 SEEA and Green accounting conceptually, is using principles of thermodynamics and uses
293 solar energy as a single unit to describe interactions between the economy and the environment
294 (Odum, 1996; Ugliati and Brown, 1998), and it has been used in the Asia and Pacific region
295 (Chen and Chen, 2007). Also converting human-environment interactions into a single unit is
296 the ecological footprint framework (7% of articles) (and sometimes discussed in relation with
297 emergy (Shao et al., 2013)), which converts human appropriation of natural capital into a metric
298 of sustainable use of biologically productive areas (Wackernagel et al., 1999). A third framework
299 of this “reductionist” nature is the Material Flow Accounting (MFA; Radermacher, 1999) (3% of
300 articles), which is now one of the accounts of the SEEA CF and includes flows of emissions and
301 waste (UNSD, 2014a). Since the goal of ecosystem accounts is to go beyond the construction
302 of accounts of material flows (Weber, 2007), we find very little literature on MFA in this review.
303 These frameworks target ecological processes but do not differentiate specific ecosystems.
304 They can however differentiate between economic sectors. Similarly, the National Accounting
305 Matrix for Environmental Accounting (NAMEA) (2% of articles), is producing accounts at the
306 sectoral level on environmental impacts and can be linked to the SEEA (Dalmazzone and La
307 Notte, 2013).

308
309 All the other frameworks have been developed by specific research programs. The Agroforestry
310 Accounting System (AAS) framework (3% of articles) has been developed in Spain (Campos et
311 al., 2008) over the past decade. This framework is consistent with the exchange value criteria of
312 national accounts and that propose a full set of economic accounts with a headline indicator,
313 Environmental Income (Campos et al., 2019). All other frameworks represent less than 2% of
314 the articles included here. The Ecosystem Natural Capital Accounting (ENCA) framework
315 developed by the Convention on Biological Diversity (CBD) (Weber, 2014), has similar aspects
316 as the SEEA, including a geospatial biophysical basis, and differences as it describes the
317 integration of indicators into an index, the Ecosystem Capability Unit (ECU). The Environmental
318 Sustainability Gap (ESGAP) framework operationalizes indices of strong sustainability (Ekins et
319 al., 2003) that stems from the notion of critical natural capital as a minimum level of natural
320 capital that is not substitutable (Ekins & Simons, 1999). China’s Gross Ecosystem Product is a
321 more recent endeavor, valuing in monetary terms ecological degradation to produce macro-
322 economic indicators (Ma et al., 2020; Yang et al., 2021). Other frameworks discuss forms of
323 structuring environmental information, such as the FDES of the United Nations (Bartelmus,
324 2015) and the evaluative information systems for conservation (EISC) (Feger et al., 2017).

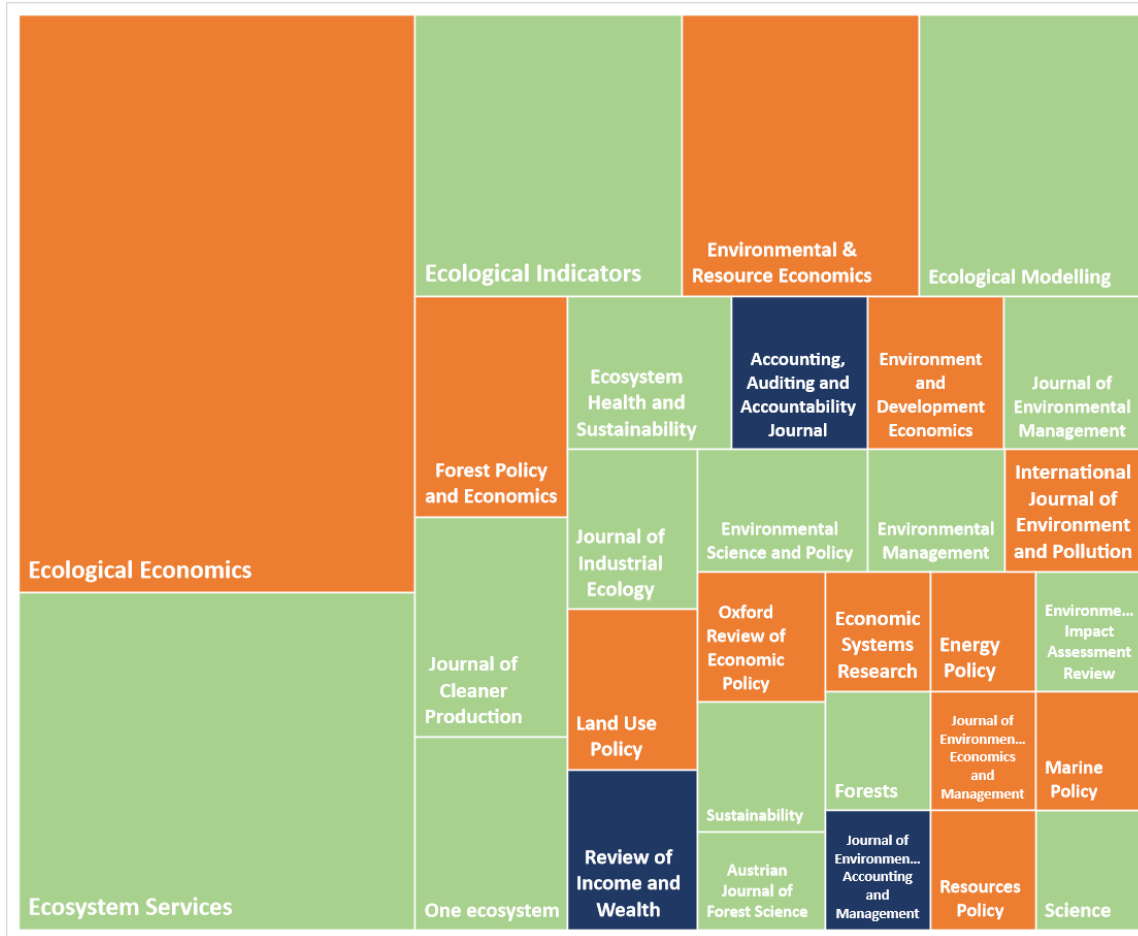
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Figure 3: Evolution of the number of articles published over the years. Distinction has been made between articles following the SEEA or other frameworks, and articles with or without application (“applied” or “theoretical”)

