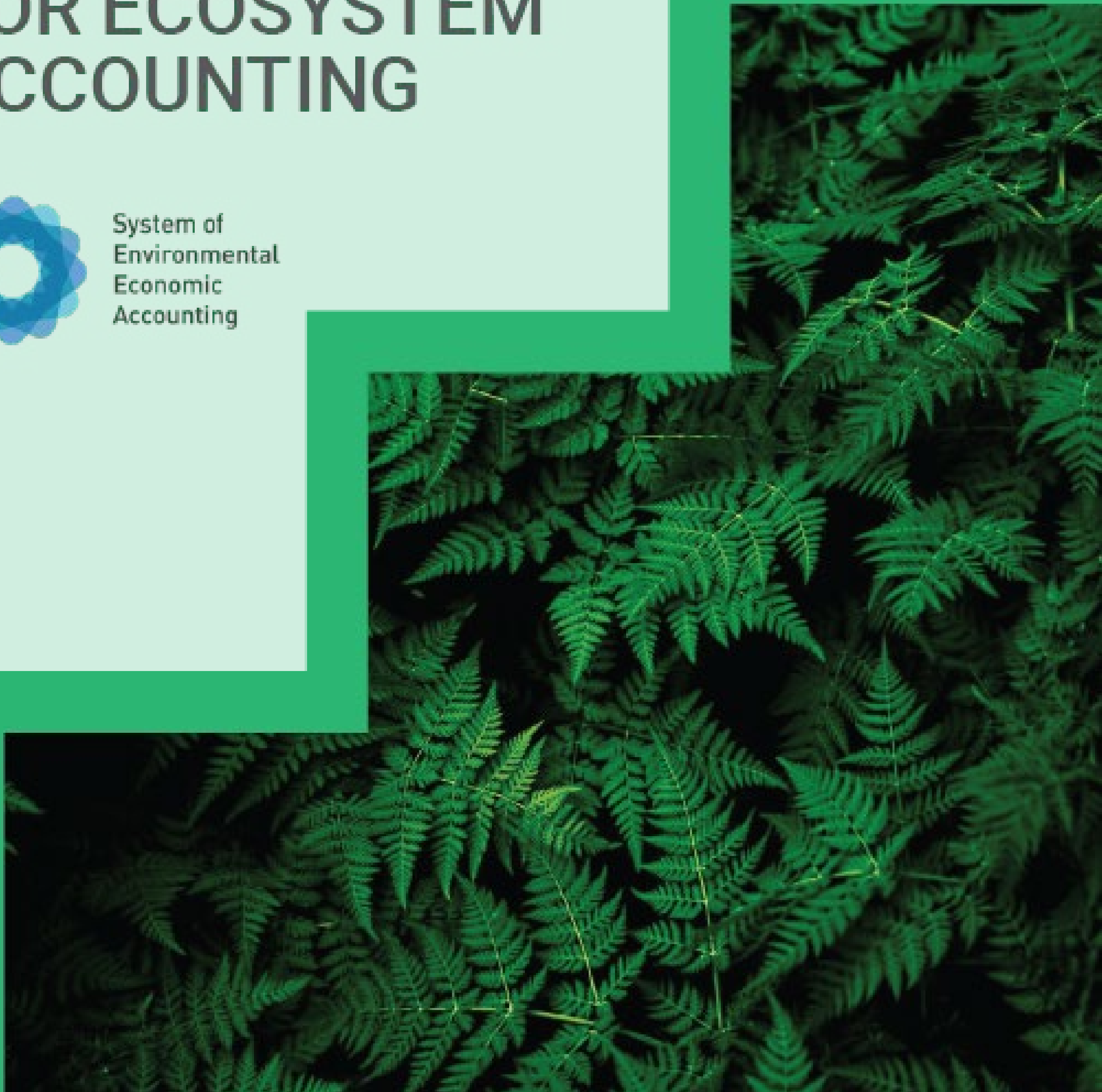
United Nations | Department of Economic and Social Affairs

GUIDELINES ON **BIOPHYSICAL MODELLING** FOR ECOSYSTEM ACCOUNTING

System of Environmental Economic Accounting



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Suggested citation: United Nations (2022). Guidelines on Biophysical Modelling for Ecosystem Accounting. United Nations Department of Economic and Social Affairs, Statistics Division, New York.

Given the fast-paced development of modelling of ecosystem services and global data sources, several tables as indicated in the document will be made available as living documents on the SEEA website: https://seea.un.org/ecosystem-accounting/biophysical-modelling

Acknowledgements

These guidelines are an output of the Natural Capital Accounting and Valuation of Ecosystem Services (NCAVES) project. They have been developed under the auspices of the System of Environmental Economic Accounting Ecosystem Accounting (SEEA EA) Technical Committee, a committee that has been established by the UN Committee of Experts on Environmental-Economic Accounting (UNCEEA) to further the development and implementation of SEEA EA.

An editorial board was established to provide expert advice and guidance on the drafting of the text. The editorial board consisted of: Rosimeiry Portela (Conservation International, Chair); Michael Bordt (UNESCAP); Ken Bagstad (USGS), Lars Hein (Wageningen University), Bethanna Jackson (Victoria University of Wellington), Justin Johnson (Stanford University), Glenn-Marie Lange (previously with the World Bank), Francois Soulard (Statistics Canada), Stephanie Tomscha (Victoria University of Wellington). Bram Edens (UNSD) provided the Secretariat for the Group.

Stephanie Tomscha drafted the initial version of the document and Bram Edens edited the document to reflect the comments received during the global consultation. Mahbubul Alam (Conservation International), Miroslav Honzak (Conservation International), Alessandra la Notte (EU-JRC), Joachim Maes (EU-JRC), Timothy Wright (Conservation International) reviewed specific sections of the document. The UNSD staff from the Environmental Economic Accounting Section, Alessandra Alfieri, Julian Chow, Jessica Chan, Marko Javorsek, Elsa Begne de Larrea and Mariana Camacho reviewed the final draft. In addition, a large number of experts who have been involved in the revision process of the SEEA EA have also contributed to various drafts and provided comments.

The guidelines draw upon the SEEA EA and the issue papers that were developed in support of the SEEA EA revision process: https://seea.un.org/content/seea-experimental-ecosystem-accounting-revision

The guidelines have gone through a formal process of global consultation among all the national statistical offices globally and a wide community of experts, during 2021. The report was produced with the financial support of the European Union, under the NCAVES project.

Funded by the European Union

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Abbreviations and Acronyms

ARD	Analysis Ready Data
ARIES	Artificial Intelligence for Ecosystem Services
ANCA	Advancing Natural Capital Accounting
BII	Biodiversity Intactness Index
BSU	Basic Spatial Unit
CBD	Convention on Biological Diversity
CCI	Climate Change Initiative
DEM	Digital Elevation Model
EAA	Ecosystem Accounting Area
EA	Ecosystem Asset
EARD	Ecosystem Accounting Ready Data
ES	Ecosystem Service(s)
EBV	Essential Biodiversity Variables
EFG	Ecosystem Functional Groups
ECI	Ecosystem Condition Indicators
ESA	European Space Agency
FAIR	Findable, Accessible, Interoperable and Reusable
GDM	Generalized Dissimilarity Modelling
GET	Global Ecosystem Typology
GGIM	Global Geospatial Information Management
GIS	Geographical Information System
GLCC	Global Land Cover Classification
GSGF	Global Statistical Geospatial Framework
IGBP	International Geosphere-Biosphere Programme
InVEST	Integrated Valuation of Ecosystem Services and Trade-offs
IUCN	International Union for Conservation of Nature
LAI	Leaf Area Index
LCCS	Land Cover Classification System
LiDAR	Light Detection and Ranging
LPI	Living Planet Index
LUCI	Land Utilization Capability Indicator
MODIS	Moderate Resolution Imaging Spectroradiometer
MSA	Mean Species Abundance

NASA	National Aeronautics and Space Administration
NBSAP	National Biodiversity Strategy and Action Plan
NCAVES	Natural Capital Accounting and Valuation of Ecosystem Services
NDVI	Normalized Difference Vegetation Index
NPP	Net Primary Production
NTFP	Non-timber forest products
RLE	Red List of Ecosystems
SDM	Species Distribution Models
SEEA	System of Environmental-Economic Accounting
SEEA CF	SEEA Central Framework
SEEA EA	SEEA Ecosystem Accounting
SEEA AFF	SEEA Agriculture Forestry and Fisheries
SH	Shannon Index
SMAP	Soil Moisture Active and Passive
SNA	System of National Accounts
SoLVES	Social Values for Ecosystem Services
SWAT	Soil and Water Assessment Tool
TEEB	The Economics of Ecosystems and Biodiversity
USGS	United States Geological Survey
WAVES	Wealth Accounting and the Valuation of Ecosystem Services

1 Biophysical modelling for SEEA EA

1. The System of Environmental-Economic Accounting - Ecosystem Accounting (SEEA EA) (UN et al., 2021) is the integrated statistical framework for ecosystem accounting.[1] The SEEA EA comprises a system of accounts that organizes information on ecosystems and the benefits that they provide to society. Accounts that are included in the SEEA EA are: ecosystem extent, ecosystem condition, ecosystem services in physical and/or monetary units, and monetary asset accounts. Ecosystem accounting aspires to provide integrated geospatial information, in which multiple layers of information (geographical, environmental, ecological, and economic) are brought together and summarized in accounts.
2. Several challenges remain when compiling ecosystem accounts. Firstly, the data that is needed to assemble ecosystem accounts are not typically captured in the traditional data sources that statistical offices usually rely on, such as surveys, administrative data, and censuses. Secondly, ecosystem accounts are spatially explicit, i.e. they are constructed using spatial data sets of both ecosystems and ecosystem services. This is a unique characteristic of ecosystem accounts which sets them apart from other types of accounts. It implies that even information which can be used to measure ecosystem services (e.g. from agricultural surveys) needs to be spatialized. Thirdly, reporting environmental data as accounts without oversimplifying complex ecological and socioeconomic processes underpinning ecosystem services is challenging.
3. Biophysical modelling can fill data gaps where information is not readily available, as well as spatially allocate data that is not *de facto* spatially explicit. Diverse models and tools to estimate the extent and condition of ecosystems and/or their services have proliferated over the past decade and are constantly evolving. While most biophysical models are not developed specifically for accounting purposes, many models either produce results that can be used directly in SEEA EA or produce results that can be modified for use in SEEA EA. Identifying tools and modelling

[1] The SEEA EA was adopted by the United Nations Statistical Commitssion UNSC) at its 53rd session in March 2021 with the chapters on the framework and physical accounting as a statistical standard. The SEEA EA builds on the SEEA Experimental Ecosystem Accounting (UN 2014b) which was endorsed in March 2013, as the basis for commencing testing and further development of this new field of environmental-economic accounting.

platforms that produce results aligned with SEEA EA, as well as associated best practices, will facilitate the compilation of ecosystem accounts.

4. While biophysical modelling may be instrumental to advance the implementation of the SEEA-EA, modelling can never replace data collection processes, since the compilation of robust ecosystem accounts requires the combination of different data sets and tools. For instance, earth observation data sets need ground-truthing for validation (or training) purposes. And biophysical modelling relies on *in situ* data to inform model development and to adjust model setup to local circumstances (e.g. to perform model calibration).
5. Guidance on how to select the correct tools for different purposes has grown more common (Wittmer et al., 2013; Neugarten et al., 2018). Despite their growing number, none address the specific needs of the statistical community. In general, as there are few people who are trained specifically in biophysical modelling, let alone for SEEA EA, easy-to-follow guidelines that provide instructions for both modelling practitioners and managers in statistical organizations are becoming especially needed.
6. The intended audience of these guidelines consist first and foremost of statistical agencies interested in compiling ecosystem accounts. Chapter 2 is intended more for project managers and line managers involved in the process of accounts compilation. The rest of the document focuses on compilation of ecosystem accounts and assumes familiarity with the main concepts of the SEEA EA but does not assume knowledge of biophysical modelling.
7. The objective of this guide is to provide an overview of how biophysical modelling can be applied to facilitate SEEA EA accounts compilation. As a result, these guidelines focus on terrestrial and freshwater ecosystems, including primarily terrestrial data sets, definitions, modelling approaches and challenges.[2] The guide explores several key questions that facilitate both operational and technical production of SEEA EA accounts using biophysical modelling that meet statistical standards for data quality.
8. **How can organizations start the compilation of SEEA EA?** Implementing SEEA EA requires statistical agencies to seek new, and sometimes unfamiliar, expertise and resources. This guide outlines, in Chapter 2, approaches for streamlining this

[2] Some of the principles, data sources, classifications and approaches also relate to coastal and marine accounting.

process. As an inherently interdisciplinary endeavour, collaboration is key to successful compilation of ecosystem accounts. The guide also covers practical and institutional aspects of compiling ecosystem accounts: what software, expertise and institutional best-practices can facilitate the compilation of these accounts? The guide highlights the importance of forming strategic partnerships to ensure that the adoption of the accounts compiled using biophysical modelling is supported at multiple agency levels.

9. **How can biophysical modelling be used to produce extent, condition, and ecosystem service accounts?** Starting from the expected format and content of SEEA EA maps and tables, this guide reviews tools and modelling approaches for use in ecosystem accounts (in Section 3), with an emphasis on biophysical accounts.[3] The guidelines focus on explicitly linking biophysical models to the compilation of standardized SEEA EA accounts (extent in Chapter 4, condition in Chapter 5, and ecosystem services in Chapter 6). Each of these chapters follows a similar structure. First, the guidelines give a brief overview of each account as presented in the SEEA EA and explain the role of biophysical modelling in producing these accounts. Then the main challenges of biophysical modelling for each account are presented. Finally, examples of different accounts are shown.
10. **How is it ensured that reporting produced from biophysical modelling is sufficiently accurate?** Biophysical modelling for SEEA EA is spatially explicit, and thus, presents unique challenges, as it must encompass standards from spatial, measured, and modelled frameworks. Nonetheless, frameworks for modelled-data quality do not need to be established from scratch as closely related fields, such as ecological and hydrologic modelling, have well-established methods for evaluating model fit and quality. Chapter 7 describes issues around data quality and uncertainty assessments for biophysical models for ecosystem assets and ecosystem services.
11. **What is the future of this rapid evolution of biophysical modelling for ecosystem services?** Chapter 8 reflects on the rapidly developing field of biophysical modelling's future and its role in compiling ecosystem accounts.
12. Finally, the Annexes contain further information on modelling techniques, global data sources, and cartography essentials. The references include a large number of academic papers that serve as the basis for preparing the guidelines.

[3] Guidance on valuation is developed in a separate document.

13. Given the fast-paced development of modelling of ecosystem services and global data sources, several tables, as indicated in the document, have been made available as living materials on the seea.un.org website and will be updated on a regular basis, see: https://seea.un.org/content/supplemental-materials-and-tables-guidelines-biophysical-modelling. Users of these guidelines and biophysical model developers are encouraged to submit updates or additions to these tables to seea@un.org.

2 Starting compilation of SEEA EA

14. Developing ecosystem accounts can be challenging given the multi-disciplinary nature of the accounts, as well as the technical challenges inherent in working with spatial data and novel techniques that are required for compiling certain accounts. This chapter provides advice on the process of developing the accounts, building on insights gained through the implementation of ecosystem accounting in several countries.[4] The chapter is structured along the phases described in the SEEA Implementation Guide (UNSD, 2014c) but focuses on compiling ecosystem accounts and its specific challenges. The phases of building SEEA EA accounts include: i.) Strategic planning; ii.) Building mechanisms for implementation; iii.) Compiling and disseminating accounts; iv.) Strengthening national statistical systems (see, for example, Figure 1). The last phase is described in this document as the "Institutionalisation" of the accounts.

2.1 Strategic planning

15. Strategic planning involves bringing together key stakeholders and determine a plan for establishing SEEA EA in the short and medium term based on national policy priorities and data available. There are two key steps in the strategic planning phase envisioned here. First, a core group of stakeholders should be established and, second, an assessment report (generally at a national level) of policy and data needs should be developed.

2.1.1 Constitute a core group

16. A core group with representatives of key stakeholders in ecosystem accounting should be created in the initial scoping stages of the project. This group should provide a clear mandate to advance this novel area of statistics. Likely candidates might include representatives from the statistical agency who are/will be involved in the compilation of the accounts, representatives from relevant line ministries (e.g. the Ministry of Environment/ Natural Resources) who are key producers of input data and users of the accounts, and agencies (e.g. planning, finance) who are involved in coordinating and facilitating these accounts. In addition to the ministries and

[4] The guidelines draw upon experiences gained with accounts compilation in pilot projects in several countries, such as through WAVES/GPS, projects by Conservation International, the Natural Capital Project, TEEB (The Economics of Ecosystem and Biodiversity), and NCAVES (see list of acronyms).

agencies mentioned above, the compilation of the SEEA EA requires collaboration with the agency responsible for mapping (e.g. the cadastre or a mapping agency) with expertise in spatial data infrastructure. Representatives from academia and/or civil society could also be considered given their expertise in biophysical modelling and estimation of relevant ecological variables.

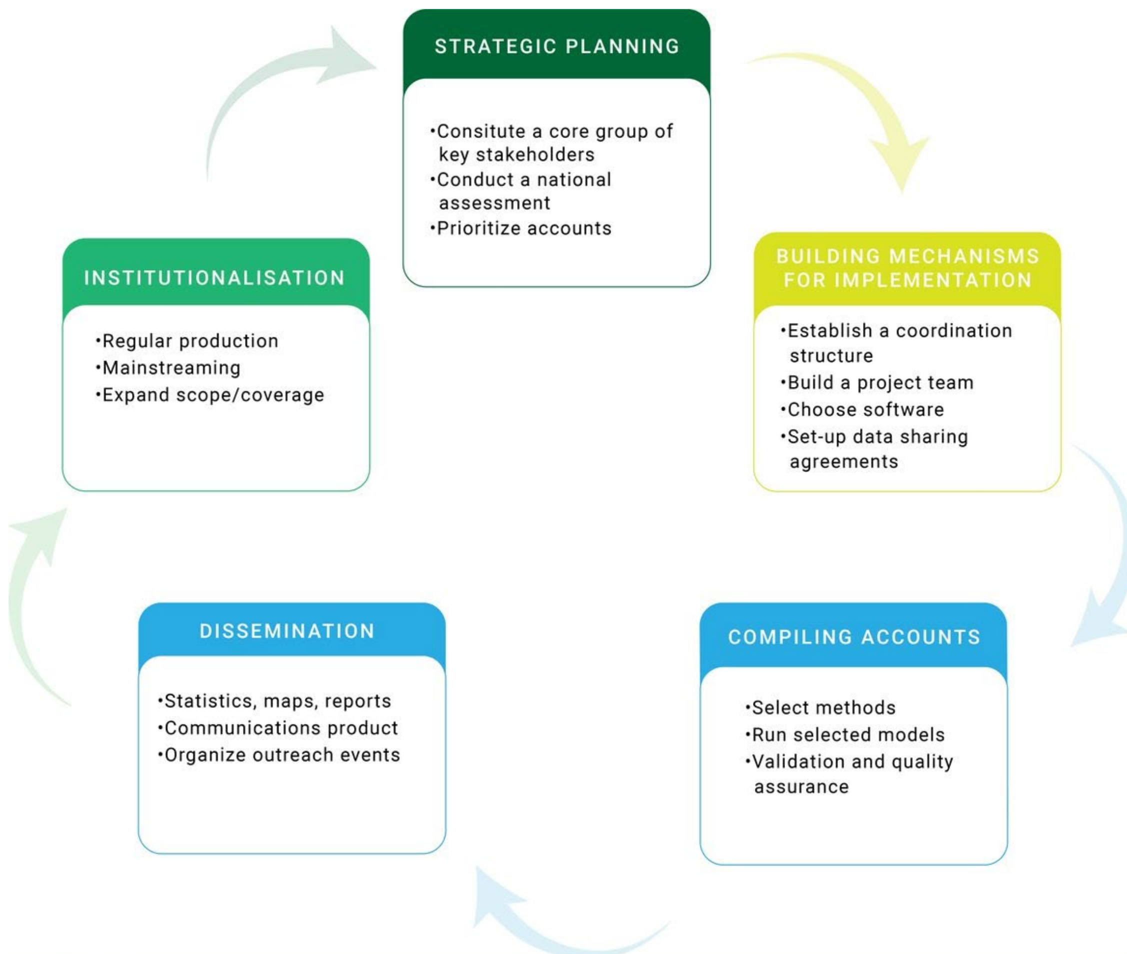

Figure 1: *The process of implementing SEEA starts with priority setting. This process is repeated for every reporting cycle.*

2.1.2 Conduct a national assessment

17. As its initial focus, this core group would be tasked to complete an initial national assessment report to assess, among others:

- Policy mapping: assess policy priorities and how the accounts could inform those. This would involve reviewing the national development plan, the national biodiversity strategy and action plan (NBSAP), the voluntary national review (VNR), the nationally determined contribution (NDC), poverty reduction strategy, strategic plans for water, energy, etc., as well as the national strategy for the development of statistics (NSDS).

- Stakeholders: identify key stakeholders (data producers, data collaborators, data users) in the country and identify existing mechanisms that the accounts could support;
- Data sources: identification and assessment of relevant data sources in governmental and non-governmental agencies. This includes biophysical as well as monetary data;
- Literature review: assess previous studies and projects that the accounts can build upon.

18. Whichever process is followed, they have in common that a stakeholder workshop needs to be organized *ex ante* to prepare for the assessment and/or *ex post* to discuss and disseminate the results of the assessment, to validate outcomes of the assessment and to discuss possible accounts to prioritize based on the assessment of the policy needs and data availability. The required updating frequency of the accounts is an important aspect influencing the selection of suitable datasets.
19. It is also important to have regular stakeholder meetings to keep everybody informed of progress made and further continue the strategic discussion on priorities.

POLICY

- **What** are the priorities related to environment and natural resources identified in the existing plans? (e.g. the national development plan, poverty reduction strategies, NBSAP, NDC)

INSTITUTIONS

- **Who** are the main stakeholders? (e.g. Ministry of Planning, Ministry of Environment, Ministry of Water Resources)

DATA AND KNOWLEDGE

- **What** are the main data sources available (e.g. land cover/use, agricultural survey, forest resource assessment, hydrological data), and **who** compiled this data?
- **What** ecosystem service assessments have been done, and **which** models were applied?

PROGRESS

- Are there any existing SEEA accounts? (e.g. forest or water accounts)

***Figure 2:** Contextual diagnostic questions to guide scoping for SEEA EA programme development (adapted from the SEEA diagnostics tool).[5]*

2.2 Building mechanisms for implementation

20. This phase consists of several steps that enable the successful implementation of the SEEA EA including the establishment of a coordination mechanism, building a project team as well as tools that are necessary for the compilation of the accounts such as GIS software and data sharing arrangements. In the next phase several steps are

[5] See: https://seea.un.org/content/tools-and-e-learning

important from establishing a coordination structure and building a project team to enabling factors such as the choice of GIS software and data sharing arrangements.

2.2.1 Establishing a coordinating structure

21. Building on the initial core group established during the scoping phase, it is important that a clearly defined authorized senior board or national steering committee is formed to oversee the development of the accounts. Alternatively, an existing structure may be used, if it has a similar objective and can take on the additional task of overseeing the development of ecosystem accounts. While there is no standardized approach to a governing process, Figure 3 represents a generic template based on experiences in various countries and projects.

22. The national steering committee usually deals with the mainstreaming of the accounting data and indicators into policy, setting priorities as well as resource mobilisation. As such it is usually chaired by a senior official from the Ministry of Planning or Environment.

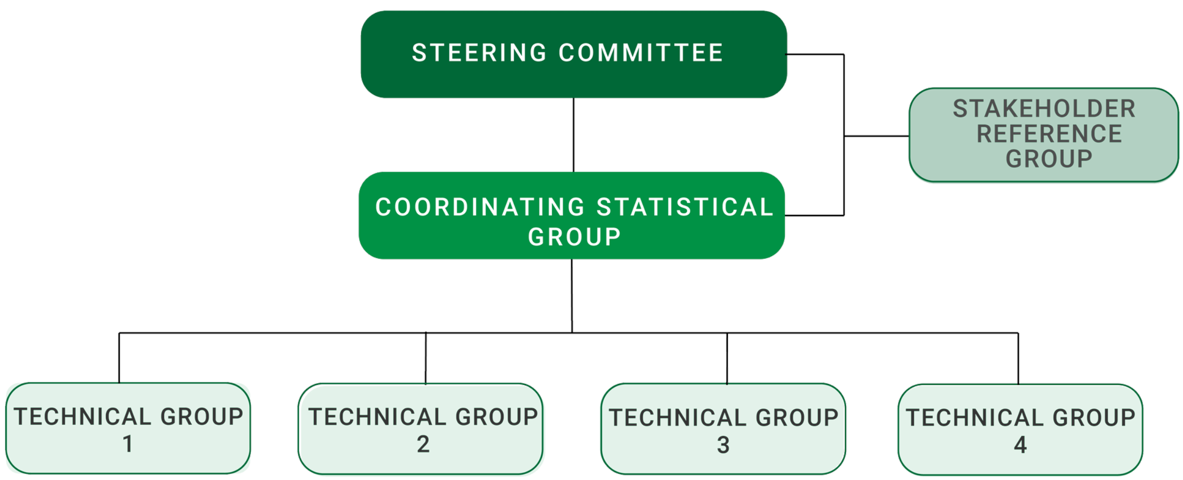

Figure 3: *An example of a governing and collaborative structure for implementing SEEA EA*

23. The coordinating statistical group is responsible for the compilation of the accounts and would be commonly led by the national statistics office (NSO), possibly in collaboration with the Ministry of Environment. Several technical working groups can be formed, for instance on spatial analysis and biophysical modelling with representatives from the NSO, technical agencies, non-governmental organizations

and academia that have worked on specific ecosystem services; on valuation with economists from government, research groups, academia, etc. These technical working groups could be structured by type of account (e.g. ecosystem extent, condition, etc.) and/or thematically (water, forest, ocean, biodiversity, etc.).

24. The role of the stakeholder reference group is to provide guidance from a user perspective to ensure that the accounts compiled respond to the identified policy needs and priorities.

2.2.2 Building a project team

25. Ecosystem accounting is a multi-disciplinary undertaking. Required expertise includes statisticians and accountants, (environmental) economists, spatial analysts/GIS (geographical information system) experts, ecologists and hydrologists, among others. Establishing partnerships with academic institutions will likely be beneficial because of their expertise in modelling and valuation of ecosystem services as well as analysing complex data. Given the spatial nature of ecosystem accounts, ensuring GIS expertise in the team is considered essential. New disciplines such as data science can also play an important role.

26. It should be noted that statistical offices are often not used to working with biophysical models. Generally, their regular production process involves manipulating data that comes from administrative sources (e.g. tax data) or surveys, and only more rarely big data or data that result from biophysical modelling. The situation is changing rapidly, and national statistical offices are increasingly asked to develop real time statistics and to use data from non-conventional sources.

27. Building capacity through targeted training may be useful, depending on the teams' needs. A range of resources such as e-learnings are available.[6] Specialized training in GIS and spatial data sets may be useful for those undertaking biophysical modelling for SEEA EA, given the spatial nature of ecosystem accounting (see also the Annex on cartography essentials). It may also be beneficial for project team members to participate in an international community of practice.[7]

[6] See for instance: https://seea.un.org/content/tools-and-e-learning
[7] For instance the NCA CoP for the African region: https://ecastats.uneca.org/ncacop

28. Given the multidisciplinary aspects of the accounts, terminology, concepts and practices differ in the different subject areas and thus there is a need for continuous exchange in particular among the core team members. It will be therefore important to facilitate continuous discussions to ensure that the members of the team are speaking a common language, for instance by organizing workshops.

2.2.3 Software

29. Depending on which accounts are prioritized, available data and expertise in the country, different ecosystem extent, condition and service models may require different software. However, software for displaying spatial data will likely be needed regardless of which accounts are created. It is recommended to take this decision in consultation with experts in GIS either within the NSO or the mapping agency. Common software includes ArcGIS and QGIS. The commercial software ArcGIS is one of the most widely used GIS packages while QGIS (Quantum GIS) is a free open-source geographical information system, a good alternative for agencies that cannot afford or are not allowed to use proprietary software.
30. Some additional elements to consider – although opinions may differ in terms of pros and cons of both software products – when making a choice are the following:
    1) Most of the models discussed in this guide can be run in QGIS, however ArcGIS may be needed to run certain modelling platforms;[8]
    2) Some features available in ArcGIS are not (yet) available in QGIS. The larger set of predefined functionalities makes ArcGIS sometimes easier to utilise for certain types of analyses;
    3) QGIS can be installed on all common operating systems, while ArcGIS only runs on Windows;
    4) For some problems ArcGIS provides more efficient handling of large data volumes/more complex calculations;
    5) Both software products can be linked to various machine learning approaches and both products are regularly updated.

[8] See Chapter 3 for more details on the main platforms.

31. Other web-based platforms to consider may be Google Earth Engine[9] or Microsoft's planetary computer.[10] Programming languages like R or phyton have several packages for spatial analysis that can facilitate efficient workflows in the production of results and reports.

2.2.4 Set-up data sharing arrangements

32. For ecosystem accounting, a wide range of data sources, often spatially explicit, will be required. In many countries data are often held by different agencies and getting access can be one of the first challenges in compiling ecosystem accounts. A good practice is to establish data sharing arrangements, as soon as critical data sources have been identified, such as through Memoranda of Understanding (MOUs) with service level agreements. The steering committee can be instrumental in this regard, as a multi-institutional group that may help overcome silos in data gathering and sharing, which are typically found across government agencies. An example is the EU's Infrastructure for Spatial Information in the European Community (INSPIRE) Directive[11] that aims to create an EU infrastructure for spatial data to support EU environmental policies and other policies or activities which may have an impact on the environment.
33. While fully open data may not be possible in some national contexts, open data has strong scientific advantages in terms of improved transparency and reproducibility; open-data policies are thus worth consideration if possible.[12] All data, including open data, should be subject to validation and comparison with national standards.

[9] https://earthengine.google.com/
[10] https://planetarycomputer.microsoft.com/
[11] https://inspire.ec.europa.eu/
[12] A well-documented example is Landsat data that has become freely accessible as of 2008 (Zhu et al., 2019). The US (Warnell et al., 2020) and Rwanda (Bagstad et al., 2019) are examples where the underlying ecosystem accounts data have been fully open as part of a data release.

2.3 Compiling and disseminating accounts

2.3.1 Compiling the accounts

34. This phase is at the heart of the compilers' tasks and involves most of the technical and measurement challenges confronted in the implementation process. Biophysical modelling is a technique used in this phase.

35. A general ambition in the implementation of environmental-economic accounts should be to first develop experimental accounts at an aggregated level using available data, which may include global data sets. This phase is usually a learning phase and it is very important to demonstrate the policy relevance and the feasibility of compilation. "Learning-by-doing" is an essential aspect of implementation. Compiling and releasing pilot accounts in a relatively short time frame is very important to keep the users engaged and interested in the process. Based on feedback and increasing confidence in compilation, it should be possible to progressively develop better quality accounts with expanded scope and coverage.

2.3.2 Disseminating the accounts

36. Disseminating the accounts in a way that is useful to the users is a very important step to obtain the buy-in from the various types of users and further the cooperation with the data producers. For example, some users may find it useful to have access to the micro data, while some may want simplified data tables and analysis, and others may want indicators and summary interpretation. Disseminating the accounts also allows to demonstrate the information that is generated and establish a discussion on the possible uses and applications that the accounts can support. Active engagement of the various stakeholders is important throughout all the phases of implementation including the dissemination phase.

37. Regardless of the level of detail of the disseminated product, it is imperative to be transparent on the model, the input data and the coefficients that are used, etc., in order to ensure that the results are replicable and comparable across years. For the SEEA EA, as integral to official statistics, general quality assurance frameworks should apply (UN, 2019a). Because ecosystem accounts are a new area of statistics, it is important to provide clear explanations to the users the possible interpretations and applications of the accounts. This is particularly important when monetary

estimates are released as interpretation and use of the results may be particularly sensitive.

2.4 Institutionalisation

2.4.1 Regular production

38. Once the experimental accounts have been produced, the next step will be to move towards regular production and include the accounts as part of the regular statistical work programme. This entails the formalisation of regular input data collection, of accounts compilation, and documentation of sources and methods, including detailed meta-data and the description of quality assurance procedures. Securing funding and appropriate resources are an essential part of this step.

39. Where possible, regular accounts production should also be embedded in a broader context of work, such as the 2030 Agenda for Sustainable Development or other national priorities. Accounts compilation could contribute to establishing a business case for a national spatial data infrastructure (NSDI) to support integration of environmental and socio-economic data (UN, 2019b).[13]

2.4.2 Mainstreaming into policy

40. Although the engagement with the users is important throughout the implementation of the accounts, mainstreaming the accounts into policy is particularly important to ensure institutionalisation. Promoting the use and policy uptake of the accounts will depend on a successful outreach and communication programme. Good experiences exist in countries with the organization of national fora/workshops.[14] Presenting the results, as well as a narrative inherent with the data (e.g. in the form of policy briefs) makes the accounts appealing to potential users including not only government agencies but also the research community and the broader public, including media and non-government organisations.

[13] Under the umbrella of the UN Global Geospatial Information Management (GGIM), work is ongoing on developing the Global Statistical Geospatial Framework (GSGF), which provides (i) a common approach to integrating socio-economic and environmental information, (ii) five principles to guide and inform the spatial enablement of statistical data, and (iii) acts as a bridge between the statistical and geospatial communities to integrate statistical and geospatial standards, methods, workflows, and tools. See: https://ggim.un.org/meetings/GGIM-committee/9th-Session/documents/The_GSGF.pdf

[14] E.g. the National Forum on NCA held in South Africa in 2019. See: https://seea.un.org/SA_NCA_Forum

41. Sharing best practices and lessons learned at the national level as well as the broader compiler community can help to obtain feedback to streamline the process as well as the quality of the accounts compiled (Figure 1). Engagement with the user communities is particularly important in this phase to understand users' needs and possibly capitalize on the users' demand to expand the scope and coverage of the accounts.

3 Modelling for ecosystem accounts

42. Biophysical models can be useful for compiling many of the extent, condition, as well as supply and use tables and maps produced in SEEA EA. For instance, measuring ecosystem services directly is often difficult. Spatial and temporal coverage of ecosystem service data is sparse. Many ecosystem services represent spatiotemporally dynamic processes, which are costly to measure in situ. Furthermore, ecosystem services, considering both supply by ecosystems and their use by beneficiaries, may be heterogeneous across small spatial extents or may not be visible in satellite imagery. Modelling can be used to fill in these spatial and temporal gaps.

43. Biophysical modelling is also frequently used to identify ecosystem classes, when compiling an extent account.[15] Modelling can also be used to spatialize data that are nonspatial, which is relevant when compiling condition accounts where, for instance, data from streamflow gauges is used.

44. Global-scale applications of models using globally available data exist (e.g. Chaplin-Kramer et al., 2019), but countries typically want models customized with local data and parameters, which increases their reliability and acceptance. The use of national data also helps validation of global models and can improve the accuracy.

45. This chapter will provide the foundation for these guidelines by providing an overview of various modelling approaches (Section 3.1), the main modelling techniques (Section 3.2), and the most commonly used modelling platforms (Section 3.3). As countries differ in their technical capacity, data availability, as well as resources, we will distinguish in these guidelines between different "Tiers" for biophysical modelling for SEEA EA. This is followed by a concluding section (Section 3.4) that discusses advantages and disadvantages of using the various presented approaches.

[15] For instance, the NASA-CI partnership uses satellite imagery with a technique called GDM (generalized dissimilarity modelling) to determine classes. See: http://www.gaboronedeclaration.com/blog/2019/11/17/nasa-conservation-international-partnership-supports-gdsa-goals-toward-mainstreaming-ecosystem-accounting-in-africa

3.1 Modelling approaches for SEEA EA

3.1.1 The SEEA EA's spatial framework

46. A key feature of the SEEA EA is that it follows a spatially explicit framework. For the results of a biophysical model to be compliant with this spatial framework, they must be able to be aggregated and/or disaggregated to reflect the SEEA EA's basic spatial characteristics. The SEEA EA distinguishes between four different types of units that correspond with distinct spatial areas (Table 1). Currently, the spatial characteristics of SEEA EA accounts are somewhat flexible. For example, these spatial areas can be as coarse or fine resolution as suitable for specific situations.

47. Ecosystems assets (EAs) are contiguous spaces of a specific ecosystem type characterized by a distinct set of biotic and abiotic components and their interactions. They are mutually exclusive areas that cover the entire ecosystem accounting area (EAA). Individual ecosystem assets (e.g. a specific forest or wetland) can be grouped together into ecosystem types (ETs) (e.g. forests, or wetlands). Because the SEEA EA relies on maps, an understanding of basic mapping principles is helpful for building SEEA EA accounts (see Annex on Cartography essentials for a brief introduction to cartography for the SEEA EA).

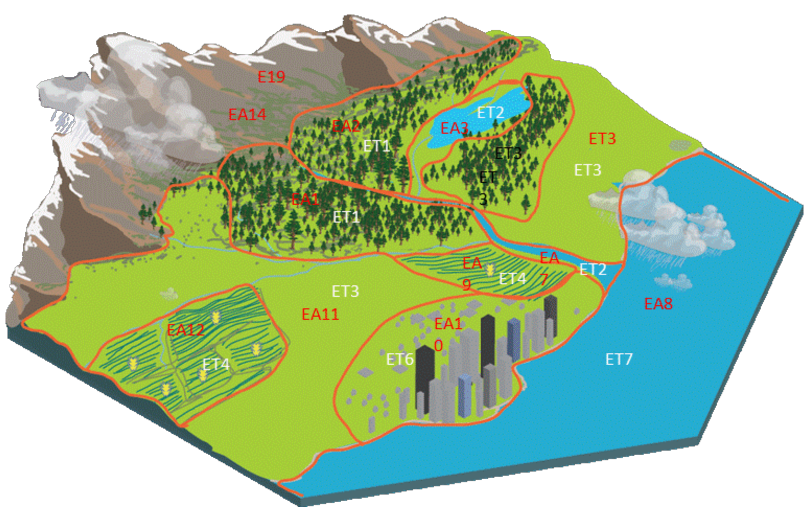

Figure 4: *Visualization of the SEEA EA spatial framework. The ecosystem accounting area (EAA) consists of the shown tile. Ecosystem assets (EAs) are delineated by the red lines, indicated and numbered in red letters. EAs are classified into different ecosystem types (ET1-Forest ET2 – Freshwater etc.) shown in white letters.*

Table 1: *Key terms for the SEEA EA's spatial framework.*

Spatial areas	**Abbreviation**	**Definition**	**Example**
Ecosystem Accounting Area	**EAA**	This is the reporting unit, the area for which the accounts are compiled. Typically, administrative or watershed boundaries.	Region, state, hydrological units
Ecosystem Type	**ET**	A more generalized view of ecosystem assets, often not including management information. There may be multiple ecosystem assets within an ecosystem type. Reflects a distinct set of abiotic and biotic components and their interactions.	Deciduous forest, wetland
Ecosystem Asset	**EA**	Contiguous spaces of a specific ecosystem type characterized by a distinct set of biotic and abiotic components and their interactions.	An individual forest or wetland
Basic Spatial Unit	**BSU**	Smallest spatial areas where spatial information can be ascribed. Comparable to statistical units in a business register. Geometric constructs, typically a grid, but can also be polygons.	Grid/raster Polygons Cadastral parcels

3.1.2 Defining biophysical modelling

48. Taking a broad perspective, for the purpose of these guidelines, we define **biophysical modelling** as the quantitative estimation of biophysical phenomena or processes that are difficult to fully observe directly. Commonly, biophysical modelling uses algorithms describing system properties to estimate how different physical factors influence complex systems.

49. Here, we also distinguish between models and modelling platforms. Although models are highly diverse in purpose and approach, many are set-up to analyse a specific problem (e.g. a model to estimate carbon sequestration). Some tools (e.g. InVEST or ARIES) consist of multiple models designed to analyse a set of ecosystem services. To make this distinction - although arguably not always easy to make – we will reserve the term **modelling platform** for tools consisting of multiple models**.**

50. Another important distinction for biophysical models is the difference between **model inputs** (i.e. a given model input layer such as precipitation or land cover) and **model outputs** (the result of model inputs being passed through a mathematical set of equations to provide desired outputs, e.g. flow estimates produced from a hydrological model). Model inputs are oftentimes themselves the result of modelling and are therefore best referred to as **data models**. However, to avoid confusion, data models will be oftentimes referred to as data layers. Most reputable data layers will include some form of accuracy assessment and verification.

51. In addition to biophysical models and modelling platforms, other important tools are available to guide the selection of models, modelling platforms, and assessment approaches as well as to help stakeholders determine the importance of certain ecosystem services or assess trade-offs between services. Such meta-tools will be referred to as **selection guidance**. Please note that the word "tool" will be used in a generic sense to cover models, platforms, selection guidance and other instruments.

52. These guidelines focus on biophysical phenomena and therefore generally have limited coverage of cultural services. Some models (e.g. SolVES - Social Values for Ecosystem Services) and techniques often used to explicitly assess these services (e.g. participatory mapping approaches) are therefore not detailed in these guidelines.

3.1.3 Tiered approach to modelling

53. In this report, we propose a "Tiered" approach for biophysical modelling to implement the SEEA EA, thereby allowing countries (or users) to build a model in accordance with their needs, data, resources, and expertise (Martínez-López et al., 2019). The use of a tiered approach mirrors IPCC approaches for carbon accounting (IPCC, 2006), highlighting three broadly defined tiers. Each tier measures the same statistical concepts but advances in spatial detail, computational complexity, and local accuracy, and hence better approximating these concepts as follows:

- **Tier 1:** Biophysical modelling that relies on globally available data sets and pre-constructed ecosystem service models using freely available tools, requiring very little user input.
- **Tier 2:** Biophysical modelling that relies on national data sets, requiring some customization and validation of ecosystem service models.

- **Tier 3:** Biophysical modelling that is implemented based on the best available local data using customized models that have been parametrized for local contexts.

