Guidance for the Biophysical Modelling and Analysis of Ecosystem Services in an Ecosystem Accounting Context

V3.1

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1. Summary

This document provides guidance on the biophysical modelling and analysis of ecosystem service flows and assets for the purpose of ecosystem accounting. The document is prepared in the context of the EU Horizon 2020 Mapping and Assessment for Integrated ecosystem Accounting (MAIA) project. The MAIA project aims to support EU member states in the implementation of natural capital accounts, following the methodology of the System of Environmental Economic Accounting - Ecosystem Accounting (SEEA-EA). This document intends to provide a summary and review of approaches, data, tools and results of existing and previous ecosystem accounting work focusing on biophysical modelling. Compared to previous work eliciting how models can be used for ecosystem accounting, this document provides an updated and extended analysis of how models can be applied. The document pays specific attention to ensuring consistency with system of national accounts (SNA) principles, discusses both temporal and spatial modelling approaches, discusses explicitly modelling for the purpose of asset accounting, and includes a chapter (Chapter 4) that describes available data sources for ecosystem modelling in an accounting context. This chapter includes a summary and review of how existing global and national spatial datasets, including remote sensing imagery, such as the Sentinel satellites, can be applied in support of ecosystem accounting.

Biophysical modelling, in the context of this guidance document, is defined as the modelling of biological and/or physical processes in order to understand the biophysical elements of an ecosystem account. The scope of this document is to provide general guidance on the type of biophysical modelling approaches that can be used to analyze ecosystem service flow. This document builds upon the SEEA EEA guidelines, on the basis of experiences gathered with spatial and biophysical modelling of ecosystem services as described in the scientific literature as well as national and global assessments such as the Millennium Ecosystem Assessment (MA, 2005), The Economics of Ecosystems and Biodiversity (TEEB, 2010), EC (2011), UK National Ecosystem Assessment (UK NEA, 2011), the Convention on Biological Diversity (CBD, 2014) and the Intergovernmental Science-Policy Platform of Biodiversity and Ecosystem Services (IPBES) documents..

Ecosystem accounting aims to analyze natural capital in a way that is consistent with the national accounts. There is an increasing national and international interest in ecosystem accounting. A first major step in the development of ecosystem accounting procedures and guidelines was the ‘SEEA Experimental Ecosystem Accounting (EEA) Framework’ (EC/OECD/UN/World Bank, 2013). This document lays out the basic concepts, the relation between ecosystem accounting and environmental economic accounting and national accounting. Detailed Technical Recommendations in support of SEEA EEA were published by UNSD in 2019. Between 2019 and 2021 the SEEA-EA was revised in a consultative process involving statisticians, researchers and other experts and users. In March 2021 the 52nd United Nations Statistical Commission adopted part of the System of Environmental-Economic Accounting—Ecosystem Accounting as a statistical standard.

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2. Ecosystem accounting

2.1 Introduction

The System of Environmental-Economic Accounting (SEEA-EA) is a spatially-based, integrated statistical framework which provides information on the status and trends in ecosystem capital. The SEEA-EA integrates biophysical information about ecosystems, tracks changes in ecosystem extent and condition. Furthermore, it is developed to provide information about a comprehensive set of ecosystem services (including provisioning, regulating and cultural services) in both biophysical and monetary terms—as well as linking ecosystem assets to measures of economic and human activity. Ecosystem accounts developed following the SEEA-EA framework can serve as a satellite to the system of national accounts (SNA) in order to provide information required for decision making on environmental and natural resource related issues. The SNA (UN et al 2009) is an international statistical standard for the compilation of national accounts, providing a comprehensive description of economic activity. The SNA accomplishes this by describing the transactions (e.g. buying a product; or paying a tax) between institutional units such as households or enterprises (Edens and Hein, 2013). SEEA EA complements the SNA by using the same accounting principles as the SNA for physical and monetary measures concerning the environment.