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).

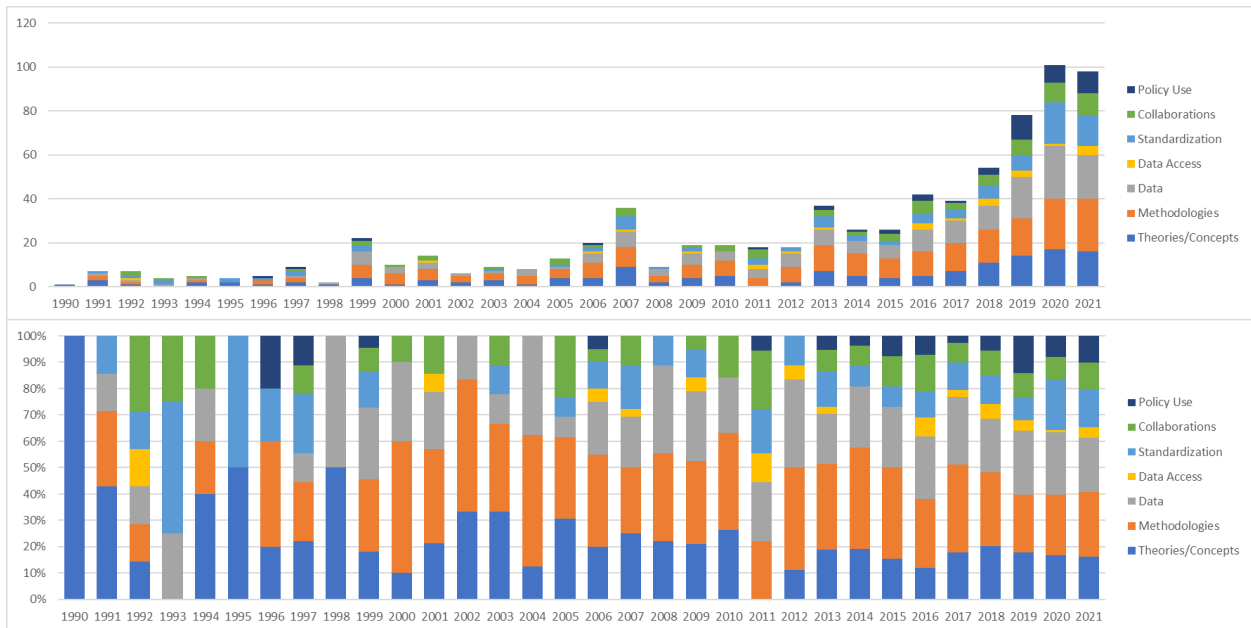


348
 349 Figure 4: Journals publishing three or more of the articles reviewed here. Size represents the
 350 relative share of articles published, color represents main topic of the journal
 351 (Orange=economics, Light Green=ecology, Dark Blue=accounting).
 352
 353

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

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

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 373
 374 Figure 5: Evolution of the topics addressed by the scientific literature, in number of articles per
 375 year (top) and distribution of articles by types per year (bottom).
 376
 377

378 The topics identified in the literature on constructing ecosystem accounts are important
 379 elements to guide future research. Part of the literature focuses on concepts to construct
 380 ecosystem accounting frameworks. For instance, a clear definition of ecosystem services (ES)
 381 is a prerequisite to the accounting of ES flows and their inclusion in adjusted-macro-aggregates
 382 (Boyd, 2007). Concepts and methodologies represent more than 50% of the topics that the
 383 literature addresses (Figure 5). The number of articles focusing on conceptual topics is still
 384 increasing, but its relative share in the topics covered in the literature is decreasing.
 385 Methodological issues pertaining to ecosystem accounting are now the main topic that the
 386 literature is attempting to address. Still a minority, an increasing number of articles over the
 387 recent years addresses issues of data access, standardization, and collaborations.
 388 Collaborations between different disciplines (ecology, economics, and accounting) and between
 389 different stakeholders (public and private sectors) are now seen as crucial for the establishment
 390 of natural capital accounts (Boyd et al., 2018; Hein et al., 2020).
 391