54. A Tier 3 approach is ideal for accuracy, however, rough estimates based on global models and global data sets are a first step towards locally parametrized models, and many organizations may choose to initiate ecosystem accounts compilation using a Tier 1 approach. A disadvantage of choosing a Tier 3 approach is that for ecologically diverse countries, it may require multiple parameterizations within the same country.

    When a country changes the Tier of a specific account (due to availability of an improved data source or application of a better model), it is recommended to redo compilation also for earlier years, so as to generate a consistent time series.

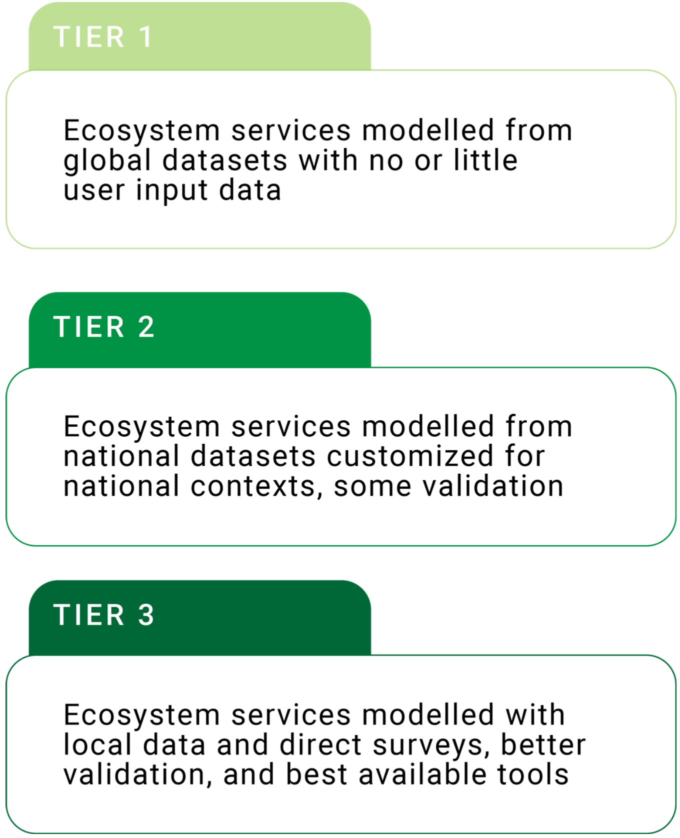

Figure 5: *Diagram of SEEA EA biophysical modelling tiers, each tier with varying levels of comprehensiveness.*

3.1.4 Resolution, complexity and fitness for purpose

55. Another dimension to consider when choosing a modelling approach is the required resolution of the accounts. Table 2 distinguishes between spatial resolution, temporal resolution and thematic resolution, which are all important elements to consider in whether an account is “fit for purpose”, meaning that it serves the policy purposes for which it was constructed. Because models hold many attributes, drawing sharp lines between Tiers is challenging. For example, spatial resolution does not necessarily increase with increasing Tiers. A model may be in Tier 1 for some attributes, while having Tier 3 characteristics for others. In some cases, high resolution spatial models with more parameterization may be comparable in resolution to low resolution data sets with limited parameterization, which means that moving towards higher tier approaches is not always warranted (Bagstad et al., 2018).

56. Models vary greatly in their complexity. While complex models are sometimes more accurate, they are not always the best choice, as they may require specialized expertise and greater computational power or other resources. Instead, model complexity should be driven by the model's purpose (Bagstad et al., 2013). For example:

- Tier 1 models give 'order of magnitude' aggregate estimates of annual flow of ES which are significantly reliable and adequate for awareness raising purposes;
- Tier 2 biophysical models are sufficiently documented statistically and sufficiently accurate to identify national trends in ecosystem services across periods, including disaggregation at national sectoral level;
- Tier 3 methods can identify trends in ES at the property boundary level, providing sector specific aggregates at municipal level, and serving also as a basis for land-use planning policies or instrument design at property level.

57. Furthermore, some model features are interlinked and have trade-offs. Highly detailed thematic resolution will likely lead to lower accuracy. For example, one way to improve accuracy of a land cover map is to reduce the number of classes identified, as there is less probability of making mistakes given that similar classes are grouped into a higher-level class. This may increase cross-country comparability of the results, but it also may limit the usefulness of the account in supporting local policy and decision making.

Table 2: *Features of biophysical models for SEEA EA, and examples of how they are typically defined in a SEEA EA context.*

					Example definition for different Tiers		
		Definition	**Example**	**Details for SEEA EA approach**	**Tier 1**	**Tier 2**	**Tier 3**
Data model and model output features	**Spatial resolution**	The smallest object discernible by measurement methods. Higher spatial resolution means more detail can be observed. For vector data (common for soil and land cover data), the minimum mapping unit defines the smallest unit that can be resolved in a map. Above the minimum mapping unit, features are defined by polygons.	An ecosystem map may have a minimum mapping unit of 5 ha, which means that features such as lakes that are smaller than 5 ha are not displayed.	A flexible approach to spatial resolution is espoused by SEEA EA, in part because for many data sets, only coarser resolution data sets are considered "state-of-the-art science", and the availability of data sets at different spatial scales are constantly evolving. For example, contemporary climate data is commonly found at a 1 km resolution.	500 m-1km	30-300m	1 - 10m
	Thematic resolution	How much each concept (such as an ecosystem or ecosystem service) is generalized compared to the underlying diversity in the concept.	Crop production can be generalized as the total volume of all crops, but there are a suite of different crop types underpinning this concept, (e.g. corn, soybeans, apples). The ecosystem services of recreation can be aggregated or disaggregated (e.g. fishing, boating, hiking), provision of timber (e.g. cedar, pine, maple), fish available for harvest, non-timber forest products, and water supply (e.g. riverine, groundwater) can also be aggregated.	Many regulating ecosystem services require no further disaggregation, including carbon sequestration, air filtration from vegetation, and water quality amelioration, though others such as pest control, crop pollination (i.e. for different crops), sediment retention (wind vs. soil erosion and susceptibility and retention by vegetation), or air filtration (i.e. of different air pollutants) can be disaggregated.	e.g. crop production reported as the total volume of all crops	e.g. several crops distinguished	e.g. individual crops distinguished across the range of crops produced
	Temporal resolution	The amount of time between measurements of data in the same location	Crops may be harvested annual or seasonally. To capture this temporal variability, measurements would need to be taken at each harvest. Similarly, water abstraction and water flows may vary seasonally, and as such annual measurements may mask variability.	An annual resolution is an objective for ecosystem accounting, but when this is not feasible, measurements every five years may be useful. For some ecosystem services such as water flow regulation seasonal temporal resolution may be important to support decisions.	e.g., decadal to annual resolution	e.g, annual resolution	e.g., seasonal resolution

3.1.5 Criteria for selecting a suitable model

58. A wide range of modelling platforms, models, and guidance for assessing ecosystems and the services they provide are available. However, most, if not all of these tools were not designed with a goal of supporting accounting in mind. This restricts their use since definitions of services or assets are not necessarily aligned with the definitions and classifications used in accounting. For example, models may not be applicable or tested at the aggregation level (national) required for accounting, or they may require data exchange with external servers, which may not be possible given privacy agreements followed by statistical agencies.

59. Thus far, there are no guidelines establishing the types of models that are acceptable for the SEEA EA. Because data availability and capacity vary greatly in different locations, a flexible approach to understanding models and their suitability is preferable. Nonetheless, models useful for the SEEA EA hold several features. Firstly, measured data form the basis of models suitable for the SEEA EA. Even though models can be used as a tool for estimating data in locations for which no direct measurements are available, they often require some type of measured or otherwise observed input data to make predictions. Second, temporal dynamics are inherent in this framework, as environmental accounts typically require reporting on an annual basis. As such, models might be sensitive to annual variability, and in some cases, such as for understanding floods and dry season water availability, even finer temporal resolution may be needed. Third, ecosystem accounting is applicable at various scales (site-level; sub(national); regional), so it is imperative that model outputs are scalable. Fourth, model outputs should be spatially explicit. Fifth, underlying physical characteristics of models must also be examined for coherence (e.g. consistency with accounting concepts), which must be done on a model-by-model basis.

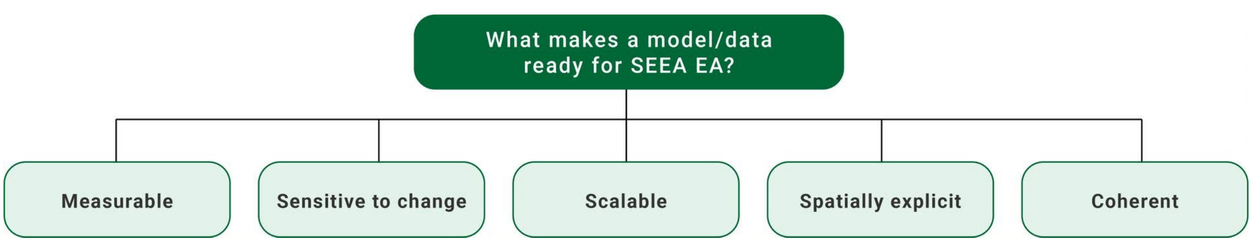

Figure 6: *Characteristics of models suitable for ecosystem accounts*

60. Using a tiered approach may result in outputs with different purposes. For example, Tier 1 and Tier 2 approaches may be best for awareness raising or analysis of broad spatio-temporal trends, while Tier 3 approaches may be used for local-scale decision-making. Tier 2 models could be used to monitor the consequences of different polices across distinct reporting units. Mid-resolution results may be useful for screening purposes, such as identifying which locations need more target management or accounts.

3.2 Overview of modelling techniques

61. Table 3 gives a summary description of the various modelling techniques involved in ecosystem accounting (the Annex gives a more detailed description of these techniques). These broad techniques vary greatly in data needs and difficulty of implementation. Each of these modelling techniques may differ in its relationship to the use of scientific knowledge versus data. For example, machine learning relies heavily on the use of data, while process-based models rely on a combination of scientific knowledge and data.

62. Compilation of ecosystem accounts usually requires the application of multiple different techniques. For example, ecosystem accounting may require one type of technique to produce spatially complete maps of ecosystem extent, while another technique may be needed to estimate the biophysical supply of ecosystem services. Many modelling techniques are available in "standard" GIS packages, such as ArcGIS or QGIS or extensions thereof.

3.3 Modelling platforms

63. Biophysical models for mapping extent and measuring ecosystem services have proliferated over the past two decades (Neugarten et al., 2018). The science and disciplinary-specific models that underpin these ecosystem services models have been developing for decades prior to these multiservice models, albeit often not under the ecosystem service framework. Multi-model platforms facilitate comparisons of ecosystem accounting spatial units (e.g., EAAs and BSUs) and evaluations of trade-offs in ecosystem services. Table 4 provides the characteristics of the most widely used modelling platforms, focusing on multi-service modelling platforms that produce results that may either be used directly or modified for use in SEEA EA.

__Table 3:__ Comparison of frequently used modelling techniques

Model technique	Definition	Data needs	Efforts involved in applying the model	Freeware software available	Reliability and examples of accuracy approaches	Further details
Look-up Table	Specific values for an ecosystem service or condition variable are attributed to every pixel in a certain class, usually a land cover, land use, or ecosystem type class.	Limited	Easy	Yes (QGIS, R)	Sensitivity analyses - accuracy depends on thematic resolution of underlying data sets	Values per pixel need to be derived from the (scientific or "grey") literature, for ecosystems that are comparable in ES provision or characteristics underpinning ES delivery, such as vegetation, soil, climate, etc.
Spatial interpolation	Creates surfaces from measured points	Moderate	Moderate	Yes (QGIS, R)	Cross-validation and validation	Specific techniques exist. Inverse distance weighted and radial basis functions are exact interpolators, while global polynomial, local polynomial, kernel interpolation with barriers, and diffusion interpolation with barriers are inexact interpolators.
Geostatistical models	Statistical algorithms predict the value of un-sampled pixels based on nearby pixel values in combination with other characteristics of the pixel.	Moderate	Moderate	Yes (ArcGIS, QGIS, R)	Produce error or uncertainty surfaces, giving an indication of how good the predictions are in terms of the spatial errors (note that the values themselves may also be prone to uncertainty).	The most widely used form of geostatistics is kriging, and its different variations. These include ordinary, simple, universal, probability, indicator, and disjunctive kriging.
Statistical models	Values of pixels are assigned based on a set of underlying variables. The relation between the value and the independent variables is developed with a regression analysis.	Moderate	Moderate	Yes (R, Python)	- Data splitting (testing and training methods) - K-fold cross validation - Leave one out validation - Goodness of fit	A well-known example of such a tool is Maximum Entropy modelling (Maxent, Phillips et al., 2006).
Dynamic systems (such as process-	Dynamic systems modelling uses sets of differential equations to describe responses of a dynamical system to all possible inputs and initial conditions. The equations include a set of state	High	High	Often available, depends on process	Taylor series and Monte Carlo techniques. The systems approach can contain non-linear dynamic processes, feedback	A challenge to process-based models is that management variables may not be known with sufficient (spatial) resolution and accuracy. Process-based models are

Model technique	Definition	Data needs	Efforts involved in applying the model	Freeware software available	Reliability and examples of accuracy approaches	Further details
based models)	(level) and flow (rate) variables in order to capture the state of the ecosystem, including relevant inputs, throughputs and outputs, over time. Most process-based models are examples of dynamic systems models that predict ecosystem services supply or other variables based on a mathematical representation of one or several of the processes describing the functioning of the ecosystem.			being modelled.	mechanisms and control strategies, and can therefore deal with complex ecosystem dynamics, such as thresholds in ecosystem responses or hysteresis.	typically used for modelling hydrological services. Examples of process models include AGNPS, AnnAGNPS, ANSWERS, CASC2D, DWSM, HEC-HMS, HSPF, KINEROS, MIKE SHE, PRMS, SWAT and SWIM. Lotka–Volterra equations are a well-known example used for understanding predator prey dynamics in ecology.
Machine learning	A type of artificial intelligence. Machine learning uses training data to build algorithms to make predictions without explicit programming.	High	Moderate	Yes (various)	- Logarithmic loss measures how well a classification model performs by comparing true values to probabilities in the model. - Confusion matrices, which are also common in evaluating land use classifications, can also be used to evaluate the results of a machine learning model - Area under curve - F1 Score - Mean absolute error - Mean squared error	Well-known examples of machine learning algorithms are random forests and convolutional neural networks, though a wide range of other machine learning algorithms exist and have been applied to scientific modelling.

***Table 4:** Overview of modelling platforms with potential use in SEEA EA.*
We reviewed only tools that are accounting compatible and open source[16]
(as of May 2020 – for latest version of the table see: https://seea.un.org/ecosystem-accounting/biophysical-modelling)

Modelling platform	Primary goal of platform	Annual time step feasible	Spatially explicit	Scalable	Economic valuation tools	Coverage
ARIES (Villa et al., 2014)	ARIES (Artificial Intelligence for Ecosystem Services). Provides easy access to data and models through a web-based explorer and using Artificial Intelligence to simplify model selection, promoting transparent reuse of data and models in accordance with the FAIR principles.	Yes	Yes	Yes	Yes	Extent, Condition, Ecosystem Services
Data4Nature[17]	Data4Nature (formerly known as EnSym - Environmental Systems Modelling Platform) is a decision support tool that is designed to answer questions about where organizations should invest in their natural resources. Data4Nature is specifically designed with SEEA EA in mind.	Yes	Yes	Yes	No	Extent, Ecosystem Services
ESTIMAP (Zulian et al., 2018)	ESTIMAP (Ecosystem Services Mapping tool) is a collection of models for mapping ecosystem services in a multi scale perspective (it can be applied at different scales) (Zulian et. al 2018).	Yes	Yes	Yes	No	Ecosystem Services
InVEST (Sharp et al., 2018)	A compilation of open-source models for mapping and valuing ecosystem services. InVEST is the flagship tool of the Natural Capital Project and has been the most widely used ecosystem service modelling tool globally.	Yes	Yes	Yes	Yes	Ecosystem Services, Condition
i-Tree[18]	i-Tree is a tool developed by the USDA Forest Service with capabilities of modelling ecosystem services related to trees, particularly in urban settings (i.e. air	Yes	Yes	Yes	Yes	Ecosystem Services (forest related)

[16] Neugarten et al. (2018) review a larger number of tools, including Tessa, MIMES, PABAT, and Co$ting Nature and WaterWorld. The latter are closed-source platforms that provide easy entry points for ecosystem services modelling, see: http://www.policysupport.org. Co$ting Nature (Mulligan et al. 2020) is a web-based tool for analysing ecosystem services, that departs from a large number of pre-loaded global data sources. The analysis is spatially explicit (1km2 or 1ha2), and it has wide functionality for doing policy scenario analysis. WaterWorld has the same approach, but focuses on hydrological services. It can be used to assess water, land use and climate policies. Both platforms allow the user to upload own data sources.
[17] The D4N website (as of Jan. 2022) is still a draft: http://www.data4nature.com.au/resources/ For EnSYM see: https://ideeagroup.com/ensym/
[18] "I-Tree Canopy. iTree Software Suite," n.d., http://www.itreetools.org/

Modelling platform	Primary goal of platform	Annual time step feasible	Spatially explicit	Scalable	Economic valuation tools	Coverage
	filtration, carbon storage urban heat island mitigation, and rainfall interception and infiltration).					
Nature Braid (Jackson et al., 2013)	The Nature Braid (formerly LUCI/Polyscape) provides a suite of high spatial resolution ecosystem services models designed to improve decision-making around restoration and land management. The Nature Braid is particularly well suited for mapping soil, water and chemical transport processes at high resolution.	Yes	Yes	Yes	No	Extent, Condition, Ecosystem Services (hydrological, soil)

3.3.1 ARIES

64. ARIES (ARtificial Intelligence for Ecosystem Services; Villa et al., 2014) aims to enhance accessibility of ecosystem service models by (1) providing easy access to data and models through a web-based explorer and (2) using artificial intelligence to simplify model selection, promoting transparent reuse of data and models in accordance with the FAIR principles (see Chapter 7). ARIES provides a suite of readily available ecosystem services models that can be run at a global scale including carbon storage, crop pollination, flood regulation, outdoor recreation, and sediment regulation. Two of these models produce biophysical values (sediment regulation and carbon storage), while the remaining others have been translated into physical and monetary values that are compatible with the SEEA EA using national statistics in an application of SEEA EA accounts for Italy. These models may provide the first step for countries hoping to estimate ecosystem services when custom data is unavailable (Tier 1 approach). Substitution of custom data to replace global data enables the achievement of Tier 2 analysis. ARIES also has several more intensive models for pollination services and water supply, which are too computationally intensive to be run globally, but may be appropriate at regional scales (Martínez-López et al., 2019) and constitute a Tier 3-style approach. While ARIES does provide ecosystem services models, its main aim is to provide an integrated modelling platform where researchers from across the globe can add their own data and models to web-based repositories, where consistent naming and reuse rules enables their interoperability and reusability. This consistency would create an environment where data and models can be adopted and customized by utilizing the best available information in each location.

65. A novel development that may provide countries with a jump-start in ecosystem services modelling is the ARIES Explorer webtool. The ARIES Explorer automates model selection based on user specifications i.e. it chooses the most appropriate model to the location, spatiotemporal resolution, and observable specified (e.g. an ecosystem service or condition variable). Based on its generic syntax and large number of pre-loaded global, national, and local data layers, the tool generates the optimal model results for the specified query and reports on their provenance (i.e. data sources and underlying algorithms, as well as a pre-generated report describing the models and results). The outcomes can be inspected and downloaded for further analysis in GIS software.

66. Specially, the ARIES for SEEA Explorer application[19] allows users to generate ecosystem accounts for any user-specified terrestrial area in the world (such as a country, administrative region, watershed, etc.), by using freely available global remote-sensing derived data and models, and rapidly compute these accounts online, using a web browser. The accounts are consistent with the SEEA Ecosystem Accounting framework. ARIES for SEEA is available on the UN Global Platform, a cloud-service platform supporting international collaboration in the development of official statistics using new data sources and innovative methods. The current Explorer functionalities include: assessing ecosystem extent (based on the IUCN Global Ecosystem Typology); condition (for forest ecosystem types); and selected ecosystem services in physical and monetary units using basic models as a starting point. The outcomes can be analyzed and downloaded to further explore the results (either through a spreadsheet or GIS software). The Explorer automatically generates a comprehensive ecosystem accounts report, fully documenting the data, models, coefficients and methods used.

3.3.2 Data4Nature

67. Data4Nature was designed to meet and comply with the SEEA EA (specifically Section 3.5 Considerations in the delineation of spatial units) so users can easily produce biophysical ecosystem, carbon, water, land and species accounts. Data4Nature is comprised of several tools: a native vegetation regulations tool, a site assessment tool, a landscape preference tool, biophysical simulation modelling, and a hydrology tool. These Data4Nature models are able to evaluate: land management practices such as vegetation removal and farming, sediment, and water quantity and quality. Data4Nature's hydrology tool uses MODFLOW[20] for hydrological modelling. It also has a climate change impact model.

68. The following ecosystem services can be modelled and reported in Data4Nature: biomass provisioning services - crops, grazing, wood and water supply; regulating and maintenance services – global climate regulation services and rainfall pattern regulation services (at national, sub-continent, farm); local (micro and meso) climate

[19] https://seea.un.org/content/aries-for-seea
[20] MODFLOW is the USGS's modular hydrologic model for simulating and predicting groundwater conditions and groundwater/surface-water interactions. See: https://www.usgs.gov/mission-areas/water-resources/science/modflow-and-related-programs?qt-science_center_objects=0#qt-science_center_objects)

regulation services; soil quality regulation services - soil erosion control services; water purification services (water quality regulation) - retention and breakdown of nutrients; water flow regulation services - baseline flow maintenance services and peak flow mitigation services; flood control services - river flood mitigation services; nursery population and habitat maintenance services; and ecosystem and species appreciation – species and ecosystem distribution modelling.

3.3.3 ESTIMAP

69. ESTIMAP (Ecosystem Services Mapping tool) is a collection of models for mapping ecosystem services in a multiscale perspective. Its development started in 2010 at the Joint Research Centre (JRC), the European Commission's science and knowledge service. ESTIMAP currently includes 12 models for ecosystem services (pollination, nature-based recreation, air quality regulation, microclimate regulation, coastal protection, flood control, carbon sequestration, erosion control, habitat maintenance, habitat quality and pest control). ESTIMAP has been applied at several geographical levels and for different purposes. Scientific papers are available describing the methods developed in ESTIMAP (for instance Zulian et al., 2013; Paracchini et al., 2014; Liquete et al., 2013; Zulian et al., 2014). In addition, several reports and scientific papers are available, describing application in different contexts, scales and at different levels of complexity, from Tier 1 to Tier 2 or 3 (Grizzetti et al., 2019; Liquete et al., 2016; Maes J., et al., 2015; Ihtimanski et al., 2020; Baró et al., 2016; Stange et al., 2017; Zulian et al., 2017; Cortinovis et al., 2018; Fernandes et al., 2020; Suárez et al., 2020; Maes et al., 2020). The type of modelling approach implemented depends on the ecosystem service modelled. For instance nature-based recreation and pollination models use an advanced look-up table approach, while air quality regulation and microclimate regulation models use a regression approach.
70. ESTIMAP was originally developed to model ecosystem services, and more recently, it has been further enhanced to develop ecosystem service accounts, including monetary valuation as well. The first applications of ESTIMAP on accounting were developed for pollination and recreation (Vallecillo et al., 2018). Further accounting applications of ESTIMAP include flood control (Vallecillo et al., 2019), habitat and species maintenance and soil retention (La Notte et al., 2021). ESTIMAP's models can be set up using any GIS platform, following the methods described in the papers.

Currently, a set of QGIS plugins using ESTIMAP for accounting are under development. They will become available on the following website: https://ecosystem-accounts.jrc.ec.europa.eu/.

3.3.4 InVEST

71. InVEST (Integrated Valuation of Ecosystem Services and Trade-offs) is a compilation of open-source models for mapping and valuing ecosystem services (Sharp et al., 2018). InVEST is the flagship tool of the Natural Capital Project and has been the most widely used ecosystem service modelling tool globally. InVEST has a wide range of models that may produce outputs suitable for compiling ecosystem accounts (Bagstad et al., 2019). InVEST includes a wide selection of spatially explicit models for carbon, coastal blue carbon, coastal vulnerability, crop pollination, fisheries, habitat quality, habitat risk assessment, marine fish aquaculture, offshore wind energy, recreation, reservoir hydropower production (water yield), scenic quality, sediment retention, water purification, and wave energy. Like most of the other tools evaluated here, InVEST was not designed explicitly for SEEA EA. Some outputs may require further modelling or modification for incorporating in ecosystem service accounts, for instance where the models produce indices rather than biophysical values (e.g. coastal vulnerability). InVEST also allows users to compute monetary values for a number of services.

3.3.5 i-Tree

72. i-Tree is a tool developed by the USDA Forest Service with capabilities of modelling ecosystem services related to trees, particularly in urban settings (i.e. air filtration, carbon storage, urban heat island mitigation, and rainfall interception and infiltration). i-Tree blends both tools that quantify values and benefits of trees with tools to facilitate forest inventories for better management. i-Tree is especially well-suited to understanding urban ecosystem services, and its hydrology model was especially designed for this purpose. Benefits are often calculated per calendar year, making the output well-suited for SEEA integration. However, in some cases, the output is not spatially explicit, which may limit its adoption for the SEEA EA.

3.3.6 The Nature Braid (formerly LUCI)

73. The Nature Braid (a next generation implementation of LUCI, the Land Utilisation and Capability Indicator) provides a suite of high spatial resolution ecosystem services models designed to improve decision-making around restoration and land management. It was originally a hydrology-based tool and is well suited for mapping hydrologic processes at high resolution, with readily available models for nutrient retention (N and P), sediment retention, agricultural production and flood mitigation. It also has several aggregation tools to aid with SEEA EA condition accounts. It is well parameterized for temperate and tropical climates, with its most extensive applications in the United Kingdom, New Zealand, the Philippines and Vietnam. Applications in colder climates and/or arid climates require more setup time and also caution around applicability of some of the embedded tools.

74. The developers of Nature Braid have a few tools to characterize ecosystem condition that are being tested in a SEEA EA context, and a freely available open-source version ("LUCI for SEEA") exists.[21] A grid generation tool allows areas to be broken up into grids of user-desired size for aggregate condition and biodiversity metrics. Additionally, a tool is available in the LUCI toolkit that takes this user-produced grid and then provides richness, patch size, Shannon and Simpson entropy indices (See Chapter 5) on soil, land cover, or similar data sets. LUCI also supports land accounts and a SEEA-EA relevant version of the RUSLE (Revised Universal Soil Loss Estimation) has also been included. These are currently available in beta form and are being further refined. For next steps, a tool automating the process of calculating species richness on IUCN data is in development, as is a tool allowing fragmentation and connectivity of habitat or similar data to be calculated which is a modification of the connectivity algorithms already in use (Jackson et al., 2013).

3.4 Conclusions

75. This chapter has shown that various approaches, models and modelling platforms exists. This section provides several additional considerations that can help inform model selection.

[21] It can be downloaded from https://github.com/lucitools/LUCI_SEEA. This requires an ArcGIS license to operate, but some more limited functionality not requiring ArcGIS is also available via the web at https://model.lucitools.org.

76. Models found on multi-service modelling platforms often rely on similar input data across services, because such platforms were designed to encourage the modelling of multiple ecosystem services rapidly. They often provide easy entrance points for novice modellers, as well as for people without specialized disciplinary expertise, making them especially suitable for countries with fewer resources within statistical agencies. An additional benefit of using a platform is the similarity of interface, data needs, etc., as well as output metrics, making it time-efficient to model multiple services. The use of a modelling platform may also make it easier to compare outputs across countries.

77. On the other hand, multi-service models have several limitations. Some multi-service platforms require collaboration with model developers. While in theory, these platforms are free, technical support directly from developers or building local technical capacity may be necessary to ensure model outputs are repeatable over time. In addition to this, in some cases (e.g. InVEST), models may be overly simplified to ensure applicability under a wide range of conditions which are not necessarily present in the ecosystem accounting area. Users may find that customized models are needed to integrate data collected by national statistics agencies. Furthermore, using models created and maintained by outside organizations creates a risk that these models may evolve or no longer be available in the future. Nonetheless, many of these modelling platforms have been around a decade or more suggesting they have some staying power in the research community and/or the ability to continuously develop. Also, many platforms are open source (e.g. ARIES, InVEST, and the Nature Braid), which may alleviate some of these issues.

78. Compared to multi-service modelling platforms, the accuracy of using (combinations of) single service models will generally be considerably higher, since these models can be fine-tuned to national available data. Several ecosystem services are relatively easy to model in a standard GIS environment and learning new platforms may not be warranted. For example, using a look-up table approach technique to model carbon stocks or sequestration, or modelling erosion control with the universal soil loss equation only requires basic GIS expertise. For more complex ecosystem services, in particular for hydrological services, a variety of specific models are available (e.g. SWAT, MODFLOW, SedNET) that can be integrated in a GIS environment. An advantage of not being prescriptive here is that expert centres in different countries

may have experience with and data availability for different hydrological models, and the hydrological model most familiar in the country may be applied.

79. However, it is important not to create a false dichotomy. In many circumstances, both individual models and modelling platforms have a role to play, depending amongst others upon data availability, resources available and modelling expertise. In addition, the newest generation of platforms (such as the ARIES explorer) allows users also to customize models and upload/use national data sets.

80. One of the main limitations of both individual, disciplinary specific models and multi-services platforms is that they have not been specifically designed for SEEA EA (with the exception of Data4Nature and ARIES for SEEA). However, many platforms are considering how to facilitate the use of their models in SEEA EA (e.g. LUCI/Nature Braid, ESTIMAP). Outputs may require further processing before they produce table and map outputs consistent with the SEEA EA framework. Some models may aggregate outputs by watershed or political boundaries, and as such, these outputs may require additional modelling for spatial disaggregation. Furthermore, in several instances, the output of multi-service models are indices (e.g. coastal vulnerability) rather than the quantities required for accounts.

81. Several guides in the form of handbooks or reports have been developed to help with the selection of models and platforms. For example, the Canadian government has developed a tool for ecosystem service assessments in a decision-making context (Value of Nature to Canadians Study Taskforce, 2017). This guidance is complementary to the guidance produced by the World Resources Institute, which also highlights experiences in ecosystem service tool selection in data-poor contexts (Bullock and Ding, 2018). Another useful guidance for selecting ecosystem service models was developed by Conservation International, which highlights useful modelling platforms for understanding ecosystem services in protected areas (Neugarten et al., 2018). These guides are less restricted to specific results formats, unlike the SEEA EA which specifies clear guidelines for the structure and format of data. Nonetheless, these tools may compliment this guide.
Another very comprehensive overview is the book *Mapping Ecosystem Services* (Burkhard and Maes, 2017).

4 Modelling for extent accounts

4.1 Introduction

82. Spatial areas are at the heart of ecosystem accounting. The conceptual model of the SEEA EA delineates areas within a country or region into contiguous, mutually exclusive (tessellated) units, each covered by a specific ecosystem, i.e. dynamic complex of plant, animal and micro-organism communities and their non-living environment interacting as a functional unit (CBD, 1992, Article 2, Use of Terms). Each of these units comprises an ecosystem asset (EA), and these form the conceptual base for accounting (see Chapter 3 of the SEEA EA for details on the spatial framework). A classification describing the ecosystem types and a map showing their coverage within an EAA are essential components of ecosystem accounting. The extent account summarizes the occurrence, area and changes of ecosystem types during the accounting period for a specific EAA.

83. The spatial delineation of ecosystems may be based on a range of ecological and non-ecological characteristics, including vegetation type, soil type, hydrology, climate, land management, land use and ownership (Bogaart et al., 2019). Approaches to classifying ecosystems will depend on the classification's application. The revised SEEA EA emphasises choosing a classification that has a sound ecological basis for extent accounts, thereby drawing a sharper distinction between ecosystem extent accounts and land accounts.[22]

84. The distinction between land and ecosystem extent can be explained as follows. According to the SEEA CF "land is a unique environmental asset that delineates the space in which economic activities and environmental processes take place and within which environmental assets and economic assets are located." (UN et al., 2014a, para 5.239). In physical terms, land accounts describe both land area and their changes over an accounting period. Different types of land accounts are described in the SEEA CF (para 5.263): land cover accounts, land use accounts and accounts of land ownership either by industry (economic sector) or by institutional

[22] This recommendation differs from the SEEA Experimental Ecosystem Accounting (2012) and the more recent Technical Recommendations (2019) that considered the use of an interim, land-cover classification as a starting point for an ecosystem classification. However, it was recognized that this classification is very coarse, and lacks a clear ecological basis. (Bogaart et al., 2019). Because land cover classes may be the product of historical uses and ownership, they are not always ecologically meaningful (UNEP-WCMC and IDEEA, 2017).

sector. For example, a forest that is recently harvested, may have as land cover “bare area” while its land use remains “forest”.

85. In most cases land cover maps may provide a good starting point for building an ecosystem extent account, and in some cases, land cover will align with ecosystem type. However, in order to compile an ecosystem extent account, one usually needs additional data layers such as those for climatic variables and elevation (i.e., topography). For instance, tropical, sub-tropical, temperate, and boreal forests may all share a common land cover (vegetation type – i.e., forest cover), but they are very distinct ecosystem types, which one could distinguish if also taking climatic variables into account.

86. Notwithstanding, and despite the differences in measurement purposes between ecosystem extent and land accounts, land cover/use maps remain foundational to any ecosystem accounting exercise, as they provide inputs into many biophysical modelling exercises. In other words, land accounts may not be a replacement for ecosystem extent accounts but they are complementary.

87. For overlaying an extent map with land-use or land-ownership maps allows to connect extent accounts with economic units. This subsequent step is important to be able to attribute ecosystem services to users and beneficiaries.

88. Biophysical models for extent accounts should be the first in the sequence of models adopted by statistical agencies, in part because these accounts can underpin subsequent accounts, but also because there are a wide range of spatially contiguous measurements that can easily be linked to ecosystem extent accounts. Modelling techniques can be used to classify pixels into different ecosystem or land cover types. Modelling can also be used to fill in gaps where coverage (e.g. of satellite imagery) is patchy, as well as to identify ecosystem types not distinguishable with satellite imagery.

89. In this chapter, we will first discuss ecosystem classifications for extent accounts (Section 4.2). In Section 4.3, we will discuss modelling approaches and main steps in compiling extent accounts. In Section 4.4, we provide an overview of existing remote sensing and land cover products that can be used for compiling extent accounts. Section 4.5 provides various country examples.

4.2 Classifications of ecosystems

90. To achieve standardization in national reporting and to allow for comparability of results across nations, a global reference classification for ecosystem types is required. As part of the SEEA EA revision process, a set of criteria was established for such a reference classification, and a number of classifications was assessed (Horlings et al., 2019).

- IUCN Global Ecosystem Typology[23]
- USGS/Esri/GEO Global Ecosystems Mapping Products (Sayre et al., 2014)[24]
- Existing habitat classifications:
  - EUNIS habitats classification[25]
  - IUCN Habitats Classification Scheme v3.1[26]
- EU MAES ecosystem types (Vallecillo et al., 2019)
- WWF ecoregion classification[27]
- Existing land cover classifications (e.g. FAO LCCS[28]; Corine[29])

91. A consensus was reached to use the IUCN Global Ecosystem Typology level 3 units, ecosystem functional groups (EFGs), as the global reference classification for ecosystem extent accounts, as this typology satisfies all the design criteria (Bogaart et al., 2019). As a global reference classification, the GET fulfils the same role as, for instance, the International Standard Industrial Classification of All Economic Activities (ISIC) plays within economic statistics: nearly all countries will have their own ecosystem type classification of some sort that will be the starting point for their work, but the GET provides a reference point, both for comparison of data as well as for ensuring that all national (and other) classifications can be compared to a sound and agreed conceptual base.

92. One limitation of the GET approach is that while it provides occurrence maps of individual EFGs[30], there does not currently exist a single global integrated map with

[23] See: https://iucnrle.org/about-rle/ongoing-initiatives/global-ecosystem-typology/; Indicative IUCN-GET EFG Distribution maps: https://zenodo.org/record/4018314#.YIwlNLVKiMo
[24] See also the World Terrestrial Ecosystems map: https://storymaps.arcgis.com/stories/a4a6b1f779be4b64816d1876cfe669b9
[25] See: https://www.eea.europa.eu/data-and-maps/data/eunis-habitat-classification
[26] See: http://www.iucnredlist.org/technical-documents/classification-schemes/habitats-classification-scheme-ver3
[27] See: https://www.worldwildlife.org/publications/terrestrial-ecoregions-of-the-world
[28] See: http://www.fao.org/3/y7220e/y7220e00.htm#Contents
[29] See: https://land.copernicus.eu/pan-european/corine-land-cover
[30] See: https://global-ecosystems.org/

mutually exclusive classes[31]. Another is that the use of the GET requires further country testing. The USGS/Esri maps (and underlying data) may provide a method to map some EFGs, especially when no ground observations are available, but requires a crosswalk to identify potential congruencies and gaps.

93. Countries may have their own national classification system of ecosystems (or ecological areas[32]) that could be used for the extent accounts. In such cases, developing a bridge or concordance (often called a schema crosswalk in GIS) of this national classification system with the GET reference classification may facilitate comparability across countries.

94. In many cases, the EFGs units may be too coarse for accounting on a national scale, and countries may seek finer disaggregation of units. A flexible approach to ecosystem extent accounts ensures that the most important ecosystems and their characteristics are identified. Certain ecosystem classes, such as narrow riparian ecosystems, may require higher resolution imagery with greater spectral resolution or on-ground surveying, than ecosystems that cover large areas, such as vast boreal forests, and may require supplementary data sets.

95. In certain cases, complementary classifications exist (e.g. vegetation maps, detailed forest classifications, or the Local Climate Zone Framework in case of urban areas).[33, 34] Such classification could provide an alternative disaggregation nested within biomes or EFGs.

96. Several key questions might help guide your selection of ecosystem classes:

- Are there specific policies in place that are based on a typology of ecosystems that would need to be respected?
- What are some of the key ecosystems of concern in your country?
- What biophysical properties characterize these ecosystems? Are they likely to be spectrally distinct (visible using remote sensing data) or will landscape context (i.e. other data sources aside from remote sensing data) be needed to distinguish these ecosystems?

[31] The ARIES for SEEA Explorer is able to distinguish (as of December 2021) 29 different EFGs using methods aligned with IUCN GETs, with plans to expand towards 60-70.
[32] For example, Statistics Canada *Ecological Land Classification 2017*: See https://www.statcan.gc.ca/eng/subjects/standard/environment/elc/elc2017

[33] See: http://www.wudapt.org/lcz/
[34] Grenier et al. (2020)

- Have the ecosystems in your area been characterized by other agencies or previous research in your country?

97. Answers to these questions could/should come out of the initial national assessment described in Chapter 2. Most countries have National Biodiversity Strategies and Action Plans that may contain relevant information and provide a good starting point.

__Box 1__. IUCN- Global Ecosystem Typology

The IUCN Global Ecosystem Typology (GET) has been developed by the IUCN Red List of Ecosystems Thematic Group (Keith et al., 2020). It represents a global typological framework that applies a process-based approach to ecosystem classification across the whole planet. It is a scalable framework that support generalizations about groups of functionally similar ecosystems and recognizes different expressions within these groups defined by contrasting biotic composition. Ecological assembly theory is used to identify key properties that distinguish functionally related ecosystems, and synthesize traditionally disparate classification approaches across terrestrial, freshwater and marine environments.

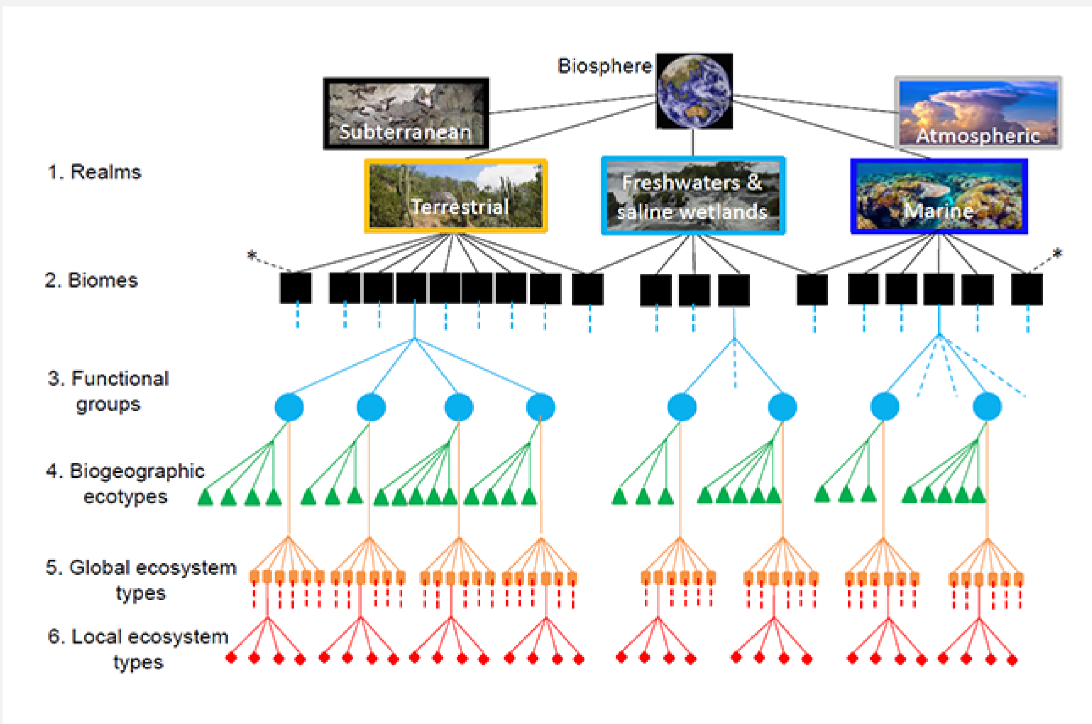

Figure 7: *IUCN Global Ecosystem Typology, source: Keith et al. 2020;* [*https://global-ecosystems.org/page/typology*](https://global-ecosystems.org/page/typology)

The hierarchical structure consists of six levels: the three upper levels differentiate functional properties. The top level of the classification defines four realms of the biosphere: marine (M); freshwaters and saline wetlands (F); terrestrial (T); and subterranean (S). The second level of the classification broadly follows the 'modern biome concept' (Mucina, 2018) and distinguishes 25 biomes: four marine; three freshwater; seven terrestrial; four subterranean; and seven transitional realms. Many of the units recognized at level 2 by their distinctive ecological traits are familiar as 'traditional' biomes, including rainforests, deserts, reefs, freshwater lakes and others. In addition, four biomes are 'anthromes' defined by anthropogenic processes, where human activity is pivotal to ecosystem assembly and maintenance of ecosystem components and processes. Level 3 of the classification describes functionally distinctive groups of ecosystems within a biome i.e. ecosystem functional groups (EFGs). There are currently 108 ecosystem classes defined in the GET, defined by shared ecological traits, but 10 of those are subterranean systems not currently addressed by SEEA.