Characteristic for Ecosystem Accounting is that a spatial approach is followed, in recognition of the large spatial diversity of ecosystems and the services that they provide. A spatial approach also facilitates the integration of ecological data and data on ecosystem use in the accounts. As with 'standard' statistical approaches, a sampling strategy will often be required to analyze ecosystem use and management. However, in many cases this has to be combined with (spatial) models to assess ecosystem services supply and use. Contrary to most other economic activities, the spatial component of ecosystems is crucial, scaling up of survey data requires consideration of the soils, climate, vegetation etc. properties of the sampled location; scaling up without consideration of spatial ecological variability will lead to substantial errors. The fact that all biophysical modelling of ecosystem services is based on data from a sample generalized to a whole accounting area indicates the importance of specifying the uncertainty associated with ecosystem service mapping for accounting. The confidence bounds on ecosystem service predictions at the spatial resolution of the model (used to quantify accounts) will determine which of the applications of ecosystem accounts described below are meaningful.

Constructing ecosystem accounts for multiple years allows monitoring the degree of environmental sustainability: a decline in ecosystem capital points to a decreasing capacity of ecosystems to sustain human welfare over time. Ecosystem Accounting aims to explicitly account for changes in the stock of ecosystem capital (ecosystem assets). The stock of ecosystem capital is related to the capacity of the ecosystem to generate ecosystem services at present and in the future. The latter aspect also allows a systematic treatment and accounting for the degradation and rehabilitation of ecosystems: these two aspects are reflected in the capacity of the ecosystem to provide services. In this way, ecosystem accounting provides a comprehensive tool to analyze the sustainability of natural resource use. In addition, ecosystem accounting supports a number of additional policy applications. For instance, ecosystem accounting can support land use planning or zoning by identifying areas critical to the supply of specific ecosystem services. This is based on the spatial approach followed in ecosystem accounting:

ecosystem services flows, and the capacities of ecosystems to generate services, are generally mapped for the specific areas for which an ecosystem account is developed.

2.2 Concepts of ecosystem accounting

In order to start with ecosystem accounting it is crucial to have clear concepts and definitions. Any biophysical modeling exercise starts with a very specific definition of the scope of the model (in terms of spatial area, time boundary, resolution of the model). After setting the scope, the set of ecosystem services to be included in accounts need to be considered), followed by the selection of indicators to measure these ecosystem services. Selection of these indicators requires that the concepts to be measured are well defined. This section presents, in some detail, several key concepts for ecosystem accounting.

Table 1 Concepts of ecosystem accounting.

Concept	Abbrev.	Description
Ecosystem		A dynamic complex of plant, animal and microorganism communities and the abiotic environment, interacting as a functional unit
Ecosystem asset	EA	A contiguous space of a specific ecosystem type (e.g. a forest stand, a coral reef) characterized by a distinct set of biotic and abiotic components and their interactions
Ecosystem accounting area	EAA	Large, mutually exclusive units delineated for the purpose of accounting, e.g. a country, province or watershed. the spatial element underlying the Ecosystem Account
Ecosystem type	ET	Recurrent abstract units of assessment (e.g. deciduous forests) that represent complexes of organisms and their associated physical environment within an area (Keith et al., 2015, based on Tansley, 1935), for which the ecosystem services can be quantified.
Ecosystem extent		The extent of different ecosystem types (e.g. forests, wetlands, agricultural areas, marine areas) within an ecosystem accounting area
Ecosystem condition		The quality of an ecosystem measured in terms of its biotic (e.g. structural, functional and composition) and abiotic characteristics (e.g. chemical and physical).
Ecosystem services		The contributions of ecosystems to benefits used in economic and human activity.
Benefits		The goods and services that are ultimately used and enjoyed by people and society
Ecosystem capacity		The ability of an ecosystem to generate an ecosystem service under current ecosystem condition, management and uses, at the highest yield or use level that does not negatively affect the future supply of the ecosystem services from that ecosystem

2.2.1 Ecosystem Extent

The ecosystem extent account serves as a common starting point for ecosystem accounting. The SEEA-EA ecosystem extent account organizes information on the extent of different ecosystem types (e.g. forests, wetlands, agricultural areas, marine areas) within a spatial area in terms of area. It describes the environment in terms of sets of mutually exclusive (i.e. non-overlapping) ecosystem assets (EA, section 2.2.4). These assets can be classified by different ecosystem types (ET, section 2.2.5) such as forests, wetlands, cropland etc. All assets together populate the Ecosystem Accounting Area (EAA, section 2.2.7), a spatial area like an administrative region (e.g. municipality, country etc.), or a river basin.