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

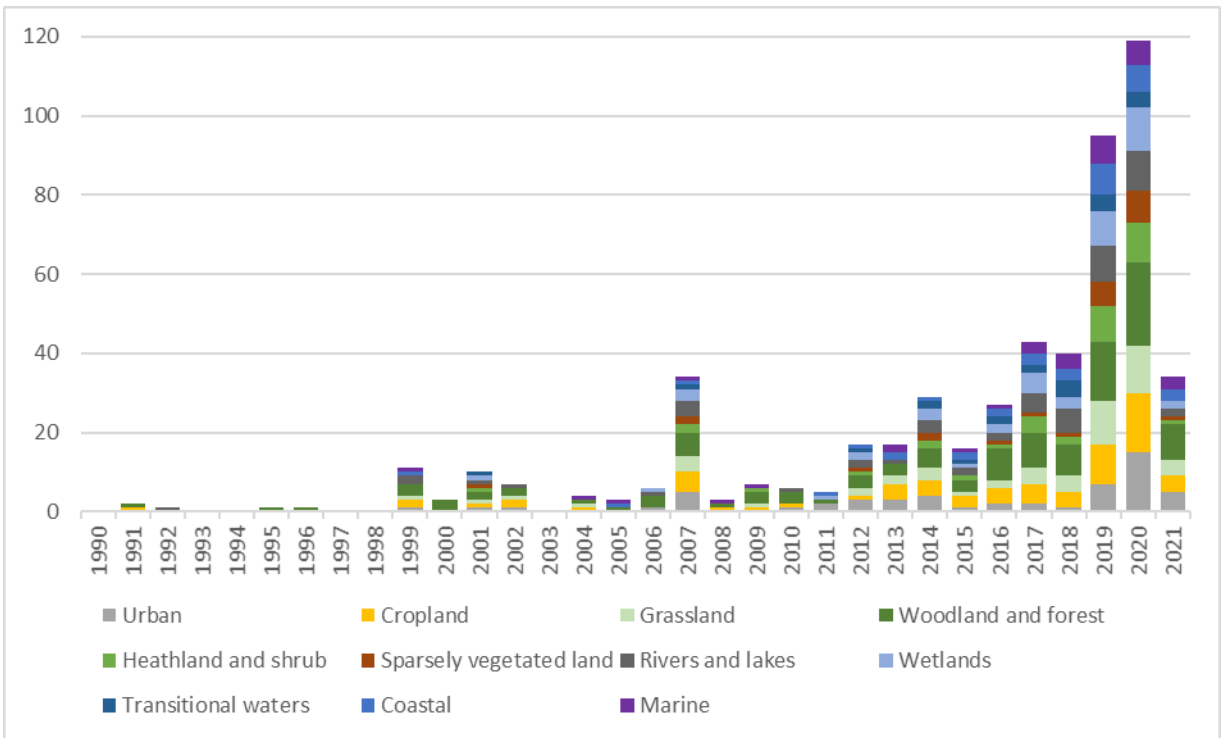
397 that include a discussion on policy describe in a general way how correcting national accounts
398 would give a more accurate picture of economic activity and therefore help decisions which are
399 based on the use of these figures (e.g. Ochuodho, & Alavalapati, 2016). Some articles are
400 looking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

406
407 Differentiating the topics that are the most addressed across the main conceptual frameworks of
408 ecosystem accounting shows that methodological gaps are the main focus across the main
409 frameworks. The frequency of the other topics varies greatly between the different conceptual
410 frameworks. One clear result is the focus of green accounting on conceptual issues, with less
411 emphasis on issues related to constructing accounts empirically (data, data access,
412 standardization issues). Indeed, economic theory on the value of natural capital and its
413 implication for wellbeing has emerged within the green accounting field (Arrow et al., 2012;
414 Dasgupta, 2009; Cairns, 2000). On the contrary, the SEEA framework has been the focus of
415 both theoretical but also empirical research articles. Collaboration is the subject of 30% of
416 articles within the NAMEA framework, while only 3% of the investigations of emergy/exergy
417 identify this topic. The ecological footprint is still being pursued, including by studies
418 commissioned by the World Wildlife Fund, and this remains a policy relevant indicator.
419 Potentially, in the future data from the SEEA ecosystem accounts could be used in support of
420 assessing national or even global ecological footprints.

421 422 3.2 The scope of applications

423
424 Here are presented details on which ecosystems are studied in applications, what are the
425 underlying values behind these accounts, what kind of methods are used to produce accounts,
426 and the links between ecosystem accounts and national accounts.

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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.

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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; Dvarskas, 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.