4.3 Modelling approaches

4.3.1 Decision tree and Tiers

98. Figure 8 depicts an example of a decision tree that can help determine the best overall approach for ecosystem extent. In the case where an authoritative ecosystem map is already available - especially when it is regularly updated which allows for assessing changes over time - it is sensible to use this map as the foundation for the extent account. It is important to develop a crosswalk to an international reference classification such as the GET.

99. When no existing classification and/or map of ecosystem types is available, or deemed suitable for the purposes of accounting, one could opt to use a freely available global land cover product as the foundation (see Section 4.4.2 for an overview). Such a Tier 1 approach may be appealing when resources and/or technical capacity are low.

100. In cases where technical capacity exists, a Tier 2 approach could draw on mid-resolution satellite imagery such as Landsat to create custom mid-resolution classifications (see Section 4.4). Classification algorithms will be essential to create custom maps. Remap is a tool developed to help delineate the IUCN's Red Listed ecosystems. This tool and approach are especially useful for groups with little experience classifying remotely sensed data (see Section 4.3.3). Alternative approaches, such as using climate data to predict where certain ecosystems are likely to occur, is another path for creating ecosystem extent maps in locations where coverage of satellite images is incomplete. Tier 2 approaches would likely need to use several modelling approaches including combining remote sensing images with other data sets and potentially interpolating gaps in remote sensing images.

101. Tier 3 approaches could draw upon high-resolution satellite imagery or multispectral aerial photographs that may be specific to the contexts of different countries. These approaches are resource intensive and require high technical capacity.

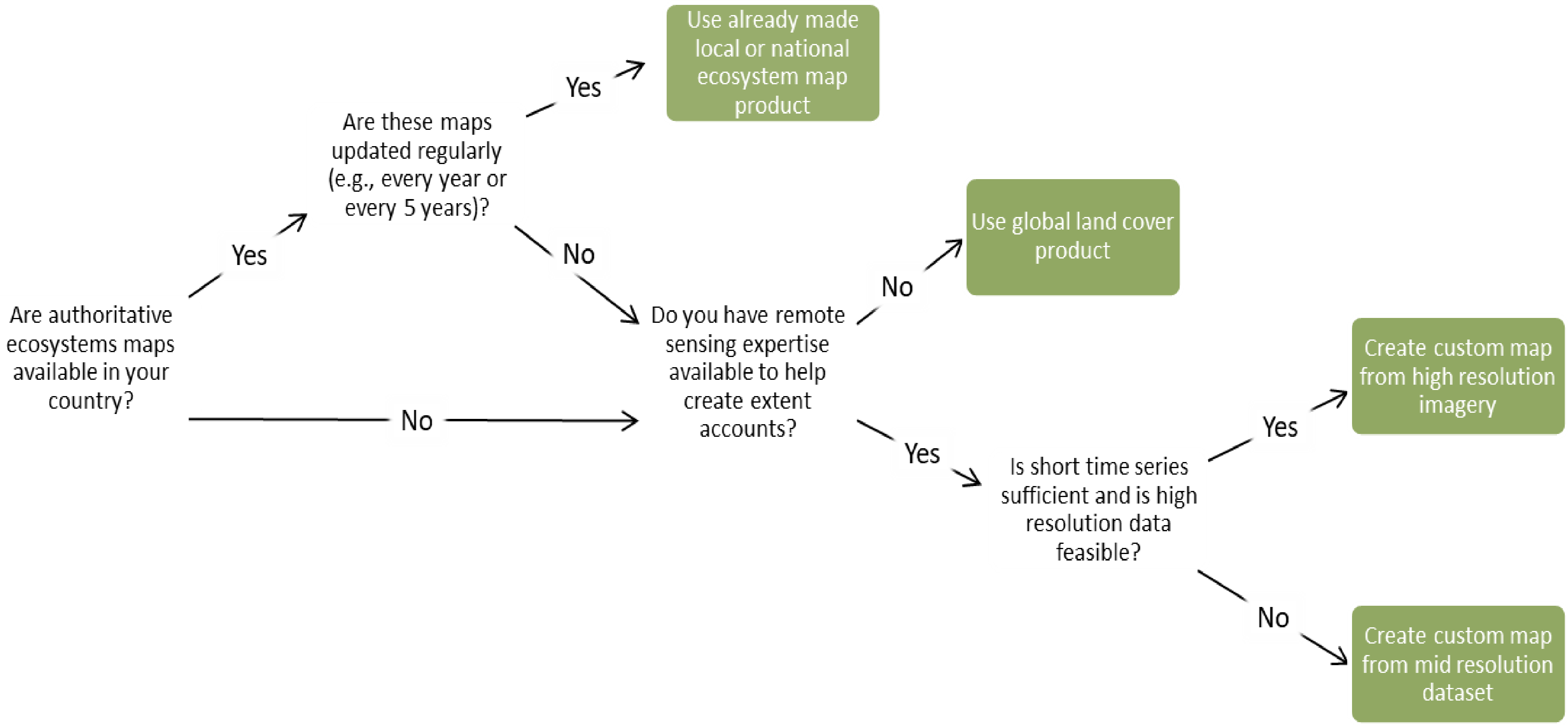

Figure 8: *Decision tree to help determine the best approach for ecosystem extent accounting for different contexts. Each of final approaches could include additional landscape context information (climate, distance to water, elevation) added to improve classifications of those ecosystems which are difficult to detect.*

4.3.2 Modelling steps

102. In the absence of an existing classification and/or map for ecosystems, a number of steps will be required for producing ecosystem extent maps. There are two main options, corresponding with a Tier 1 and Tier 2/3 approach (Figure 9). The first step for both options is determining which ecosystem classification to use and which classes to include. The easiest option for creating ecosystem extent maps is using maps that have already been created using global land cover products (Section 4.4.2 for examples of global land cover products). Using these data sets would require no additional modelling but should involve understanding the underlying process used in creating these data sets. To create these land cover products, classification algorithms were likely used.

103. Developing a crosswalk between the selected land cover product and the chosen classification of ecosystems (in case it would differ) is necessary. The land cover foundation could also be enriched by overlaying this map with other layers with ancillary ecological information (e.g. climate, biomes, habitat, soil types etc.).

104. The alternative option is to create ecosystem maps using remote sensing and other complementary data sets. Identifying an appropriate remote sensing product is an important step in this process, and it will depend on the most practical or desired spatial resolution as well as depending on the types of ecosystem classes the user hopes to distinguish. The basis of extent accounts are basic spatial units; typically the maximum recommended unit is 500m x 500m. These mapping units are then aggregated and summarized into tables. For example, some sensors have a greater number of spectral bands, which may help distinguish ecosystem types which look similar using only the visible spectrum. Then, methods to classify remote sensing products must be established. Classifying remote sensing images typically requires specialized software.

105. Creating custom ecosystem maps is more time consuming because it requires modelling to classify ecosystems as well as to fill data gaps. A representative ground reference data set for training and validation is important for supervised classification models. Ideally these data should be collected *in situ*, but also *ex situ* reference data can be used as a fall-back option (e.g. collected from visual inspection of high-resolution imagery using expert knowledge, or through very high-resolution imagery assisted with artificial intelligence). In a large country with poor

accessibility in remote regions, an *in-situ* approach may not be feasible. Both approaches will benefit from using ancillary data sets to improve ecosystem classifications, and both approaches require accuracy assessments.

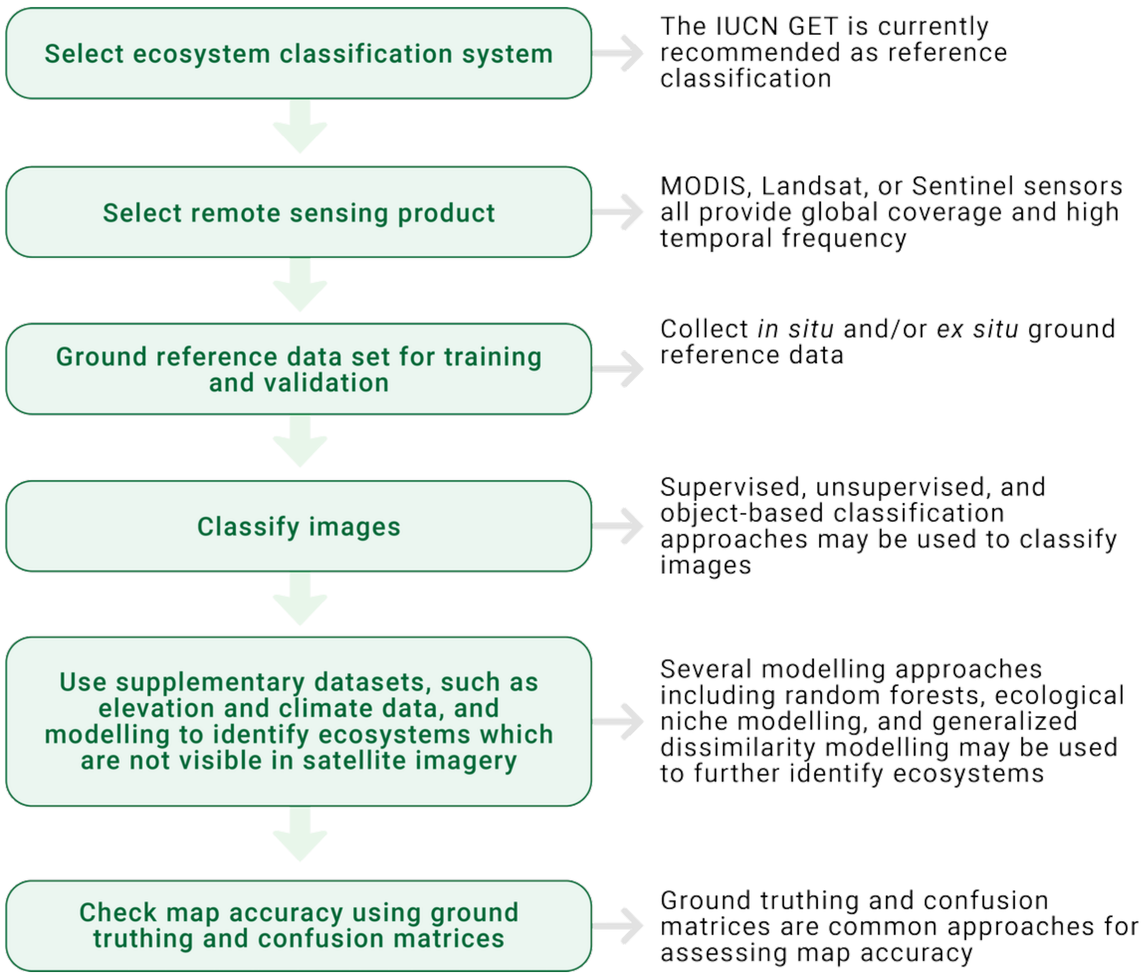

Figure 9: *Steps for creating ecosystem extent accounts for teams with remote sensing expertise*

4.3.2.1 Selecting remote sensed imagery

106. Satellite imagery often forms the basis of extent accounts. These data are collected using electromagnetic reflectance, and subsequently, reflectance data are used to help classify ecosystem types. For countries that choose to create custom ecosystem extent maps, one of the biggest challenges is selecting the appropriate satellite imagery. There are trade-offs between the types of imagery selected. For example, coarse scale imagery, which is classified over broad areas is typically low in accuracy, especially over locations with high ecosystem and/or topographic

variability (Herold et al., 2008). These inaccuracies are compounded when ecosystem classes are compared over time. However, high-resolution imagery, which may be more accurate, may be expensive to collect and more difficult process.

107. There are two main types of remote sensing images: optical and radar. Optical images are the most commonly used, and measure reflected sun light. in visible and infrared wavelengths. A disadvantage of optical sensors is that they cannot penetrate clouds and visible wavelengths are reflected only during daytime.[35] Radar sensors do not have these problems but have their own disadvantages such as lower resolution and relatively greater susceptibility to interference from other signals. Additionally, LiDAR is a remote sensing technology, which uses pulses of light to survey the Earth's surface. LiDAR can be used to measure tree canopy structure and tree height. A limitation of LiDAR is its relatively limited availability across large extents/long time series and at adequate spatial resolution. Much LiDAR data is collected by drone or from airplanes. Because different remote sensing platforms have various strengths and weaknesses, some remote sensing products increasingly seek to combine images from various sensors to maximize the value of information they provide.

108. Satellites collecting information on land cover that are most applicable at the global level are Landsat, and Sentinel.[36] For most locations, Landsat and Sentinel, which have 30 m and 10 m resolutions respectively, will likely be detailed enough for ecosystem accounting purposes in most countries. Countries with more sophisticated remote sensing experience may be able to produce custom classifications, but they should expect this to be challenging and time consuming.

4.3.2.2 Interpolating gaps in remotely sensed images

109. Another way that modelling might be useful is for creating more detailed land cover maps where satellite images are not available, or where high-resolution imagery is only available for a portion of an area. These data gaps may occur in locations with high cloud cover, where sensors are defective (Shen et al., 2015), or where high-resolution satellite images are collected for detailed mapping of key areas, such as urban areas, but do not extend across large swaths of land.

[35] Night time thermal and infrared "night lights" data have various applications related to urban and population mapping.

[36] These data sources are described in the "remote sensing product" section.

110. For locations where data are missing, there are several modelling approaches for filling these gaps. Identifying gaps in information is the first step of this process. In some cases, these gaps may be obvious, with locations showing as no data. In other cases, such as with cloud cover, these features may have their own spectral signatures making these gaps difficult to detect (Shen et al., 2015). There is a move in Earth Observation science towards so-called analysis ready data (ARD). For instance, Landsat data has recently provided ARD which pre-removes clouds, performs additional pre-processing, and stacks tiles for a given location within a time series.[37]

4.3.2.3 Classifying satellite imagery into ecosystem types

111. Another challenge of creating ecosystem extent accounts is classifying reflectance data from remote sensing images into important ecosystem types. A distinction should be first made between pixel-based approaches (that classify each pixel into a land cover class based solely on its spectral properties) and object-based approaches[38] (that also take the relationship between pixels into account; for instance object-based image analysis segments an images by grouping pixels together into objects such as roads or rivers). In both approaches techniques for classifying reflectance data derived from satellite imagery into classes are well-established, as are methods for estimating the accuracies of these classification. As such, compilers who choose to create custom classifications should find suitable guidance within the scientific literature. These techniques include supervised classification methods (maximum likelihood and minimum-distance classification), and unsupervised classification techniques, such as clustering algorithms, K-means, and ISODATA methods.

4.3.2.4 Combining remote sensing and other biophysical data sets

112. In some cases, mapping ecosystems using remote sensing images alone may be impossible. Characteristics of important ecosystems may be indistinguishable using satellite imagery because their reflectance data is not distinct from other ecosystems. For example, wetland forests may be difficult to distinguish from upland forests. In these cases, combining optical and radar imagery may achieve desired results. In other cases, modelling approaches may help characterize the locations of these ecosystems.

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[37] See: https://www.usgs.gov/land-resources/nli/landsat/us-landsat-analysis-ready-data?qt-science_support_page_related_con=0#qt-science_support_page_related_con

[38] https://gisgeography.com/obia-object-based-image-analysis-geobia/

113. For ecosystems not distinguishable with satellite imagery, the first step for this process is deciding which data sets may provide ecologically meaningful information. Biophysical attributes, such as digital elevation models, climate, soil data, infrastructure and distance to water bodies, etc., may help further distinguish different ecosystems by identifying an ecosystem's landscape position, climate, soils, or other relevant attributes. Forest inventories are another useful data set, which are available in some countries. Forest inventories often rely on additional plot-based measurements or high-resolution air photo interpretation, which may provide additional information to determine the extent of rare ecosystems. Forest inventories may provide point-based measurements needed for subsequent modelling.

114. Several types of modelling may be important for combining remote sensing with other biophysical data sets:

- Random forests is a machine learning approach. A random forest classifier creates decision trees based on a set of training data, then subsequent data (e.g. the spectral signature of pixels) are assigned to different categories based on these decision trees.
- Ecological niche modelling may be particularly useful and can be combined with ground truthing to improve the accuracy of ecosystem classification techniques. Ecological niche modelling pairs environmental data such as digital elevation model (DEMs) and climate data to produce maps of ecosystems. Ecological niche modelling is typically either a statistical or geostatistical approach.
- Another approach for modelling ecosystem extent is generalized dissimilarity modelling (GDM), which integrates earth observations and plant species data sets (Ferrier et al., 2007).

4.3.3 Available tools

115. Several classification tools are available to improve the accessibility of remote sensing methods for those with limited experience. A valuable tool for mapping the IUCN Red List of Ecosystems (RLE) is called *Remap*[39], which allows for rapid image

[39] Remap (https://remap-app.org/) runs using Google Earth Engine.

classification based on a suite of spectral and environmental characteristics. This model requires a set of known point locations of ecosystem types and uses a random forests classifier. These could be obtained through ground truthing or through visual identification in aerial photography. In addition to this, R tools have been developed including *redlistr*, which facilitates aggregation methods and tools for tracking changes in RLE over time (Calvin Lee et al., 2019).

116. Several modelling platforms described in Chapter 3 can be used to model extent or build an ecosystem extent account. For example, Data4Nature can be used to overlay various maps (ensuring proper alignment and error detection) and summarize them in the form of accounting tables describing land cover change. Likewise, the ARIES for SEEA can generate an extent account for a user specified area and accounting period, based on global data sources.

4.4 Global data sources (as of 2021)[40]

4.4.1 Remote sensing products

117. For compilers with high technical capacity, customized ecosystem data can be produced using remote sensing data. Customized data sets ensure the greatest flexibility in ecosystem classes. There are also a number of satellites with the capacity to track land cover changes over time (Gómez et al., 2016), which aligns with the SEEA EA's aim to track ecosystem change. Improved image compositing approaches mean gap-free images over a time series are more feasible and readily available, even over broad extents (Gómez et al., 2016). Analysis ready data are lowering data processing requirements for users. This section focuses on a very small subset of satellites with global coverage with high temporal resolutions, allowing the output to be readily adopted for SEEA EA accounts. Data products from these satellites are made available systematically and free of charge to all data users including the general public, scientific and commercial users.

Landsat

118. The Landsat program offers the longest continuous global record of the Earth's surface, dating back to 1972. Landsat is a collaboration between NASA and the U.S.

[40] This overview represents the status as of 2021. The speed at which remote sensing based products are released may render this overview obsolete fairly quickly. It is recommended for countries to ask their data providers what products (global or national) are forthcoming before embarking on compilation.

Geological Survey (USGS). Landsat 8 was launched in 2013, and Landsat 9 in 2021. Landsat data have been applied in a wide range of research fields including agriculture, geology, forestry, water resources, environmental pollution and regional planning.

MODIS

119. MODIS (or Moderate Resolution Imaging Spectroradiometer) was developed by NASA. The satellite views the entire surface of the Earth every one to two days with a 16-day repeat cycle. Its detectors measure 36 spectral bands, and it acquires data at three spatial resolutions - 250m, 500m and 1,000m. The many data products derived from MODIS observations describe features of land, oceans and the atmosphere that can be used for studies of processes and trends on local to global scales.

Sentinel[41]

120. Sentinel-1 is the first of the Copernicus Programme satellite constellation conducted by the European Space Agency (ESA). Sentinel-1 constellation consists of two polar orbiting satellites that collect C-band synthetic aperture radar (SAR) data and has a revisit time of 6 days between the two satellites. There are a wide range of applications for the data collected via the Sentinel-1 mission. A few of these uses include sea and land monitoring, emergency response due to environmental disasters, and economic applications. Recently, researchers have used data from Sentinel-1 and the NASA SMAP (Soil Moisture Active and Passive) satellite in conjunction to help achieve more accurate soil moisture estimates.

121. Sentinel-2 is a new generation of multispectral satellite imagery that was launched in 2015 by the European Space Agency. The satellite collects data across 13 spectral bands at 10m, 20m, and 60m spatial resolution. The revisit time of the Sentinel-2 constellation is every 5 days.

122. Sentinel-3 consists of an ocean and land mission composed of three satellites, using multiple sensing instruments. Satellites 3A and 3B were launched in 2016 and 2018, respectively. Sentinel-3 has a revisit time of 27 days, providing there is a global coverage of topography data at a mesoscale, with a primary orbit sub-cycle of approximately 4 days.[42] Data from Sentinel-3 may prove useful for a range of

[41] See: https://sentinel.esa.int/web/sentinel/
[42] See: https://sentinel.esa.int/web/sentinel/user-guides/sentinel-3-altimetry/coverage/revisit-time

accounts, including ocean accounting and extent and condition accounts.

4.4.2 Processed land cover products

123. Several global land cover products may be useful for the SEEA EA (see Table 5). They may be used as the basis of extent accounts or used as inputs to models for ecosystem condition and supply/use maps and tables. A recent review (Grekousis et al., 2015) notes 21 global land cover products (though numerous new products have been released since this 2015 study) which are available at various spatial and temporal resolutions and are produced from a combination of different satellites. Most land cover products are based on AVHRR, MODIS, Landsat, SPOT, Sentinel, or MERIS sensors.

124. One limitation of many of these global land cover products is that they do not describe change over time. The most promising of these products, from a temporal perspective, is the ESA Climate Change Initiative (CCI) land cover data set, with annual land cover maps including 24 land cover classes at 300m resolution (MODIS similarly produces an annual product at 500m resolution).

125. In order to construct temporally variable land cover accounts, these data sets need to be harmonized to one ecosystem extent classification. A key challenge to using these land cover products for ecosystem accounting is that they use different land cover classification systems. In particular, there are no land cover products which directly align with the global reference classification proposed for SEEA EA (IUCN's GET). The number of land cover classes identified in these products ranges from 9 to 24, whereas the IUCN's GET classification contains 98 different EFGs. For countries using these land cover products, developing a crosswalk with the GET is recommended.

Climate Change Initiative (CCI) Land Cover

126. This data set was produced by the ESA as part of their Climate Change Initiative (CCI) to improve their existing global land cover products such as GlobCover2009 (Bontemps et al. 2013). It has a resolution of 300m, and a time series from 1992 to present. The availability of different epochs has been used in global studies of land cover change and transitions. More recent annual land cover classifications are also available (Li et al., 2018). The CCI-LC2 classification system is based on the UN/FAO LCCS (Land Cover Classification System).

MODIS-based Global Land Cover Climatology

127. The purpose of this data set is to provide a representative global land cover data set based on MODIS images from 2001 to 2018 (Sulla-Menashe et al., 2019). When compared to the Global Land Over (GLC) 2000 data set, both were in general agreement at the class aggregate level but are more disparate at the detailed land cover classes (Giri et al., 2005). While the previous version of this data set (version 5) used the International Geosphere-Biosphere Programme (IGBP) classification, which has been cross-referenced with the UN/FAO LCCS classification used by GLC2000 and the ESA CCI land cover data sets, the most current version to date (version 6) uses a hierarchical classification model based on structural differences in land cover. However, it is not recommended that this product is compared across years due to uncertainties in land cover labels.

Copernicus Global Land Service Land Cover

128. Copernicus Global Land Service Land Cover (CGLS-LC100) has a resolution of 100m covering a time series of 2015-2019. It contains some analytical improvements compared to the CCI-LC. It is based on fused 100m and 300m Proba-V satellite images, and distinguishes 10 land cover classes, as well as several other fractional layers, which describe the percentage of ground cover per pixel. Land cover is based on the FAO LCCS.

GlobeLand30

129. GlobeLand30 was produced by the National Geomatics Centre of China (NGCC) (Jun et al., 2014). This freely available product provides 30m resolution land cover, produced using Landsat imagery. The classification consists of ten land cover types for the years 2000 and 2010.

FROM-GLC

130. FROM-GLC (Finer Resolution Observation Monitoring) is a new data product that has produced a global land cover map at 10m resolution (Gong et al., 2019).

Table 5: *Key properties of freely available global land cover products*
(as of May 2020 – for latest version of the table see: https://seea.un.org/ecosystem-accounting/biophysical-modelling)

Land cover data set	Resolution	Developer	Source	Accuracy	Coverage	Year	Data Access	Citation and licensing
Climate Change Initiative (CCI) Land cover v2	300m	European Space Agency	Data from the MERIS 2003 to 2012 archive, SPOT-Vegetation	70 to 74%	Global	Annually from 1992 to 2019	https://www.esa-landcover-cci.org/, https://www.esa-landcover-cci.org/?q=node/158	Official documentation: http://cci.esa.int/sites/default/files/CCI_Data_Policy_v1.1.pdf
MODIS-based Global Land Cover Climatology	500m	USGS Land Cover Institute	MODIS images from 2001 to 2010	73.6% overall	Global	Annually 2001 to 2018	https://lpdaac.usgs.gov/products/mcd12q1v006/	Official documentation: https://www.sciencedirect.com/science/article/pii/S0034425718305686
Copernicus Global Land Service Land Cover	100m	Copernicus	Proba-V	80%	Global	2015 - 2019	https://lcviewer.vito.be/download	Buchhorn et al. (2019)
GlobeLand	30m	National Geomatics Center of China (NGCC)	Landsat primarily, MODIS NDVI, global geographic information, global DEM, thematic data (global mangrove forest, wetland and glacier, etc.) and online resources (Google Earth, Bing Map, OpenStreetMap and Map World)	80.33%	Global between 80N and 80S	2000 and 2010	http://www.globallandcover.com	Chen et al. (2014)
FROM-GLC	10m	Tsinghua University, Beijing	Landsat, Sentinel 2	72.8%	Global	2017	http://data.ess.tsinghua.edu.cn	Gong et al. (2019)

4.4.3 Other global products for ecosystem extent

131. There are also a number of global products that can be helpful for mapping specific ecosystem types (Table 6). These specialized products may provide higher resolution maps of ecosystems of specific interest. For example, Hansen et al. (2014) provide estimates of forest cover change over time, using Landsat data. In addition, the Surface Water Explorer provides maps of changes in surface water and is also produced using Landsat data. Several data sets that detail the locations of human settlements with 10m and 30m resolutions are available (though only available for certain years so care must be taken if combining these in models with annual land cover data sets). These represent much higher resolution data then the best available time series of land cover data products (CCI LC 300m).

132. This section is by no means an exhaustive list of products. There are other "continuous field" products for water, grassland, shrubland and bare ground that give percentage values per grid cell (i.e., (0-100 per cent tree/shrub/water cover). These continuous data sets give flexibility to develop custom land cover and ecosystem type maps for Tier 2 and Tier 3 approaches, as the categorical land cover data (forest, shrubland, grassland, etc.) typically rely on thresholds (e.g., for tree or shrub cover) that may be applicable for certain ecosystems but not widely generalizable.

133. The FAOSTAT Agri Environmental Indicators Land Cover domain contains data on area by land cover class, aggregated at national level following the international land cover classification of the SEEA Central Framework. The FAOSTAT land cover data are compiled by national aggregation of geospatial information derived from remote sensing and distributed via publicly available Global Land Cover maps products. The following land cover data are distributed in FAOSTAT: 1) SEEA-MODIS, containing annual land cover area data for the period 2001-2017, derived from the International Geosphere-Biosphere Programme (IGBP) type of the MODIS Collection 6 Land Cover product (MCD12Q1); 2) SEEA-CCI-LC, containing annual land cover area data for the period 1992-2015, produced by the Catholic University of Louvain Geomatics (CCI-LC) as part of the ESA CCI. However, it should be noted that FAOSTAT Agri-environmental Indicators are calculated by FAO and may not coincide with data

reported by member countries to relevant international processes. They are intended primarily as an analysis tool and a useful international reference.[43]

[43] See: http://www.fao.org/faostat/en/#data/LC/visualize

__Table 6:__ Overview of specialized ecosystem extent products, which may be useful for developing more detailed maps of specific ecosystem types

Product	Developer	Spatial resolution	Satellite	Dates available	Access	Citation and licensing
Hansen Forest Cover	University of Maryland	30m	Landsat	2000-2018	http://earthenginepartners.appspot.com/science-2013-global-forest	Freely available and fully redistributable Hansen et al. (2013), Data available on-line from: http://earthenginepartners.appspot.com/science-2013-global-forest
Surface water explorer	EC JRC/Google	30m	Landsat	Annual and interannual 1984-2018	https://global-surface-water.appspot.com/	Freely available and fully redistributable Pekel et al. (2016)
World settlement footprint	German Aerospace Center (DLR)	up to 10m	Landsat-8 and Sentinel-1 data	Images from 1985 and 2015	https://urban-tep.eu/puma/tool/?id=567873922	See: https://urban-tep.eu/
Global Human Settlement Layer	Joint Research Centre (JRC) and the DG for Regional Development (DG REGIO) of the European Commission	30m	Landsat	1975, 1990. 2000 and 2014	https://urban-tep.eu/puma/tool/?id=567873922&lang=en	Data set: Corbane et al. (2018) Concept & Methodology: Corbane et al. (2019)
Copernicus Global Land Service Land Cover (continuous data set for 10 ecosystem types)	EC	100m	Proba-V	2015 - 2019	https://land.copernicus.eu/global/products/lc	Buchhorn et al. (2020)

4.5 Accuracy assessments and challenges

134. A wide range of uncertainties arise from developing thematic maps. Because a map is a generalization of what is on the ground, like any model, it will contain errors (Foody 2002). As such, it is important to communicate the accuracy and quality of these maps for different purposes. Classification accuracy assessments are the main approach for documenting the quality of land cover or ecosystem maps. These assessments evaluate the correctness of a map. To do this, a map is assessed either using a more detailed map or ground control points (i.e. ground truthing). These points are cross tabulated against each map class to produce a suite of metrics (Table 7). These cross tabulations are called confusion matrices, which can report both overall accuracy of maps and class-level accuracy. For example, a confusion matrix could determine if forests and urban cover are commonly confused for one another (Table 8).

135. National accuracy assessments may be available for certain countries. For instance, Canada does a 2 per cent annual forest sample to validate satellite data. Accuracy assessments may be easier for some countries than others; generally, the larger the country the larger the undertaking. For large countries, higher resolution images may be used for accuracy assessments rather than ground truthing. Further research is needed to determine the relative benefits of using higher resolution imagery. In the case of global products, data quality and coverage are usually not uniform across countries.

Table 7: *Example of a confusion matrix - Numbers in this table represent ground control points that fall under each class either in both the reference data set and the classified map. Cells along the diagonal indicate correctly classified grid cells.*

		Reference Data (i.e. more detailed map or ground points)			
		Forest	**Water**	**Urban**	**Total**
Classified Data	**Forest**	37	3	7	**47**
	Water	9	25	5	**39**
	Urban	11	2	43	**56**
	Total	57	30	55	**142**

Table 8: *Common accuracy metrics produced by a confusion matrix*

Accuracy metric	Definition and purpose	Example using numbers in Table
Overall accuracy	How many of all reference sites were mapped correctly? This metric is expressed as a percentage.	100 *((37+25+43)/142) = 73.9%
User's accuracy	Accuracy from the viewpoint of the map user. This metric shows how often the class on the map will be present on the ground.	e.g. user's accuracy for forests 100*(37/57)= 64.9%
Producer's accuracy	Map accuracy from the viewpoint of the data producer. The metric shows how often features on the ground are classified correctly in the data.	e.g. producer's accuracy for forests 100*(37/47)= 78.7%
Kappa Coefficient	Evaluates how well the classification performs compared to randomly assigning classes.	Statistical test

4.5.1 Modelling challenges

136. Challenges in classifying remotely sensed images underpin many issues for extent accounts. For example, some ecosystems are spectrally indistinguishable, but they may contain different and unique flora and fauna. Riparian areas and wetlands may be especially difficult to detect. As such, including information from Digital Elevation Models (DEMs) to better define that landscape position of riparian and wetland ecosystems may facilitate their distinction. Another issue is that high resolution aerial photography, which may be needed to distinguish ecosystems, is often not available annually or across large spatial extents.

Table 9: *Key challenges for extent accounts and proposed solutions*

Challenge		Solution
Imagery selection	Selecting appropriate remote sensing imagery which provides adequate spatial, temporal and spectral resolution. Trade-off between data with a long period of record and data with higher resolution. Challenges exist when operating in cloud-covered environments.	Landsat or Sentinel likely provide a good solution in most locations across the globe. For example, Landsat data has a long period of record (reliable time series become available around 1985) and 30 m resolution. Sentinel has 10 m resolution but shorter time period. Use analysis-ready data where possible. Use data from cloud-free days or wavelengths that can penetrate clouds (e.g. RADAR).
Lack of expertise	Classifying remote sensing images requires expertise and is highly time consuming.	Use global land cover products such as ESA's CCI, when remote sensing expertise is too expensive or not available.
Ecosystem classification	Deciding which ecosystems to include in classifications	Start with the IUCN-GET classification to ensure your accounts align with standards going forward.
	For teams using pre-existing land cover products not specifically designed for the SEEA, designing a crosswalking system to harmonize across data sets may be challenging, if multiple data sets are used.	To date, CCI is updated on an annual basis, which would be a good place to start for ecosystem accounting. No crosswalking systems for CCI to the SEEA EA are currently available.
Lack of accuracy	Trade-off between including many ecosystems types and map accuracy. Classifications with more ecosystem types are typically less accurate.	Understanding how ecosystem classifications are affecting the accuracy of your maps is an iterative process. Merging classes typically improves the accuracy of your maps.
	Inaccuracies in land cover compound when classes are compared over time, which may be poorly quantified.	Ground truthing land cover types should be a priority data need for statistical agencies compiling SEEA EA accounts, which can be done using higher resolution images or through on the ground surveys. Confusion matrices can be used to estimate this error.
Misaligned data sources	Integrating data sources that are not aligned as they use different cartographic projections / spatial grids. Sometimes also different delineations of coastlines cause difficulties.	Define a standard grid / basic spatial layer to integrate all data sources.

4.6 Examples of ecosystem extent accounts

137. Ecosystem extent accounts form the basis of other accounts. Many countries have used land cover as a proxy for ecosystem extent, and as such, there are a plethora of examples of land cover accounts across many nations but fewer examples of ecosystem extent accounts. Here, we highlight examples from Uganda, Guatemala, Liberia and Gabon, and the Netherlands.

Table 10: *Examples of countries that have implemented ecosystem extent accounts and the approach they have used*

Country	Overall approach	Years accounted for	Type of model used	Data sets used	Classification system	# of ecosystems classified	Accuracy reported	Limitations of approach
Uganda UNEP-WCMC and IDEEA, 2017)	Used biomes to identify historical ecosystems, and compared these to the "natural classes" of land cover maps produced by the National Forest Authority and the FAO.	1840 (baseline), 1990, 2005, 2010 and 2015	None	Langdale-Brown Biomes based on aerial photography interpretation and ground surveys -Land cover maps produced for Uganda by the National Forest Authority (NFA) (as described in Diisi 2009)	FAO LCCS	5	No	- Does not include managed systems, such as plantations and farmland. - Combining maps generated from satellite data vs. historical records such as land surveys makes accuracy assessments challenging.
Guatemala (IARNA-URL 2018)	Holdridge life zone approach, which is based on bioclimatic zones defined by precipitation, bio-temperature (all temperatures above freezing), and the ratio of potential evapotranspiration to mean total annual precipitation.	2001-2010	Bioclimatic envelope	WorldClim (2005) - precipitation - temperature - evapotranspiration	Holdridge life zones	15 (38 potential classes)	No	- A biome approach is static in the sense that the climate changes relatively slowly, and as such this approach does not allow for interannual comparisons.

Country	Overall approach	Years accounted for	Type of model used	Data sets used	Classification system	# of ecosystems classified	Accuracy reported	Limitations of approach
Netherlands (van Leeuwen et al., 2017)	Produced using a composite of sources as well as manual interpretation.	2006, 2013	None reported, but input data sets may have used models	- Digital Cadastral maps - Crop plots - Statistics Netherlands regiobase - Statistics Netherlands Dwelling registrar - Statistics Netherlands Addresses Geographical base registrar - Coupling Object ID and coordinate - Base Register Addresses and Buildings - Base register topography - Statistics Netherlands Land Use Map - Boundary Dunes - Ecological Network - Boundary Riverbed	Own classification	11 for extent change 32 for ecosystem type	No	- Combining maps from multiple sources makes accuracy assessments challenging.
Liberia and Gabon (Sousa et al., 2020)	30-m resolution land cover maps were developed using the Google Earth Engine (GEE) cloud platform for an integrated method of pixel-based classification.	2015	Machine Learning (using the Random Forest classifier	Landsat 8 Operational Land Imager Surface Reflectance imagery archive available on the GEE cloud platform and ancillary data.	Own classification	10	83% and 81% for Liberia and Gabon, respectivel y	- The binary classification strategy has a disadvantage that the order in which the classification is performed may, to some extent, introduce commission and omission errors into the final output. However, it is unlikely that a different order will produce a highly different output and potentially compromise the overall accuracy of the final map.

5 Modelling for condition accounts

5.1 Introduction

138. Condition accounts assess the overall quality and characteristics of ecosystems, using a set of key indicators, known as ecosystem condition indicators. The SEEA EA has developed an ecosystem condition typology (ECT, Czúcz et al., 2021a), consisting of six main classes (Table 11). The SEEA EA does not prescribe specific variables, but it does recommend including at least one indicator from each ECT class. Condition accounts are usually compiled for (broad) ecosystem types (e.g. forest, cropland), although the framework does allow for further aggregation.

139. In contrast with ecosystem services, most of the variables that describe condition are directly measurable characteristics of the ecosystems, for instance through field visits or monitoring stations in rivers. Accordingly, when constructing condition accounts primary (measured) data should be preferred to modelled data as much as possible.

140. Ecosystem condition accounts require ecosystem-specific comparisons over time, whereby indicators are obtained by comparing contemporary values of selected variables with a reference condition (Table 12). Ideally, a reference level is provided as a comparison for each of the chosen variables. An essential feature of a condition account is that it compares at least two different years to track changes over time (labelled as opening and closing values).

141. In addition to individual indicators, composite indices of ecosystem condition may be derived based on the ecosystem condition accounts. These composite indices aggregate individual indicators to provide an overall picture of ecosystem quality. Indicators from thematic accounts, such as the biodiversity accounts, may also be included.

142. Here, we explore a number of potential condition indicators within the SEEA ecosystem condition typology. We highlight modelling approaches that are suitable for spatializing indicators. Because the specifics of condition accounts are still being established, we will not use a tiered approach in this chapter.

143. The outline of this chapter is as follows. Section 5.2 describes steps and tools for modelling condition. Section 5.3-5.5 describes various condition indicators and how they can be measured/modelled, following the proposed typology of condition

indicators. Section 5.6 discusses examples of selected global indices and their relationship with condition accounts. Section 5.7 discusses reference conditions. Section 5.8 discusses composite condition indices. Section 5.9 discusses various modelling challenges. Section 5.10 lists several examples of condition accounts.

Table 11: *SEEA ecosystem condition typology (ECT), with illustrative indicator examples (Czúcz et al., 2021a)*

ECT groups	ECT class	Indicators category	Indicator examples
Group A: Abiotic ecosystem characteristics	Class A1. Physical state characteristics: physical descriptors of the abiotic components of the ecosystem (e.g. soil structure, water availability)	Water availability	Hydrological flow
			Reservoir stock
			Groundwater table
		Soil	Impervious surface
			Soil Organic Carbon
	Class A2. Chemical state characteristics: chemical composition of abiotic ecosystem compartments (e.g. soil nutrient levels, water quality, air pollutant concentrations)	Air quality	Pollutant concentrations
		Water quality	Pollutant concentrations
			Dissolved oxygen
			Chlorophyll a
		Soil quality	Nitrogen content
			Heavy metal content
Group B: Biotic ecosystem characteristics	Class B1. Compositional state characteristics: composition / diversity of ecological communities at a given location and time (e.g. presence / abundance of key species, diversity of relevant species groups)	Species	Species richness of specific taxonomic groups (birds, butterflies) or specific guilds (soil organisms)
			Presence or absence of typical species.
			Red-list indices/conservation status
	Class B2. Structural state characteristics: aggregate properties (e.g. mass, density) of the whole ecosystem or its main biotic components (e.g. total biomass, canopy coverage, chlorophyll content, annual maximum NDVI)	Vegetation/ Biomass	Vegetation density
	Class B3. Functional state characteristics: summary statistics (e.g. frequency, intensity) of the biological, chemical and physical interactions between the main ecosystem compartments (e.g. primary productivity, community age, disturbance frequency)	Processes	NPP Diversity of pollinators Abundance of pollinators
		Disturbance	Fire risk
			Invasive species
Group C: Landscape level characteristics	Class C1. Landscape and seascape characteristics: metrics describing mosaics of ecosystem types at coarse (landscape, seascape) spatial scales (e.g. landscape diversity, connectivity, fragmentation)	Composition	Landscape diversity
		Connectivity /fragmentati on	Number of barriers in a river
			Patch size

Table 12: *Example ecosystem condition accounting table*

SEEA Ecosystem Condition Typology Class	Indicators	Ecosystem type					
		Variable values		Reference level values		Indicator values (rescaled)	
	Descriptor	**Opening value**	**Closing value**	**Upper level (e.g. natural)**	**Lower level (e.g. collapse)**	**Opening value**	**Closing value**
Physical state	*Indicator 1*	0.4	0.25	0.7	0.1	0.5	0.25
	Indicator 2	10	30	0	100	0.9	0.7
Chemical state	*Indicator 3*	0.05	0.04	0.08	0	0.625	0.5
Compositional state	*Indicator 4*	85	80	90	0	0.94	0.89
	Indicator 5	1	0	1	0	1	0
Structural state	*Indicator 6*	110	65	200	20	0.5	0.25
Functional state	*Indicator 7*	15	10	15	0	1	0.66
Landscape/ waterscape characteristics	*Indicator 8*	50	20	100	0	0.5	0.2

5.2 Steps for creating ecosystem condition accounts

144. As condition accounts are flexible, individual country priorities should drive their overall development (Figure 10). The first step is to identify which condition indicators underpin important issues in the studied ecosystem type for the country. This step is a collaborative process among stakeholders and experts (Czúcz et al., 2021b). One of the main criteria in this process is that the indicators selected need to have a clear directional interpretation, i.e. for each change in the indicator it should be possible to decide if it is an 'improvement' or a 'decline'.