2.2.2 Benefits

Benefits from ecosystems can be described as the goods and services that are ultimately used and enjoyed by people and society. The "use" of ecosystems includes both the transformation of materials (e.g. use of timber to build houses or for energy) and the passive receipt of non-material ecosystem services (e.g. amenity from viewing landscapes). In the context of ecosystem accounting, two types of benefits can be distinguished: (i) the products generated by a joint production process involving inputs from the ecosystem (i.e. the ecosystem service) and inputs from economic units (i.e. businesses, households, government), for instance food, water and recreation; and (ii) the benefits that accrue to individuals that are not produced by economic units, e.g. clean air. The first category can be referred to as SNA benefits since the measurement boundary is defined by the production boundary used to measure GDP in the System of National Accounts (SNA). This includes goods produced by households for their own consumption. The second category of benefits can be referred to as non-SNA benefits reflecting that the receipt of these benefits by individuals is not the result of an economic production process defined within the SNA (Edens and Hein, 2013). To generate SNA benefits human interventions are often needed. For instance, fish in the sea need to be captured to generate the benefit harvested fish.

2.2.3 Ecosystem

The Convention on Biological Diversity defines an ecosystem as 'a dynamic complex of plant, animal and microorganism communities and the nonliving environment, interacting as a functional unit'. Generation of ecosystem services depends on the functioning of the ecosystem as a whole, rather than that of specific ecosystem components in isolation. Ecosystem accounting extends to both natural and modified ecosystems. Distinguishing between natural and modified ecosystems is not always easy to make, because there usually is a gradient in terms of intensity of ecosystem management. Ecosystem accounting aims to measure the contribution of ecosystems to economic activity, and this contribution, in a relative sense, decreases with increasing intensity of human management. For instance, in highly intensive systems, many of the inputs (nutrients, water, seedlings, weed control, etc.) are provided by people. Where possible, indicators for ecosystem services need to be found that as much as possible reflect the contribution of the ecosystem, and these indicators may well differ between ecosystems that are defined as 'natural' or 'human managed' in the SNA. In EA ecosystem services are related to the harvest of use of the service at the time the service is actually used (e.g. in the case of timber plantations the service only materializes at the moment in time the timber is harvested), while in the

SNA, the contribution of the ecosystem in human managed systems is measured in terms of an increase in volume (for instance of standing timber).

2.2.4 Ecosystem asset (EA)

An ecosystem asset is defined as a distinct contiguous spatial area covered by a specific ecosystem (e.g. a single deciduous forest). Ecosystem assets can also be blue green structural elements, such as individual trees in the context of urban accounts. Ecosystem assets are the basic building blocks of the SEEA EA accounting framework. They represent the stock of ecosystems. The spatial delineation of an ecosystem asset is required for accounting purposes and should be considered a statistical representation of an ecosystem. Based on similarity in species composition and environmental conditions, ecosystem assets can be aggregated to ecosystem types (e.g. deciduous forests, heath land, perennial crops etcetera).

2.2.5 Ecosystem types (ET)

A specific type of ecosystem or land cover (e.g. deciduous forests) that can have heterogeneous biophysical properties, for which the ecosystem services can be quantified. The SEEA EA provides an agreed reference classification of ecosystem types based on the IUCN Global Ecosystem Typology. However, in the initial development phase countries may also choose to use their classification of ecosystem types, existing land cover classes or based on the MAES or EUNIS typology. Ecosystem types can be used to present the accounts on a detailed level.