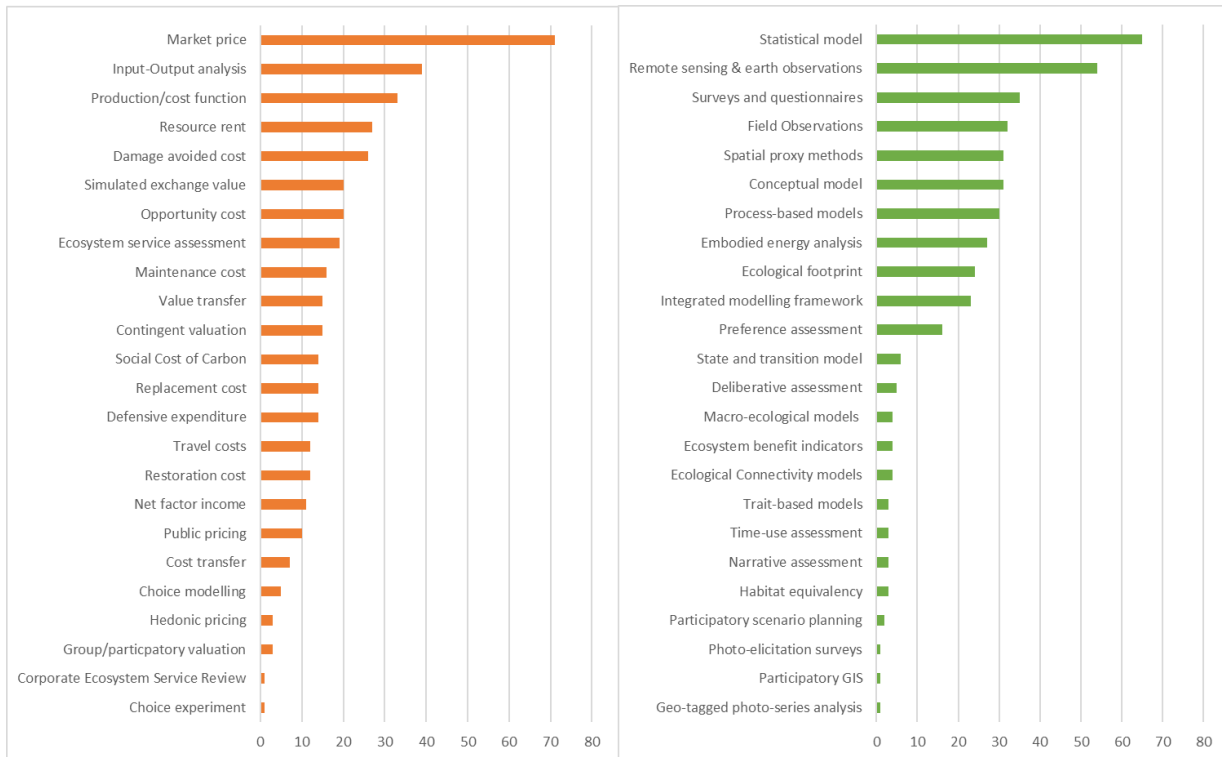
	Anthropocentric Instrumental	Anthropocentric Relational	Non-anthropocentric instrumental	Non-anthropocentric Intrinsic
Theoretical	64%	26%	36%	5%
Applied	77%	15%	40%	3%
All articles	74%	17%	42%	4%

451
452 Table 2: Percentages of articles belonging to four dimensions of values. As multiple values are
453 possible, the sum of percentage across the four categories of values is higher than 100%.
454

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

470
471 While there is ongoing research on eliciting different definitions and measurements of these
472 different values (Arias-Arévalo et al., 2017; Jacobs et al., 2018), our crude approach can be
473 used to analyze the differences between what values are discussed in theory vs. in practice.
474 The applied articles are more inclined to use instrumental as opposed to relational and intrinsic
475 values (70%, Table 2), which is associated with the fact that instrumental values are more easily
476 quantifiable, and a large amount of methods has been developed to quantify instrumental
477 relationships between ecosystems and the economy. There is a spike in instrumental values in
478 2007 linked to the special issue on accounting in the journal Ecological Economics that
479 introduced advances in the 2003 version of the SEEA (Lange, 2007). Relational values are
480 more difficult to quantify and indeed we find more theoretical than applied articles discussing
481 this type of value. For example, Sullivan & Hannis (2017) criticize economic quantification of
482 nature in environmental accounting, which (according to them) misses the point of "value" of
483 nature and is set in a specific political setting where natural capital is a rent that rewards private
484 ownership of nature.

485
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487



489
 490 Figure 7: Number of applied articles using monetized methods (left, orange) and non-monetized
 491 methods (right, green) to construct accounts
 492

493 There are mainly two types of methods to produce ecosystem accounts: monetized methods
 494 and non-monetized (i.e. biophysical and socio-cultural) valuation methods (Santos-Martin et al.,
 495 2018; Schröter et al., 2016). These are not mutually exclusive, as producing monetary values of
 496 ecosystem services often relies on surveys, questionnaires, and other types of assessments. A
 497 large variety of methods are used in the literature to produce accounts, which we classified in 24
 498 non-monetized methods and 24 monetized valuation methods (Figure 7). This result parallels
 499 the predominant use of instrumental and to a lesser extent intrinsic values above relational
 500 value.

501
 502 Looking specifically at the monetized valuation methods, market prices are the most used
 503 methodology, which is consistent with the use of exchange values recommended in the SNA
 504 (SNA, 2008). Many articles use preference-based methods to conduct economic valuation of
 505 ecosystem accounts since 2000 (Figure 7). For instance, articles developing the AAS
 506 framework use preference-based methods to estimate simulated exchange value and not the
 507 consumer surplus or other welfare measure (Campos et al., 2021). Several propositions on the
 508 measurement of the cost of degradation are starting to offer consistent complementary accounts
 509 to the current structure developed in the SEEA Ecosystem Accounts (Ogilvy et al., 2018; Comte
 510 et al., 2020).

511
 512 Biophysical quantification and representation on maps is fundamental for ecosystem
 513 accounting. The UN is working on updated valuation guidelines for SEEA EA that will parallel

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

523
524 It is becoming increasingly clear that Artificial Intelligence (AI) and Machine Learning (ML) will
525 greatly enhance our capacity to model and understand ecosystem services, in particular
526 regulating and cultural services that require modelling of complex, spatially variable processes
527 involving large amounts of data. For example, Duku and Hein (2021) analyze the rainfall
528 maintenance service in Africa using ML, Araza et al. (2021) produce an above ground biomass
529 map of the Philippines that can be extended to map carbon sequestration and Havinga et al.
530 (2021) analyse landscape aesthetic quality with ML. The results obtained in these models could
531 not have been achieved with traditional, e.g. process-based, modelling approaches. It is clear
532 that, with large datasets increasingly available and the new generation of students increasingly
533 schooled in ML this type of analysis will soon dominate the field of ES modelling.