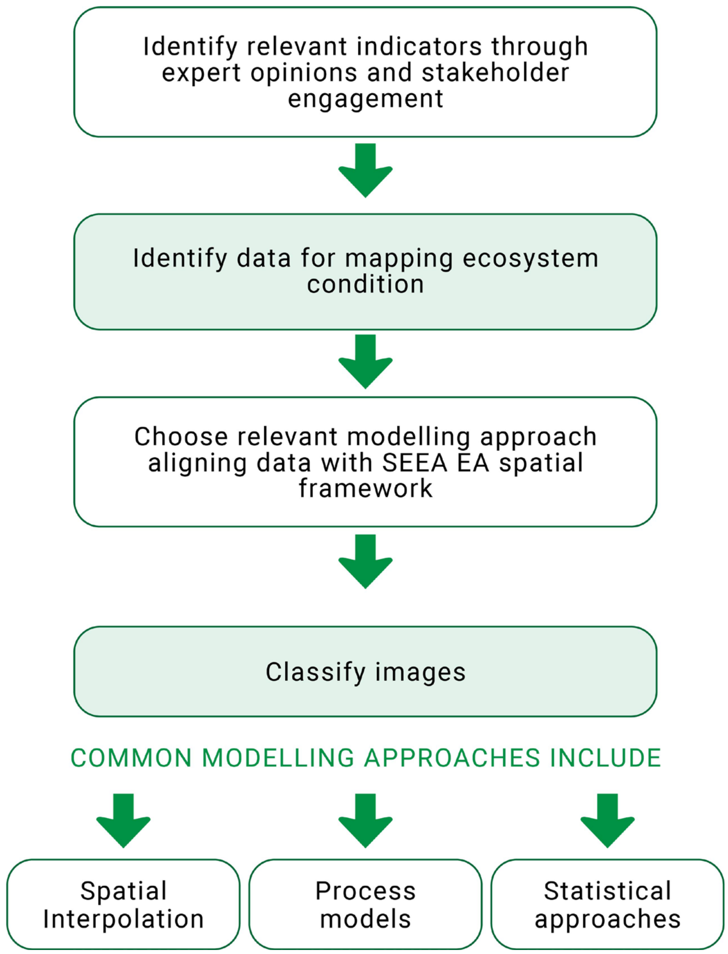

Figure 10: *An overview of the process of creating condition accounts. Modelling approach will vary depending on the desired indicator.*

145. The next step is to identify data to represent these indicators. Some countries may have authoritative data already available for certain indicators that could become the first iteration of the account. These data are likely to be the best choice. If national

data are not available, global data exists that may be used in some cases. The next step, regardless of the data source used, is to process the data to fit within the SEEA EA spatial framework. This step may require modelling, or it may require geospatial processing to summarize data within BSUs.

5.2.1 Tools for ecosystem condition

146. In addition to ArcGIS, R, and QGIS, several tools may be helpful for creating ecosystem condition accounts. Several of these are described below.

Trends.Earth

147. Trends.Earth is a tool for characterizing trends in land degradation and productivity as well as changes in forests and carbon. Running in QGIS, Trends.Earth integrates NDVI, soil moisture, precipitation, evapotranspiration, land cover, soil carbon and agroecological zones data from a variety of sources. Trends.Earth is well suited to understand changes in ecosystem condition. One advantage of the Trends.Earth tool, in relation to SEEA, is that it can provide annual estimates of change. Trends.Earth also provides a range of methods for various carbon model parameters. Options for customized area calculations mean Trends.Earth is amenable to SEEA EA's approach to BSUs and EAAs.

OpenForis/Collect Earth

148. OpenForis is a tool that simplifies data collection analysis and reporting, with applications for a range of purposes including forest inventories, socio-economic data, climate change and biodiversity. One of the main advantages of OpenForis is that the data it collects are spatially explicit, making it an especially suitable tool for validation of existing social or ecological maps. OpenForis allows for the import of existing surveys and contains survey templates available for use.

ARIES for SEEA

149. ARIES for SEEA Explorer currently includes models to measure the condition of forest ecosystem types, covering 6 variables: drought index, Leaf Area Index, NDVI, Net Primary Productivity, forest fragmentation, and burned area. Other ecosystem types/condition variables are relatively easy to add when data are made interoperable.

5.3 Abiotic ecosystem characteristics

5.3.1 Physical state characteristics

150. Physical state indicators include measurements of the abiotic environment (Czúcz et al., 2021a). There are two main indicator categories for physical state characteristics: water availability and soil quality (Table 13).

5.3.1.1 Water availability

151. Water availability underpins many ecosystem services, and thus is a key indicator of ecosystem condition. Several sources of water are typically used for ecosystem services. These include water found in natural surface waters (streams, rivers, lakes), reservoirs, and aquifers. Each of these water sources may have distinct uses, which means that separate measurements may be useful to understand their state and trend over time. Furthermore, each of them may require different modelling approaches. For estimating hydrological flow, the most common approach is to use process-based models, which often draw on digital elevation models, precipitation estimates, soil type and land cover to determine how much water will flow through an area. Both hydrological flow and reservoir stock are related to hydropower production, while groundwater are tightly linked to agriculture and drinking water.

5.3.1.2 Soil quality

152. Soil quality underpins many ecosystem services. Soil quality supports agricultural productivity. Soil Organic Carbon (SOC) is an important condition indicator, which also has an important role in measuring land degradation. SOC is one of the 3 sub-indicators of SDG 15.3.1 - the proportion of land that is degraded over total land area, and UNCCD (2020) provides detailed guidance on measurement and data sources.

153. Soil sealing has an impact on the amount of run-off that is generated.

Table 13: *Major categories and examples of physical state indicators for ecosystem condition accounts (as of May 2020 – for latest version of the table see: https://seea.un.org/ecosystem-accounting/biophysical-modelling)*

Indicators category	Indicator examples	Definition	Unit	Common modelling approach	Available models	Global data sources
Water availability	Hydrological flow	Volume of water discharged by a watershed or river over a timeframe	Volume	Process-based models	- InVEST - LUCI/Nature Braid - WaterWorld - VIC (semi-distributed macroscale model) - SWAT - WaterWorld	Global surface water explorer: https://global-surface-water.appspot.com/#features Hydrosheds: https://www.hydrosheds.org/page/overview
	Groundwater table	Upper surface of the zone of saturation	Depth	- Spatial interpolation - Numerical models	-	-GGIS provides maps of aquifers across the globe, as well as other ground water data, typically at the country level: https://www.un-igrac.org/global-groundwater-information-system-ggis -Global Ground Water Monitoring Network (https://ggmn.un-igrac.org/) allows for interpolation between ground stations -The GRACE model detects changes in gravity which are used to assess changes in water stocks: http://www2.csr.utexas.edu/grace/gravity/
Soil	Impervious surface (soil sealing)	Paved surface areas (e.g. buildings, roads)	Area (percentage)	Earth Observation data	-	-The GMIS data set available from CIESIN consists of two components: 1) global percent of impervious cover; and 2) per-pixel associated uncertainty for the global impervious cover. These layers are co-registered to the same spatial extent at a common 30m spatial resolution, see: https://sedac.ciesin.columbia.edu/data/set/ulandsat-gmis-v1 -Global impervious surface area (GISA) dataset (30m) from 1972 to 2019. based on Landsat images (Xin Huang et al. 2021)
	Soil Organic Carbon Content	The amount of carbon stored in soil	- Stock (tC/ha) or - Concentration (g/kg)	- Look-up tables Spatial interpolation - Geostatistical models	S-world model has maps and accounts detailing soil organic carbon concentration in (%, 0-30cm) and (%, 30-100)	GSDE Global soil data set for Earth Systems Modelling http://globalchange.bnu.edu.cn/research/soilw ISRIC SoilGrids: https://soilgrids.org/ FAO Global Soil Organic Map GSOC: http://54.229.242.119/GSOCmap/

5.3.2 Chemical state characteristics

154. Chemical state indicators track pollutant concentrations in the air, water and soil. Modelling approaches for chemical state indicators depend on the chemical, as well as the medium in which the chemical is present. Ideally, these models are parametrized using local measurements (Table 14). Many countries have agencies which monitor pollutant concentrations in respect to legal limits. Drawing on data and approaches used by these agencies is the best approach for incorporating chemical state indicators in SEEA EA.

155. Nonetheless, one major limitation of understanding chemical states is the lack of data availability in many locations. For example, water quality can be modelled using a wide range of tools and is ideally parameterized using instream measurements. However, the lack of instream measurements is a key issue for SEEA EA globally. Another common issue is that water quality monitoring networks are developed to satisfy the needs of environmental policies, and therefore the gauging stations are located there where it is expected that water quality will be degraded. Water sampling networks are not statistically representative of the territory as a whole. Data can therefore be fundamentally biased.

156. Water quality models need estimates of both pollutants and flow levels. Furthermore, as some pollutants are highly temporally dynamic (e.g. with peaks occurring during and after storm events), periodic sampling at set times may miss these peaks and underestimate concentrations of pollutants. Other pollutants may face similar problems in scarcity in both spatial and temporal coverage of measurements. Modelling can help in extrapolating (both in spatial and temporal units) location specific measurements.

Table 14: *Chemical state indicators for ecosystem condition accounts.*
(as of May 2020 – for latest version of the table see: https://seea.un.org/ecosystem-accounting/biophysical-modelling)

Indicator category	Indicator example	Definition	Modelling approach	Available models	Global data sources
Air quality	Pollutant concentrations	The amount of pollutants (e.g. micrograms per cubic meter (µg/m3) parts per million (ppm)), such as particulate matter and nitrogen dioxide, that cause damage to human health or the environment.	Typically modelled with an air pollution dispersion model, photochemical modelling, and receptor modelling. These models estimate concentrations based on meteorological data, pollution sources and chemical reactions.	The EPA provides access to several air pollutant models: https://www.epa.gov/scram/modelling-applications-and-tools	World air pollution: https://waqi.info/ PM 2.5 grids: https://sedac.ciesin.columbia.edu/data/set/sdei-global-annual-gwr-pm2-5-modis-misr-seawifs-aod
Water quality (inland freshwater including lakes, rivers, and streams)	Pollutant concentrations	The amount of pollutants, such as nitrogen or other chemicals that cause damage to human health or the environment.	Process-based models are common including export coefficient approaches	InVEST, LUCI/Nature Braid, ARIES, SWAT all provide approaches for water quality modelling. Different pollutants may require different models and approaches	SDG 6.3.2 core parameters: total phosphorus, total nitrogen, pH and dissolved oxygen in rivers, lakes and reservoirs or aggregated for a particular country or catchment: https://gemstat.org/data/maps/
	Dissolved oxygen	The amount of oxygen dissolved in water, which is available for biota and enters via diffusion from the atmosphere. Rapidly moving water will typically have more dissolved oxygen than stagnant water, as will water with lower amounts of biomass.	Spatialization of point data	Spatial extrapolation; Machine learning	Ibid
Water quality (inland freshwater including lakes, rivers, and streams)	Chlorophyll-a	A photosynthetic pigment used as an indicate algal levels in water	For large water bodies, multispectral imagery, such as MERIS have been used to map chlorophyll-a concentrations in lakes		Approaches for oceans have been modified for use in large lakes e.g. Ocean data available: https://oceancolor.gsfc.nasa.gov/atbd/chlor_a/

Indicator category	Indicator example	Definition	Modelling approach	Available models	Global data sources
Soil quality	Heavy metal content	The concentration of heavy metal, such as lead, which are detrimental to human health Especially relevant in urban areas	Spatial interpolation, geostatistical models		

Table 15: *Compositional state indicators for ecosystem condition accounts.*
(as of May 2020 – for latest version of the table see: https://seea.un.org/ecosystem-accounting/biophysical-modelling)

Indicator category	Indicator example	Definition	Unit	Modelling approach	Available models	Global data sources
Species	Species diversity	The varied species on Earth	Total number of species or number of species within different taxonomic groups (e.g., birds, fishes) or guilds (e.g., soil biota)Functional Diversity	Species Area Relationships Species Distribution Models (SDMs) Macroecological models		www.iucnredlist.org (See Section 5.4.1 for more details) Global Biodiversity Information Facility (GBIF) database https://www.gbif.org/occurrence/search; the PREDICTS database; https://www.predicts.org.uk/pages/outputs.html
	Species abundance	The number of individuals of a single species. The number of individuals belonging to the same species	Abundance (number of individuals),	-Species Abundance Models;	Maxent, R,	www.iucnredlist.org Global Biodiversity Information Facility (GBIF) database https://www.gbif.org/occurrence/search

	Relative species abundance	The abundance of a species relative to the total number of organisms	Shannon’s Index, Simpson’s Index,	Stacked species distribution and species abundance models		
	Red-list indices/conservation status	Species-level risk of extinction	Risk category	https://sis.iucnsis.org/apps/org.iucn.sis.server/SIS/index.html	https://www.ramas.com	www.iucnredlist.org Global Biodiversity Information Facility (GBIF) database https://www.gbif.org/occurrence/search
	Biodiversity Intactness Index; Mean species abundance	Indices to measure how much of local biodiversity remains intact		GLOBIO measures MSA by combining the impact of land use change, climate change, atmospheric N deposition, biotic exchange, atmospheric CO2 concentration, fragmentation, infrastructure, harvesting, human population density, and energy use on biodiversity loss (Alkemade et al., 2009)	GLOBIO (also available within the InVEST modelling framework)	

Table 16: *Structural state indicators for ecosystem condition accounts.*
(as of May 2020 – for latest version of the table see: https://seea.un.org/ecosystem-accounting/biophysical-modelling)

Indicator category	Indicator example	Definition	Unit	Modelling approaches	Available models	Global data sources
Biomass	Density	Biomass density	Growing stock volume (m3/ha) Above ground biomass (AGB) (ton/ha)			http://globbiomass.org/wp-content/uploads/GB_Maps/Globbiomass_global_dataset.html

Table 17: *Functional state indicators for ecosystem condition accounts.*
(as of May 2020 – for latest version of the table see: https://seea.un.org/ecosystem-accounting/biophysical-modelling)

Indicator category	Indicator example	Definition	Unit	Modelling approaches	Available models	Global data sources
Processes	Net Primary Productivity (NPP); Dry matter Productivity (DMP)	The rate at which an ecosystem accumulates biomass.	cg/cm3/year DMP uses units customized for agro-statistical purposes (kg/ha/day).	Dynamic Vegetation models General Ecosystem Models Leaf Area Index (LAI). Models include variables such as solar radiation, nitrogen, CO_2, water, temperature, fraction of photosynthetically active radiation.	MODIS satellite imagery provides estimates, LPJ DGVM (Lund–Potsdam–Jena Dynamic Global Vegetation model)	NPP: https://neo.sci.gsfc.nasa.gov/view.php?datasetId=MOD17A2_M_PSN DMP: https://land.copernicus.eu/global/products/dmp LAI: https://land.copernicus.eu/global/products/lai

Table 18: *Landscape and seascape characteristic indicators. Here we highlight only landscape characteristics[44] (as of May 2020 – for latest version of the table see: https://seea.un.org/ecosystem-accounting/biophysical-modelling)*

Indicator category	Indicator example	Definition	Unit	Modelling approaches	Available models	Global data sources
Composition	Diversity	The abundance and evenness of different species within a BSU. This indicator may also be aggregated for EAs, ETs, or EAAs.	Richness, Shannon's Index, or Simpson's Index	Metric calculated based on thematic maps	- Vegan package in R - LUCI/Nature Braid	Ecosystem extent accounts likely form the basis for these indicators Global Biodiversity Information Facility (GBIF) database, can also be used as input: https://www.gbif.org/occurrence/search
Connectivity/ fragmentation	Barrier density	The number of barriers, such as roads or dams, which may prevent the migration of species.	Number per area or length per area	Metric calculate based on point or line data	ArcGIS, QGIS	Dams for freshwater barriers: http://globaldamwatch.org/data/ Road maps: https://sedac.ciesin.columbia.edu/data/set/groads-global-roads-open-access-v1 https://www.openstreetmap.org/
	Patch size	Mean patch size (MPS) is the average size of all patches of all habitats over a landscape.	Area (ha, m, or km)	Calculated metric based on thematic maps	Frag stats (R stats version is available)	Ecosystem extent accounts likely form the basis for these indicators.
	Shape	Several shape indices are available, typically based on edge to area ratios.	Ratio of perimeter to edge	Calculated metric based on thematic maps	Frag stats (R stats version is available	Ecosystem extent accounts likely form the basis for these indicators.

[44] Some approaches may be adapted for oceans as well (e.g. diversity).

5.4 Biotic Ecosystem Characteristics

5.4.1 Compositional state characteristics

157. Compositional state characteristics highlight the distribution and abundance of species across EAAs. From a SEEA EA perspective, our limited understanding of how biodiversity contributes to ecosystem service flows provides an important reason to include this indicator in condition accounts. In addition to diversity being at risk, specific (e.g. iconic or economically important) species, may warrant further attention.

158. Biodiversity data should have several features to be suitable for ecosystem accounting. The data should be at a suitable resolution for integrating into accounts, which will facilitate mapping to specific EAs. Furthermore, data should be collected at temporal scales relevant for accounting (i.e. at the opening and closing of accounting periods). Similarly, data sets collected should also be comparable across space. More specifically, these data sets should also be comparable to a reference condition whenever possible. Finally, aggregating biodiversity data is important, and as such, data sets must be amenable to aggregation into a simple aggregation index (UNEP–WCMC, 2015).

159. Diversity metrics typically focus on one or few important taxonomic groups of the studied ecosystem type. Several commonly used metrics from biological diversity research are applicable to soil, habitat, and species diversity (e.g. Ibáǹez et al., 1995) and be used to compile condition indicators (Table 15). Simple and intuitive, *richness* is the most commonly used diversity metric (Gotelli and Colwell, 2011), defined as the number of different objects (e.g. landscape classes, species, or soil types) within a community, landscape, or area (Ibáǹez et al., 1995). One drawback of the richness index is that it ignores the relative *abundance* of each object type. There is also a lack of directionality: high species richness is not necessarily related to ecosystem condition (Canterbury et al., 2000; Lamb et al., 2009; Alexandrino et al., 2017).

160. Diversity measures aim to incorporate both richness and abundance. A well-known diversity index is the Shannon Index (SH) (Jost, 2006). An SH value of zero indicates only one type (e.g. species, soil, land cover) in the area of interest, and hence no diversity (McBratney and Minasny, 2007). A larger SH value indicates greater overall diversity. SH gives greater weighting to richness rather than evenness, and therefore is particularly influenced by rare objects. Similarly, Simpson's Index (SI) incorporates

richness and relative abundance in its calculation but is less affected by rare/uncommon classes. It is weighted more towards evenness (Magurran, 1988). Simpson's diversity increases when objects are more evenly distributed. These indices are just several of many diversity indices.

161. For a broad picture of diversity, understanding how diversity varies across sites may also be useful for SEEA EA accounts. There are a several ways for comparing diversity across sites, ecosystem and scales, known as alpha, beta, and gamma diversity. Local diversity or diversity at each site is known as alpha diversity. While there is no consensus on which scale alpha diversity should be measured, for SEEA EA accounts, alpha diversity is likely to be the diversity within a EA. Alpha diversity can be expressed as the mean number of species per unit. Beta diversity contrasts the difference in species between the ecosystems being compared (e.g. contrasting grasslands to riparian forests, which species are unique to riparian forests and which species are found only in grasslands). For SEEA EA, beta diversity would be the difference between species in ETs or EAs. Gamma diversity is the total number of species within an area. From a SEEA EA perspective, gamma diversity would be the total number of species within an EAA.

162. Networks focused on harmonizing global collections of biodiversity data have made strides in outlining processes for producing standardized data for assessing the states and trends in biodiversity (Kissling et al., 2018). These networks leverage species data that has already been collected. Examples of efforts to collect and use species abundance and distribution data include the Christmas bird count. DNA-based techniques are growing in availability and may become an increasingly efficient way to examine species distributions. Leveraging already collected data is an efficient way to build species accounts. Nonetheless, developing methods to combine heterogeneous methods is not trivial (ibid).

163. A diversity of approaches exists to measure compositional status (IPBES methodological report on scenarios and models). Species Distribution Models (SDMs) are the most widely used approach. These models estimate the relationship between observed, in-situ species occurrences and the environmental and/or spatial characteristics of those locations. SDMs use raster-based layers such as land use/land cover, elevation, precipitation, temperature, and vegetation indices, as predictors of suitable habitats; this information is then combined with ground-

collected presence data in statistical models to determine if a habitat is ideal for a particular species.[45]

164. Key efforts to standardize approaches for measuring biodiversity have been undertaken by the Group on Earth Observations Biodiversity Observation Network (GEO BON). Their approach focuses on Essential Biodiversity Variables (EBV), which include 22 potential indicators across genetic composition, species populations, species traits, community composition, ecosystem functioning and ecosystem structure.[46] Species distribution and abundance are considered EBV, but in addition to this, population structure (age) is also considered important.

165. Another data set that may be useful for biodiversity and condition accounting is the IUCN Red List of Threatened Species. The IUCN Red List standardizes assessments over space and time as well as across different agencies (UNEP-WCMC, 2015). Furthermore, methods for downscaling at the national level are available. This data set is available globally.

166. One possible approach is measuring Mean Species Abundance (MSA) which is an indicator of intactness, with the model GLOBIO.[47] MSA is the mean abundance of original species relative to their abundance in undisturbed. An area with an MSA of 100 per cent means biodiversity is similar to an undisturbed system, whereas an MSA of 0 per cent indicates a destroyed ecosystem, with no original species. The MSA is calculated for each driver, using cause-effect relationships, per grid cell of the map. MSA can be considered a proxy for species abundance.[48] Where possible it would be relevant to compare different approaches to assess uncertainties inherent in any single approach.

5.4.2 Structural state characteristics

167. Structural state characteristics (UN et al. 2021, para 5.36) primarily focus on the vegetation and biomass of the sites, comprising metrics describing the local amount

[45] Baaed on: https://earthdata.nasa.gov/learn/pathfinders/biodiversity/species-distribution
[46] See: https://geobon.org/ebvs/what-are-ebvs/
[47] See: https://www.globio.info/what-is-globio/how-it-works/impact-on-biodiversity
[48] MSA is similar to the Biodiversity Integrity Index, the Biodiversity Intactness Index (BII) and the Living Planet Index (LPI). The main difference between MSA and BII is that every hectare is given equal weight in MSA, whereas BII gives more weight to species rich areas. The main difference with LPI is that MSA takes the pristine situation as a baseline, whereas LPI compares to the situation in 1970.

of living and dead plant matter (vegetation, biomass) in an ecosystem (Table 16). This class includes all characteristics of vegetation density and cover, either related to the whole ecosystem, or just specific compartments (canopy layer, belowground biomass, litter etc.). For marine and freshwater ecosystems this class can include chlorophyll concentrations, phytoplankton abundance, or plant biomass (e.g. seagrasses). There is some overlap between compositional and structural state metrics, particularly for foundation-species-based ecosystems such as mangrove, or where species groups and vegetation compartments coincide (trees on savanna, lichens on mountain rocks). Such cases should be registered in this class.

5.4.3 Functional state characteristics

168. Functional state characteristics summarize ecological processes and functions (Table 17). Ecological functions are processes that change over time. They are often described in terms of rates. For example, flood and fire risk could be quantified as the return interval to a location. Another important example of a metric describing the functional state of ecosystems is its capacity to acquire biomass. Net primary productivity, for example, describes the rate of biomass accumulation (Šímová and David Storch, 2017). Land productivity is also one of the three sub-indicators of SDG 15.3.1, which can be assessed with NPP as a productivity index. UNCCD (2020) provides detailed guidance on its measurement and relevant data sources.

169. Ecological functions occur across different ecological levels. Ecosystem condition accounts can include population-level to ecosystem and biome level functions. For example, populations of specific species provide key functions, such as pollination and decomposition, while flood risk occurs at a landscape scale. Taken together, characterizing ecosystem function provides a better insight into how quickly an ecosystem can recover from disturbance, as well as provide insight into the health of an ecosystem.

5.5 Landscape characteristics

5.5.1 Connectivity/fragmentation

170. Habitat that is divided into smaller and smaller fragments over time can compromise ecosystem services and biodiversity. Habitat loss simultaneously leads to changes in the size and distance between habitat patches, and now more than 70 per cent of

global forests are within 1km of the forest edge (Haddad et al., 2015). Changes in forest patterns are linked to changes in ecosystem services such as carbon sequestration, as tree mortality increases near forest edges (Brinck et al., 2017). At highly local scales, fragmentation indicators are linked to metrics of water quality (Ruan et al., 2019). Landscape composition is the number and arrangement of land cover types within an area, and can be expressed via diversity metrics (such as those presented in Table 18). Fragmentation and connectivity explore how different ecological patches interact with one another.

171. There are a wide range of tools available for calculating landscape characteristics. Fragstats is one of the most commonly used tools to estimate habitat fragmentation, which is a standalone tool. Fragstats metrics is also available as a package in R statistical software (Vanderwal et al., 2015). Fragmentation can be measured using a wide range of indicators, and most of these indicators are associated with total area of a land cover or ecosystem class (Wang et al. 2014). As such, metrics that are comparable over time regardless of land cover class abundance are preferred. These metrics include core area, shape, proximity/isolation, contrast and contagion/interspersion.

172. A main challenge for mapping and modelling habitat fragmentation and connectivity is accounting for the total area of the habitat and ensuring that metric is interpretable given the complex relationship between fragmentation metrics and area of land cover. Attributing changes in ecological function to landscape pattern alone is difficult because it is directly correlated to habitat area (Ruan et al., 2019). Further testing of fragmentation indicators within condition accounts may be needed to identify when these issues matter. Furthermore, the accounts would be highly sensitive to the size of BSUs. Spatial heterogeneity and patch size can easily be misinterpreted if the size of the BSU is not suitable to the spatial extent of the ecosystem.

173. Another important indicator of landscape pattern is connectivity. Species are likely to survive only within networks of patches that are sufficiently connected by dispersing individuals. Various metrics have been used for the purpose of measuring connectivity. Often, connectivity is measured using a spatial graph-based approach (i.e. networks). Landscape connectivity assessments can reveal important habitat for maintaining species populations. Connectivity metrics focus on determining which

habitat areas and links to prioritize in the face of landscape change. These metrics can indicate ecosystem degradation, especially for sensitive species.

174. Methods based on distance are also common, ranging from simple nearest neighbour metrics examining only the cost of crossing hostile terrain to more complex ones considering occurrence of multiple habitat patches, patch size, shape, etc. (Kindlmann and Burel, 2008). Such methods generally use a cost-distance approach, where the cost of crossing a non-habitat landscape element is a function of the Euclidean distance across the element and a measure of permeability: the more hostile the environment (e.g. a highway to a salamander trying to cross it), the less permeable the terrain will be. Assigning different permeabilities to different types of hostile terrain and land cover etc., allows for varying mortality risks as well as different movement patterns and boundary crossings to be implicitly considered. Parameterisation of the permeability values in cost-distance modelling is challenging; this is usually defined based on expert advice and depends on the taxa, region, and threats of interest (Janin et al., 2009).

175. Tools for examining connectivity include Conefor (Saura and Torné, 2009), which is a freely available software tool, which can calculate several connectivity metrics. Conceptualizing habitat patches as a graph, metrics available include both binary and probable connectivity metrics including the total number of links, number of components. The GUIDOS toolbox provides measures of structural connectivity (https://forest.jrc.ec.europa.eu/en/activities/lpa/gtb/).

5.6 Global Indices and SEEA EA

176. Table 19 provides examples of selected global indices that may be included in condition accounts departing from global data sources. A large number of global biodiversity indicators is being developed (GEO BON, 2015), so the Table is by no means comprehensive. Several of these indicators have been derived with BILBI (Biogeographic Infrastructure for Large-scaled Biodiversity Indicators)[49] which integrates heterogenous spatial and temporal data collection methods in biodiversity research by merging them into a space-time cube. These cubes have cells that represent species presence/absence.

[49] See: https://research.csiro.au/macroecologicalmodelling/bilbi/bilbi-outputs-and-applications/

177. The Local Biodiversity Intactness Index (LBII) [50] – previously known as BII –contrasts current species abundance with species abundance prior to broad human impacts in order to estimate how much of an area's biodiversity remains.[51] The LBII generates data on both species-richness and mean abundance.[52]

178. Biodiversity Habitat Index (BHI): represents the proportion of biodiversity retained within a given area (such as a country or an ecoregion) in relation to the degree of habitat loss, degradation and fragmentation experienced.[53]

179. Protected Area Representativeness and Connectedness Indices (PARC): represents the diversity of biological communities within a protected area system, as well as how connected protected areas are within the broader landscape.[54]

180. Bioclimatic Ecosystem Resilience Index (BERI): assesses capacity of ecosystems to retain biological diversity under climate change.

181. One disadvantage of using broadly available composite indicators for condition accounting is that they come in a highly aggregated format that cannot be easily aligned with the structure of the condition accounts (Keith et al., 2020). They often combine data from several SEEA ECT classes (thematic units) or accounting areas (spatial units), and handle their reference levels 'internally', in a way that is possibly incompatible with the rest of the account. In such cases, the good practice is to use the original data (underlying the composite indicator), assigning them to the appropriate ECT classes (and spatial units), and do all subsequent steps (reference levels, aggregations) in the ecosystem condition accounts. This approach should be feasible if the composite indicator follows the FAIR principles (as discussed in Chapter 7). While disaggregating a composite indicator demands more work than

[50] R J Scholes and R Biggs, "A Biodiversity Intactness Index" 434, no. March 2005 (2005): 45–50.
[51] See https://www.predicts.org.uk/pages/policy.html
[52] LBII is strongly complementary to the Biodiversity Habitat Index (BHI). LBII's focus is on average local biotic intactness, which reflects species' persistence within the landscape and the local ecosystem's ability to provide many ecosystem services; BHI, by contrast, focuses on how the overall diversity of a larger region is hit by habitat loss and degradation. See: https://www.ipbes.net/sites/default/files/Metadata_GEO_BON_PREDICTS_Local_Biodiversity_Intactness_Index.pdf
[53] It is used to report on Aichi Target 5 - by 2020, the rate of loss of all natural habitats, including forests, is at least halved and where feasible brought close to zero, and degradation and fragmentation is significantly reduced. BHI has been developed by CSIRO (Australia's national science agency), working in partnership with GEO BON, GBIF, Map of Life and the PREDICTS project. See: https://www.bipindicators.net/indicators/biodiversity-habitat-index.
[54] It is used to report on Aichi Target 11 - by 2020, at least 17 per cent of terrestrial and inland water, and 10 per cent of coastal and marine areas, especially areas of particular importance for biodiversity and ecosystem services, are conserved through effectively and equitably managed, ecologically representative and well connected systems of protected areas and other effective area-based conservation measures, and integrated into the wider landscapes and seascapes.

simply reusing it, sometimes this is the only option to maintain the internal coherence of the accounts. One of the main functions of the SEEA ECT typology is to provide a standardised aggregation scheme that can be meaningfully used across ecosystem types, countries and continents. Composite indicators that violate this function should be handled with care.

__Table 19:__ Examples of global indices that may be included in ecosystem condition accounts

Index	Theme/Scale	Overview	Input variables
LBII (or BII)	Biodiversity, 1km grids, global coverage of terrestrial ecosystems, 2001-2020	BII = average abundance of naturally present species, relative to an unimpacted baseline, across many taxonomic groups, averaged across all land uses within the region of interest, excluding novel species.	Various global data sources
BHI	1km grids, global coverage of terrestrial ecosystems, 2005-2015	Based on a fine-scaled grid covering the entire terrestrial surface of the planet. For each cell in this grid an estimate is derived of the proportion of habitat remaining across all cells that are ecologically similar to this cell of interest. The index indicates the proportional retention of habitat across finely-mapped environments supporting relatively distinct assemblages of species within a given reporting unit.	Various global data sources, including CSIRO's statistically downscaled land-use dataset, climate, terrain, and soils, and best-available occurrence records for plants, vertebrates and invertebrates.

5.7 Reference conditions

182. Reference levels can be used as a comparison to current levels with the purpose of creating an indicator (Keith et al., 2019). Generally, the reference condition provides a comparison point for subsequent measurements. The definition of reference levels (sometimes called benchmarks, baselines or counterfactuals) in SEEA EA has been debated. Determining a reference condition that is suitable across multiple accounts and countries is not clear-cut (UN, 2019b). One key question regarding reference levels is: At which date (or alternative state) should we set our reference condition? Several options for a reference condition have been considered, including a "zero ecosystem service reference" condition, "an alternative state" reference, a "bare ground" reference, a recent date (e.g. 1990) reference, or a historical condition such as pre-modern state. Each of these options holds different pros and cons (UN et al., 2021, Chapter 5.3). Reference conditions should be clearly distinguished from a desired value (policy objective), a prescribed value (such as a legislated quality measure), or a threshold value (an indicator value above or below which there is evidence that ecosystem condition is sub-optimal). Hence, different indicators can be derived from the same variable when different reference levels are assigned.

183. While using a specified date as a reference condition will always be somewhat arbitrary, one option is contrasting contemporary conditions to a less modified state. For example, in Australia the date 1750 is typically used to highlight the magnitude of change from pre-European settlement conditions. For the IPCC, the reference condition is preindustrial levels. However, choosing a previous year as reference is difficult in locations with longer histories of settlement and fails to recognize the management of indigenous peoples.

184. Using a more recent reference condition (e.g. 1990) is another option. One benefit of using a more recent reference condition is that it would highlight the magnitude of contemporary interannual annual changes, which may seem miniscule compared to the vast losses from a historical state to now.

5.7.1 Modelling approaches

185. Apart from a "zero-reference" level, which would require no modelling, most other approaches would require different modelling considerations. A historical condition may be the most challenging to model, because historical data sources, especially

pre-industrial data sources can be rare and inconsistent, particularly at national to global scales. Furthermore, many historical data sources are not as spatially detailed as contemporary data sources and it is not possible to assess their accuracy. For establishing a historical reference condition, the first step to biophysical modelling is assessing data sources, which may be unique regionally. Records are highly variable in availability and quality in different contexts.

186. There are a range of benefits to using a historical reference level. Many nations may want to understand how historical practices have contributed to environmental dynamics. This can help nations design policies that avoid past oversights as well as policies that draw on the strengths of historical management. Historical estimates are also essential for tracking rates of change. Inherent in this approach is measuring historical extent, condition and volumes of ecosystem services. Furthermore, because we cannot change the past, or the past measurements we took, biophysical modelling is essential for estimating historical extents and condition of ecosystems as well as estimating the volume of ecosystem services produced in past contexts. While contemporary modelling approaches may be useful for processing historical data, new approaches may also be needed as data sources typically grow scarcer further back in history. Historical data sets may play different roles in estimating ecological extent condition, etc. Establishing historical baselines for ecosystem services is a one-time exercise, with ongoing benefits.

187. From a modelling perspective, the benefit of using contemporary data is that better input data are available, from potentially similar data sources as current sources, meaning data would likely be more comparable over time.

188. While current context may be an appropriate baseline, many nations are aiming to track changes that have already experienced decline and which has motivated the inclusion of the environment into accounting. As such, establishing baselines requires hindcasting.[55]

[55] Hindcasting (or back-casting) is the use of models to estimate past conditions.

Table 20: *Different reference points considered for SEEA EA including a brief description and definition of these*

Reference point	Definition	Modelling considerations	Modelling approach
No ecosystem service	a zero value	No modelling needed, as the baseline or reference value is zero.	None
An alternative state	The same ecosystem services would be established for a different ecosystem state (e.g. forest vs. grassland).	Model inputs and approaches would be similar for the reference as for contemporary measurement, substituting only the ecosystem type.	Same as contemporary
Bare ground	A system given no living organisms would be established.	Model inputs and approaches would be similar for the reference as for contemporary measurement, substituting only the ecosystem type for bare ground.	
Recent past comparison (e.g. 1990)	A comparison to a historical date, but a more recent state than considered in an intact condition	While this is still a historical state, it likely considers a more recent state, which may mean similar data sets may be used to model ecosystem services.	Typically substitute historical data sets in models when possible (climate, land cover)
Historical state (e.g. preindustrial)	A representation of an intact ecosystem that might have existed in a location historically	Historical records or evidence could be used to establish ecosystem types present historically, other data sets may be similar. Landsat imagery, historical aerial photography, and historical cadastral maps may be useful in establishing historical condition.	
Desired value	Policy objective	Model inputs and approaches would be similar for the reference as for contemporary measurement, substituting different land cover or climate scenarios. This reference level option would be difficult to make spatially explicit, as land use/cover configurations might result in the same desired value.	Scenario-based modelling

Reference point	Definition	Modelling considerations	Modelling approach
Threshold value	An indicator value above or below which there is evidence that ecosystem condition is sub-optimal	Model inputs and approaches would be similar for the reference as for contemporary measurement, substituting different land cover or climate scenarios. This reference level option would be difficult to make spatially explicit, as land use/cover configurations might result in the same desired value.	Scenario-based modelling
Prescribed value	Legislated quality measure	Model inputs and approaches would be similar for the reference as for contemporary measurement, substituting different land cover or climate scenarios. This reference level option would be difficult to make spatially explicit, as land use/cover configurations might result in the same desired value.	

189. Modelling challenges will vary depending on the reference level used. If a historical condition or even a recent historical condition is selected as a reference level, the accuracy of the reference level may be lower than contemporary estimates.

190. On the other hand, for prescribed, desired and threshold references, a scenario modelling approach will likely be most suitable. Reaching these desired reference levels may be achieved using multiple approaches.

5.8 Composite Indices

191. The flexibility and comprehensiveness of ecosystem condition accounts means many indicators may be adopted. However, to facilitate easier interpretation of trends in ecological condition, composite indices may be useful and that aggregate underlying condition indicators. Composite indices summarize indicators for specific ecosystem types such as rivers or wetlands. Composite indices may also summarize specific indicator categories, such as abiotic ecosystem characteristics or landscape characteristics, which are called sub-indices (see Table 21).

192. There are different modelling approaches that can be used to obtain indices from underlying indicators such as taking a (un)weighed sum, doing principal components analysis, or applying a precautionary "one-out – all out" approach, as is done for instance in deriving SDG 15.3.1 indicator on land degradation.[56] Whichever approach taken, it should have a clear rationale.

Table 21: *Ecosystem condition indices reported using rescaled indicator values (source: UN et al. 2021)*

SEEA Ecosystem Condition Typology Class	**Indicators**	**Ecosystem type**				
		Indicator value			Index value	
	Descriptor	Opening value	Closing value	Indicator weight	Opening value	Closing value
Physical state	Indicator 1	0.5	0.25	0.05	0.025	0.013
	Indicator 2	0.9	0.7	0.05	0.045	0.035
	Sub-index				*0.07*	*0.048*
Chemical state	Indicator 3	0.625	0.5	0.1	0.063	0.05
Total Abiotic characteristics					0.133	0.098
Compositional state	Indicator 4	0.94	0.89	0.067	0.063	0.062
	Indicator 5	0.75	0.50	0.033	0.025	0.017
	Sub-index				*0.088*	*0.079*
Structural state	Indicator 6	0.5	0.25	0.12	0.06	0.03
Functional state	Indicator 7	1	0.66	0.08	0.08	0.053
Total Biotic characteristics					0.228	0.162
Landscape and seascape characteristics	Indicator 8	0.5	0.2	0.5	0.25	0.1
Ecosystem condition index	**Index**			**1.0**	**0.611**	**0.360**

5.9 General modelling challenges for condition accounts

193. Condition accounts can be assembled from underlying maps of the various indicators. As with all ecosystem accounts, ecosystem condition accounts should also adhere to the spatial framework outlined in Chapter 3. Ecosystem condition accounts are flexible, in that a wide range of appropriate reference levels for condition can be used. Furthermore, there are a wide range of potential metrics. However, this flexibility begets several challenges. For example, some indicators are only meaningful when aggregated to appropriately large spatial scales, making spatial disaggregation to EAs/BSUs challenging. Although this problem is not unique to

[56] Good Practice Guidance SDG Indicator 15.3.1 Version 2.0 December 2020.

condition accounts, it is more pronounced than for many of the other accounts. For example, a measure of soil quality (e.g. carbon stock or heavy metal content) makes sense at multiple scales (i.e. it is reasonable to describe at 25m resolution, 1km resolution, or more aggregate scales). However, metrics such as connectivity and fragmentation, or measures of diversity such as SH, are not meaningful at small scales – they only make sense when spatially aggregated above particular threshold extents.

Table 22: *Overview of the main challenges for producing condition accounts*

Challenge		Solution
Selecting metrics	Large number of possible indicators	Select indicators most relevant to your country as a starting point.
Scale	Some metrics only meaningful above a certain spatial scale i.e. not all metrics are scalable	In ecosystem condition accounts, metrics should be reported at meaningful scales, which may mean aggregating above the BSU scale.
Data availability	Data scarcity and lack of consistency in methods for species data collection. The actual coverage of measured data may be scarce for soil.	Many global data sets are available for different ECIs. Use best available data where possible, and modelling may help achieve a higher resolution output.
Model transferability	Transferability of biodiversity models, or the ability to use a model in novel environments to produce accurate predictions of biodiversity.	
Temporal dynamics	Species distribution maps have often been assumed to be static (based on inputs like land cover, climate, elevation, fragmentation, etc.); data that changed as underlying land cover and climate change.	Look towards working groups such as the Group on Earth Observations Biodiversity Observation Network for latest metrics describing biodiversity.

5.10 Examples of ecosystem condition accounts

194. The experience to date with compiling SEEA EA condition accounts is fairly limited. Table 23 provides some country examples. This table is not an exhaustive list. More examples are given by Maes et al. (2020).

Table 23: *Examples of ecosystem condition accounts. Some countries have created multiple ecosystem condition accounts*

Country	ECIs	Overall approach	Type of model used	Data sets used
Norway	Biodiversity	The Nature Index measures how biodiversity changes in ecosystems, and over developments in selected species groups and themes.	Estimation from monitoring programs, expert judgment, model predictions	National Data – see: https://www.nina.no/english/Environmental-monitoring/The-Norwegian-Nature-Index
South Africa (Nel and Driver, 2015)	Condition Index for Rivers	Ecological condition was determined using a combination of flow, instream habitat condition, stream bank/riparian condition and water quality. Modification scores were assigned to rivers, as well as an aggregated index.	Expert review, index	National data
Peru (UNEP-WCMC, 2015)	Biodiversity	Generalised Dissimilarity Modelling (GDM), which is community-level modelling. differences in environmental conditions are represented in by their effect on species composition for whole biological groups.	BILBI	
Ecosystem integrity index (CONABIO/INECOL)[57]	Ecosystems/National	The EII seeks to reflect the structural integrity of ecosystems in a single figure. Integrity is evaluated in terms of how different an actual ecosystem is from some original or desired condition.	Bayesian Network analysis	Multiple data inputs used, such as: -Field measurements of forest structure variables (e.g. average tree height, average DBH, average canopy diameter, proportion of dead trees standing, tree density, etc.)

[57] The Mexican National Biodiversity and Ecosystem Degradation Monitoring System, Nashieli Garcia-Alaniz, Miguel Equihua, Octavio Perez-Maqueo, Julian Equihua Benıtez,Pedro Maeda, Fernando Pardo Urrutia, Jose J Flores Martınez, Sergio A Villela Gaytan and Michael Schmidt,, Current Opinion in Environmental Sustainability 2017, 26–27:62–68.

				-Functional features of ecosystems (such as annual gross primary productivity, annual net photosynthesis, etc.) - Factors that can affect the condition of ecosystems, such as the presence of human settlements, fields, pastures, etc.
Netherlands (Lof et al., 2017)	Biodiversity	Average population trend for 361 land and freshwater animal species, from 1990- present	Living Planet Index	https://www.cbs.nl/en-gb/artikelen/nieuws/2010/48/water-birds-tend-to-migrate-less-far-to-the-southwest/network-ecological-monitoring
	Soil organic matter	Detailed soil maps are available for the Netherlands, but soil properties such as organic carbon are not available in these maps. As such, Soil organic carbon stocks are expressed as: SOC = SOM% * C_content * BulkDensity * 100 * SoilDepth.	Typically soil maps are created using geostatistical interpolation	https://library.wur.nl/WebQuery/wurpubs/498774 (Conijn and Lesschen, 2015)

6 Models for ecosystem service accounts

6.1 Introduction

195. The ecosystem services flow accounts follow the structure of a supply and use table (SUT) as described in the SNA and SEEA CF. The SUT in the SEEA EA describes which ecosystems provide what services to which users (see Table 24 for the supply table).

196. Supply and use tables in SEEA EA are reported in both biophysical terms and monetary terms, but this Chapter focuses on physical estimates. This layout facilitates side-by-side presentation of ecosystem service supply and use from different ecosystem types. This also implies that the results of biophysical modelling must be provided in a unit that is suitable for valuation. In cases where ecosystem service models yield indices, biophysical indices need to be combined with statistical data to provide monetary estimates. While some of these units of individual ecosystem services are still under wider debate, when working with biophysical models, understanding the final measurement unit is essential.

197. Several features characterize a SEEA EA perspective of the biophysical supply of ecosystem services (see Chapters 6 and 7 of the revised SEEA EA for more details). Conceptually, ecosystem services are defined as the contributions that ecosystems make to benefits, not benefits per se. Furthermore, an important distinction exists between final ecosystem services (flows between ecosystems and the economy) and intermediate ecosystem services (flows between ecosystems that are an input into final ecosystem services) (see UN, 2020; section 6.3.2). The measurement focus of SEEA EA lies on final services.

198. Final ecosystem services only arise when there is a user for the services i.e. they are realised. It is possible to estimate the theoretical supply (sometimes called potential ecosystem services), but within SEEA EA these are part of the concept of ecosystem capacity or capability, which is not the focus of this chapter. It is important to stress that due to the transaction-based nature of the accounts, supply always equals use, however the units in which the supply-use pair is recorded can differ based on the specific service (e.g. provisioning services may be in tons, cultural services in number of visits). Finally, ecosystem service supply and use tables are in many

cases underpinned by maps depicting where services are generated and where their users are located.

199. One of the key challenges to compiling a SUT in physical units is selecting the right modelling approach and/or platform to achieve outputs desired in SEEA EA tables and maps.

200. The outline of this Chapter is as follows. Section 6.2 provides an overview of the modelling approaches for ecosystems services, and how the results can be integrated into SUT. Section 6.3 links common ecosystem service modelling platforms to SEEA EA aligned outputs for ecosystem services. Section 6.4 provides an overview of approaches for the modelling of ten of the most commonly measured ecosystem services. Section 6.5 provides a table of exemplar ecosystem service accounts.

Table 24: *Example ecosystem service supply table in physical units (based on SEEA EA Table 7.1a) . Ecosystem services and ecosystem types shown here are indicative only.*

				Selected ecosystem types (based on Level 3 - EFG of the IUCN Global Ecosystem Typology)																		
				Terrestrial												Freshwater			Marine			
				T1 Tropical-subtropical forests				T2 Temperate-boreal forests and woodlands				...		T7		F1	...	FM1	M1	...	MFT1	
				Tropical-subtropical lowland rainforests	Tropical-subtropical dry forests and scrubs	Tropical-subtropical montane rainforests	Tropical heath forests	Boreal and temperate high montane forests and woodlands	Deciduous temperate forests	...	Temperate pyric sclerophyll forests and woodlands	...	...	...	Derivied semi-natural pastures and old fields	Permanent upland streams	...	Intermittently closed and open lakes and lagoons	Seagrass meadows	...	Coastal saltmarshes and reedbeds	Total Supply resident ecosystem assets
SUPPLY			**UNITS OF MEASURE**	T1.1	T1.2	T1.3	T1.4	T2.1	T2.2	...	T2.6	...	...	...	T7.5	F1.1	...	FM1.3	M1.1	...	MFT1.3	
Selected ecosystem services (reference list)																						
Provisioning services																						
	Biomass provisioning	Crop provisioning																				
		Timber provisioning																				
		...																				
	Water supply																					
	...																					
Regulating and maintenance services																						
	Global climate regulation services																					
	Air filtration services																					
	Soil erosion control services																					
	...																					
Cultural services																						
	Recreation-related services																					
	...																					

6.2 Modelling approaches for ecosystem services

6.2.1 Why ecosystem accounting is spatial

201. The production of ecosystem services may occur in different locations (service providing areas) from where the benefits accrue (service benefiting areas). Different ecosystem services may hold certain spatial characteristics and may also follow certain flow paths (Costanza, 2008; Bagstad et al., 2013). Linkages can occur via several pathways (see Figure 11):

1) In situ ecosystem services highlight that the benefits from ecosystem services can accrue in the same place that they are produced. Most provisioning services fall in this category.
2) Omnidirectional ecosystem services provide benefits to the surrounding landscape and beyond. Carbon sequestration being an example where the benefits are global, but the ecological process can occur in any ecosystem.
3) Some ecosystem services are directional in their flows, with benefits accruing downstream or downslope from where they are produced. For example, water may be purified upstream from where the consumption of water occurs.
4) Directional ecosystem services can also depend on spatial proximity, whereby people need to be near the ecosystem, but not necessarily in the ecosystem to receive benefits.

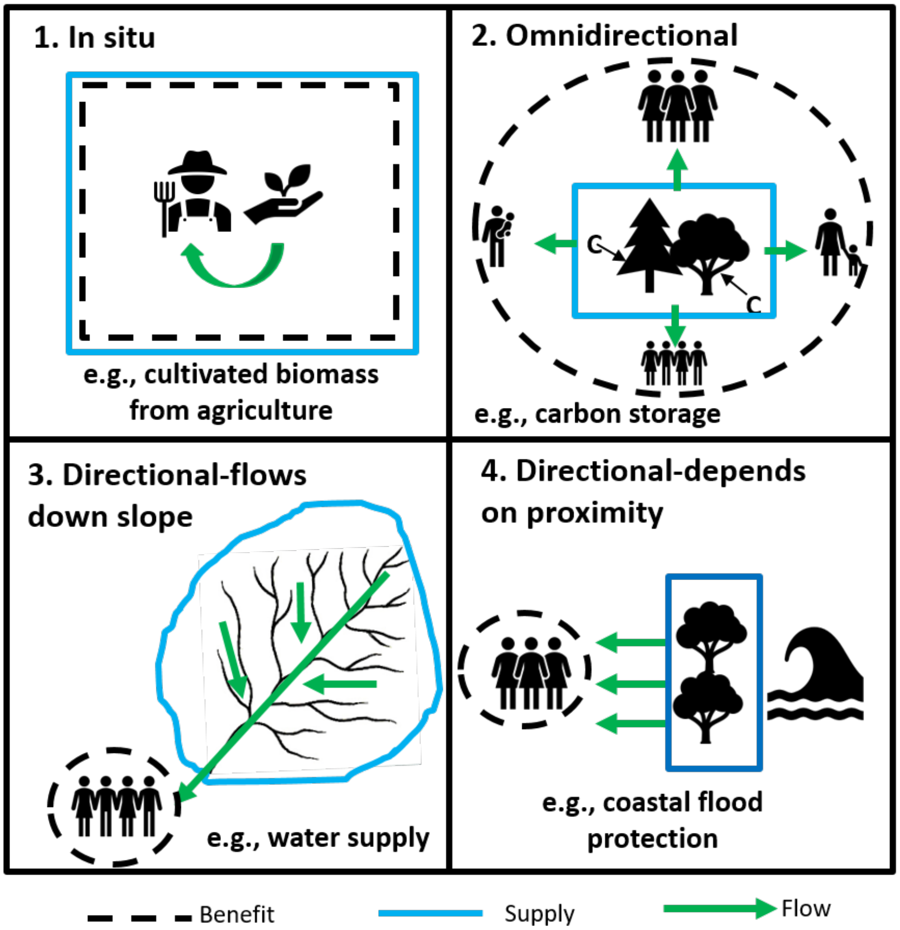

Figure 11: *A framework highlighting the spatial characteristics of ecosystem services. Figure adapted from Fisher et al. (2009).*

6.2.2 Compiling supply and use tables

202. In ecosystem accounting, ecosystem services are conceived as transactions between ecosystems (the suppliers) and economic activities and households (the users). By definition the supply of an ecosystem service equals its use. Ecosystem services are defined as the ***contributions of ecosystems to benefits used in economic and other human activity***. This implies that ecosystem services are recognized only when there is a direct beneficiary. For instance, air filtration that takes place in a remote area, and without the presence of humans to benefit from the service, will not be recognized in the supply and use table. This implies that when modelling ecosystem services, the demand/use is often important, for instance the location of the population when looking at air filtration or nature-based recreation.

203. In order to compile the supply use table, it is necessary to quantify the various ecosystem services spatially. For some services, we start from the supply side and then compare with the users. For example, when assessing air filtration, we often first estimate tons of dust filtered by vegetation, which is then compared with the use side to assess how much of that filtering takes places in areas where humans benefit. For other services (e.g. timber provisioning), it is common to start with the use side and then model the supply. For instance, we may know how much timber is harvested (e.g. based on a household survey), which we then spatially allocate to the landscape.

204. In order to compile the supply table, the service flows need to be allocated to the various ecosystem types generating the services. This can be done by overlaying the various modelled ecosystem services flow maps with the ecosystem extent map. For certain services, multiple assets can be involved in generating the service flows, in which case the service flow can be apportioned based on their per pixel values within the various EAs in scope of the EAA (SEEA EA Para A10.17).

205. For the compilation of the use table, the various ES need to be allocated to their users. For several services, the use can be assigned by default (e.g. to agriculture in case of crop provisioning services, or to the water supply industry in case of provisioning of water, or to households in the case of air filtration nearby residential areas). For certain other services (e.g. flood protection) multiple users (e.g. various economic activities) may exist, and allocation can be done, for instance based on the location of economic activities (e.g. using a geo-coded business register when it exists), based on population density or the value added of industries in the service benefiting area. In the case of pure public services (e.g. climate regulation services), it is recommended to allocate these to government final consumption due to their non-rival and non-excludable nature (SEEA EA Para 7.32). Finally, in some transboundary cases the beneficiaries may be downstream or abroad, which may be recorded as exports (imports) of ecosystem services (SEEA EA Section 7.2.6).

6.2.3 Steps for compiling ecosystem service accounts

It is recommended to follow these steps when compiling the ecosystem service supply and use tables:

1. Prioritize ecosystem services based on needs (e.g. policy relevance), as described in Chapter 2.
2. Evaluate ecosystem service models which would be the best fit for the service and policy question (look at example accounts).
3. Assess data resources (which data sources are typically used?) and modelling capacity (how experienced is your team? Is it feasible to create a model in your geographical area?).
4. Decide on which Tier approach to take and model each of the service flows.
5. Compile an ecosystem service supply and use table for the EAA by:
    a. allocating the results of the individual ecosystems services to ecosystem types and users
    b. integrating and aggregating the results of all modelled services.

6.3 Modelling platforms for ecosystem services

206. The number of multi-ecosystem service modelling platforms that are freely available has been growing over the past decade, but few of these were designed specifically for ecosystem accounting. For ecosystem accounts, the model results must hold several key features (see Chapter 3). For example, some of these modelling platforms are only parameterized for specific geographic locations, meaning they are only available for some countries. Other models may only be parameterized for specific land cover types or ecosystems. Table 25 focuses on assessing several common multi-service platforms and their coverage of the ecosystem services which are distinguished in the SEEA EA reference list of ecosystem services (focusing on provisioning and regulating services).

207. As can be clearly seen, several ecosystem services are not part of these commonly used platforms, and other approaches need to be followed, such as the construction of own tailor-made models or applying a suitable value transfer technique.

Table 25: *Ecosystem service modelling platforms and their capacity to provide estimates of ecosystem services (in physical terms) for SEEA EA supply and use tables. This list of modelling platforms is not comprehensive but illustrative (as of May 2020 – for latest version of the table see: https://seea.un.org/ecosystem-accounting/biophysical-modelling)*

			ARIES	**InVEST**	**LUCI/Nature Braid**	**ESTIMAP**	**DATA4 NATURE**	**i-TREE**
Provisioning services	Biomass provisioning	Crop provisioning	X	X	i		X	
		Grazed biomass provisioning	X		X		X	
		Timber provisioning	X				X	
		Non-timber forest products and other biomass provisioning	m					
		Fish and other aquatic products provisioning		X				
	Water supply		X		X		X	
	Genetic material							
Regulating and maintenance services	Global climate regulation services		X	X	X		X	X
	Rainfall pattern regulation services				X		X	
	Local (micro and meso) climate regulation services		i		X		X	X
	Air filtration services					X		X
	Soil erosion control services		X	X	X	X	X	
	Water purification services			X	X	X	X	
	Water flow regulation services			X	i	X	X	
	Flood mitigation services (coastal or riverine)		X	i	X	X	X	
	Storm mitigation services				X	X		X
	Noise attenuation services							
	Pollination services		X	X		X		
	Pest control services					X		
	Nursery population & habitat maintenance services					X	X	

		ARIES	InVEST	LUCI/Nature Braid	ESTIMAP	DATA4 NATURE	i-TREE
	Soil waste remediation services						
	Other regulating and maintenance services					X	
Cultural services	Recreation- related services	X	X		X		

Table notes:

- i denotes index value – this would need to be transformed in order to include in the ES SUT

- m denotes that the model is only available in monetary units

- x indicates covered by.

208. Despite some modelling platforms having complete coverage at the global level, consideration of other models may be warranted. Other models may have been parameterized using local data, so they may be better adapted or more trusted by scientists and stakeholders in the country.

6.4 Modelling individual ecosystem services

209. This section currently provides guidance and examples for 10 ecosystem services: crop provisioning, wood provisioning, air filtration, soil erosion control, water supply, water purification, water flow regulation, global climate regulation, pollination and recreation-related services. These services were selected based upon feedback received during the global consultation process. Additional ecosystem services will be covered through additional technical notes.

6.4.1 Crop provisioning

6.4.1.1 Definition and context

210. Crop provisioning services are the ecosystem contributions to the growth of cultivated plants that are harvested by economic units for various uses including food and fibre production, fodder and energy (UN et al. 2021). As detailed in SEEA EA Section 6.4, a distinction is made in accounting between cultivated and non-cultivated production practices. In case of the latter, all the harvested biomass is considered the

ecosystem contribution, and the gross quantity of biomass harvested (including any losses during the harvest) should be recorded.

211. In cultivated production processes, agriculture is a form of joint production in which natural processes of biomass growth intersect with human interventions (e.g. application of fertilizers). While there exist a wide variety of production contexts and management practices ranging from very limited human involvement to intensive involvement (e.g. greenhouse cultivation), the conceptual intent is always to measure the ecosystem contribution.

212. Clearly, many services, such as pollination, pest prevention and nutrient inputs from soil, as well as flows of water are used together with human inputs (e.g., fertilizers) for agricultural production. Data permitting, these services can be modelled separately and recorded as final ecosystem services. Alternatively, they can be recorded as intermediate service(s) (e.g. a pollination service supplied by hedge rows, used by cropland) in combination with a final crop provisioning service thereby avoiding double counting. The employed assessment technique may influence whether ecosystem services are treated as intermediate or final. For example soil retention and/or pollination can be embedded in an agricultural production function to assess crop provisioning (facilitating an intermediate recording) or be assessed through ad hoc models and be disentangled from crop provision (facilitating a final recording).

213. Harvested crops (tons) can be used as a proxy for the crop provisioning service, but where feasible, harvest should be adjusted with a factor that accounts for management practices, recognizing that ecological contributions between more natural and more artificial agricultural practices are different. These adjustment factors could be a continuum ranging from 100 percent ecosystem contribution in systems with no artificial inputs (or in case of uncultivated circumstances, such as berry picking in the forest), to almost 0 percent ecosystem contribution in greenhouse systems. Vallecillo et al. (2019) have developed a model in which emergy (embodied energy content) is used to isolate the input from nature vis-à-vis

human inputs. This essentially yields spatially explicit fractions, which can be used to multiply with the yield of crops to obtain estimates of the ecosystem contribution.[58]

6.4.1.2 Modelling approaches

214. Biophysical modelling can play several roles in estimating crop provisioning services. For example, biophysical modelling provides approaches for spatializing agricultural census data, where spatially explicit data are scarce. Modelling can also be used to estimate yields based on environmental suitability for certain types of agricultural production. Furthermore, biophysical modelling can expand our understanding of ecological contributions to crop provisioning by facilitating connections to ecosystem condition, as well as by reporting on intermediate services for crop production.

215. Approaches available in different geographical locations depend primarily on the availability and granularity of agricultural statistics (e.g. on yield, management practice). Most countries conduct an agricultural census supplemented by regular agricultural farm-level surveys on a range of variables. As the service is used in situ (see Figure 11), no modelling step is required for compiling use tables. Below, we suggest how to approach modelling crop provisioning for SEEA EA using the "tiers" perspective outlined in the introduction of this document.

6.4.1.3 Data sources and Tiers.

Tier 1

216. In the absence of national agricultural statistics, international data sources can be used to provide a first rough estimate of crop provisioning services. Estimates of crop provisioning services can be produced using global models, such as InVEST. The InVEST Crop Production Model uses two approaches – first, a statistical approach to map and estimate crop yields for 12 crops (Sharp et al., 2018). The 12 staple crops are: barley, maize, oil palm, potato, rapeseed, rice, rye, soybean, sugar beet, sugar cane, sunflower and wheat. Second, for 175 crops worldwide, InVEST models include percentile models (i.e. identifying yields that are considered to be in 5th, 50th, 75th and 95th percentiles by climate bin). Models are based on FAO data as well as global data sources on climate and irrigation and are mapped at an

[58] This approach can also be used for the monetary valuation of ecosystem services by multiplying the fraction with the market value of the crop.

unspecified spatial scale. The outputs provide maps of yields (as well as nutritional content), and tables which can be converted into standardized SEEA EA tables. One of the main limitations of this approach is that it does not account for variation in yields based on landscape position, such as differences in slopes or valley bottoms, as the model only includes climate, fertilization, and irrigation (ibid). Also – the model requires the user to specify a table that maps each landcover type to a single crop type – so the user needs to have basic information about what types of crops occur in the accounting area.

217. ARIES for SEEA includes a crop provisioning model covering the same twelve globally important crops mentioned above. Lacking the subnational time series of agricultural statistical data needed to produce credible spatially disaggregated crop production data, it relies on crop production data from the Spatial Production Allocation Model (SPAM) for 2010, replaced with national data where available.[59] To account for changes in crop provisioning over time, cell-level values are adjusted upward or downward based on yearly changes in crop production using FAOSTAT data.[60] In a subsequent step, the ecosystem contribution to crop production is estimated following Vallecillo et al. (2019) as the ratio of natural inputs to natural plus human inputs, in energetic terms (using crop-specific values provided for EU nations, for non-EU nations the EU average is used).

218. In 2021, the FAO updated its global agro-ecological zones (GAEZ) data portal.[61] This portal includes various themes, for the purposes of ecosystem accounting especially relevant are:

- Theme 4: Suitability and Attainable yield. Theme 4 combines agro-climatic potential yields with soil/terrain evaluation results, i.e., yield reduction factors due to the constraints induced by soil limitations and prevailing terrain-slope conditions, to provide information for 53 crops.
- Theme 5: Actual yields and Production are highly relevant. Theme 5 includes mapped distributions of harvested area, yield and production at 5 arc-minute

[59] Spatial Production Allocation Model (SPAM). 2020. MapSPAM. Accessed October 13, 2020 from: https://www.mapspam.info/
[60] FAOSTAT. 2020. FAOSTAT Food and Agriculture Data. Accessed October 13, 2020 from: http://www.fao.org/faostat/en/
[61] https://gaez.fao.org/pages/data-viewer

resolution (about 8.3 km at the equator) for 26 major crops/crop groups, separately for rain-fed and irrigated cropland, for the years 2000 and 2010. Country totals are based on FAOSTAT statistics for the years 2009-2011. Also included are estimates of the spatial distribution of total crop production value and the production values of major crop groups (cereals, root crops, oil crops), all valued at year 2000 international prices, separately for rain-fed and irrigated cropland.

The GAEZ v4 datasets have been published by FAO as dynamic web services that allow for visualization, analysis and extraction of raster-based datasets.

219. It should be stressed here that all Tier 1 approaches provide very coarse results, many are limited to the roughly 10 km^2 spatial resolution common to key global crop datasets (Monfreda et al. 2008, SPAM 2020).

Tier 2

220. There are several approaches, which may be considered Tier 2 approaches depending on existing national data on yield and/or land use. In case of available agricultural statistics (e.g. on yields per region) these statistics could be spatialized using biophysical modelling techniques. This spatialization can be done based on information on agricultural land use, or auxiliary information on suitability of land for specific crops. In the most basic approach, there is only information on agricultural land use – not which types of crops are grown where (or for what rotation cycles).

221. In an intermediate approach, some information is available on which crops are grown where, or this information could be deduced using information from other data sources (e.g. soil maps). These other data sources allow for the development of maps with computed yield factors. These factors will differ based on the aggregation of the survey data.

222. Another approach could be taken, if information on crops (e.g. detailed land use maps) is available, but there is no information on yield. In this case, a look-up table approach using yield factors from the literature could be applied. Other modelling approaches may include regression analysis in which yields are linked to land cover or extent accounts. Models such as LUCI may produce these more sophisticated estimates of potential crop production.

223. The ARIES modelling platform has infrastructure to take a wide range of input data into account, in various modelling frameworks, including soil fertility, irrigation, water availability and soil management to estimate crop yield. The ARIES modelling platform is developing machine learning models for crop and timber production, which are currently available in the ARIES Explorer. These models have only been tested in Western Europe, so more widespread testing is needed for it to be reliable in diverse contexts.

Tier 3

224. More accurate yield models may be designed using national data. For example, LUCI / the Nature Braid estimates the potential of a location to produce crops, based on soil fertility, aspect (i.e. orientation of hillslope, such as north or south facing), and climate, which could be linked to estimates of yield. Detailed spatial and temporal information on tillage techniques, fertiliser and irrigation can be input if available, and if not available the model assumes regional averages, which have to date only been compiled for a small number of countries in the Asia Pacific. The advantage of this approach is that it could rely on freely available and more spatialised data to create more accurate linkages to yield, taking tillage techniques, fertilizers, and landscape context into account without relying on farm census data. However, for most countries this is still a custom approach that requires additional steps beyond the more easily obtainable outputs provided by other modelling platforms.

225. Custom models may include yield data parameterized using national data or detailed microdata or farm-scale surveys. Tier 3 accounts should aim for high-resolution or moderate resolution outputs.

226. A recent development is the Sen2-Agri system[62], which uses high-resolution Earth Observation (EO) data to generate a number of different products including: monthly dynamic cropland masks (separating cropland from other areas); cultivated crop type maps at 10 m resolution for main crop groups, delivered twice along agricultural seasons. The Sen2-Agri system is free and open source. It requires national data that can be used as a training data set for validation purposes of the EO data. While it has great spatial and temporal detail, it covers only 5 main crop types (per region).

[62] See: http://www.esa-sen2agri.org/products/crop-type-map/

6.4.1.4 Challenges

227. One of the main challenges of producing maps of crop provisioning is that different crops have different nutrient, water and seasonality requirements. This means that several models are needed for a single ecosystem service.

228. Secondly, statistical agencies are usually not allowed to share spatially explicit data (or microdata with agricultural census results) publicly due to confidentiality rules. Social / institutional aspects may also be important. For example first nations may want to consider sacred sites in ES provision but do not want the sites to become identifiable for others. Advances in modelling technology and information sharing will likely include approaches that can draw on spatially explicit data, while simultaneously honouring privacy agreements as well as remaining legally compliant (e.g. data remains encrypted while being used in models). Technology for privacy preserving techniques has already been developed but is currently only available commercially, however these technologies are scheduled to become available on the ARIES ecosystem service platform. This privacy feature would make key input data nonviewable/non-downloadable if private, while still allowing models to run and outputs to be visualized.

6.4.2 Wood provisioning service

6.4.2.1 Definition and context

229. Wood provisioning services are the ecosystem contributions to the growth of trees and other woody biomass in both cultivated (plantation) and uncultivated production contexts that are harvested by economic units for various uses including timber production and energy (UN et al. 2021). This service excludes contributions to non-wood forest products (ibid). Conceptually, wood provisioning shares many similarities to crop provisioning. The relative human contributions to wood vary globally depending on the type of forest management. While the SNA distinguishes between cultivated forests and uncultivated forests, the SEEA EA recognizes that all ecosystems are influenced by people to some degree, and thus, the degree of human inputs to biomass from forest timber occurs along a gradient.

230. UN et al. (para. 6.92) explains that in line with SNA time of recording treatments, ecosystem services in cultivated production contexts are recorded progressively over the life of the biomass. Thus, services associated with timber production from plantation forests should be recorded progressively as the timber resource grows in line with the recording of the growth of this resource in the national accounts as a work in progress). In case it is difficult to isolate the ecological contribution to the growth, the SEEA EA framework suggests mapping and tabulating the gross volume of timber (to be) harvested as the appropriate proxy unit for measuring the ecosystem service.

6.4.2.2 Modelling approaches

231. An important distinction exists between approaches that model wood provisioning from the supply perspective or from the demand/use perspective.

232. A wide range of models can be used to estimate this ecosystem service from the supply side. These models draw on a long history of forestry research. Models include empirical models which estimate biomass production by associating climate data with plot-level measurements of productivity (Haberl et al., 2014), as well as dynamic vegetation models that simulate physiological processes. Dynamic systems modelling may be particularly well-suited for understanding the temporal dynamics of timber production in different landscape contexts. Such approaches generally provide estimates of potential supply but need an additional step to estimate the realised supply.

233. From the use perspective, the natural starting point would be information about actual timber harvest. While records of timber harvests are common in many countries, a challenge to mapping timber supply is the spatial attribution of harvest data (which may be available only at administrative levels) to different locations. Data sources such as climate data, digital elevation models, roads, as well as land ownership maps may facilitate more detailed forest harvest maps and may be used in dynamic system modelling or in multilevel look-up table approaches. Other relevant data sources are databases on concessions provided to forest companies, and maps of the management regime in place for forests (e.g. protected; sustainable use etc.), which can be used to create maps of timber harvest volume.

234. Another modelling approach which may be useful in locations where data is scarce is the use of look-up tables, for instance based on average harvest by forest type using global data sets.

6.4.2.3 Data sources and Tiers

235. Producing different tiered accounts for biomass from forest-timber depends primarily on the availability of forest harvest data in national statistics. Many countries conduct forest inventories, for instance, as part of the Forest Resources Assessment[63] that would provide data that can be used for modelling this ecosystem service. These estimates can come from plot measurements, aerial photography-based assessments and sophisticated LiDAR (Light Detection and Ranging) measurements. When national data are not available, forest harvest by country are estimated by the FAO and may be used as starting point.

236. An important step in spatial models of forest harvest is mapping forest cover change. Satellite imagery may help identify actively managed forests. Many types of forestry can be readily seen in satellite imagery. For example, in Western Canada clear-cut harvest practices were mapped with 84 per cent accuracy (Jarron et al., 2017). Practices such as selective harvesting can be less visually obvious. Detailed remote sensing imagery may also be used for distinguishing tree species. These species-specific maps can be used to create more detailed timber harvest maps where species-level harvest data are available.

Tier 1 Coarse estimates using global data

237. The most basic SEEA EA accounts for uncultivated forest production for timber can be produced using global models and data. A first step towards timber harvest models for SEEA EA involves producing spatially explicit data for forests and estimating the volume of production. ARIES is the main multi-service platform with this capability. OpenForis may be a useful tool for expediting the collection of forest data, while Trends.Earth may be a useful tool for tracking land cover change.

[63] http://www.fao.org/forest-resources-assessment/en/

Tier 2 Spatialized official statistics or global models with national data

238. In an intermediate variant on forest production models, more information on where forest harvest takes place is available. These other data sources allow for the development of maps with computed yield factors. These factors will differ based on the aggregation of the forest harvest data. Where country-specific data are available, such as national forest inventory data and national land use maps, look-up tables can also be used to create maps of timber volume by linking harvest reports to maps of forest cover.

239. In another approach, information on detailed land use is available, but limited information on harvest/production. In this case, a look-up table approach using yield factors from the literature could be applied.

Tier 3 Sophisticated country specific models

240. More accurate yield models may be designed using national data. Custom models may include yield data parameterized with national data by using dynamic systems models. For countries that depend heavily on timber production, these models may be highly sophisticated, and using output data from these is recommended. Tier 3 accounts should aim for high-resolution or moderate resolution outputs.

6.4.2.4 Challenges

241. A key issue for tracking timber provisioning, especially where information on historical harvest is desired, are data gaps in time series, as methods for assessing forests were historically time intensive.

242. Illegal timber harvesting is an issue in several countries, which by its nature tends to escape statistical observation. However, through a discrepancy analysis, e.g. by comparing various data sources on the supply and demand of timber, estimates may be obtained for illegal logging. The ecosystem service would include both legal and illegal harvest, but could indicate the amount of illegal harvesting as an *of which* item.

6.4.3 Air filtration from vegetation

6.4.3.1 Definition and context

243. Air filtration services are the ecosystem contributions to the filtering of air-borne pollutants through the deposition, uptake, fixing and storage of pollutants by ecosystem components, particularly plants, that mitigates the harmful effects of the pollutants (UN et al. 2021). Interactions among vegetation, weather, and the chemistry or concentration of different pollutants all play a role in spatial heterogeneity in air filtration. These interactions are difficult to measure directly, and modelling can play a role in estimating air filtration from vegetation over both small and large spatial scales. From a biophysical perspective, the capture of pollutants by vegetation is the relevant process for this ecosystem service. To link biophysical processes to human use, estimating the proximity of beneficiaries of pollutant removal is needed. The latter step is particularly important for valuing the service. Here, the focus is on the first step, modelling the biophysical capture of pollutants.

6.4.3.2 Modelling approaches

244. The most common approach to model air filtration estimates this as (Horlings et al., 2020):

ABSORPTION = SURFACE*PERIOD*FLUX

245. Typically LAI (Leaf Area Index) is used as a proxy for SURFACE. LAI is a dimensionless index characterizing tree canopies and vegetation structure. LAI is typically defined as the one-sided leaf area per ground area for deciduous trees and half the total needle surface area per ground area for coniferous forests (Myneni and Knyazikhin, 2015).

246. PERIOD is defined as the period of analysis, multiplied by the proportion of dry days a year, multiplied by the proportion of in-leaf days per year (or tree phenology).

247. FLUX is defined as the deposition velocity multiplied by the ambient concentration of the pollutant that is being assessed (e.g. $PM_{2.5}$ or PM_{10}).

248. Many of the inputs to air filtration models are point-based. For example, both surface weather stations and air quality monitoring stations capture pollution measurements at fixed points. As such, spatial interpolation methods are an important part of creating estimates of air filtration from vegetation. Land use can be used in both

spatial interpolation of pollutant concentrations and LAI estimates. A look-up table approach based on land cover may also be used to link air pollution concentrations to specific locations.

249. Input variables to models for air filtration from vegetation models also have a strong temporal component. LAI varies across and within seasons, weather is variable across and within days, and pollutant concentration varies with concentration of vehicles, etc. Modelling approaches must determine how to account for this temporal variability. For SEEA EA, annual aggregation is typically appropriate.

6.4.3.3 Data sources and Tiers

250. LAI can be measured directly by taking a sample of leaves and leaf litter within a fixed area plot, but direct measurements are difficult to scale to the national level, because of LAI's high spatial and temporal heterogeneity (Hu et al., 2014). Therefore, indirect methods are more commonly used over large spatial extents. One common indirect estimate used in air quality models is MODIS satellite imagery.[64] LAI obtained from MODIS has been validated across a wide distribution of locations and time periods through ground truthing and validation efforts.[65] LAI can also be derived from parameters that are observed with satellites (e.g. using NDVI), which is subsequently estimated based on statistical relationships between spectral signatures and ground-based estimates. These models are not readily available for all ecosystem types. Sometimes coefficients from the literature are applied (e.g. from Powe and Willes, 2004) – but in this example coefficients are calibrated to UK temperate deciduous forests, and cannot be simply transferred to other ecosystem types.

251. Data on leaf-days (i.e. the number of days a year that trees carry leaves) and pollutant concentration will usually be available from national meteorological offices, although global data sources can also be used (e.g. worldwide air quality modelling stations).[66]

252. A tiered approach to air filtration focuses on increasing spatial resolution and coverage of point-based measurements of weather and pollutant measurements, increasing spatial resolution and approach of LAI measurements, and broadening the range of

[64] See : https://modis.gsfc.nasa.gov/data/dataprod/. See also Inge Jonckheere et al. (2004).
[65] The product is an 8-day composite data set with 500 m resolution, using an algorithm that selects the best pixel in an 8 day timeframe (Myneni and Knyazikhin, 2015)
[66] See: https://aqicn.org/sources

pollutants measured. Concentrations of different harmful pollutants may vary with location, and as such, SEEA EA allows flexibility surrounding which pollutants to track. The size of pollutant captured is highly relevant, because the greatest health hazard is posed by small pollutant particles ($PM_{2.5}$), which may be an important place to start for those nations wishing to reduce health risks. Furthermore, this ecosystem service is specifically important in urban areas, where pollution is produced and filtered locally, which means detailed analyses in certain locations may be prioritized. In our tiered approach, we outline how higher resolution data and better verification highlight different tiers of air filtration accounts.

Tier 1 / Tier 2

253. Air pollutant removal from vegetation is estimated based on mid-resolution estimates of LAI and land cover extent, such as Landsat or Copernicus Global Land Service, and national-scale weather and air quality stations. Land Use Regression Models, which look at air pollution levels in a certain location and explore the surrounding land use and how this affects outcomes, are a suitable approach for this tier. These models explore the strength of different sources and sinks for pollutants in urban areas. Here, land use and land cover are proxies for sources and sinks, including roads, industrial areas, etc. (Rao et al., 2014). These approaches are important for deriving site-specific air pollutant reduction factors. ESTIMAP also includes approaches for estimating air filtration from vegetation (Zulian et al., 2014), which is an example of the Land Use Regression model. The ESTIMAP approach to air purification uses NO_2 dry deposition velocity (with NO_2 as a proxy for other air pollutants), where land cover and wind speed are inputs to the model. ESTIMAP is especially suitable where specific tree structural information is not available, since the model can be applied to different regional contexts and scales.

Tier 3

254. A Tier 3 approach would rely on high-resolution LAI (for instance using tools like SNAP[67] that are able to generate LAI maps at 10-20m spatial resolution from Sentinel-2) and pollution concentration estimates, especially within urban areas and locations with high pollutant exposure such as industrial sites. A Tier 3 approach would track chemical-specific removal, covering multiple pollutants. Customized

[67] SNAP (SeNtinel Application Platform) toolbox, https://step.esa.int/main/download/snap-download/

models and land use regression models are based on high resolution land cover mapping. One model freely available for estimating pollutants captured by vegetation is i-Tree, (https://www.itreetools.org/). i-Tree uses Leaf area index (LAI) derived from satellite imagery, surface weather, land cover and air pollutant concentration to estimate rates of dry deposition of air pollutants. One advantageous feature of i-Tree is that it provides guidelines on how to collect field data. With these field data, i-Tree estimates various benefits from trees. i-Tree's quantification of pollutant removal is the product of deposition velocity (*F*; in g m^{-2} s^{-1}) and pollutant concentrations (C; in g m^{-3}). A downside of using field data is that this may be too costly to collect at national scales.

6.4.3.4 Challenges

255. It is important to correctly interpret the results of the air filtration service, which holds also more generally for many regulating services, by distinguishing between the various factors determining supply such as pollutant concentrations and LAI. For example in the account created by the Netherlands, yearly PM_{10} capture (kg $PM_{10}ha^{1}$) was estimated for two different years (Remme et al., 2018). It was found that air filtration was lower overall in 2013, as ambient PM_{10} was also lower in 2013, not because the ecosystem was capable of providing a smaller amount of air filtration. Specifically, when it comes to monetary valuation of the service, it is not just the supply, but also the demand that is important - for example rising population makes air filtration more valuable.

6.4.4 Soil erosion control / sediment retention

6.4.4.1 Definition and context

256. Soil erosion control services are the ecosystem contributions, particularly the stabilising effects of vegetation, that reduce the loss of soil (and sediment) and support use of the environment (e.g., agricultural activity, water supply) (UN et al 2021). This service is sometimes also described as soil erosion prevention or sediment control. Vegetation holds sediment in place, providing a foundation of fertile soil for forestry and agricultural productivity. Soil retention is also linked to natural-hazard reduction by stabilizing slopes and preventing landslides, which is

seen in SEEA EA as a separate (sub) ecosystem service.[68] Sediment retention contributes to water quality amelioration, turbidity in water and sediment-bond nutrients (Burkhard et al., 2019). Soil is also important for stable locations for infrastructure. The target unit for sediment retention for SEEA EA ecosystem service supply accounts is the volume of sediment per year retained due to the presence of ecosystems. In the case of countries with arid/semi-arid conditions, it may be worth trying to develop accounts for wind erosion prevention as well as water-based erosion prevention. Here, the focus is solely on modelling approaches based on water-based erosion.

6.4.4.2 Modelling approach

257. Several process-based models are available to quantify this metric and better understand movement of sediment through landscapes. Foundational to many of the sediment retention models is the USLE (Universal Soil Loss Equation) and the RUSLE (Revised Universal Soil Loss Equation) and its associated models such as the Unit Stream Power Erosion and Deposition (USPED) model (Mitasova et al., 1996). USLE was originally parameterized at the farm field scale in the United States. The strengths and limitations of the USLE and RUSLE have been extensively reviewed (Benavidez et al., 2018).

258. Many ecosystem service modelling platforms use the RUSLE family of models equations as the basis to model sediment retention. Among these are InVEST, ARIES, ESTIMAP[69] and LUCI/Nature Braid. Soil erosion is primarily driven by water and wind and land use practices. Of these, wind is not captured in these erosion equations. RUSLE also does not consider certain types of erosion, such as gully and stream bank erosion or mass wasting (i.e. erosion occurring during landslides or slope failures). RUSLE is an empirical model (Estrada-Carmona et al., 2017) based on several key variables:

$$\mathbf{RUSLE = R_i * K_i * LS_i * C_i * P_i}$$

[68] Landslide mitigation services are the ecosystem contributions, particularly the stabilising effects of vegetation, that mitigates or prevents potential damage to human health and safety and damaging effects to buildings and infrastructure that arise from the mass movement (wasting) of soil, rock and snow (UN et al. 2021).

[69] ESTIMAP uses an additional dimensionless indicator which measures the capacity of ecosystems to avoid soil erosion and gives scores to land pixels between 0 and 1 (Maes et al. 2015).

259. Here, R_i is rainfall erosivity, K_i is soil erodibility, LS_i in classic implementations is a unitless slope length-gradient factor although some modern applications adapt it to consider topographical flow accumulation, C_i is a unitless crop-management factor, and P_i is a support practice factor. Since the RUSLE model output is sediment loss per year and SEEA EA aims to measure sediment retained per year, a further conversion of this RUSLE output is needed to obtain sediment retained. One approach for this conversion is assessing the difference in RUSLE outputs assuming current land cover versus assuming bare land (i.e. by running the model twice, based on the current/actual situation, and the situation in the absence of vegetation).

6.4.4.3 Data sources and Tiers

260. For sediment retention, a tiered approach moves from using global data sources to local data sources with greater calibration and spatial resolution. Many of the available tools are already flexible on spatial resolution, and as such, understanding which model suits the type of erosion most problematic in your country is the greatest challenge in choosing the correct approach.