534
535 In the context of ecosystem accounting, it is important to highlight ARIES, developed by
536 researchers at the Basque Centre for Climate Change. This tool is an integrated, open-source
537 modelling platform for environmental sustainability, where researchers from across the globe
538 can add their own data and models to web-based repositories. In particular, the ARIES for
539 SEEA Explorer application allows users anywhere in the world to produce rapid, standardized,
540 scalable and customizable ecosystem accounts for their area of interest that are consistent with
541 the SEEA Ecosystem Accounting framework.

542
543 In the ecosystem service supply and use account, most studies focus on provisioning and
544 regulation services (both discussed by 32% of the articles reviewed), as opposed to cultural
545 services (22% of articles). The tendency to discuss or even assess more provisioning and
546 regulation services has also been highlighted in other papers containing ecosystem service
547 assessments like in Campagne et al. (2020) which show that in 108 papers using the matrix
548 approach (Burkhard et al. 2014) to assess ecosystem services, 94% assessed regulation
549 services, 87% assessed provisioning services and 83% assessed cultural services. Similar
550 tendency with more assessments of regulation services has been highlighted also in Egoh et al.
551 (2012); Crossman et al (2013); Haase et al. (2014); Malinga et al. (2015); Englund et al. (2017)
552 and Hölting et al. (2019).

553
554 Our literature review shows that an impressive number of accounts has been published. We
555 count more than 25 unique types of accounts produced by the 253 applied articles reviewed
556 here, among which the 6 core accounts and 5 thematic accounts proposed in the SEEA EA, but
557 also ecological footprint accounts such as the embodied ecological overshoot account in China

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

568
 569

3.3 Zooming into applications of the SEEA EA

570

571
 572 After the adoption the SEEA EA framework as a global statistical standard (UN et al., 2021),
 573 several guidelines and technical reports are being developed to support the implementation
 574 strategy of ecosystem accounts: Guidelines on Biophysical Modelling (UN 2022); a Technical
 575 report on Monetary Valuation of Ecosystem Services and Assets (Interim version); as well as
 576 tools to support compilation such as ARIES for SEEA.

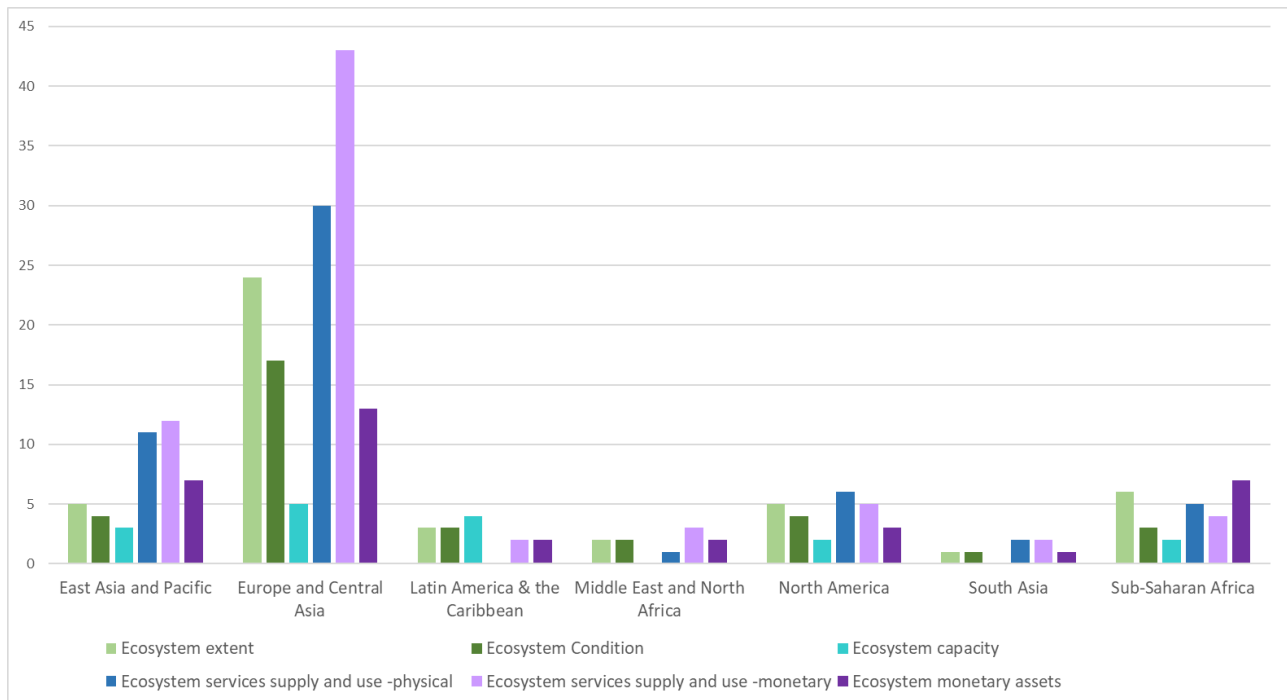
577

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

580

581

582



583

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

586
587 The main accounts discussed in the literature on the SEEA are the ecosystem services flows
588 accounts, both in biophysical and monetary terms (Figure 7; e.g. Schröter et al., 2016; Lai et al.,
589 2018; Remme et al., 2015). The least discussed accounts are the condition account and the
590 capacity account. Even though some interesting developments have attempted to operationalize
591 ecosystem capacity account as a measure of sustainability (Schröter et al, 2014; La Notte et al.
592 2019a; Hein et al., 2016), this account does not appear in the last version of the SEEA EA
593 (UNSD, 2020), but could be integrated in the condition account (Comte et al., 2020).