Tier 1

261. Sediment retention modelling that relies on globally available data sets and pre-constructed ecosystem service models (i.e. InVEST, ARIES, ESTIMAP, LUCI/Nature Braid), uses freely available tools and requires very little user input. Inputs to the model include raster data sets of climate, soil, elevation, land use and land cover, as well as look-up tables for crop management and support practice factors (Hamel et al., 2015). A key benefit of the InVEST and LUCI/Nature Braid models is that they quantify the connectivity of each pixel to streams. In other words, these models can calculate the sediment that is likely to leave a given pixel, as opposed to just potential erosion. ARIES currently implements the RUSLE to estimate sediment retention in its global models (Martínez-López et al., 2019).

Tier 2

262. Sediment retention modelling that relies on national data sets, requiring some customization and instream sediment measurements for validation. Models such as LUCI/Nature Braid may be suitable. Traditionally, the LUCI/Nature Braid model provided estimates of sediment erosion based on the Compound Topographic Index. A limitation of this approach is that it provides values on the risk of erosion without

providing volumes of retained sediments. New supplementary LUCI/Nature Braid algorithms now provide models based on the RUSLE (Revised Universal Soil Loss Equation), which provides annual estimates of the amount of soil retained. LUCI/Nature Braid is parameterized with global datasets, but in more detail for the UK, New Zealand, the Philippines, as well as other Asia-Pacific locations. For nationally specific applications, LUCI/Nature Braid requires a range of inputs including soil type, land cover, precipitation and evapotranspiration. Choices must also be made to sensibly calculate rainfall erosivity soil erodibility factors.

Tier 3

263. For a Tier 3 approach, sediment retention models are implemented using the best available local data using customized models that have been parametrized and calibrated for local contexts. An example model is the Unit Stream Power Erosion and Deposition (USPED; Mitasova et al., 1996) model providing information regarding sources and sinks of erosion and deposition within watersheds.[70]

264. SWAT is a semi-distributed model, which is also suitable for estimating the amount of soil retained annually. SWAT can run at a daily temporal scale. SWAT's soil retention model is very data intensive requiring a wide range of inputs. SWAT is typically applied at the local/watershed scale and not at the national level. The model is typically calibrated using daily stream flow data. The SWAT model – once up and running – can be used to assess a range of ecosystem services.

6.4.4.4 Challenges

265. Lack of calibration data on sediment loads in rivers is a major challenge. Another difficulty is representing retention and remobilization processes in rivers (Mueller et al., 2010). A further difficulty that can occur is the choice of the counterfactual. For example, bare ground could be used in contrast to the contemporary intact ecosystem or a different ecosystem could be used.

[70] A simple GIS implementation is described here: http://fatra.cnr.ncsu.edu/~hmitaso/gmslab/denix/usped.html

6.4.5 Water supply

6.4.5.1 Definition and context

266. Water supply services reflect the combined ecosystem contributions of water flow regulation, water purification, and other ecosystem services to the supply of water of appropriate quality to users for various uses including household consumption (UN et al. 2021). A range of factors contribute to the availability and quality of water (ibid, para 6.92). In the SEEA EA framing, these factors are water flow regulation and water purification services, and they are seen as inputs into the water supply service.

267. The SEEA EA recommends that water flow regulation and purification are independently measured and recorded as final ecosystem services. In that case, to support comparability of the accounts across countries, also flows of abstracted water should be recorded in the ecosystem accounts but as a so-called abiotic flow (ibid para 6.104).[71] In case water flow regulation and/or water purification cannot be separately measured, SEEA EA recommends to use the "volume of water abstracted" as a proxy for the ecosystem service (ibid para 6.103) – called water supply. We will focus in this section on the latter situation, i.e. modelling water supply.

268. The measurement focus for water supply lies on estimating water abstraction, not water consumption. The latter is defined as the amount of water that is not immediately available for further use, because it has been embodied in products (e.g. crops; soft drinks) or evapotranspired. Only abstraction of water that involves an ecosystem contribution is within the scope of the water supply ecosystem service. Rainwater harvesting (in tanks / rooftops) would be out of scope, as would be abstraction from (deep) aquifers (sometimes called fossil water) and (in most cases) instream water used for hydropower generation. The water supply service includes both the water abstracted from the soil transpired by plants (sometimes called "green water") as well as water abstracted from surface and groundwater resources (known as "blue water").

6.4.5.2 Modelling approach

269. What distinguishes SEEA EA from SEEA-Water is the intent of SEEA EA to spatially allocate the ecosystem service to different ecosystems contributing to the service.

[71] Abiotic flows are environmental flows that do not meet the definition of ecosystem services, for instance the flows of geophysical and geological resorces such as extraction of minerals (SEEA EA Section 6.2.5).

The two main approaches for SEEA EA are modelling from the supply side or the demand side.

270. When modelling water demand, it is useful to separately model the different economic activities. Ideally national water-use reports will summarize water use across space and time in a nationally consistent manner. Agriculture is often one of the largest consumers of water. This can be modelled using coefficients on water requirements per crop type (and climate) for different types of crops in combination with crop statistics. To model irrigation, information from water permits (or the number of wells / boreholes) can be used. Information may also be available in agricultural surveys. The water supply sector is also often one of the largest users of water. Information is usually available from company reports or from information about water permits. Oftentimes information from water distributors may be available. Some countries conduct specific surveys on water use by different industries. Household water use is sometimes available through households surveys. These data are also collected and available through FAO's AQUASTAT[72], which provides information on water use by industry by country.

271. The spatial allocation of water use can be based on points or areas of water abstraction. Several data sources mentioned above may be already spatialized to a certain extent (for instance data on water permits). In addition – specifically for estimating green water use, there is a range of global data sets that can be drawn upon, such as: WaPOR - the FAO portal to monitor water productivity – covering 26 countries in Africa and the Middle East[73]; AQUAMAPS[74] which is AQUASTAT's online geospatial database on water and agriculture covering datasets on Hydrological basins; River and water bodies; Irrigation and infrastructures; and Climate. The disadvantage of using location of abstraction for the spatial representation of the service (e.g. a water inlet in a river), is that it does not provide information on ecosystem functioning leading to the availability of water for abstraction (e.g. upstream ecosystems). In order to do so, we need to use a biophysical model of water yield i.e. use a supply side approach.

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[72] https://www.fao.org/aquastat/en/
[73] https://www.fao.org/aquastat/en/geospatial-information/wapor/
[74] https://www.fao.org/aquastat/en/geospatial-information/aquamaps/

272. Two main supply side approaches can be distinguished. According to Portela et al. (2019) these are[75]:

- **Modelled runoff generated over land-cover**: for the watershed above any given abstraction point, the runoff generated from modelling is 'binned' according to the landcover providing estimates of contribution from each landcover type. The underlying assumption here is that the terrestrial ecosystem is regulating the timing of the supply without explicitly accounting for or modelling it. The advantage of the method is that it is relatively straightforward to apply using most rainfall-runoff models. The main disadvantage is they generally focus on only surface flow with regulating features estimated through calibrated or uncalibrated parameters.
- **Modelled partitioning of flow**: this approach attempts to account for ecosystem' influence (and the soil layer they protect) in partitioning of flow into the "quick" surface runoff and "slow" shallow/sub-surface flows. In principle, this "slow" component may then: contribute to baseflow of surface water systems, improving timing of water availability; allow recharge to aquifers and explore alternate (and more extensive) flow routes for water, improving location and regional range of water availability. Data requirements for this step are high covering both the surface and groundwater domain, and the delineation of the contributing area will be different for surface and subsurface features.

[75] The descriptions in this paragraph are taken from Portela et al., 2019.

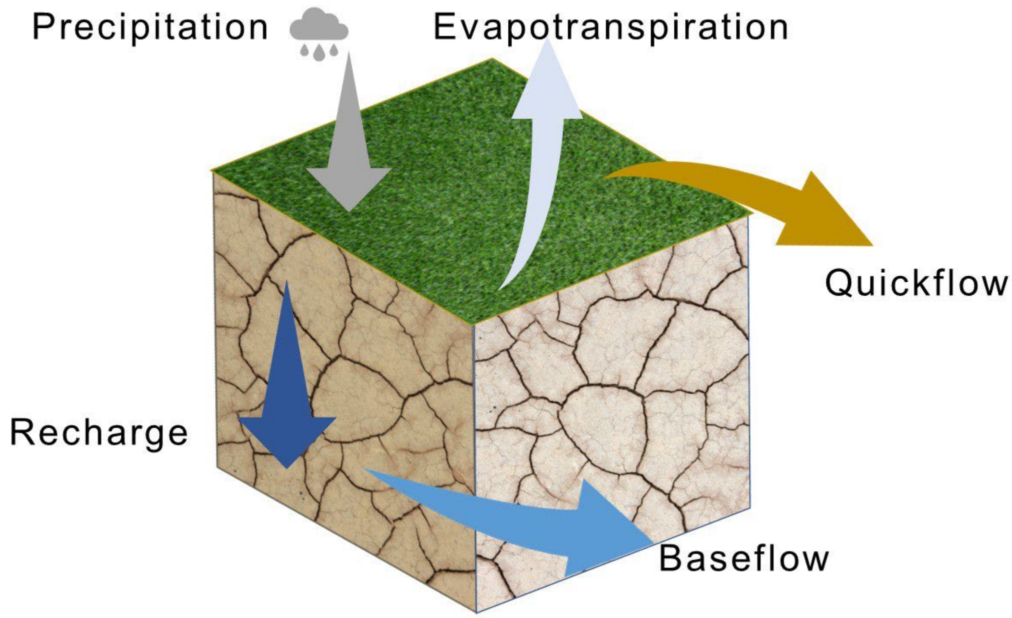

Figure 12: *Water balance at the pixel scale with main flows. Figure adapted from InVEST user guide, https://invest-userguide.readthedocs.io/en/latest/seasonal_water_yield.html#baseflow.*

6.4.5.3 Data sources and Tiers

273. Various hydrological models exist and have been used for water accounting including WEAP, PATRICAL, TOPKAPI, RIBASIM (Esen and Hein, 2020). Most models provide more of a hydrological perspective than an ecological landscape perspective and are less suited for the purposes of ecosystem accounting as they do not link changes in water flow to changes in land cover/use. This section will focus on InVEST and SWAT models as illustrations of the various Tiers.

274. One of the most commonly used models is the InVEST annual water yield model (Sharp et al., 2018).[76] It consist of three parts that can be run sequentially, the first part is most relevant for our purposes: a water yield model.[77] The water yield model is able to estimate the relative contributions of different parts of the landscape to water yield. The model runs on a user-specified gridded map and determines the amount of water running off each pixel as precipitation minus evapotranspiration.

[76] See: https://invest-userguide.readthedocs.io/en/latest/annual_water_yield.html.
[77] The second part, the realized supply model, subtracts user-specified water consumption data from water yield estimates to provide realized supply per watershed. The consumptive use data need to be specified per land cover type and are evenly distributed across all pixels of each land cover type in the model.

The pixel-based approach allows to take into account drivers of water yield such as land cover type and precipitation. The model assumes that all water yield from a pixel reaches the point of interest (the model focuses on hydropower stations, but can also be used for any water intake location), and hence does not distinguish between surface water flow and baseflow (which it does in its more sophisticated seasonal water yield model). While the model results in pixel-based outputs, due to the basic nature of the model, the InVEST guidelines state clearly that these should not be used for decision-making – it is better to use results at user-specified (sub)watershed level. The model requires in addition to basic maps of land cover, precipitation and watersheds a number of specific (spatial) parameters such as for plant available water content, root restricting layer depth, as well as model calibration parameters. The InVEST Guidelines (Sharp et al., 2018) give specific suggestions for sources for each of the required user-specified data sets. It is important to point out that green water use is integrated in the model as evapotranspiration from croplands.

275. The InVEST seasonal water yield model (Shap et al., 2018)[78] is more sophisticated as it adds a temporal aspect to the model thereby distinguishing between quickflow (run-off occurring during or shortly after rain events) and baseflow (occurring during dry weather) – see also Figure 12 above. Hereto, the model requires additional inputs such as a digital elevation model; monthly precipitation maps; and a rain events table. A key element is the use of curve numbers (CN)[79] which estimate potential runoff based on the type of land cover in combination with the hydrological properties of different types of soil. The elevation map is used to model streams. The InVEST Guidelines emphasize however that the seasonal water yield model uses a simplified approach to estimating quickflow and base flow. ARIES for SEEA will implement a version of the InVEST seasonal water yield model in 2022.

276. The Soil and Water Assessment Tool (SWAT) is a widely used watershed model for predicting the impact of land management on soil erosion and water quality (USDA ARS, 2018). SWAT is a semi-distributed model, which means results are aggregated at the sub-watershed scale, rather than distributed across a raster surface. As such,

[78] See: https://invest-userguide.readthedocs.io/en/latest/seasonal_water_yield.html
[79] https://engineering.purdue.edu/mapserve/LTHIA7/documentation/scs.htm

its results may require further modification before they are suitable for SEEA EA accounts. SWAT uses Hydrological Response Units (HRUs) to model water flows and water stocks, and the processing takes place within these units. The model operates with daily time steps and can therefore be used to model flood regulation throughout the year (through retention of water in upstream HRUs) and maintenance of dry-season water flow (through retention and gradual release of water in upstream HRUs). In order to link land use change to hydrology, SWAT needs to be extended with a landscape module, which allows modelling and integration of overland processes such as run-off and run-on and the deposition of soil particles in streams and waterways. SWAT also allows a range of processes affecting water quality such as denitrification. When SWAT is combined with modules connecting grid-based information on land cover and use to hydrological response units, the effects of changes in ecosystems can be more easily related to water flows (Duku et al., 2015).

277. However, SWAT and HSPF (Hydrological Simulation Program—Fortran) require a significant amount of data and empirical parameters for development and calibration. In the case of SWAT, ideally some four years of daily streamflow data for multiple stations in a watershed are needed to calibrate the model.[80] SWAT is also somewhat less easily adopted to include reservoirs in the watershed, which can be done more readily, for example, with the Hydrologic Modelling System model of the US Army Corps of Engineers (HEC-HMS).[81]

Tier 1

278. A Tier 1 approach would apply a basic rainfall-runoff model (such as InVEST's annual water yield model or one of the models on the other modelling platforms). The modular outputs (supply side) in the form of maps can be used to spatially distribute water abstraction data from the water accounts if they are available i.e. based on the demand side for water, to the landscape. Green water (evapotranspiration) can be modelled separately using water requirements per crop type together with crop statistics.

[80] By comparison, the Dynamic Watershed Simulation Model (Borah et al., 2002) has efficient physically (process) based simulation routines and therefore has a smaller number of calibration parameters.
[81] HEC-HMS is also available as open source software. It can comprehensively simulate hydrologic processes of watershed systems. See: https://www.hec.usace.army.mil/software/hec-hms/

Tier 2

279. A Tier 2 approach would follow the same approach as Tier 1, but apply a more sophisticated water model that partitions water flows into surface water run-off, and recharge / base flows such as InVEST's seasonal water yield model.

Tier 3

280. A Tier 3 approach would apply a detailed water model such as SWAT or HEC-HMS that also allows to take groundwater flows into consideration. The selection of the model will depend upon data availability, priority elements of the service to be understood (water quality/peak flows/baseflows), prior experience of the modeller, as well experience in the country with use of a specific model.

6.4.5.4 Challenges

281. Challenges in modelling water supply include resolving differences in economic units in administrative boundaries and biophysical units, as rivers and watersheds often span these boundaries. Another complexity in water supply modelling is that both surface and ground water contribute to its availability, and while they are intertwined, they are driven by different factors. Finally, the pathway by which water yield becomes water supply must be resolved, especially for *in situ* uses.

282. A range of environmental factors contribute to water availability, including precipitation, vegetation, soils and topography. For example, vegetation type affects transpiration. However, these factors vary widely across sites, and as such, building a model that is applicable across spatial scales is difficult.

283. Calibration of models is important to ensure they provide a reasonable representation, but can be difficult especially for watersheds with few monitoring stations. There are also global databases with runoff data that can help such as the Global Runoff Data Centre (see Annex – Table 28).

6.4.6 Water purification[82]

6.4.6.1 Definition and context

284. Water purification services are the ecosystem contributions to the restoration and maintenance of the chemical condition of surface water and groundwater bodies through the breakdown or removal of nutrients and other pollutants by ecosystem components that mitigate the harmful effects of the pollutants on human use or health (UN et al. 2021). Most water quality amelioration models focus on nitrogen and phosphorous, but other pollutants may be important in different contexts. The reasons for the focus on N and P are that 1) these nutrients are readily incorporated into plant biomass, leading to their removal from the water column; and, 2) high loads of nitrogen and phosphorous to aquatic ecosystems may lead to the growth of algal biomass – a phenomenon called eutrophication - which has all sorts of adverse consequences on ecosystem condition and indirectly on ecosystem benefits such as recreation. Excessive nitrogen loads may also lead to high nitrate concentrations in groundwater which impairs the use of water for drinking purposes.

285. Water purification is a complex service to model. The transport and the eventual fate of pollutants depend on their chemical structures and binding properties and involves various chemical, physical and/or biological processes. Importantly, these processes can and do take place in both terrestrial and aquatic ecosystems.

6.4.6.2 Modelling approach

286. A key distinction should be made between models that focus on N (or P) retention by terrestrial ecosystems before it reaches water bodies and models that focus on the temporary or permanent removal of nitrogen in aquatic ecosystems. The former type of models assess nitrogen as captured by vegetation and soil (and therefore are sometimes called nitrogen retention). The latter type of models looks at processes such as denitrification, or burial in sediments (La Notte et al 2017; Grizzetti et al., 2015).

287. An example of the former is the InVEST nutrient delivery ratio model (Sharp et al. 2018) which is a process-based model.[83] The model requires user specified inputs of nutrient loads (kg per ha per year for each land cover class). Subsequently it models

[82] This section draws upon La Notte et al. (2019).
[83] https://invest-userguide.readthedocs.io/en/latest/ndr.html

how nutrients move through the landscape until they reach streams, distinguishing between surface and subsurface flows. For each pixel, based on its properties such as its location in the landscape as well as properties of pixels in the same flow path, N and P delivery factors are calculated. In addition to basic maps of land cover, elevation, watersheds, and runoff potential (based on hydrological models), the model requires various user specified parameters such as a specification of the maximum retention efficiency for each land cover class. InVEST does not capture any in stream processes. The model's outputs include pixel-based nutrient loads and exports. From these, cell-based nutrient retention values can be calculated.

288. An example of the latter is the ESTIMAP model of water purification (Grizzetti et al. 2015, La Notte et al. 2017). This model covers the whole EU area and is based on a statistical model of nitrogen balances for watersheds (Vysna et al. 2021, La Notte et al. 2021). The model requires inputs of diffuse and point sources of nitrogen; of basin retention (based on precipitation) and river retention (based on river length). The main model output is spatial data with river and basin retention.

289. The SWAT model (Soil and Water Assessment Tool – see also section on water flow regulation) has been used extensively for modelling both water quantity and water quality in river basins. The model is able to assess nutrients and sediments, as well as pesticides. It works on a daily timestep and requires a high number of input variables. As such, using SWAT may require a high level of training or expertise. Furthermore, results from SWAT would need to be summarized on an annual time scale. SWAT includes a simple plant growth model. SWAT provides estimates of nutrient removal via root growth, transpiration, and biomass production (Vigerstol and Aukema, 2011).

290. In certain locations including temperate and tropical watersheds LUCI/Nature Braid is also suitable for Tier 3 models. LUCI's hydrology models are computationally efficient and based on simplified Richards equations.[84] LUCI/Nature Braid is spatially explicit and is optimally run with a 5m Digital Elevation Model. LUCI/Nature Braid reports nutrient storage and fluxes at monthly to annual timesteps which is suitable for ecosystem accounts.

[84] A nonlinear partial differential equation that describes the movement of water in soils, https://en.wikipedia.org/wiki/Richards_equation

Tier 1/2

291. A Tier 1/2 approach would be to apply the InVEST, ESTIMAP model, depending on the focus of measurement (nutrient retention and/or instream water purification).

Tier 3

292. A Tier 3 approach would apply SWAT or LUCI/Nature Braid. A limitation of LUCI/Nature Braid in contrast with SWAT is that the LUCI model only has a very basic treatment of instream processes of nutrient removals. Furthermore, SWAT may be more suitable in locations with snowmelt and storage processes.

6.4.6.3 Challenges

293. For modelling water purification, it is important to calibrate the discussed models using observed data (on water quantity and quality), for instance from monitoring stations in rivers, when those data are readily available.[85] In some cases, calibration can prove difficult and require trade-offs between which parameters better track observed measurements. Tier 3 models like SWAT are data intensive and difficult to set-up across larger areas, such as a whole country.

6.4.7 Water flow regulation

6.4.7.1 Definition and context

294. Water regulation services consist of baseline flow maintenance services and peak flow mitigation services. Water regulation services are the ecosystem contributions to the regulation of river flows and groundwater and lake water tables. They are derived from the ability of ecosystems to absorb and store water, and gradually release water during dry seasons or periods through evapotranspiration and hence secure a regular flow of water (UN et al 2021). Likewise, this ability mitigates the effects of flood and other extreme water-related events (ibid).

295. While all sorts of vegetation play a role in regulating water flows, there has been a lot of research on the role of forests in water flow regulation. Portela et al. (2019; Box 1)

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[85] This is substantially more challenging than calibration for water yield models, because stream gages continually measure water flow (so the data are often there for water yield calibration) but continuous samples of water quality typically require people to go out and collect samples (as many times a year as possible, to get an accurate profile of the seasonal and storm-based dynamics of water quality). Samples often have to be processed in a lab, then results have to be converted from concentration to loads (requiring co-location with a stream gage).

provide a summary of the main insights. For instance, deforestation at local scales tends to increase water yield (due to there being less evapotranspiration), while large scale deforestation may reduce water yield (as rainfall patterns are impacted). Forests also play a key role in transferring surface water to ground water by infiltration processes, thereby increasing baseflows.

6.4.7.2 Modelling approach

296. In order to model water flow regulation, it is essential to use a model with at least a monthly time scale such as the InVEST Seasonal Water Yield model[86] or SWAT (daily time step). The water flow regulation service can be estimated by comparing the current water yield patterns with existing land cover with the water yield that would arise in a counterfactual situation of bare soil i.e. the absence of vegetation. The difference between the two situations allows quantification of the service.

297. A different approach is taken by the ESTIMAP model of flood control (Vallecillo et al., 2019), which defines flood control as the regulation of water flow by ecosystems that mitigates or prevents potential damages to economic assets and human lives. [87] Firstly, potential runoff retention is modelled based on the curve number for land cover classes, corrected for imperviousness, slope and semi-natural land covers in riparian zones. Based on certain thresholds, the model delineates flood control providing service areas. Secondly, the demand for flood control services is based on the location of economic assets and population, leading to the delineation of service demanding areas. The actual service flow is obtained (as a dimensionless number) by calculating for each spatial unit within the service demanding areas, the share of the upstream area to that unit that provides flood control services. This approach therefore does not require precipitation and/or evapotranspiration data as inputs.

298. There are different metrics that can be used to quantify the service depending also on the model that is used. A good option is to use baseflow or local recharge (see Turpie et al. 2021). An alternative is to use a metric that captures the change in

[86] While the InVEST SWY model has monthly quickflow (as an output) it does not seem to provide monthly local recharge as output, which may require additional calculations.
[87] Please note that flood control services are defined in the SEEA EA slightly differently: they consist of coastal protection services and river flood mitigation services; the latter are defined as the ecosystem contributions of riparian vegetation which provides structure and a physical barrier to high water levels (UN et al., 2021).

volatility of stream flows.[88] The curve number component of InVEST's SWY model is sometimes used as a proxy of runoff in relation to water flow regulation.

6.4.7.3 Data sources and Tiers

299. See section on water supply. The default assumption when modelling water flow regulation is that the service is fully demanded (in case there are beneficiaries downstream). In the ESTIMAP approach the actual service flow is modelled by comparing the spatial relation between supply and demand for flood control services.

Tier 1 /2

300. Apply a model such as the InVEST seasonal water yield model or ESTIMAP's flood control model.

Tier 3

301. Apply a model with a daily time step such as SWAT.

6.4.7.4 Challenges

302. Water flow regulation is commonly modelled at the river basin scale. Obtaining national estimates would imply running the model in all basins in scope of the ecosystem accounting area and then aggregating.

6.4.8 Global Climate Regulation

6.4.8.1 Definition and context

303. Global climate regulation services are the ecosystem contributions to reducing concentrations of greenhouse gases (GHG) in the atmosphere through the removal (sequestration) of carbon from the atmosphere and the retention (storage) of carbon in ecosystems. These services support the regulation of the chemical composition of the atmosphere and oceans (UN et al., 2021). The SEEA EA considers climate regulation services as a single service consisting of two components, similar to the treatment of services such as warehousing in the national accounts: entering into

[88] Such as the RB-Flashiness index which is calculated "by dividing the pathlength of flow oscillations for a time interval (i.e., the sum of the absolute values of day-to-day changes in mean daily flow) by total discharge during that time interval. Index", see: https://onlinelibrary.wiley.com/doi/10.1111/j.1752-1688.2004.tb01046.x

storage (sequestration) and storage itself (retention). While the scope includes all GHGs, the focus here lies on carbon.

304. The carbon retention component measures the benefit of avoided damages that ecosystems provide by keeping carbon stored. In physical units, the service can be proxied by tons of carbon stored.[89] Sequestration measures the net uptake by ecosystems. UN et al. (2021; para. 6.115) explains this as follows. In principle, carbon retention and carbon sequestration components should be measured for all ecosystem assets. In practice, it is likely that different ecosystem assets will provide different contexts for measurement. In stable ecosystems, carbon retention will be the primary component while in those ecosystems where there is clear expansion in the stock of carbon, then carbon sequestration may be the focus of measurement. Of high relevance will be ecosystems whose stock of carbon is at risk of emission, for example due to land use practices (e.g., draining of peatlands, deforestation) or extreme events (e.g., fires). In these cases there may be little carbon sequestration and the focus of measurement should be placed on measuring carbon retention.

305. The SEEA EA (paragraphs 6.112 - 6.113) specifies a number of measurement boundaries when it comes to carbon retention:

-stocks are limited to carbon stored in above ground and below ground living and dead biomass in all ecosystems and soil organic carbon (including lake, river and seabeds);

-in the case of peatlands and relevant organic carbon rich soils, only the carbon stored to a maximum of 2 meters below the surface should be included;

-inorganic carbon stored in freshwater, marine and subterranean ecosystems is excluded from scope;

-carbon stored in fossil fuel deposits should not be considered an ecosystem service;

-storage of carbon in harvested wood products should not be considered an ecosystem service because these are products within the economy;

-carbon stored in cultivated biological resources that have a short rotation cycle (e.g., crops) should not be included in the measurement of carbon retention.

[89] This component of the service value can be monetized as the annualized avoided damage cost.

306. Regarding carbon sequestration, the following 3 equations apply (Edens et al., 2019, based on IPCC 2006):

1. **NPP (net primary production) = GPP (gross primary production) – plant respiration**
2. **NEP (net ecosystem production) = NPP – soil respiration = GPP – ecosystem respiration**
3. **NECB (net ecosystem carbon balance) = NEP – Carbon loss from Disturbance/Land-clearing/Harvest**

307. The SEEA EA specifies (para 6.114) that regarding measuring carbon sequestration:

- NECB is an appropriate metric;
- In case NECB is zero or negative, the level of service supplied by an ecosystem will be zero.

308. These guidelines recommend to measure NECB on a per ecosystem asset basis (for instance per grid cell). Carbon sequestration would hence be measured as the sum total of those ecosystem assets that provide a net uptake of carbon. Net primary productivity is considered a condition indicator for terrestrial ecosystems and is categorized in the functional class of the SEEA EA Ecosystem Condition Typology (see also Chapter 5 on condition).

6.4.8.2 Modelling approach

309. There are essentially two basic approaches to measure carbon sequestration by ecosystems (Edens et al., 2019). The first is to derive sequestration by comparing changes in stocks of carbon over time (this is called the stock-difference method in IPCC guidelines), for instance on the basis of forest inventories and soil carbon measurements. Below and above ground carbon stocks in various forms need to be included in such assessments. This approach may be called an indirect method, as sequestration can be derived as a residual. The stocks in this method can be used as proxy for the carbon retention component of the service. The second approach is to estimate carbon sequestration directly (called Gains-Loss method in IPPC guidelines) and involves the quantification of all key inflows and outflows of carbon per ecosystem unit to estimate NECB (as specified in the equations above such as NPP, soil respiration, emissions from forest fires etc.). The first approach is commonly applied in the existing carbon accounting mechanisms addressing IPCC's

categories of managed land, and also a subject of intense research on biomass mapping in support of REDD+[90]. Modelling NECB directly is a more complex process with fewer examples.

310. Given the SEEA framing of climate regulation consisting of two components, the stock-difference method is clearly preferred as it provides information both on storage and sequestration. The most common approach is to apply a look- up table approach and estimate stocks of carbon for two different points in time by multiplying hectares of land cover with suitable coefficients.

6.4.8.3 Data sources and Tiers

311. The Tiered approach suggested here generally follows the Tiers specified by the IPCC Guidelines (IPCC 2006; Penman et al., 2003). Tiers increase with better stratification of land cover and nationally applicable coefficients thereby increasing in accuracy.

Tier 1

312. Tier 1 employs the stock-difference method described in the IPCC Guidelines (IPCC 2006) and the default emission factors and other parameters provided by the IPCC as part of its Tier 1 specifications. There may be simplifying assumptions about some carbon pools. Tier 1 was established to recognize that, although ideally emission factors reflecting national circumstances should be used in GHG inventory compilation, this is not always practical and they can be costly to gather.

313. InVEST's carbon storage and sequestration model distinguishes four carbon pools: aboveground biomass; belowground biomass; soil; and dead organic matter. It calculates both storage and sequestration, but requires user-specified carbon densities for each of these 4 pools for each of the land cover classes included in the user-specified land cover map. This is an example of a single-layer look-up table.

314. ARIES for SEEA has implemented an IPCC Tier 1 approach following specifications of Ruesch and Gibbs (2008). It measures vegetation carbon and soil carbon separately. For vegetation carbon it is based on a multi-layer look-up table with IPCC coefficients that stratify according to 5 data layers, namely: land cover, ecofloristic region, continent, presence of frontier forests (proxy for forest degradation), recent

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[90] REDD stands for Reducing Emissions from Deforestation and forest Degradation; the plus indicates sustainable management of forests, and the conservation and enhancement of forest carbon stocks. See: https://www.fao.org/redd/en/

occurrence of fires. Soil carbon storage data rely on spatial data, e.g., from ISRIC (https://www.isric.org/explore/soilgrids). The model generates a basic carbon account that allows to quantify both retention and sequestration.

315. A drawback of the InVEST model is that it has a low level of stratification (only by land cover) and the carbon densities are assumed to remain stable, hence all changes in carbon storage are caused by changes in land cover. The ARIES for SEEA model has slightly better stratification and includes a dynamic component, but changes in storage are also predominantly driven by land cover change (not by ecosystem degradation), with the exception of handling frontier forests.

Tier 2

316. Tier 2 generally uses the same methodology as Tier 1 but uses emission factors and other parameters which are specific to the country (Penman et al., 2003). More highly stratified data may be needed in Tier 2 (e.g. distinguishing between different forest classes) that correspond to country-specific carbon densities and parameters for specific regions and specialised land cover / use categories.

Tier 3

317. Tier 3 approaches would apply bespoke models, and use plot level data from National Forest Resource Assessments (FRAs). These models may include GIS-based information on forest age, class, production system, as well as soil parameters, thereby integrating data sources from various types of monitoring (Penman et al., 2003). These models will likely also be climate dependent and therefore able to capture inter-annual variability (ibid).

6.4.8.4 Challenges

318. Carbon stored depends on measurement boundaries. For instance, some soil carbon stock measurements include carbon up to a depth of 2m, whereas other studies may use a different depth (e.g. 30 cm or 1 meter). As noted before, some ecosystems such as peatlands have very deep carbon layers and assumptions need to be made regarding their treatment.

319. Forest resource assessments are usually based on land use. This may lead to discrepancies with data sources based on land cover, for instance when forests are cut for their timber (change in land cover, but same land use).

6.4.9 Pollination

6.4.9.1 Definition and context

320. Pollination services are the ecosystem contributions by wild pollinators to the fertilization of crops that maintains or increases the abundance and/or diversity of other species that economic units use or enjoy (UN et al., 2021). Pollination is therefore understood in a broad sense as including contributions to crop production and/or contributions to species diversity. Most ES models have focused on crop production, which will be the focus of this section.

321. Pollination can be recorded as final service (in which case the crop provisioning service, if recorded, is limited to ecosystem services unrelated to pollination, like soil fertility, and/or to non-pollination dependent crops), or as an intermediate services (see UN et al, 2021 - Para 7.34). Common metrics used are the area of pollination dependent crops pollinated, yield attributable to pollinators or number of visits.

322. It is important to distinguish between animal pollination (e.g. by bees) and pollination generally, as some crops self-pollinate or use wind pollination; the ecosystem service pollination refers to pollination resulting from insect or other animal (e.g. bats) activity only. In addition, the focus of the service is on wild animal pollinators, thereby excluding artificial pollination through placing of hives or by hand-pollination.

6.4.9.2 Modelling approach

323. The main approach is to first estimate both the demand for pollination based on an assessment of crops requiring pollination, as well as the availability of pollinators, based on pollinator habitats and typical flight ranges (most crop pollination models address pollination by wild insects though other types of animals pollinate certain plants). The actual pollination service provision can be estimated by doing a spatial overlay of the demand and the supply, considering such aspects as the effectiveness of pollinator visits, and pollination dependency rates of the crops. While this approach generally applies, there exist differences in the specific models most commonly applied to estimate the service, such as InVEST (Sharp et al, 2018)[91] and ESTIMAP (Vallecillo et al., 2018).

[91] https://invest-userguide.readthedocs.io/en/latest/croppollination.html

324. Many pollination models, including InVEST, quantify the value of pollination received by pollination-dependent crop fields but do not subsequently attribute that value back to the surrounding ecosystems (pollinator habitat) that provide the service. As such a second step may be required to quantify service provision by ecosystems in a SEEA EA supply table.

325. A frequently used study to assess the demand for pollination is Klein et al. (2007), which classifies the 115 globally most important commodity crops into 5 classes of pollination dependence (see Table below). Information on which types of crops are grown where, together with their dependence generates the pollination demand in a spatially explicit manner (e.g. per pixel or land parcel).

*T**able 26:** Pollination dependence of crops (based on Klein et al., 2007).*

Degree of dependence	**Production reduction in absence of pollinators**	**Number of crops**	**Examples**
Essential	> 90%	13	Courgette, pumpkin, watermelon, kiwifruit, cocoa
Great	40% - 90%	30	Cucumber, buckwheat, raspberries, apple, winter rapeseed, mango, avocado, almond
Modest	10% - 40%	27	Coffee, okra, strawberries, eggplant, soybean, redcurrants, winter oilseed rape, sunflower
Little	0% -10%	21	Peanut, oil palm, red pepper, tomato, kidney bean
No increase	no reduction	7	Olive, quinoa, lentils

326. Modelling potential pollinator supply (i.e. areas covered by pollinators) can be undertaken by estimating nesting suitability of the landscape (by land cover type) in combination with average flight ranges by types of pollinators (Lonsdorf et al., 2009). In modelling, a distance-decay function of pollinator visits is usually applied. Nesting suitability is usually expressed as an index between 0 and 1 and can be based on expert judgement found in the scientific literature (for different types of land cover) and/or modelled taking into account more granular data such as the delineation of forest edges or hedgerows. Some models such as ESTIMAP also take the influence of temperature and solar irradiance on pollinator activity into account (Vallecillo et al., 2018). Finally, some sort of a threshold assumption is usually made such as to include only pollination from areas with medium and/or high pollination to support

pollinators (ESTIMAP), by using a saturation constant (InVEST) or an assumption of minimum required visitation rates for pollination (Horlings et al., 2020).

327. An alternative approach for estimating nesting suitability is to predict the occurrence of pollinators based on species distribution models departing from observational records and/or information of species habitats (see Vallecillo et al., 2018).

6.4.9.3 Data sources and Tiers

328. Key data sources include land cover maps; information about nesting suitability; biophysical data about types of pollinators present and their flight ranges; a map with information on crop types; finally, biophysical information on the pollinator dependency of the crops present in the ecosystem accounting area.

Tier 1

329. A Tier 1 approach may consist of applying the InVEST crop pollination module, which focuses on wild bees, but can be applied for multiple pollinator types based on user supplied information. The InVEST model is however an index based model and is not empirically validated / calibrated. ARIES for SEEA also includes a pollination model which is based on the ESTIMAP model, but it is currently designed only for a single generic pollinator.

Tier 2

330. A Tier 2 approach may consist of applying a more detailed, and validated modelling approach which includes multiple pollinator species (e.g. such as ESTIMAP).

Tier 3

331. A Tier 3 approach may consist of developing a model tailored to national circumstances. Tier 3 approaches should be empirically validated / grounded in observed pollinator occurrence. Tier 3 models should also take seasonal effects into account. See Horlings et al. (2017) for an example.

6.4.9.4 Challenges

332. Most models are not empirically validated as they are based on an assessment of the potential of the landscape to support pollinators, not whether pollinators are actually present. Most models are unable to take the dynamics of the pollinator population into account, which may be influenced by the presence of habitat disturbances such as pollution, pesticides or pests. Also, the effect of habitat sizes on pollinator abundance is difficult to incorporate in these models.

333. Finally, the presence of pollinators is likely influenced by fine-scale features in the landscape, such as hedgerows and small forest plots, which are difficult to capture in medium resolution land-cover data (Sharp et. al., 2018).

6.4.10 Recreation-related services

6.4.10.1 Definition and context

334. Recreation-related services are the ecosystem contributions, in particular through the biophysical characteristics and qualities of ecosystems, that enable people to use and enjoy the environment through direct, in-situ, physical and experiential interactions with the environment (UN et al. 2021). Recreation-related services are also supplied to those undertaking recreational fishing and/or hunting (ibid). Recreation related services are considered a final ecosystem service, with as main metric the number of visits.

335. It is relevant to distinguish between services provided to locals (e.g. a trip to a forest or park in the vicinity of where one lives) and non-locals (i.e. to visitors), that are both considered within the scope of this ecosystem service. In terms of non-local visits, it is important to distinguish between domestic (or resident) visitors and non-domestic (non-resident) visitors, as they obtain a different recording in the use-table: recreation services provided to non-residents are recorded as exports of services (see SEEA EA section 7.2.6). The definition of recreation related services excludes visual amenity services (e.g. views of the park from your house), but includes both recreation and tourism, where the latter is usually defined as involving an overnight stay.

6.4.10.2 Modelling approach

336. Direct observation of visit rates is the best way to analyse this service. This can be done with anonymised telephone data. However where such data are not available, a modelling approach is required. Following the distinctions and description in Barton et al. (2019), the simplest approach is to model potential visitation rates to local recreation sites based on population living in proximity to the site, assuming for instance a maximum distance people are willing to walk or bike. This type of approach however does not take site characteristics into account, nor preferences of people, and is only driven by changes in population.

337. A more sophisticated approach is to predict visitation rates using site specific characteristics together with information about visitors that can be collected through a sample survey collecting data about trip destinations, modes and lengths. In its simplest form a trip generation function or trip-distance-decay function can be estimated, showing the percentage of the population that would access a site for recreation purposes at different distances from that site. Increasingly sophisticated travel choice models (such as the UK's OrVAL model) identify site qualities (e.g. size) and individual capabilities (e.g. age, mode of transport) to identify underlying preference parameters and use those to predict the number of visits from surrounding areas.

338. The preferred approach would be to use actual visitation frequency data available from entrance registers, logbooks or overnight stays in hotels / campsites etc. At the (sub)national scale, the departure point could be to use tourism statistics, such as the number of visits or overnight stays for administrative areas (e.g. municipalities). The modelling aspect when using less granular data consists in spatializing these data, by allocating them to the landscape using suitable metrics, such as photo density or landscape attractiveness. When using tourism statistics, it is important in a first step to select only those visits with a nature purpose.

339. The InVEST recreation model uses a dataset of pictures uploaded to the social-media platform Flickr (Sharp et al. 2018).[92] These geotagged photographs have been shown to correlate with park survey data (Wood et al. 2013). Other studies have used data from apps such as Strava. In a study for the KZN province in South Africa, Turpie et al. (2021) apply a smooth contour map by scaling InVEST output to a higher spatial resolution, to correct for the fact that pictures can also be taken from a distance.[93]

340. A sophisticated approach is applied by ESTIMAP, which estimates the recreation service by comparing the potential supply with the predicted demand for the service

[92] http://releases.naturalcapitalproject.org/invest-userguide/latest/recreation.html

[93] It should be noted that photo density is one of the outputs of the InVEST recreation model. The model itself is based on a regression analysis, where photo density is correlated with user-specified spatially explicit inputs that help explain recreational behavior such as characteristics of natural capital (e.g. existence of beaches or protected areas) and/or produced capital (e.g. hotels) and/or accessibility (e.g. distance to airport). The regression analysis allows to predict number of visits in different scenarios. InVEST also has monthly outputs.

(Vallecillo et al. 2018). The recreation potential takes into account: 1) the attractiveness for recreation based on land cover type and ecological characteristics such as water quality or conservation status, as well as 2) accessibility for recreation based on infrastructure such as roads and proximity to residential areas. These two dimensions define what is called a recreation opportunity spectrum with scores ranging between 1 (low accessibility and low potential) and 9 (high accessibility and high potential). The model subsequently focuses on the highest scoring areas called areas for daily recreation. In a subsequent step the demand for recreation services is estimated using a trip generation function together with population density. The actual service flow is estimated through the overlay of supply and demand i.e. as the predicted number of visitors to service providing areas for daily recreation. This type of analysis also results in estimates of what the authors call unmet demand i.e. population with limited access to sites for local recreation.

341. ARIES has implemented a simplified version of ESTIMAP (Martínez-López et al. 2019), that for instance does not take water quality into account in estimating recreation potential. ARIES for SEEA combines park visitation data with tourism statistics to estimate nature-based tourism in physical and monetary terms.