594
595 Geographical disparities exist in the production of ecosystem accounts. Europe is the region of
596 the world that has produced the most extensive literature on EA (Figure 8). West-European
597 countries and Australia (part of the East Asia and Pacific region) or the main contributors.
598 Zooming into the ecosystem core accounts proposed in the SEEA EA, a slightly different picture
599 emerges. While Europe is still leading the scientific production, followed by East Asia and
600 Pacific, North America contributes a lot less, and Africa a bit more. North America only
601 contributed to monetary accounts until recently, but biophysical accounts have been produced
602 at the sub-national level in the United States (Warnell et al., 2020). However, SEEA accounts
603 compilation in the US could speed up rapidly now that the White House has communicated an
604 intention to start compiling SEEA EA accounts as of 2023 (
605 [https://www.whitehouse.gov/ostp/news-updates/2022/04/24/accounting-for-nature-on-earth-day-
606 2022/](https://www.whitehouse.gov/ostp/news-updates/2022/04/24/accounting-for-nature-on-earth-day-2022/)).

607
608

609 **4. Discussion**

610
611 *4.1 Frameworks and topics*

612
613 Eleven different conceptual frameworks to produce ecosystem accounts have been highlighted
614 in this review (Figure 2). These frameworks are not completely independent from each other,
615 and overlaps or cross-breeding have occurred. Comparisons and integrations of different
616 frameworks have been discussed, notably to fill conceptual gaps on the many compartments of
617 ecosystem accounting. Lawn (2007), in his review of green accounting, argues for the necessity
618 of using a broad variety of indicators, including economic indicators using the “green
619 accounting” framework and biophysical indicators using the “ecological footprint” approach.
620 Bartelmus (2003) compares material flow analysis and SEEA. Ultimately, MFA and NAMEA
621 were included in the Central Framework of the SEEA. Vargas et al. (2018) also compares the
622 SEEA, but with the more recent framework of planetary boundaries. The ENCA framework
623 developed for the CBD and work on land accounts have participated in the definition of
624 biophysical accounts in the SEEA (Weber, 2007). Research on green accounting was also used
625 as foundations for the SEEA (Mäler et al., 2008). The increase in papers is related to the
626 publication of the SEEA-EEA in 2012. Despite the evolution of topics that are the focus of the
627 literature, conceptual issues are still discussed because of the complexity of accounting for

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

630

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

645

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

659

660

661 *4.2 Sustainability*

662

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

668

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

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

681
682 Monetary valuation of ecosystems can be done based on a valuation of the ecosystem services
683 provided by the ecosystem (as in SEEA EA and in Wealth accounting) or based upon
684 alternative approaches such as the restoration cost approach. Antagonist approaches to
685 sustainability are mostly found in the monetary valuation of ecosystems (Dietz and Neumayer,
686 2007). A distinction exists between preference-based valuation and cost-based valuation
687 methods as they represent different kinds of values and are associated with weak and strong
688 approaches to sustainability respectively (Pearce et al., 2001; Levrel et al., 2014; Dietz and
689 Neumayer; 2009). Ecosystem accounting does not imply a choice for a specific sustainability
690 paradigm. The information in the accounts can be used to measure sustainability, as far as the
691 use of ecosystems is concerned, in terms of both a weak (allowing conversion of natural to
692 other types of capital) or a strong (allowing no such conversion) sustainability approach. The
693 ecosystem extent and condition accounts show the area covered by different ecosystem types
694 and their condition or state. A strong sustainability paradigm requires these areas and their
695 condition to remain intact, or potentially to allow conversion of one ecosystem type to another,
696 or a decrease in ecosystem quality in one ecosystem if compensated by an increase in quality
697 of another ecosystem. This is measured in the ecosystem accounts. In case a weak
698 sustainability approach is followed, some trade-off between ecosystem and other capital is
699 allowed. In this case, it is useful to have information on the monetary value of ecosystems and
700 the services they supply.

701
702 Hence, ecosystem accounting can support both (very) weak and (very) strong sustainability
703 assessments. Depending upon the sustainability paradigm followed, either each individual type
704 of ecosystem or the total amount of ecosystem assets needs to be at least stable (i.e. not be
705 depleted or degraded). In both cases, some type of aggregation is necessary in order to
706 compare trends in different types of ecosystem, or to analyze changes within ecosystem types.
707 Aggregation is likely to require monetary valuation – since individual biophysical indicators (e.g.
708 tons of standing biomass and soil organic matter content) cannot be summed.