6.4.10.3 Data sources and Tiers

342. Key data sources to assess relate to tourism and/or recreation statistics. Emerging data sources may consist of data from social-media or GSM/mobile network tracking of visitors' mobile phones (e.g. big data). In order to estimate landscape attractiveness for tourism usually multiple data sources are combined. Especially regarding local recreation, time use survey data may also prove relevant.

Tier 1

343. A Tier 1 approach – in the absence of information of actual visits – would consist in modelling potential visitation rates, based on population data, applying a basic model in GIS software. The ARIES for SEEA Explorer can also be used as a Tier 1 approach but the scope of the service is currently restricted to visits by international tourists (using country data from the World Tourism Organization), which it subsequently spatializes based on a landscape attractiveness model patterned after ESTIMAP.

Tier 2

344. A Tier 2 approach – assuming some data e.g. on total visitors or tourists or recreation at sub(national) level is available – would consist of spatializing those data using suitable metrics. InVEST has been applied for these purposes, however the current database of geotagged photos covers only the 2005-2017 period and appears to be no longer updated. It is also possible to spatialize existing statistics by applying a landscape attractiveness metric (such as those developed in ARIES or ESTIMAP). An advantage of using for instance tourism statistics is that tourism expenditure can be used subsequently to monetize the ecosystem service.

Tier 3

345. A Tier 3 approach would apply a sophisticated model fine-tined to national (e.g. Horlings et al., 2021) or local (e.g. Remme et al., 2014) conditions to model predicted visitation rates. For a Tier 3 approach it would be important to validate model outcomes with existing local data for specific sites in order to calibrate model parameters or trip distance functions. Travel choice models estimated from empirical information would also fall into this category.

6.4.10.4 Challenges

346. Recreation services as defined in SEEA EA is a broad concept covering both (mostly non-local) tourism and (mostly local) recreation. Different modelling approaches described above often measure different things. For instance, the ESTIMAP recreation model has been developed to estimate outdoor recreation for daily use i.e. local use, whereas approaches departing from tourism statistics tend to focus on overnight stays i.e. most likely non-local use. Depending on the country specific circumstances, a combination of models can be used to cover both local and non-local types of recreation service uses.

347. Social media and other crowdsourced datasets generally show promise in mapping, modelling, and valuing recreation services. However, they also carry important limitations that users should be aware of. Notably, such data sources can be inconsistent in their coverage of who uses the services (i.e., certain nations and/or socioeconomic groups are often over- or underrepresented in the data), their coverage over time (as certain platforms gain and lose popularity through the years), and in whether data are freely available for research and statistical purposes or must

be purchased from the company (many social media platforms now require payment for data).

348. The models described here focus on the number of visits as a metric. However length of visits (hours) is arguably a better metric for the volume of the service provided. This metric would require however the use of new data sources such as GPS tracking records, which may prove problematic to obtain due to confidentiality / privacy regulations.

6.5 Country examples

349. One way to get started with ecosystem service supply and use modelling is to explore examples from countries who have already developed SEEA EA compliant ecosystem services supply and use tables (see Table 26). Please note that the table is not comprehensive.

Table 27: *Examples of ecosystem services accounts in physical units*

Country/area	Ecosystem services covered (in original description)
Netherlands (Horlings et al., 2019)	Crop production; Fodder production; Wood production; Biomass production; Drinking water production; Carbon sequestration in biomass; Pollination; Natural pest control; Erosion control; Air filtration; Protection against heavy rainfall; Nature recreation (hiking); Nature tourism.
United Kingdom (ONS, 2019)	Agricultural biomass; Fish capture; Fossil fuels; Minerals; Timber; Water abstraction; Renewables generation; Carbon sequestration; Air pollutant removal; Urban cooling; Noise mitigation; Recreation; Aesthetic (house prices); Recreation (house prices).
China (Ouyang et al., 2020)	Ecosystem goods (agricultural crop production; Animal husbandry production; Fishery production; Forestry production; Plant nursery production); Water supply; Flood mitigation; Soil retention and nonpoint pollution prevention; Water purification; Air purification; Dust purification; Sandstorm prevention; Carbon sequestration; Ecotourism.
EU (Vallecillo et al. 2019a; 2019b; La Notte et al. 2021)	Crop provision; Timber provision; Global climate regulation; Crop pollination; Flood control; Nature-based recreation; Habitat and species maintenance, On-site soil retention; Water purification.
Rwanda (Bagstad et al., 2019)	Carbon storage; Sediment regulation; Nutrient regulation; Annual and seasonal water yield.
South Africa (Turpie et al., 2021)	Wild resources; Animal production; Cultivation; Nature-based tourism; Property; Carbon storage; Pollination; Flow regulation; Flood attenuation; Sediment retention; Water quality amelioration.
USA (Warnell et al., 2020; Heris et al., 2021)	Recreational birding; Pollution removal; Urban heat and runoff mitigation

7 Data quality for biophysical modelling

7.1 Quality assurance frameworks

350. Statistical agencies are familiar with a suite of data quality issues associated with collected data such as relevance, timeliness, accuracy and measurement error. These characteristics are described in the United Nations National Quality Assurance Frameworks (UN-NQAF) Manual for Official Statistics (UN, 2019a). Data quality frameworks for geospatial data are also developing (UN, 2019c).

351. While modelling is used in various areas of statistics - for instance the use of a Perpetual Inventory Model in the National Accounts to estimate consumption of fixed capital or the use of hedonic pricing models to estimate prices - the extent of modelling used in ecosystem accounting arguably sets it apart from other areas of statistics. Ecosystem accounts – as soon as they become part of official statistics – would need to abide by the same accepted principles and expectations inherent in official statistics, but this reliance on modelling comes with specific challenges for data quality.

352. The UN-NQAF addresses quality assurance with regard to the development, production and dissemination of official statistics. The UN-NQAF quality principles (there are in total 19 principles) and associated requirements consist of four levels, ranging from overarching institutional and cross-institutional management and statistical production processes to the outputs:

- Level A: Managing the statistical system
- Level B: Managing the institutional environment
- Level C: Managing statistical processes;
- Level D: Managing statistical outputs.

The UN-NQAF and its principles and requirements are not mandatory, and countries may choose to follow their own national quality assurance frameworks.

353. The objective of this chapter is to discuss specific issues around data quality that arise when conducting biophysical modelling. At the same time, the chapter will also highlight some best practices as they are developing within the biophysical modelling community. The focus in this chapter will be on discussing specific issues related to managing statistical outputs (Level D).

***Box 2:** Data quality dimensions*

The UN-NQAF (UN et al, 2019) distinguishes the following quality dimensions that can be used to characterize the quality of a statistical product as specified in principles 14-18:

- **Relevance:** the extent to which the statistics satisfy the needs of the users.
- **Accuracy:** the closeness of estimates to the exact or true values that the statistics were intended to measure.
- **Reliability:** the closeness of the initially estimated value(s) to the subsequent estimated value(s) if preliminary figures are disseminated.
- **Timeliness**: the length of time between the end of a reference period (or date) and the dissemination of the statistics.
- **Punctuality:** the time lag between the release date and the target date by which the data or statistics should have been delivered.
- **Accessibility:** the ease and conditions with which statistical information can be obtained.
- **Clarity:** the availability of appropriate documentation relating to the statistics and additional assistance that producers make available to users.
- **Coherence:** the ability to reliably combine statistics and data sets in different ways and for various uses. Consistency is often used as a synonym for coherence.
- **Comparability:** the extent to which differences in statistics from different geographical areas, non-geographical domains, or over time, can be attributed to differences between the true values of the statistics.

354. The chapter is structured around the main themes addressed in principles 14-19 of managing statistical outputs (see Box 2): relevance, accuracy and reliability; timeliness; accessibility; coherence; and meta-data.

7.2 Quality challenges in biophysical modelling

7.2.1 Relevance

Principle 14: Assuring relevance

Statistical information should meet the current and/or emerging needs or requirements of its users. Without relevance, there is no quality. However, relevance is subjective and depends *upon the varying needs of users. The statistical agency's challenge is to weigh and balance the conflicting needs of current and potential users to produce statistics that satisfy the most important and highest priority needs within the given resource constraints.*

355. The relevance of ecosystem accounts for different uses and users, will depend on the resolution at which the accounts are disseminated, as well as on the choice of models.

Scale and resolution

356. The outcomes of biophysical models are inextricably linked to the spatial scale of input data, as well as to the scale and aggregation of the model results. While the spatial scale of ecosystem service accounts is currently flexible in the SEEA EA framework, scale is highly important for detecting spatial patterns of individual ecosystem services as well as for detecting interactions among multiple ecosystem services (e.g. trade-offs or synergies).

357. Here, spatial resolution is defined by the BSU, while ecosystem assets and ecosystem accounting areas are different scales of aggregation. One example that illustrates this is a comparison showing how spatial scale matters for detection of ecosystem service interactions (Raudsepp-Hearne and Peterson, 2016). It is demonstrated how aggregation in 1km grids, 3km square grids, and ~9km townships affect the perceived spatial location of ecosystems (Figure 20). For example, for the ecosystem service of nature appreciation, locations that are important for different ecosystem services appear to cover a smaller extent when a 1km grid is used versus a municipal aggregation. Spatial heterogeneity in ecosystem services is also obscured when a municipal aggregation is used. For example, using a municipal aggregation for crop production shows no locations with low production of ecosystem services, whereas both 3km and 1km scales show distinct areas of low ecosystem service production.

358. Differences in perceived locations important for ecosystem services illustrate that different aggregation and spatial scales may facilitate and support different types of decision-making. For example, low resolution approaches may raise awareness, while high resolution approaches may facilitate on-the-ground decision-making and management. For decisions about infrastructure development, high resolution mapping is needed, while for decisions for conservation planning, mid-resolution maps may be sufficient. However, this may vary depending on the types of

ecosystem under consideration. For example, biodiverse riparian areas are often narrow in spatial extent, and may therefore require high-resolution methods compared to boreal forests which cover vast areas.

Figure 20: *Impact of the spatial aggregation of maps on perception and distribution of ecosystem services. This example shows indices of seven ecosystem services in Mont Saint-Hilaire Biosphere Reserve in Quebec (Raudsepp-Hearne and Peterson, 2016).*

7.2.2 Accuracy and reliability

Principle 15: Assuring accuracy and reliability.

Statistical agencies should develop, produce and disseminate statistics that accurately and reliably portray reality. The accuracy of statistical information reflects the degree to which the information correctly describes the phenomena it was designed to measure, namely, the degree of closeness of estimates to true values.

359. Decision makers are more likely to incorporate science into their decision-making if it is perceived as credible (Hamel and Bryant, 2016). Assessing and communicating

the accuracy and reliability of modelling is therefore key to its uptake. A range of qualitative and quantitative methods can be used to assess the uncertainty in a model, and uncertainty in a model can occur both due to lack of data and inherent variability in data. The accuracy of statistical outputs will depend on the accuracy of input data, as well as the reliability of the various modelling techniques applied when combining various data sources to obtain results.

360. One of the most basic ways that uncertainty can be assessed for modelling is through uncertainty matrices, which outline possible sources of uncertainty for each model (ibid). For example, these matrices could describe uncertainty in context and framing, inputs, model structure, parameters and the model's technical implementation.

Accuracy of input data

361. Input data to spatial models uses in SEEA EA may have different accuracy issues. The result of compounding inaccuracies is that the accuracy of input data may differ per BSU. For example, digital elevation models are a common input to ecosystem service models but face a range of accuracy limitations. Sampling errors, sampling resolution, and surface complexity all impact the accuracy of digital elevation models (Guo-an et al., 2001). Climate data, such as precipitation raster data, contains error from spatial interpolation of data from irregularly spaced climate stations on to grid systems. Soil data is also derived through interpolation between irregularly spaced sampling points, often using digital elevation models to create better interpolations. Accuracy assessments are one way to assess the contribution of each model parameter to its uncertainty. Another simple way to illustrate uncertainty is to contrast two data sources.

362. Another common input to ecosystem service models is land cover data. The accuracy of land cover data – for instance when remote sensing products are used – is typically lower than other data sets statistical offices use (Foody, 2002). While there are no general rules establishing what level of accuracy is "good" for land cover, the appropriate level of accuracy should be determined by the intended use of the data. Moreover, the feasible level of accuracy may depend on the type of land cover. For instance, delineating wetlands can be more difficult than delineating built-up areas. For land cover in SEEA EA context, the accuracy of the detection of change in the

maps is important, rather than simply reporting on static accuracies of individual maps.

Model validation

363. The accuracy of modelled data can be assessed, although different approaches may be needed depending on the type of model used. In other words, different modelling approaches may have different methods for determining the accuracy of a model. For some modelling approaches, accuracy cannot be determined readily. On the other hand, statistical procedures have well-established methods for determining model accuracy.

364. A look-up table approach takes ecosystem service measurements from several locations and links these measurements to locations with similar characteristics, such as land cover or climate. Look-up table approaches are especially common in mapping carbon storage and sequestration. For example, they form the basis of the payments for land holders for the New Zealand emissions trading scheme (Ministry for Primary Industries, 2017). How well look-up table approaches reflect true values depends on the number of measurements taken across the diversity of conditions within and across ecosystems. The accuracy of look-up tables can be evaluated in a similar manner as land cover accuracy assessments by taking measurements in random locations to see if they match the value of the look-up table. This approach works for ecosystem services that can be measured at the plot level (e.g. carbon storage, agricultural production). Another possibility to display uncertainty is by conducting a sensitivity analysis, evaluating the differences in outcomes, when certain input parameters are changed.

365. Most process-based models are deterministic (Larocque et al., 2015). There are a wide range of sources of error in deterministic models (Plummer, 2009). The two approaches typically used to evaluate process-based models include the Taylor series technique and the Monte Carlo technique. In many instances, it is possible to calibrate process-based models (e.g. when using SWAT, by comparing the predicted river water flows with observed water flows). The calibration process will provide a proper accuracy assessment (e.g. by estimating standard statistical measures such as Root Mean Square Error or R^2).

366. To validate models based on spatial interpolation, cross-validation is a method to determine the type of spatial interpolation that works best for your data. This works

by removing data points and then predicting the outcome of this variable based on other data points. This process allows for comparison of predicted value versus the actual value. Common approaches for evaluating the error of approaches for spatial interpolation include: Mean Error (ME), Mean Absolute Error (MAE), Mean Squared Error (MSE) and Root Mean Squared Error (RMSE).

367. For statistical models, methods for estimating and validating models are well established. Residual diagnostics are one way to explore the validity of a model. There are several common approaches for evaluating the accuracy of statistical models including data splitting (testing and training methods); k-fold cross validation; leave one out validation; goodness of fit (Plummer, 2009).

368. There are several ways to assess the accuracy of models based on machine learning. Some of these ways of evaluating are common for other model types as well. These include Classification Accuracy - which evaluates the number of correct observations divided by the total observations. Logarithmic Loss measures how well a classification model performs by comparing true values to probabilities in the model. Confusion Matrices, which are also common in evaluating land use classifications, is also a method that can be used to evaluate the results of a machine learning model.

369. As with most models, unless detailed parameterization and validation with measured data has been conducted, outputs of ecosystem services models should be seen as best estimates, rather than absolute values.

7.2.3 Timeliness

Principle 16: Assuring timeliness and punctuality.

Statistical agencies should minimize the delays in making statistics available. Timeliness refers to how quickly - after the reference date or the end of the reference period - the data and statistics are made available to users. Punctuality refers to whether data and statistics are delivered on the promised, advertised or announced dates.

370. There are clear challenges around timely ecosystem accounts, an aspect that may become more pronounced when using national data sources. Here, the use of remote sensing data and modelling approaches provides enormous opportunities to disseminate data with very short time-lags and high-frequency (Ramirez-Reyes et al., 2019). For instance, the satellites in the Sentinel 2 constellation, have a revisit time of

5 days at the equator (see Section 4.4). Furthermore, many of the data sets, such as climate data are already released at regular intervals. Staggering release dates so that the latest data sets can be used in modelling exercise will facilitate timeliness in updating models.

7.2.4 Accessibility

Principle 17: Assuring accessibility and clarity.

Statistical agencies should ensure that the statistics they develop, produce and disseminate can be found and obtained without difficulty, are presented clearly and in such a way that they can be understood, and are available and accessible to all users on an impartial and equal basis in various convenient formats in line with open data standards. Provision should be made for allowing access to microdata for research purposes, in accordance with an established policy that ensures statistical confidentiality.

371. Modelled data produced for SEEA EA have the potential to become standardized statistical data that underpin a wide range of research. Careful consideration of how these data are made available can facilitate their broader usage. The ability to reuse scientific data is an urgent need to increase the efficiency and reproducibility of science. Better data management can enhance the rate of scientific discovery, as previously collected data can be more easily integrated into new studies.

Toward FAIR approaches in SEEA EA

372. Guidelines that can inform more rapid integration of data and models, known as FAIR, have been developed and recommended by a range of stakeholders across science. Four foundational concepts underlie the FAIR principles (Findable, Accessible, Interoperable and Reusable). FAIR approaches for data sharing can accelerate knowledge production and are especially important for primary data sources such as statistical offices, in particular, as modelling grows in its frequency of use and importance. This philosophy expands on data quality frameworks espoused by statistical agencies. In addition to applying to data, FAIR principles may also apply to workflows, tools and algorithms. The FAIR principles acknowledge the increasing importance of computers in enhancing science output, and as such, advocates for an approach that allows both machines and people to recognize data and metadata through standardized approaches (Villa et al., 2014). Machines are growing in their capabilities to automate many of these processes.

Table 27: *Definitions of the FAIR guiding principles are taken directly from Wilkinson et al. (2016)*

Findable
F1. (meta)data are assigned a globally unique and persistent identifier
F2. Data are described with rich metadata (defined by R1 below)
F3. Metadata are clearly expressed and explicitly include the identifier of the data it describes
F4. (meta)data are registered or indexed in a searchable resource
Accessible
A1. (meta)data are retrievable by their identifier using a standardized communications protocol
A1.1. the protocol is open, free, and universally implementable
A1.2. the protocol allows for an authentication and authorization procedure, where necessary
A2. Metadata are accessible, even when the data are no longer available
Interoperable
I1. (meta)data use a formal, accessible, shared, and broadly applicable language for knowledge representation
I2. (meta)data use vocabularies that follow FAIR principles
I3. (meta)data include qualified references to other (meta)data
Reusable
R1. Meta(data) are richly described with a plurality of accurate and relevant attributes
R1.1. (meta)data are released with a clear and accessible data usage license
R1.2. (meta)data are associated with detailed provenance
R1.3. (meta)data meet domain-relevant community standards

7.2.5 Coherence

Principle 18: Assuring coherence and comparability.

Statistical agencies should develop, produce and disseminate statistics that are consistent, meaning it should be possible to combine and make joint use of related data, including data from different sources. Furthermore, statistics should be comparable over time and between areas.

Model choice

373. Modelling approaches have been rapidly improving, and as such, the best data and models available at a given point in time may evolve in the future. This of course also occurs when compiling regular statistics where new data sources become available, but this issue is more pronounced when depending on models. This creates challenges in including data produced from biophysical models into accounts, because best practices may change across years, and common input data, such as land cover, have been rapidly improving in recent years. However, one advantage to modelling is that past ecosystem services can often be hindcasted using the latest modelling techniques, which may either allow for updates in past data sets or for agencies to better evaluate the uncertainty of past modelling approaches by contrasting them to updated approaches. There are several examples in ecosystem service literature where the consequences of different modelling approaches have been explored. For example, in Rwanda contrasting the InVEST and WASSI models using different land cover inputs showed simple models were relatively robust to different land cover data sets, but more complex models were sensitive to these changes resulting in highly different outputs (Bagstad et al., 2018). These results show that model choice may influence findings, and thus, the consequences of model choice should be explored when several modelling approaches may be feasible in a single location.

7.2.6 Metadata

Principle 19: Managing metadata

Statistical agencies should provide information covering: the underlying concepts and definitions of the data collected and statistics produced, the variables and classifications used, the methodology of data collection and processing, and indications of the quality of the *statistical information - in general, sufficient information to enable the user to understand all of the attributes of the statistics, including their limitations.*

Data provenance system

374. As models are built using a range of data sources, a data provenance system improves users' ability to understand the fitness for purpose of data sets (Spiekermann et al., 2019). Data sets are often processed by multiple end users before they are ready for inclusion in environmental models. Data provenance systems provide a critical tool for tracking the history of a data set. For example, ARIES provides a transparent data provenance system for users of its web-based Explorer. Another example is the EBV data portal, which provides standardized metadata across data sets in a catalogue form which are uploaded and updated by data developers.

Repository systems

375. A disadvantage (and advantage) of using modelling platforms is that they are themselves developing and improving, and it may be difficult to replicate the exact conditions that applied when the first results were modelled. When using own-built models, code repository systems like GitHub, Bitbucket, GitLab, facilitate version control. These version control systems allow for multiple people to collaborate and make changes to code. Version control means users can track changes they made themselves, as well as changes made by other users, which allows them to revisit old versions of code if the latest version is not ready for release or if errors are found in the changes. The use of such tools ensures comparability over time remains, that the consequences of changes can be examined, and when made public, it maintains the transparency of model code.

7.3 Conclusion

376. Biophysical modelling comes with a specific set of challenges around data quality. One of the most prominent challenges is that uncertainty is more pervasive than in other data sets that are typically used by National Statistics Offices. This uncertainty results from combining multiple data sources each with their own uncertainty. Furthermore, spatially explicit data is highly heterogenous and in some cases, coverage can be patchy.

377. Because of these large uncertainties, validating models is essential. One of the most basic ways to do this, as a start, is by qualitatively describing all the sources of

uncertainty. Another way is to perform a sensitivity analysis. For many modelling approaches, there are a suite of quantitative approaches for validating models which may be applied.

378. These large uncertainties also mean that the transparency of approaches is essential. This transparency should ensure that not only the models and data sources, but also workflow, conceptual development, and approaches for qualitatively and quantitatively describing uncertainty are properly traced and available for examination. Metadata management as well as tools such as code repositories can facilitate transparency.

379. Adopting a tiered approach may result in model outputs suitable for different purposes, and statistical agencies should evaluate how data quality frameworks can accommodate these different types of results. For example, Tier 1 and Tier 2 approaches may be best for awareness raising or analysis of broad spatiotemporal trends, while Tier 3 accounts may be used for local-scale decision-making.

380. Data quality frameworks developed by statistical agencies currently do not include standards for modelled data. These frameworks should be expanded to encompass the specific quality issues that arise from modelled data. In particular, establishing standards for assessing uncertainty and model accuracy should be a focus of expanding data quality frameworks. Exploring commonalities in accuracy standards used for collected versus modelled data can illuminate a path forward for more comprehensive environmental reporting by statistical agencies.

8 The Future of Biophysical Modelling for SEEA EA

381. The SEEA EA has progressed rapidly with around 30 countries having compiled and published SEEA EA accounts (Hein et al., 2020). Most of these accounts used some form of biophysical modelling, which will play a critical role in the future development of SEEA EA. Nonetheless, some statistical agencies as well as stakeholders may be hesitant to adopt biophysical modelling for official statistics. Below prospects for improving biophysical modelling for SEEA EA are evaluated. We discuss research directions that would improve ecosystem service modelling, and as such, would improve the ability for us to measure and track changes in ecosystem services over time. Finally, we also note important conceptual advances that may improve applicability and uptake of SEEA EA in practice. We focus on biophysical assessments of ecosystem services as they relate to the SEEA EA. Consistent frameworks and terminology and testing of approaches at different scales and locations will not only improve the information available for decision-making, it will also improve standards for ecosystem service research.

Artificial intelligence to expedite ecosystem service mapping and model selection

382. Streamlining model and data selection will alleviate an enormous bottleneck in ecosystem services research, rendering guidelines such as this one obsolete. Working through the process of selecting the best available data, modelling platform and modelling approach is incredibly time consuming. Every organization starting SEEA EA accounts will go through a similar process, often trialling several modelling platforms before finding the right fit for their needs or discovering that there is no readily available model and bespoke models are needed. Furthermore, relevant past data collection and modelling approaches are not stored systematically, and because they were often not designed for SEEA EA, accountants can easily overlook these scattered resources before embarking on new projects. As such, this discovery process is often repeated by people over and over. Tools that streamline this decision-making would be foundational to rapid progress in this field. ARIES (Villa et al., 2014) is based on this philosophy and could grow more rapidly if ecosystem service modelling adopted standard principles for serving data and models on the web using encoding practices that enable their automated linkage.

In situ monitoring and accuracy assessments of ecosystem services maps

383. Ecosystem service maps are difficult to verify, in part because standardized indicators for *in situ* monitoring are oftentimes not established.[94] The SEEA EA approach to providing guidelines for each of these processes can ensure that ecosystem service data are collected up to the standards of statistical agencies and comparable across sites. Widespread look-up table and deterministic approaches to ecosystem service modelling means understanding uncertainty in these models in difficult. Approaches like long-term ecological research stations, that provide plot-level or in situ indicators of pressures on or the state of ecosystems, are needed for ecosystem services research. However, work on measuring ecosystem services on the ground has been limited, and standardized approaches for in situ monitoring of ecosystem services is even less well established than modelling approaches.

Spatial mismatches in ecosystem services are reconciled via multi-scale frameworks

384. Ecosystem service supply and use often occur in spatially distant locations (Koellner et al., 2019). Typologies for this have already been developed outside of the SEEA EA (Schirpke et al., 2019). Distant flows of biophysical processes have already been demonstrated as important for understanding and managing ecosystem services (Ramesh et al., 2019), and thus, could play a key role in SEEA EA. For example, transboundary flow of larvae plays a key role in fisheries production globally (ibid). More regionally, transboundary flows of ecosystem services are important at the Mongolia-China boarder, with Mongolian ecosystems providing high levels of wind prevention and sand fixation (Xie et al., 2019). Transnational flows of ecosystem services among mountain regions extend to regions far beyond the mountains, often globally (Schirpke et al., 2019). While conceptually the SEEA EA is able to accommodate such transboundary ecosystem services flows (e.g. as imports and exports of ecosystem services), their actual measurement needs further development.

Temporal patterns integrated into ecosystem service mapping

385. One of the main strengths of SEEA EA is its explicit focus on temporal dynamics, advocating a minimum of an annual time step. Nonetheless, just as spatial attributes of ecosystem services may require more detailed measurements, a more

[94] IPCC reporting standards are one example of where this has been achieved with carbon, but other ecosystem services lack such standards.

sophisticated understanding of the temporal dynamics of ecosystem services is sorely needed (Rau et al., 2019). These dynamics can be better understood by capturing both finer temporal resolutions, as well as by taking a decadal or longer perspective on ecosystem service production. For some processes, an annual time step may miss important dynamics, especially for water scarcity. Some ecosystem services may recover slowly and non-linearly (Sutherland et al., 2016) and as such, the biophysical supply of ecosystem services may be produced decades and centuries prior to use. Rather than standardizing releases across ecosystem services at a standardized time step, a more flexible approach which advocates for time steps that are relevant for different ecosystem services, taking into account detection accuracy of change and the required accuracy for the purpose of the accounts, may be preferable.

Dynamic representation of ecosystems

386. One aspect of the evolution of biophysical models is the improvement of representation of ecosystems themselves as inherently dynamic. An example in the domain of hydrology is the development of ecohydrological modelling which integrate information about terrestrial ecosystems/plant structure with hydrological information to assess their interdependence (Manoli et al., 2017). Another example of developing a dynamical representation of ecosystems on land and in the oceans are General Ecosystem Models such as the Madingley model (Harfoot et al., 2014; Enquist et al., 2020; Hoeks et al., 2020).

Better connections to the latest technology on data privacy

387. Ethics surrounding privacy are of enormous importance, but data privacy can also limit the integration of biophysical and social data, as sharing across users is difficult. Often studies are limited to using data for specific studies, and data cannot be used by others. This limitation is especially problematic in SEEA EA, as outputs require mapped data. One solution for this problem is sharing encrypted or de-identified data. While this technology is increasingly common in finance and other markets, they are less available within the environmental accounting and research communities. Adopting technologies that allow us to model data without seeing individual information will allow for greater advances in our understanding of ecosystem services.

Clearer reporting of model uncertainty

388. The lack of standardized data quality frameworks for modelled data may limit their uptake in SEEA EA implementation processes by statistical agencies. As such, a focus of SEEA EA efforts should be establishing data quality frameworks for modelled data. These frameworks should highlight the importance of transparency of the chosen approach and process. Another simple way to ensure uncertainty in models is reported qualitatively at the minimum is through uncertainty matrices (Hamel and Bryant, 2017).

Raising awareness of SEEA EA aims and collaborating with developers of multi-service modelling platforms

389. Incongruence in model outputs and SEEA EA highlight potential research directions for modelling platforms, as well as highlight data that might be integrated in an expanded SEEA EA framework. There is scope for making model outputs more useful for economic analysis and "pre-aligning" economic data to more seamlessly work with biophysical model outputs. While ecosystem service models that produce indices of ecosystem services are widespread, quantitative measurements of ecosystem services are less common. Ultimately, developers of multi-service models often share similar goals of statistical agencies to integrate ecosystem services into decision-making. Thus, these collaborations are natural partnerships with many developers already involved in SEEA EA.

Interactions between ecosystem services

390. Understanding where multiple ecosystem services co-occur can facilitate more effective management of multiple objectives. These objectives align with the well-established research interest on ecosystem service hotspots, interactions and bundles (Raudsepp-Hearne et al., 2010). Ecosystem service interactions have been a focus of this area of research since the concept's inception, and SEEA EA accounts have the potential to contribute to our understanding of ecosystem service co-occurrence and interactions through its highly standardized spatial and temporal framework. For example, redlining is an approached developed in China to avoid spatial mismatches in resource use and management (Bai et al., 2016). The redlining approach includes mapping and measuring a combination of ecosystem service hotspots, ecologically fragile locations, and biodiversity hotspots.

Novel uses of remote sensing in ecosystem service assessments

391. The potential of remote sensing to contribute to rapid ecosystem service assessments has not yet been fully realized (Ramirez-Reyes et al., 2019). One of the main benefits to using remote sensing information in ecosystem service assessments is that it delivers highly timely information with often complete coverage across large extents. For example, indices derived from remote sensing that are closely related to ecosystem services, such as Leaf Area Index, could be used to create more accurate ecosystem service maps (ibid).

392. A major barrier to more widespread adoption of remote sensing in ecosystem service models is that people trained in remote sensing are not necessarily the same people developing ecosystem service models. Better training across these fields may facilitate greater adoption of remote sensing in ecosystem service modelling. The move towards ARD (analysis ready data) and – more recently – discussion of accounting ready data are also promising developments.

Integration of terrestrial and marine ecosystem service models

393. Another important area for model development for SEEA EA is ensuring that terrestrial and marine ecosystem service models align. Given terrestrial and nearshore ecosystems are intertwined and interact, integration of these models could provide highly important information for management about how processes in each system affect one another (Fang et al., 2018). Similar themes in watershed ecology are also important, whereby upstream activities often have disproportionate impacts downstream. With terrestrial/marine interactions, these interactions are bidirectional with coastal development affecting nearshore ecosystems, and drivers such as sea-level rise influencing the distribution and extent of coastal ecosystems and the built environment.

A Annex - Global Data sets

A.1 Overview of global data sources

This is a description of available global data sources which may be helpful for building SEEA EA accounts. These data sets are especially relevant in data scarce environments. They have been selected based on the following criteria: data downloadable (not just viewable), freely available, and provide global or near global coverage.

Table 28: *Description of major data sources that can inform biophysical modelling. This table focuses on data sets that can support SEEA EA. One feature that is important for SEEA EA, especially for land cover data is coverage over multiple years.*

Data domain	Data sources	Description	Resolution	Spatial Coverage	Source	Temporal coverage	Website
Land cover	Global Land Cover Share Database	Based on contributions from various institutions by a combination of “best available” high resolution national, regional and/or sub-national land cover databases. Provides 11 major thematic.	30 arc-seconds	Global	Latham et al. (2014)	1998-2012	http://www.fao.org/land-water/land/land-governance/land-resources-planning-toolbox/category/details/en/c/1036355/
	See Section 4.4 for an overview of land cover data sources						
Forest cover	See Table 6 for an overview of Hansen forest cover data						
Soil	S-world	Combines Harmonized World Soil database and ISRIC-WISE 3.1 soil profile database along with auxiliary data summaries at 30-arc second spatial scale, such as temperature, precipitation, and topography.	30-arc second spatial scale	Global	Stoorvogel et al. (2017)	2016-static	https://onlinelibrary.wiley.com/doi/full/10.1002/ldr.2656
	ISRIC	Provides global prediction of soil properties including, organic carbon, bulk density, Cation Exchange Capacity, pH, soil texture fractions and coarse fractions. These predictions are based on	250 m grid	Global	Hengl et al. (2017)	2016-static	https://soilgrids.org/#!/?layer=ORCDRC_M_sl2_250m&vector=1 or

Data domain	Data sources	Description	Resolution	Spatial Coverage	Source	Temporal coverage	Website
		remote sensing-based soil covariates primarily derived from MODIS.					ftp://ftp.soilgrids.org/data/
	Harmonised World Soil Database (HWSD) v1.2	The HWSD used the spatial information provided by the FAO-UNESCO Digital Soil Map of the World (DSMW) and national/regional maps, along with soil profile information to create a global-scale map of soils. The database uses FAO classifications at the soil unit level (FAO-74, FAO-85, FAO-90). Aside from mapping information (classification, ID, etc.), a further range of characteristics are included at the topsoil (0 to 30cm) and the subsoil (30 to 100cm) level.	30 arc-second	Global	FAO (2009)	2009	http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/
	Global Soil Data set for use in Earth System Models (GSDE)	The GSDE is based on the Digital Soil Map of the World similar to the HWSD but uses additional databases to help improve the accuracy of the updated map. Uses mainly the FAO classification, but includes local soil classification. The data set gives information on a suite of soil properties at eight depths up to 2.3 m.	1km and 10km	Global	Shangguan et al. (2014)	2014-static	http://globalchange.bnu.edu.cn/research/soilw
	Global Soil Salinity Map	This data set contains maps for multiple years of soil salinity, with a validation accuracy in the range of 67–70%.	250m	Global	Ivushkin et al. (2019)	1986, 1992, 2000, 2002, 2005, 2009 and 2016	https://data.isric.org/geonetwork/srv/api/records/c59d0162-a258-4210-af80-777d7929c512
Soil water properties	Global High-Resolution Soil-Water Balance	This data set used input variables from the WorldClim and Global-PET gridded data sets to calculate the soil water balance at the monthly and annual scales. Available data include Mean annual AET, Monthly AET, Monthly Soil Water Stress, Priestley-Taylor Alpha coefficient.	30 arc-seconds (1km at equator)	Global	Trabucco and Zomer (2019)	2010	https://cgiarcsi.community/data/global-high-resolution-soil-water-balance/
	HiHydroSoil	Provides information about soil hydraulic properties is important for hydrological modelling and crop yield modelling. HiHydroSoil is a global	250 m	Global	De Boer (2016)	2015	https://www.futurewater.eu/2015/07/soil-hydraulic-properties/.

Data domain	Data sources	Description	Resolution	Spatial Coverage	Source	Temporal coverage	Website
		data set with information about hydraulic properties.					
Digital Elevation Models	Shuttle Radar Topography Mission (SRTM)	Consistently created global digital elevation model. STRM does not cover latitudes north of 60°. EarthEnv has STRM-like DEM to 83°N.	30 m 1 arc-second by 1 arc-second ~30m	~80% of the globe	Farr et al. (2007)	Available since 2002-static	https://www2.jpl.nasa.gov/srtm/dataprod.htm
	ASTER Global Digital Elevation Model	Generated using stereo-pair images collected by the ASTER instrument onboard Terra	90m with a resolution of 30m in the United States	~99% of the globe	NASA/METI/AIST/Japan Spacesystems, and U.S./Japan ASTER Science Team (2001)	released in June 2009-static	https://ssl.jspacesystems.or.jp/ersdac/GDEM/E/
	EarthEnv	Generated by fusing ASTER GDEM2 and CGIAR-CSI v4.1	90m	~91% global coverage	Robinson et al. (2014)	2014-static	https://www.earthenv.org/DEM.html
	MERIT 10m DEM	High accuracy global DEM at 3 arcsecond resolution (~90 m at the equator), which eliminates major error components from existing DEMs (NASA SRTM3 DEM, JAXA AW3D DEM, Viewfinder Panoramas' DEM), several other data sets were also used as supplementary data including - NASA-NSIDC ICESat/GLAS GLA14, U-Maryland Landsat forest cover, NASA Global Forest Height, JAMSTEC/U-Tokyo G3WBM water body.	3" resolution (~90 meters at equator)	Global coverage	Yamazaki et al. (2017)	2017	http://hydro.iis.u-tokyo.ac.jp/~yamadai/MERIT_DEM/
Rivers and watersheds and water	Hydrosheds	Includes a suite of information on river networks, watershed boundaries, drainage directions, and flow accumulations. Hydrosheds are a derivative of STRM data.	~3 arc-seconds (~90 m at equator) best available for some data sets, otherwise, 15 arc-second, and 30 arc-	Near global coverage	Lehner et al. (2008)	Available since 2008-static	https://www.hydrosheds.org/

Data domain	Data sources	Description	Resolution	Spatial Coverage	Source	Temporal coverage	Website
			second resolutions- Derived from SRTM data				
	Hydro 1k	Produced using the USGS's 30-arc second DEM, and includes hydrologically corrected DEM's stream basins.					
	GRACE satellite data	The twin GRACE-FO satellites follow each other in orbit around the Earth, separated by about 137 miles (220 km). From distance measurements between the two satellites, GRACE data can be used to estimate Earth's gravity field. These data are then used to monitor changes in underground water storage, the amount of water in large lakes and rivers, soil moisture, ice sheets and glaciers, and sea level caused by the addition of water to the ocean.	Base products are 1 degree, updated monthly. Approaches to disaggregate to finer spatial resolution exist.	Global	NASA https://grace.jpl.nasa.gov/about/how-to-cite/	Ongoing monthly updates	https://grace.jpl.nasa.gov/data/get-data/
	Aquastat and Aquamaps	The AQUASTAT core database provides the platform for organizing and presenting over 180 variables and indicators on water resources and their use which include water withdrawal, wastewater, pressure on water resources, irrigation and drainage, and a few components on environment and health. They can be searched and extracted, along with their metadata, for 200+ countries and for different regions over an extensive time period (from 1960 to 2017). AquaMaps is complementary to AQUASTAT, FAO's Information System on Water and Agriculture. While AQUASTAT focuses on collecting mainly statistical data and qualitative information on (sub)country level, AquaMaps concentrates on geographical information.	Variable	Global	[95]	Geography and population: Every year water resources: these are long-term average annual values and therefore remain the same over the years. Updates of data for some specific sub-categories are done in collaboration, when data	http://www.fao.org/nr/water/aquamaps/

[95] AQUASTAT Core Database. Food and Agriculture Organization of the United Nations. http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en.