709
710 Given the importance of measuring the sustainability of ecosystem use, the monetary valuation
711 of ecosystems is also for this reason (in addition to monetary indicators being easier to
712 communicate to policy makers) likely to become more important in the future. This echoes the
713 scientific efforts on the developments of the economic accounts of the SEEA EA, focused on
714 valuing benefits of ecosystem services in economic terms (Hein et al., 2016), which itself is
715 supported by the rapidly growing literature on valuing ecosystem services (Laurans et al., 2015),

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

718
719 This result suggests a gap in scientific efforts towards cost-based methods to produce economic
720 accounts for maintaining critical natural capital (Vanoli, 1995; Bartelmus, 2009). These different
721 points of view have practical implications for ecosystem accounting (Brouwer and Leipert,
722 1999). A welfare approach would include ecosystem services flows in calculation of final output
723 as they represent changes in well-being (Mäler et al., 2008), which would lead to comparability
724 and consistency issues (notably with SNA figures), according to many (Carpenter et al., 2009;
725 Ludwig, 2000; Toman, 1998; Spash and Vatn, 2006). New techniques are allowing the valuation
726 of simulated exchange values that do not include consumer surplus and therefore is not
727 considered a welfare valuation of ecosystems (Caparrós et al., 2017). These monetary
728 valuations are anchored in the weak sustainability paradigm when used to correct macro-
729 aggregate figures. The critical natural capital approach in monetary terms emphasize the state
730 of the environment as a reference and maintenance costs as a mean to attain it. It could
731 produce a stand-alone figure of an “ecological debt” in monetary terms, or be included in the
732 national accounts (Vanoli, 1995).

733
734 Another limitation in ecosystem accounts linked to sustainability is that, to date, there has been
735 relatively little attention for ecosystem regime shifts, resilience and thresholds in ecosystem
736 dynamics (e.g. Folke et al., 2004). These thresholds are critical to the safe operating space and
737 resilience concepts (Steffen et al., 2015; Vargas et al., 2018). Biophysical indicators of critical
738 natural capital need normative targets, using precautionary approaches (Farmer and Randall,
739 1998), operationalized notably through the environmental sustainability gap framework (Ekins &
740 Simon, 1999; Usubiaga-Liaño & Ekins, 2021; Comte et al., 2021). These fields still need to be
741 connected somehow. One possibility is to have reference conditions that describe the
742 boundaries of critical natural capital (Comte et al., 2020).

743
744

745 *4.3 Applications and the SEEA*

746
747 The adoption of SEE-EA as global statistical standard, and rolling out this system among
748 countries would greatly enhance the availability of data for ecosystem assessments as well as
749 support a systematic monitoring of ecosystem state and the supply of ecosystem services.
750 Implementing the SEEA EA requires biophysical modelling of ecosystem services. These
751 models should be robust and accurate, have a high spatial resolution and be applicable at local
752 to national scale. In the past decade, several approaches and lines of thinking have been
753 developed on how to model ecosystem services for accounting. In the coming years, one of the
754 main research topic will be how to apply this model for decision making and discuss
755 complementarity and synergies between approaches. For instance in Europe, the MAIA
756 (Mapping and Assessment for Integrated ecosystem Accounting) projects
757 (<https://maiaportal.eu/>) aims to promote the mainstreaming of natural capital accounting in EU
758 Member States and Norway.

759

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

783
784 A large portion of the literature from 1990 to 2021 focuses on more than one ecosystem,
785 focuses on more than one account, and uses more than one type of methodology to populate
786 these accounts. However, there is no evidence that the number of methods or accounts in a
787 single article is increasing over the years. There is however an upward trend in the number of
788 ecosystems included since 2008. The evidence is therefore not clear that more extensive sets
789 of ecosystem accounts are created over time in the peer-reviewed literature. This may not be
790 the case for several reasons: either the amount of work and the diversity of methods that have
791 to be used to produce an extensive set of ecosystem accounts is a barrier for the scientific
792 community, or the format of journal articles is not appropriate or use to report on a wide variety
793 of ecosystems and accounts in a single paper. Nevertheless, recent examples show that
794 scientific papers can assemble a wide variety of ecosystems and accounts (e.g. Hein et al. 2020
795 and Vallecillo et al., 2019). It is likely that the scientific community focuses on developing and
796 testing ecosystem accounts on specific issues, with standardization and comprehensive
797 applications being conducted outside of the academic literature by statistic offices and other
798 organizations.

799 800 *4.4 Limits*

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

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

814
815 The list of articles reviewed here does not include much of the literature on environmentally-
816 adjusted macro-aggregates such as the concepts of inclusive wealth or genuine savings (World
817 Bank, 2006). These papers, while very important to further the development of new indicators of
818 wealth, mostly consider natural resources (renewables or not) but not ecosystems per se. This
819 review also misses all the “inventories” produced in the literature, including for example
820 greenhouse gas inventories that are reported under the United Nations Framework Convention
821 on Climate Change. Inventories could be associated to satellite accounts (outside of the core
822 set of accounts described in the SNA) for the environment and aim at responding to specific
823 policy objectives, whereas ecosystem accounts should be able to give a broader overview of
824 ecosystem assets (Azqueta and Sotelsek, 2007).