Data domain	Data sources	Description	Resolution	Spatial Coverage	Source	Temporal coverage	Website
						become available.	
	Google's / JRC Global surface water	See Table 6 for an overview of Global surface water data set					
Precipitation	There are 30 globally available precipitation data sets collected at different spatial and temporal scales with some focusing on ground-based measurements and others using satellite observations (Sun et al., 2018). Examples are: TRMM (http://www.ambiotek.com/1kmrainfall/ and https://gpm.nasa.gov/) and CHIRPS (http://chg.geog.ucsb.edu/data/chirps/index.html)						
Climate	WorldClim v1 and v2: global climate data	The "current/observational" layers were created through spatially interpolating climate data from a large database of climate stations, while the future climate change conditions under the Representative Concentration Pathways were created through downscaled GCM data.	30 arc-sections to 10 minutes	Global	Fick and Hijmans (2017); Hijmans et al. (2005)	2005, 2017	https://www.worldclim.org/
	CHELSA	A high-resolution climate data set for land surface areas. It includes temperature and precipitation patterns for various time periods. CHELSA is based on a quasi-mechanistical statistical downscaling global reanalysis and global circulation model output.	30 arc-seconds	Global	Karger et al. (2017)	Multiple time series; V1.2 released 2019	https://chelsa-climate.org
	Global Potential Evapotranspiration (Global-PET) and Global Aridity Index (Global-Aridity)	The Global-PET and Global-Aridity data sets were modelled from the WorldClim data set using the Hargreaves method for PET and the Aridity Index.	30 arc-seconds	Global	Zomer et al. (2008)	V2 released 2019	https://cgiarcsi.community/data/global-aridity-and-pet-database/

Data domain	Data sources	Description	Resolution	Spatial Coverage	Source	Temporal coverage	Website
	GloREDa: Global Rainfall Erosivity Database & R-factor map	This data set used information from a large database of rainfall data and covariates from the WorldClim data set to create a spatially interpolated global map of rainfall erosivity. This map can be used as input to global studies of soil erosion using the Revised Universal Soil Loss Equation (RUSLE).	30 arc-seconds	Global	Panagos et al. (2017)	2017	https://esdac.jrc.ec.europa.eu/content/global-rainfall-erosivity
Biodiversity	IUCN Red List of threatened species	Compiled polygon data for red listed species considered to be from comprehensively assessed taxonomic groups and selected freshwater groups. Freshwater species are mapped to pre-defined river/lake catchment units. Contains spatial data for about two-thirds of the 96,500 species that they have assessed. The maps are developed as part of a comprehensive assessment of global biodiversity in order to highlight taxa threatened with extinction, and thereby promote their conservation.	30 arc-seconds	Global	http://www.iucnredlist.org	2019	https://www.iucnredlist.org/resources/spatial-data-download
	Terrestrial Biodiversity Indicators	Biodiversity indicator values (scores) for grid cells at 1-kilometer resolution, based on several pieces of information including total counts (presence) of mammals, birds, amphibians and reptiles from IUCN and Birdlife International, total counts or presence, of critically endangered and endangered mammals, birds, amphibians and reptiles, the presence of endemic species/ species unique to the region, extinction risks for species over 50, 100 and 500 years, and biome vulnerability, identified from the WWF ecoregions.	1 km	Global	IUCN (2016)	2019	https://datacatalog.worldbank.org/dataset/terrestrial-biodiversity-indicators
	Protected areas	WCMC & IUCN World Database on Protected Areas (WDPA)	Not specified	Global	UNEP-WCMC and IUCN	Updated regularly	https://www.protectedplanet.net/
	Global Biodiversity	GBIF is an international network and data infrastructure funded by the world's governments	Varies with data set	Global		Updated regularly	https://www.gbif.org/occurrence/search;

Data domain	Data sources	Description	Resolution	Spatial Coverage	Source	Temporal coverage	Website
	Information Facility	and aimed at providing anyone, anywhere, open access to data about all types of life on Earth.					
Socio-economic	Global Roads Open Access Data Set (gROADS)	A global compilation of road maps with positional accuracy of 50 m (NASA Socioeconomic Data and Applications Center (SEDAC), 2009).	Not specified	Global	CIESIN and ITOS (2013)	Ranges from 1980s to 2010 on the country (most countries have no confirmed date)	https://sedac.ciesin.columbia.edu/data/set/groads-global-roads-open-access-v1
	GDP	Gap-filled multiannual data sets in gridded form for Gross Domestic Product and Human Development Index. Sub-national data were only used indirectly, scaling the reported national value and thus, remaining representative of the official statistics.	5 arc-min resolution	Global	Kummu et al. (2020)	1990-2015	https://datadryad.org/stash/dataset/doi:10.5061/dryad.dk1j0
Population (Leyk et al. 2019)	Urban TEP	Web-based platform that uses Earth Observations and auxiliary information to assess the urban environment and monitor and predict settlement development. Includes global urban footprint data set.	Varies with product. Highest resolution is 12 m	Global	Leyk et al. (2019)	1985-2015	https://urban-tep.eu/#!
	WorldPop	Global population data are available through WorldPop, which uses a combination of census, survey, satellite and cell phone data to produce gridded outputs (Tatem 2017).	1 km for the globe and 100 m for individual country data	Global	Tatem (2017)	2000-2020 for global data	https://www.worldpop.org/
	High Resolution Settlement Layer (HRSL)	Based on recent census data and high-resolution (0.5m) satellite imagery from DigitalGlobe. Population grids are available for both urban and rural areas	1 arc-sec	140 countries	Facebook Connectivity Lab and CIESIN	2015	https://ciesin.columbia.edu/data/hrsl/#data
Pollution	Socioeconomic Data and Applications Center	Global Annual PM2.5 Grids from MODIS, MISR and SeaWiFS Aerosol Optical Depth (AOD) with GWR, v1 (1998 – 2016).	0.01 degrees	70 degrees north to 55	Van Donkelaar et al. (2018)	1998-2016	https://sedac.ciesin.columbia.edu/data/set/sdei-global-annual-gwr-pm2-5-

Data domain	Data sources	Description	Resolution	Spatial Coverage	Source	Temporal coverage	Website
	(sedac)- Air polution			degrees south			modis-misr-seawifs-aod
	World's Air Pollution: Real-time Air Quality Index	Global data on air quality. Only stations with particulate matter (PM2.5/PM10) are published.	Point data from ~12,000 stations	1000 major cities from 100 countries		Real time with variable length of availability	https://aqicn.org/sources
	GEMStat - global water quality database	Provides a global overview of the water quality of ground and surface waters of water bodies and the trends at global, regional and local levels. ~250 variables are available including instream pollution.	Point data from approximately 4000 stations. Million entries for rivers, lakes, reservoirs, wetlands and groundwater systems	75 countries		1965 to 2019	https://gemstat.org/about/
Stream flow calibration	GEMStat - global water quality database	Provides a global overview of the water quality of ground and surface waters of water bodies and the trends at global, regional and local levels. ~250 variables are available including streamflow.	Point data from approximately 4000 stations. Million entries for rivers, lakes, reservoirs, wetlands and groundwater systems	75 countries		1965 to 2019	https://www.bafg.de/GRDC/EN/01_GRDC/13_dtbse/database_node.html
Crops	Global croplands (GFSAD30 project)	Provides cropland products (e.g. croplands with rainfed agriculture) across the world at a 30 m resolution.	30 m	Global	Thenkabail et al. (2012); Teleguntla et al. (2015)	2015	https://croplands.org/home
	Earthstat	A wide range of data on the global food system, including crop and pastureland fraction from 2000, and harvested area and yield for 175 crops.	Resolution varies with data set	Global	Citation varies with data set	variable	http://www.earthstat.org/
	FAOSTAT	Food and agricultural data for 245 countries	Tabular data	Global tabular		1961 to present	http://www.fao.org/faostat/en/#home

Data domain	Data sources	Description	Resolution	Spatial Coverage	Source	Temporal coverage	Website
Other		Global Visible Infrared Imaging Radiometer Suite (VIIRS) Night-Time Lights produced by The Earth Observations Group (EOG).	15 arc second	Global	NASA	2012-YTD, Daily	https://blackmarble.gsfc.nasa.gov/

A.2 Data portals

A.2.1 SERVIR

1. SERVIR is a collaboration between NASA and USAID to increase accessibility and awareness of geospatial data for developing countries (https://www.servirglobal.net/).Their efforts have resulted in more than 70 custom tools and hundreds of data sets, although not all relevant for SEEA EA. SERVIR provides an easily accessible data catalogue which collates spatial data. Data sets available may be useful for countries hoping to build models of ecosystem service supply and use, as well as provides an overview of what types of ecosystem maps may be available. Exploring tools, projects, maps and imagery available through SERVIR is a valuable scoping exercise for organizations undertaking SEEA EA in parts of the world where SERVIR hubs exist.

A.2.2 Copernicus Global Land Service

2. The Copernicus European Earth monitoring is a global land service designed to answer the needs of multiple EU Policy areas, including agriculture and food security, biodiversity, climate change, forest and water resources, land degradation and desertification and rural development.[96]

Property	Information
Resolution	Varies between ≥ 1km, 300m, 100m and 10 m
Developer	European Commission Joint Research Center
Source	Varies, but mainly derived from satellite data
Coverage	Global, regional data sets available
Year updated	Variable
Availability	Free, registration and request required

[96] Data: https://land.copernicus.eu/global/products/

Data set themes

- Vegetation
    - Land cover
    - Fraction of photosynthetically active radiation absorbed by the vegetation
    - Fraction of green vegetation cover
    - Leaf area index
    - Normalised Difference Vegetation Index
    - Vegetation Condition Index
    - Vegetation Productivity Index
    - Dry Matter Productivity
    - Burnt Area
    - Soil Water Index
    - Surface Soil Moisture
- Energy
    - Land surface temperature
    - Top of canopy reflectance
    - Surface albedo
- Water
    - Water bodies
    - Lake surface water temperature
    - Lake water quality
- Cryosphere
    - Lake ice extent
    - Snow cover extent
    - Snow water equivalent

A.2.3 Natural Earth

3. The Natural Earth data sets are public domain map data sets available at large, medium, and small scales. The information is cultural (urban areas, parks, infrastructures), physical (coastlines, rivers, lakes), and in raster format (shaded reliefs).

Property	Information
Resolution	Varies
Developer	Natural Earth
Source	Varies, contributions from volunteers and the North America Cartographic Information Society
Coverage	Global
Year updated	Varies between data sets
Availability	Freely available

Data sets included[97]

- Cultural
    - Administrative boundaries
    - Transport infrastructure
    - Urban areas
    - Parks and protected lands
    - Timezones
- Physical
    - Coastlines
    - Land and island boundaries
    - Coral reefs
    - Rivers and lake centerlines
    - Lakes and reservoirs
    - Ice shelves
    - Glaciated areas
    - Bathymetry
- Raster
    - Shaded reliefs

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[97] The data formats vary between shapefiles and rasters, and can be downloaded here: https://www.naturalearthdata.com/

A.2.4 Socioeconomic Data and Applications Center (SEDAC)

4. SEDAC is a distribution centre for NASA's Earth Observing System Data and Information System (EOSDIS) data, and mainly focuses on human interactions in the environment.

Property	Information
Resolution	Varies
Developer	EOSDIS
Source	NASA'S EOSDIS
Coverage	Global
Year updated	Varies between data sets
Availability	Freely available with registration

Data set themes[98]

5. Not all data sets available are listed below, as the SEDAC has an extensive collection:

- Agriculture: pastures, croplands, nitrogen and phosphorus fertilizer application (1994 to 2001)
- Climate: IPCC climate change impacts, sea level rise impacts on Ramsar Sites, land surface temperature, emissions
- Conservation: world biomes, mangrove forest distribution, amphibian richness (2013) mammal richness (2013), wild areas, human footprint
- Governance: environmental sustainability, environmental performance,
- Hazards: mortality risks, exposure, economic loss risks from different disasters
- Health: hazardous waste, mortality rates, air pollution, food security
- Infrastructure: administrative boundaries and centroids
- Land use: agriculture, anthropogenic biomes, impervious surfaces, land and water area
- Marine and coastal: coastlines, chlorophyll-a
- Population: density, exposure, demographics, urban areas

[98] Data are in different formats of shapefile and raster, and can be downloaded here: https://sedac.ciesin.columbia.edu/

- Poverty: mortality, needs, prevalence
- Remote sensing: remotely sensed data from other data sets
- Sustainability: mentioned in other themes
- Urban: mentioned in other themes
- Water: mentioned in other themes

A.2.5 UNEP Environmental Data Explorer

6. This portal is a source for data sets used by the United Nations Environment Programme and includes themes of freshwater, population, forests, emissions, climate, disasters, health, and GDP.

Property	Information
Resolution	Varies
Developer	UNEP and Global Environment Outlook (GEO) partners
Source	Varies
Coverage	Global to regional
Year updated	Varies
Availability	Freely available, though some are protected

Data set themes[99]

- Climate change: annual precipitation, temperature, emissions
- Disasters and conflicts: cyclone buffers, earthquake intensity zones
- Ecosystem management: human water security, artificial surfaces, biodiversity hotspots, forests (2000 and previous times), land cover, canopy density, forest cover, primary production, irrigated areas, human impacts, protected areas, ecoregions
- Harmful substances and hazardous waste: water quality, arsenic
- Resource efficiency: infrastructures
- General: DEMs, administrative boundaries, watershed boundaries

[99] Data are in different formats of shapefile and raster, and can be downloaded here: http://geodata.grid.unep.ch/index.php

A.2.6 NASA Earth Observations (NEO)

7. This portal is a source of data sets derived from NASA satellite imagery, mainly regarding earth observational data. The data available is suitable for visualization due to processing but provides links to the original data for more rigorous scientific uses.

Property	Information
Resolution	Varies
Developer	NASA
Source	Varies
Coverage	Global
Year updated	Varies
Availability	Freely available

Data set categories[100]

- Atmosphere: aerosols, carbon monoxide, nitrogen dioxide, ozone, rainfall, water vapour
- Energy: albedo, surface temperatures, radiation, temperature anomalies
- Land: land cover classification, primary productivity, snow cover, topography, vegetation index
- Life: chlorophyll, population, leaf area index
- Ocean: sea surface temperature, salinity, bathymetry

A.2.7 GEOBON EBV portal

8. Essential Biodiversity Variables (EBVs) are defined by GEOBON (The Group on Earth Observations Biodiversity Observation Network) as the derived measurements required to study, report, and manage biodiversity change, focusing on status and trend in elements of biodiversity (Pereira et al., 2013; Fernandez et al., in review). EBVs are measured or modelled globally, ideally integrating remote sensing with in-

[100] Data are available as maps and GeoTIFF files here: https://neo.sci.gsfc.nasa.gov/

situ observations. There are currently 6 EBV classes with 21 EBV candidates. In addition, a framework is being developed for the Essential Ecosystem Services Variables (EESVs)[101] (Balvanera et al. in review).

Property	Information
Resolution	Varies
Developer	GEOBON
Source	Varies, mostly scientific or research institutes in GEOBON network
Coverage	Varies, global to local/site depending on data set
Year updated	Varies, from past to scenarios-based future
Availability	Freely available

Data set categories

- Genetic composition: intraspecific genetic diversity (allelic richness, heterozygosity), genetic differentiation, inbreeding, effective population size
- Species populations: species distributions, species abundances
- Species traits: morphology, physiology, phenology, reproduction, movement
- Community composition: taxonomic diversity, phylogenetic diversity, functional traits diversity, multi-trophic interactions diversity, biomass distribution
- Ecosystem structure: ecosystem distribution, ecosystem vertical profile, ecosystem live cover
- Ecosystem functions: primary productivity, disturbance, secondary productivity, ecosystem phenology

9. A beta version of a data portal has been established in 2020 where users can upload and download available EBV data sets with a metadata catalogue: https://portal.geobon.org/

[101] See: https://geobon.org/ebvs/what-are-ebvs/

B Annex - Land cover classifications

CCI LC

***Table 29:** Example classification system of Climate change Initiative (CCI) Land cover v2*

Value	Label
0	No Data
10	Cropland, rainfed
11	Herbaceous cover
12	Tree or shrub cover
20	Cropland, irrigated or post-flooding
30	Mosaic cropland (>50%) or natural vegetation (tree, shrub, herbaceous cover) (<50%)
40	Mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%) or cropland (<50%)
50	Tree cover, broadleaved, evergreen, closed to open (>15%)
60	Tree cover, broadleaved, deciduous, closed to open (>15%)
61	Tree cover, broadleaved, deciduous, closed (>40%)
62	Tree cover, broadleaved, deciduous, open (15 to 40%)
70	Tree cover, needleleaved, evergreen, closed to open (>15%)
71	Tree cover, needleleaved, evergreen, closed (>40%)
72	Tree cover, needleleaved, evergreen, open (15 to 40%)
80	Tree cover, needleleaved, deciduous, closed to open (>15%)
81	Tree cover, needleleaved, deciduous, closed (>40%)
82	Tree cover, needleleaved, deciduous, open (15 to 40%)
90	Tree cover, mixed leaf type (broadleaved and needleleaved)
100	Mosaic tree and shrub (>50%) or herbaceous cover (<50%)
110	Mosaic herbaceous cover (>50%) or tree and shrub (<50%)
120	Shrubland

Value	Label
121	Evergreen shrubland
122	Deciduous shrubland
130	Grassland
140	Lichens and mosses
150	Sparse vegetation (tree, shrub, herbaceous cover) (<15%)
151	Sparse tree (<15%)
152	Sparse shrub (<15%)
153	Sparse herbaceous cover (<15%)
160	Tree cover, flooded, fresh or brackish water
170	Tree cover, flooded, saline water
180	Shrub or herbaceous cover, flooded, fresh/saline/brackish water
190	Urban areas
200	Bare areas
201	Consolidated bare areas
202	Unconsolidated bare areas
210	Water bodies
220	Permanent snow and ice

C Annex - Cartography essentials for SEEA EA

10. SEEA EA is distinct from the SEEA CF in that the output should be spatially explicit. Because maps are some of the main outputs of SEEA EA, standardizing map outputs will improve comparability among different SEEA EA accounts within a country, as well as across countries. Maps are typically created using GIS. While GIS have simplified map making, default options and automation within GIS can mean basic cartographic principles underlying map production are not always understood by novice map makers. An overview of several main elements may ensure the production of SEEA EA maps are standardized. Every map contains several main elements including a coordinate system, geodetic datum, projection, scale and map elements. [102] For SEEA EA, colour will also be a common map element. We explore the importance of each of these elements for SEEA EA.

C.1.1 Datum

11. Establishing the appropriate datum is a key step for SEEA EA. The actual shape of the earth is a geoid, which is a misshapen object that resembles a spheroid. Because of terrain and changes in sea level, the shape of the earth is difficult to mathematically model. Hence, a datum is a shape used to approximate the shape of the earth (Figure 21). A datum describes positions on the Earth's curved surface and provides a reference system for different coordinate systems to be mapped. A wide range of datums are in use today, although there are several common ones. Some datums are better at representing the earth's surface in specific locations, while other provide a better fit to the globe more generally. Knowing which datum is in use is important, because the same position can have different coordinate systems depending on which datum is in use. This difference is known as a datum shift. Similar to selecting a coordinate system, checking datums used by locally reputable geospatial agencies is a first step for this process. World Geodetic System of 1984 (WGS84) is the most commonly used datum.

[102] Kremena Boyanova and Benjamin Burkhard, *3.1. Basics of Cartography*, 2017.

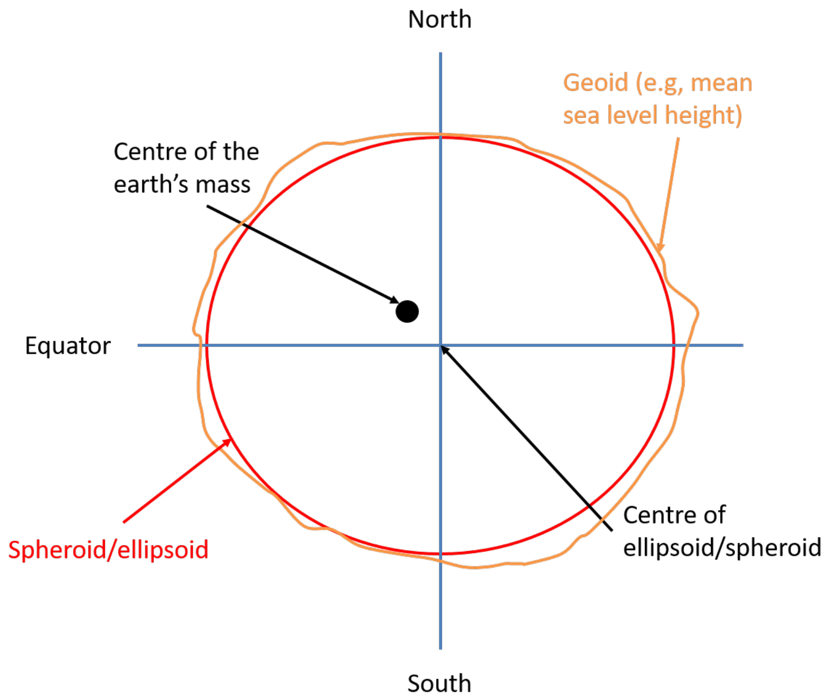

Figure 21: *The hypothetical difference between the true shape of the earth (geoid in orange) and the mathematical model of the shape of the earth (spheroid or ellipsoid in red)*

C.1.2 Establishing a coordinate system

12. Establishing a coordinate system is particularly important for creating template BSUs, which will subsequently be used to aggregate and spatialize ecosystem and ecosystem service data. A coordinate system references the locations of objects in space. There are several types of coordinate systems including projected coordinate systems, geographic coordinate systems and vertical coordinate systems. Both projected coordinate systems and geographic coordinate systems are horizontal coordinate systems, which means they focus on the horizontal locations on the global rather than elevation or height, as with vertical coordinate systems.

13. Geographic coordinate systems are referenced in latitude-longitude and are based on spheroid and angular units. As part of a geographical coordinate system, either a sphere or a spheroid is selected to best approximate the shape of the Earth. Geographical coordinate systems are sometimes called datums, which is incorrect. However, in order to use a geographic coordinate system a datum is needed. Geographic coordinate systems are commonly used in Global Positioning Systems (GPS), and as such, are suitable for mapping field data. Projected coordinate

systems translate latitude-longitude information to a flat surface. As such, they always depend on an underlying geographic coordinate system.

14. A projection transforms spherical information onto a flat surface. Projected coordinate systems are based on linear units, such as meters or kilometres. Projected coordinate systems require a projection to be displayed. Choosing an appropriate projection can be challenging, but the best projection typically minimizes distortion in your area of interest.
15. EPSG stands for European Petroleum Survey Group, which maintains a geodetic parameter database with standard codes, called EPSG codes, for coordinate systems, datums, spheroids, units etc. Every geographic object (coordinate system, spheroid, unit etc.) gets assigned a unique number. The database is under active maintenance.[103]
16. Vertical coordinate systems establish the height and depth of objects. Vertical coordinate systems are particularly useful for ocean accounts, which may be three dimensional.
17. Deciding which coordinate system suits your purposes should be one of the first steps to producing consistent maps. To do this, first identify the area or interest. Your coordinate system will depend on the spatial extent and location of your maps. The next step should include exploring coordinate systems typically used in the area of interest. For novice map makers, usual coordinate systems, such as those used by the government geospatial agency in your nation, will be a good choice.
18. Please note that many GIS systems use the coordinate system of the first map layer added as the default coordinate system. Most GIS systems can automatically detect the coordinate system of a map layer. If two layers are added with different coordinate systems, often the second map layer will be displayed in the first coordinate system in the GIS, however, the underlying data will remain unchanged. However, the coordinate system can be reset to suit the needs of the SEEA EA accounts, provided a consistent system is used for a particular set of national or subnational SEEA EA accounts. Furthermore, transformation between coordinate systems is possible. As such, if coordinators of SEEA accounts wish to change a coordinate system, the coordinate system can be transformed with just a few steps

[103] Based on: https://support.virtual-surveyor.com/en/support/solutions/articles/1000261353-what-is-an-epsg-code-. Online registries can be found at: https://spatialreference.org and https://epsg.org/home.html

in most GIS systems. Transformations always introduce horizontal inaccuracies for the data, so reprojections should always be done with care and not multiple times. If the wrong coordinate system is used for a data set, it can look distorted, and the maps may poorly represent distances on the ground.

C.1.3 Understanding Scale

19. The scale is the ratio between the distance on a map and the true distance on the ground. For example, a map produced at a 1:10000 scale means one m on a map is equivalent to 10,000m on the ground. While small and large scale may have different connotations in different disciplines, for mapping, a large-scale map indicates there is more detail in the map, while a small-scale map typically represents a greater extent. The meaning of large- and small-scale maps is often misinterpreted because the smaller the reference number, the larger the scale of the map. For example, 1:10000 scale map is a large-scale map suitable for local navigation, while a 1:5 million scale map is a small scale map, which could cover the extent of Australia. Selecting an appropriate scale depends on the purpose, size, and detail of the map (Boyanova and Burkhard, 2017).

C.1.4 Understanding Resolution

20. Resolution is the smallest distance between adjacent positions that can be recorded. Scale and resolution are the same in paper maps, because the size cannot be changed. However, in digital maps which allow the user to navigate the map by zooming in and out to gridded data sets, such as with SEEA EA's BSUs, scale and resolution are not static. Appropriate resolution for SEEA EA maps will depend on input data and modelling outputs. Some data sets, like climate data or others interpolated from few data points, may naturally have coarser resolution while those detected directly using high-resolution instruments (i.e. drone-based LIDAR) can have much finer resolution (i.e., < 1m).

C.1.5 Implication of colour usage in maps

21. Colour is one of the main ways to display geographical data. If not used properly, colour can obscure data or mislead the map reader. SEEA EA has predefined areas (BSUs,

EAA, etc.). Filling in these areas with different colours based on underlying statistical data is known as a choropleth map. Choropleth maps will be the most common approach to colour usage in maps for SEEA EA. Choropleth maps are typically shaded based on the underlying data, visualizing variation in measurements of the data.

22. There are three main types of colour schemes that may be used in SEEA EA maps: Qualitative, sequential, and diverging. For SEEA EA, colour will be a common way to emphasize locations with high or low levels of ecosystem services. Sequential or diverging colour schemes would likely be the best choices in this case. Diverging colour schemes are useful where data have a centre, such as a 0 value with both negative and positive values. Colour may also be used to emphasize different categories (non-numeric data). Here, qualitative colour schemes would likely be the best choice. For sequential or diverging data sets, understanding how your GIS system is placing different colours into different "bins" is essential. Default options may not be ideal.

23. Because colour-blindness is common among the general population, colour-blind-friendly palettes are recommended for greater accessibility. There are several online tools to help select colour blind friendly palletes, including ColorBrewer[104] and Chroma.Js.[105]

24. A useful reference on the use of color and graphic design in disseminating ecosystem services is Weil (2017). Recent articles have also experimented with accounting tables in colour that align with the underlying maps (e.g. Warnell et al 2020; Bagstad et al., 2019; Heris et al., 2019), to aid in the interpretation of SEEA accounting tables.

[104] See: https://colorbrewer2.org/

[105] See: https://gka.github.io/palettes/#/9|s|00429d,96ffea,ffffe0|ffffe0,ff005e,93003a|1|1

D Annex - Detailed descriptions of modelling approaches

D.1 Look-up Tables

25. The simplest of the spatial modelling tools available in general GIS packages for the modelling of ecosystem services is called the "Look-up Tables" approach. In the look-up tables approach, specific values for an ecosystem service or other variable are attributed to every pixel in a certain class, usually a land cover, land use or ecosystem type class. These values need to be derived from the (scientific or "grey") literature, for ecosystems that are comparable in ES provision or characteristics underpinning ES delivery, such as vegetation, soil, climate, etc. For instance, every pixel in the land cover class "deciduous forest" could be given a specific value for its carbon stock, say 250 tons C/ha, based on studies that analysed the carbon contents of this forest type in a specific agro-ecological zone. The accuracy of this model depends on the number of land cover, land use or ecosystem extent classes (i.e. thematic resolution), the grid size and the accuracy and representativeness of the data within each class. Clearly, it may be that there is substantial variation within classes, for instance the moist evergreen forest could include intact as well as strongly degraded forest patches with very different carbon stocks. The approach does not allow the analysis of spatial uncertainties involved with the model, however, sensitivity analyses are one approach for estimating these spatial uncertainties. Look-up tables are also not able to track changes over time that may occur within ecosystem type classes. For instance, in the case of carbon stocks, forest degradation may lead to a gradual reduction of these stocks in some parts of the forest, but this would not be shown by a model unless it distinguished between degrees of forest degradation in both input data and the look-up table.

26. There are four types of look-up tables (LUT) that may be useful for ecosystem service modelling (Schröter et al., 2015). Binary LUT assess ES with the presence or absence based on land use/land cover. Qualitative LUT weigh different land use/land cover classes according to their capacity to provide ES (e.g., from 0 to 5). A similar approach, called the matrix approach, has been popular in European ecosystem service mapping (Urkhard and Maes, 2017). Aggregated statistics LUT assign values of ES based on statistics or research findings to land use/land cover data or

administrative units. Finally, multiple layer LUT assign ES values to land units based on cross tabulations that are created by the overlay of different layers (e.g. land cover, soils, and climate). The applicability of these approaches depends upon data availability and mapping requirements. In general, the most commonly used LUT in ecosystem accounting is the third approach, “aggregated statistics LUT”, which assigns specific values for an ecosystem condition or more typically flow of ecosystem services based to each type of ecosystem based on the literature.

D.2 Spatial *inter- and extrapolation*

27. Spatial interpolation and extrapolation techniques can be used to produce spatially continuous data generated from point data. These methods assume that things that are close to one another are more alike than those that are farther apart. In principle, there are two main groupings of interpolation techniques: deterministic and geostatistical. *Deterministic interpolation* techniques create surfaces from measured points. A deterministic interpolation can either force the resulting surface to pass through the data values or not. An interpolation technique that predicts a value that is identical to the measured value at a sampled location is labelled an “exact interpolator”. An inexact interpolator predicts a value that can be different from the measured value; this can be used to avoid sharp peaks or troughs in the output surface. The most basic exact interpolator is called the Inverse distance weighted (IDW) interpolation. To predict a value for any unmeasured location, IDW uses the measured values surrounding the prediction location. The measured values closest to the prediction location have more influence on the predicted value than those farther away. IDW assumes that each measured point has a local influence that diminishes with distance. It gives greater weights to points closest to the prediction location, and the weights diminish as a function of distance, hence the name IDW. However, several other exact techniques have been developed such as radial basis functions which involve different assumptions on the relation between distance and values that can be attributed to points in a landscape. Exact interpolators can be used when it can be assumed that things that are close to one another are alike. This may often not be the case with ecosystem extent, condition or services supply, in particular in case of heterogeneous landscapes (e.g. because of small landscape elements, or diverse topography). In addition, since deterministic models do not

provide prediction standard errors, it is difficult to analyse the uncertainty of the model.

D.3 Geostatistical interpolation

28. These techniques rely on statistical algorithms to predict the value of un-sampled pixels based on values of nearby pixels in combination with other pixel characteristics. The most widely used form of geostatistics is kriging, and its different variations. These include ordinary, simple, universal, probability, indicator, and disjunctive kriging, and are available in commonly used software. Kriging is divided into two distinct tasks: quantifying the spatial structure of the data and producing a prediction. Quantifying the structure involves fitting a spatial-dependence model to the data. To make a prediction for an unknown value for a specific location, kriging will use the fitted model from variography, the spatial data configuration, and the values of the measured sample points around the prediction location. Because geostatistics is based on statistics, these techniques also produce error or uncertainty surfaces, giving an indication of how good the predictions are – at least in terms of the spatial errors (note that the values themselves may also be prone to uncertainty). Kriging can be expected to yield better results when there are several data sets that help explain spatial variation in the condition or service indicator to be mapped. For instance, timber productivity may be related to productivity in nearby pixels, with consideration of the land cover (forest cover) as well as potentially other indicators such as soil fertility. Kriging and related techniques normally require the combination of a range of data sets including thematic maps, surveys for specific administrative or ecological units, and point data from specific studies.

D.4 Statistical approaches

29. Statistical approaches to map ecosystem services, capacity and condition seek to quantify statistical relationships among environmental variables and ecosystem services. Here, we focus on approaches that involve a more limited analysis of spatial relationships in the landscape (compared to the previous group of methods). In the case of purely statistical approaches, values of pixels are assigned based on a set of underlying variables. The relation between the value (e.g. for an ecosystem

condition or ecosystem service indicator) and the independent variables (e.g. soil type, distance to road, etc.) is developed with a regression analysis. Statistical approaches are increasingly used also to map the suitability of ecosystems for other services, such as recreation (Sherrouse et al., 2011). A well-known example of such a tool is Maximum Entropy modelling (Phillips et al., 2006). Maxent has traditionally been used to map habitat for different species. The model predicts the potential of a species or ecosystem attribute/service occurrence by "finding the distribution of maximum entropy (i.e. closest to uniform) subject to the constraint that the expected value of each environmental variable under this estimated distribution matches its empirical average" (ibid). In other words, Maxent analyses the likelihood of occurrence of a species (or ecosystem service) as a function of predictor variables such as habitat type, distance to road or village, etc., based on an analysis of the occurrence of that species in those data points where the species occurrence has been recorded. Maxent requires only presence points, and the accuracy levels can also be calculated (using the area under receiver operating characteristic (ROC) curve (AUC), whose value ranges from 0 to 1; an AUC of 1 indicates a perfect accuracy). In ecosystem accounting, it can be used to analyse habitats (for the biodiversity account) and to analyse the attractiveness of an area for tourism and recreation (note, this does not result in the flow of the service but in a measure of the potential of the ecosystems in a landscape to provide such a service).

D.5 Process based modelling

30. Process based modelling involves predicting ecosystem services supply or other variables based on a set of environmental properties, management variables and/or other spatial data sources. The methods can be used to model provisioning, regulating and selected cultural services. For provisioning services, however, a key input that is required is the land use/management, since this kind of services always represents a physical flow of goods from the ecosystem to society, and this flow is determined both by the capacity of the ecosystem to sustain the flow and by the actual management and extraction patterns. A challenge to process based models is that management variables may not be known with sufficient (spatial) resolution and accuracy. For instance, in a case study in Kalimantan, wood production was not reliably modelled with process-based models since the spatial pattern of extraction

was not available (there were only estimates for administrative units as well as relatively few point estimates of extraction rates) (Sumarga and Hein, 2016). Crop forecast models, on the other hand, have a long history of using process-based approaches, as a function of environmental properties (e.g. soils), weather patterns, and management (e.g. cropping system). The potential applicability of process-based models to analyse provisioning services needs to be assessed based on local ecosystem services, ecosystem management and data availability.

31. Process based models are also valuable for modelling regulating services. For instance, soil erosion and erosion control are often modelled with the USLE approach (despite USLE's variable reliability beyond the US, where it was developed). Compared to provisioning services, process-based models are more easily applied to regulating services since regulating services are less dependent on human management directly (of course, the ecosystem generating the service is often dependent on management, but this management is revealed through the ecosystem condition itself).

32. Process-based models are typically used for modelling hydrological services. The provision of hydrological services is usually analysed according to three dimensions: (i) quantity (i.e. total water yield), (ii) timing (i.e. seasonal distribution of the flow including peak and low season flows) and (iii) quality (i.e. removal and breakdown of pollutants and trapping of sediments). Process based models for modelling hydrological processes or services include a wide range of models such as for example AGNPS, AnnAGNPS, ANSWERS, CASC2D, DWSM, HEC-HMS, HSPF, KINEROS, MIKE SHE, PRMS, SWAT and SWIM. Borah and Bera (2004) and performed detailed analysis with three among the most widely applied of these: SWAT, HSPF and DWSM (Borah and M Bera, 2004). They found SWAT and HSPF suitable for predicting yearly flow volumes, sediment and nutrient loads. Monthly predictions were generally good, except for months having extreme storm events and hydrologic conditions. Daily simulations of extreme flow events were less good. DWSM reasonably predicted distributed flow hydrographs, and concentration or discharge graphs of sediment, nutrient, and pesticides at small time intervals resulting from rainfall events.

D.6 Dynamic systems modelling

33. Dynamic systems modelling is a specific type of process modelling, but it is most often applied for simulations in time, for instance in order to forecast how an ecosystem has evolved as a function of environmental variables and management, and how it may develop in the future. Dynamic systems modelling uses sets of differential equations to describe responses of a dynamical system to all possible inputs and initial conditions. The equations include a set of state (level) and flow (rate) variables in order to capture the state of the ecosystem, including relevant inputs, throughputs and outputs, over time. These equations can describe, for example, how the ecosystem, and for instance its capacity to supply services, changes over time as a function of pressure variables and management. For example, a lake may be subject to increasing pollution loads, or overfishing, and dynamic systems models can be used to predict if and when a change in the supply of ecosystem services (such as supplying fish) may occur (e.g. Hein, 2010). Dynamic systems modelling can be combined with spatial models – e.g. generic differential equations may be used (in a GIS) across a specific ecosystem type in a landscape, but each pixel in the landscape may evolve differently because of different initial conditions, or different management regimes. The systems approach can contain non-linear dynamic processes, feedback mechanisms and control strategies, and can therefore deal with complex ecosystem dynamics, such as thresholds in ecosystem responses or hysteresis (ibid).

34. Complex ecosystem dynamics include irreversible and/or non-linear changes in the ecosystem as a response to ecological or human drivers. These complex dynamics occur in a wide range of ecosystems and have a major impact on the future flows of ecosystem services. For example, irreversible changes in ecosystems occur when the ecosystem is not, by itself, able to recover to its original state following a certain disturbance. Multiple states are relatively stable configurations of the ecosystem, caused by the existence of feedback mechanisms that reinforce the system to be in a particular state. In addition, the ecosystem may also develop as a consequence of stochastic natural conditions, for instance when ecosystem change is driven by fires or high rainfall events. However, it is often a challenge to understand these complex dynamics, and their spatial variability, and data shortages may be a concern in the context of ecosystem accounting that requires large scale analysis of ecosystem

dynamics and forecasted flows of ecosystem services, as such, applying a dynamic systems model for SEEA EA is highly ambitious.

35. In SEEA EA, temporal modelling – for which dynamic systems modelling (as well as other types of models) can be used - is required to forecast the capacity of the ecosystem to generate ecosystem services over time. In particular, the ecosystem asset depends upon the capacity to generate ecosystem services over time. This capacity is a function of the standing stock (e.g. of a timber stand), the regrowth due to natural processes (e.g. growth in timber volume due to regrowth of the forest following harvesting), losses due to natural processes (e.g. storm damage) and ecosystem management (e.g. fire control, pruning, etc.). A dynamic systems model may contain, for instance, the amount of standing biomass (state), the harvest of wood (flow), and the price of wood (time dependent variable). If the asset is valued in monetary terms, the asset value reflects the Net Present Value (NPV) of the expected flow of ecosystem services (e.g. the discounted net value of the flow of timber during the discounting period). Hence, the flow of timber (and other ecosystem services) needs to be modelled, for every accounting unit.

D.7 Models based on machine learning

36. Models based on machine learning may be used for a large variety of purposes including complex modelling exercises such as modelling hydrological services or the classification of remote sensing images for specific (e.g. condition) indicators. Well-known examples of machine learning algorithms are random forests and convolutional neural networks (CNNs), though a wide range of other machine learning algorithms exist and have been applied to scientific modelling. Random forests mines large data sets looking for patterns, for instance to regress a dependent variable (e.g. hydrological service performance or carbon sequestration or stock) against many independent variables in order to produce the regression equation that has the highest explanatory power. Spatial patterns can be included in the analysis, for instance the coordinates of each pixel or distance to a riverbed may be included in the data set of independent variables. CNN can also be used to analyse large data sets and, in addition, is also able to analyse spatial patterns in the landscape, e.g., having a classification influenced by the regularity of the ecosystem

type class (e.g. a plantation may typically have a hard, linear boundary, which is likely to be picked up by CNN if there is sufficient data).

37. Machine learning performs well when there is a lot of data on which to base the algorithms– but compared to process models is much less sensitive to missing data or data sets. It is also relatively efficient and very versatile (i.e., can be used for a large set of condition and services indicators). It can use open access data sets on the internet, e.g. photos via social media. Specifications for modelling requirements for machine learning for ecosystem accounting include large but not complete data sets, diverse patterns, and the need for rapid processing without detailed disciplinary knowledge of say hydrological processes. Clearly, much further work is needed to test machine learning for ecosystem accounting, and so far, there are very few published studies doing so. However initial (unpublished) testing indicates that machine learning algorithms may greatly facilitate ecosystem accounts compilation in the coming years.

38. There may be many places where traditional process-based models may remain more appropriate, because machine learning models have notable downsides. For example, they (intentionally) overfit relationships in search of the highest R^2 values. Furthermore, machine learning models are data driven, and are thus, not based in theory. Finally, their coefficients are difficult to interpret. Combining machine learning models and process-based models (known as process-guided machine learning models) is an innovative way of getting the best of both worlds, and a potentially promising future approach for ecosystem service modelling (Read et al., 2019).

D.8 Agent-based models

39. Agent-based models are bottom-up approaches, where the decisions of individuals are simulated and scaled up to the level of a system (i.e., ecosystem). Agent-based modelling can be effective for measuring collective decision-making based surrounding land or other resource use. Agent-based models are comprised of 1) agents, 2) an environment, and 3) time. Agents are people, organizations, or other entities which make decisions. The environment can be theoretical or actual, but in the case of the SEEA EA, it would likely be the ecosystem accounting area. Agent-based models must run over some timeframe during which agents make decisions.

Agent-based modelling has been instrumental for ecosystem service scenario building and research, but its applications for SEEA EA are less straightforward.

D.9 Participatory modelling

40. Participatory modelling involves engaging with stakeholders to create representations of reality. These methods are particularly relevant for understanding less tangible ecosystem services, such as aesthetics and non-use values. These approaches can also help establish credibility and buy-in from user groups, which is greatly improved through a participatory process (Zulian et al., 2018). Participatory modelling involves co-constructing a model, alongside key stakeholders (Vukomanovic et al., 2019). According to Garcia-Diez et al. (2020) including ecosystem services mapping within land-use planning and policy-making agendas is highly important to ensure the conservation of areas supplying cultural services that are critical for societal wellbeing. Such an approach is especially important for urban environments as the presence of ecosystem services near large cities could play a fundamental role in the well-being of urban inhabitants.

41. Participatory mapping or public participatory GIS (PPGIS) is a similar approach which may be important for producing maps of ecosystem services not visible in satellite imagery or amenable to biophysical modelling (Brown and Lars Brabyn, 2012). Here, people are asked to map locations that are important to them for different reasons. In a SEEA EA context, these data may be useful for establishing the locations of some provisioning services like non-timber forest products as well as for understanding preferences for aesthetics, recreation, and other cultural ecosystem services. Typically, participatory mapping would be combined with other geospatial data sets to provide a better understanding of where ecosystem services occur. SolVES is an ecosystem service assessment tool that uses PPGIS (ibid). Because SEEA EA has not focused on non-use values, and the fact that these models produce index numbers as results and that there are challenges in applying them at the national scale, adopting PPGIS for SEEA EA is not common at this stage.

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10 Glossary

Biophysical modelling: the quantitative estimation of biophysical phenomena or processes that are difficult to fully observe directly.

Modelling platform: tools that consist of multiple models to assess a range of ecosystem services.

Data model (= data layer or model inputs): a given input layer such as precipitation or land cover that is required by a model.

Model outputs: the result of running a model (e.g. a flow estimates produced from a hydrological model.

Selection guidance: meta-tools to guide the selection of models, modelling platforms, or assessment approaches and/or help stakeholders determine the importance of certain ecosystem services or assess trade-offs between services.

Spatial resolution: the smallest object discernible by measurement methods. Higher spatial resolution means more detail can be observed.

Thematic resolution: how much each concept (such as an ecosystem type or ecosystem service) is generalized compared to the underlying diversity in the concept

Temporal resolution: the amount of time between measurements of data in the same location

Look-up table: specific values for an ecosystem service or other variable are attributed to every pixel in a certain class, usually a land cover, land use, or ecosystem type class

Spatial interpolation: creates surfaces from measured points

Geostatistical model: statistical algorithms predict the value of un-sampled pixels based on nearby pixel values in combination with other characteristics of the pixel

Statistical models: values of pixels are assigned based on a set of underlying variables. The relation between the value and the independent variables is developed with a regression analysis.

Process-based model: predicting ecosystem services supply or other variables based on a set of environmental properties, management variables and/or other spatial data sources

Dynamic systems: dynamic systems modelling uses sets of differential equations to describe responses of a dynamical system to all possible inputs and initial conditions. The equations include a set of state (level) and flow (rate) variables in order to capture the state of the ecosystem, including relevant inputs, throughputs and outputs, over time.

Machine learning: a type of artificial intelligence. Machine learning uses training data to build algorithms to make predictions without explicit programming.

Random forests modelling: a random forest classifier creates decision trees based on a set of training data, then subsequent data (e.g. the spectral signature of pixels) are assigned to different categories based on these decision trees. Random forests is a machine learning approach and can be used for both classification and regression tasks

Ecological niche modelling: pairs environmental data such as DEMs and climate data to produce maps of ecosystems. Ecological niche modelling is typically either a statistical or geostatistical approach.

Generalized Dissimilarity Modelling: another approach for modelling ecosystem extent which integrates Earth observations and plant species data sets using Google Earth Engine.