825
826 The uptake of the literature in policy documents is outside the scope of this paper because we
827 do not focus on the grey literature but would be an important avenue for future work. Moving
828 forward, it is recommended to include decision-makers, and not limited to statistical offices but
829 also other departments and ministries at every level of decision, in order to assess the possible
830 use and demands for building ecosystem accounting systems (Vardon et al., 2016; Hein et al.,
831 2020). This dialogue could potentially lead to reappraising the sets of accounts to be developed,
832 which may not be aligned with current scientific proposals (Bartelmus, 2015; Comte et al.,
833 2020). For instance, van den Bergh & Grazi (2014), argue that while the ecological footprint
834 framework has gained attention in science and the general public, it is not useful for policy-
835 making. Because a diverse set of indicators should be developed to produce useful information
836 for policy-making (Lintott, 1996), we hope that the description of the scientific efforts’ breadths
837 towards ecosystem accounting presented here will promote its implementation and
838 development across geographies.

839
840 **5. Conclusion**

841
842 Ecosystem accounting has grown to become an important theme of research, with increasing
843 number of articles and depth of scope. It first started as an emerging field with theoretical and
844 methodological developments going in different directions. A second phase of structuring and
845 refinement of the concepts and methods, aligned with the principles of accounting, ecology, and
846 economy emerged, around the SEEA. The next phase that is just starting now revolves around
847 testing, engagement, and adoption of ecosystem accounting. More applications are coming out,

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

850
851 It is also paramount to better connect SEEA ecosystem accounting efforts to IPBES, that could
852 benefit from the comprehensive data in the ecosystem accounts in the countries where they are
853 produced. However, the main next step in ecosystem accounting needs to be to connect
854 ecosystem accounts to the user, including national and local policy makers, civil servants
855 informing policy makers, research bodies and environmental assessment agencies informing
856 civil servants informing policy makers, etc. Compiling ecosystem accounts requires substantial
857 investments in data, capacity and forging institutional set-up for data sharing etc. and this will
858 only be sustained if the policy makers and the ministries deciding upon budgets are convinced
859 of the added value of ecosystem accounts. Amongst others, this requires providing easy access
860 to users to all data in accounts, developing the guidance that users need to interpret the data in
861 ecosystem accounts, and showcasing policy applications of accounts. In addition to further
862 enhancing the quality of the accounts, these should be priorities for the accounting community
863 in the coming years.

864

865

866 **Acknowledgements**

867

868 This work was supported by the EU Horizon 2020 grant 817527 (MAIA). We thank David Barton
869 for his input on the design of the study. We thank Emily Bank and Hristina Prodanova for their
870 help conducting the review. We also thank the three anonymous reviewers for their constructive
871 reviews that greatly contributed to the quality of this manuscript.

872

873

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875

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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

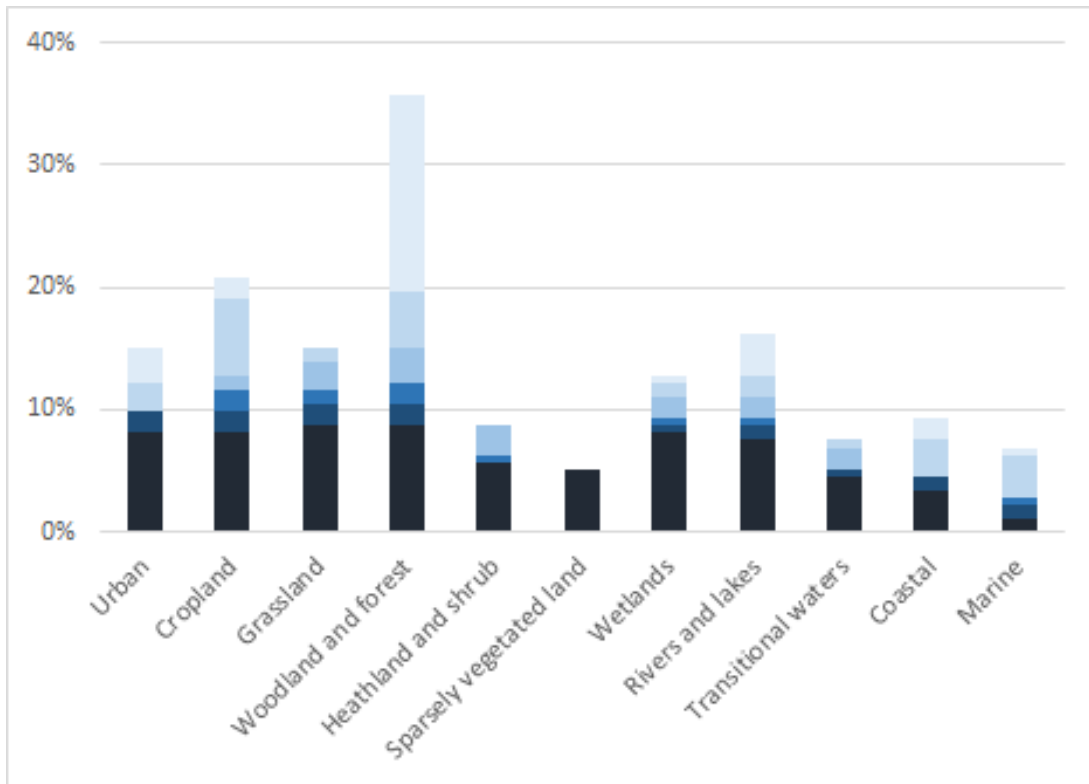
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Accounts	Justification
Core accounts (SEEA EEA)	Following the SEEA-EEA
Thematic accounts (SEEA EEA)	Following the SEEA-EEA
Accounts (non-SEEA)	From the literature
Categories of ecosystem services	Based on the CICES classification (Haines-Young and 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.