2.2.6 Ecosystem accounting area (EAA)

The ecosystem accounting area is the geographic area for which the ecosystem account is compiled. This can for instance be a country (within the country borders), an administrative area within a country (like a department or a municipality), a water catchment area or a nature reserve.

2.2.7 Ecosystem condition

Ecosystem condition is the quality of an ecosystem measured in terms of its biotic and abiotic characteristics. Condition accounts assess the overall quality and characteristics of ecosystems, using a set of key indicators, known as ecosystem condition indicators. Ecosystem condition indicators should contain biotic (e.g. structural, functional and composition), abiotic (e.g. physical and chemical) and landscape characteristics. For example, condition indicators may provide information on nutrient and hydrological cycles in the ecosystem, and species composition and productivity of the ecosystem. Indicators should be measurable, scalable, and sensitive to change (i.e. the key processes and components affected by ecosystem change should be reflected in the indicator set). One condition indicator can be relevant for multiple ecosystem services, and, at the same time, the capacity to supply a specific service will normally depend on multiple condition indicators.

2.2.8 Ecosystem services

Ecosystem services are defined as the contributions of ecosystems to benefits used in economic and human activity (UN, 2021). In the EA framework, ecosystem services serve as the connecting concept between ecosystem assets and the production and consumption activity of businesses, households and governments (UN, 2021). Therefore, the measurement of ecosystem services is central to describing an integrated set of ecosystem accounts. The SEEA accounting for ecosystem services approach builds upon work of various initiatives, among others the Millennium Ecosystem Assessment (MA; MA, 2003), The Economics of Ecosystems and Biodiversity initiative (TEEB; TEEB, 2010), the Mapping Assessment of Ecosystems and their Services framework (MAES; Maes et al., 2013), the Integrated system for Natural Capital Accounting project (INCA; Vallecillo et al., 2019).

Provisioning services. Provisioning services are those ecosystem services representing the contributions to benefits that are extracted or harvested from ecosystems. For all provisioning services, the contribution of the ecosystem needs to be combined with other inputs in order to produce a tangible benefit. For instance, even though forests supply wood, labor and equipment are needed in order to produce timber out of standing wood. Or, landed fish require both the presence of fish in the sea (the ecosystem service) and the activities of people in order to harvest these fish. In the monetary valuation of the ecosystem service, the costs of these activities need to be deducted following the appropriate methods (UN, 2021b). In Ecosystem Accounting, the principle should be that the ecosystem service is the flow/output most directly connected to the ecosystem (e.g. the standing stock of timber that is harvested or the grass that is extracted from the pasture), while recognizing that this flow is, in the case of many ecosystems, the consequence of a combination of natural/ecological processes and man-made inputs (Edens and Hein, 2013). For crop production, the ecosystem service has been defined as the contribution of the ecosystem to crop production in the form of nutrient retention and supply, water retention and supply, and providing a substrate for cultivation (EC et al., 2013). Since these different aspects are difficult to quantify and express in one or a small set of indicators, the current working hypothesis established in discussions that took place in the context of (EC et al., 2013) is that the service crop production can be approximated in physical terms with respect to the amounts of crops produced, and that valuation needs to account for the whole set of human inputs into crop production, following a resource rent approach.

Regulating services. In the SEEA-EA, regulating and maintenance services are those ecosystem services resulting from the ability of ecosystems to regulate biological processes and to influence climate, hydrological and biochemical cycles, and thereby maintain environmental conditions beneficial to individuals and society. The capacity to regulate or maintain environmental conditions becomes a flow if there are people benefiting from this capacity (aligned with the modelling of ecosystem services in for instance within the ARIES[1] modeling framework (Villa et al. 2014)). For instance, in this interpretation, erosion control is a capacity wherever it occurs, and this environmental process becomes an ecosystem service flow if there are people living in the area that experiences a reduction in erosion risk (e.g. who live in the area downslope where mudflows do not, or less occur because of vegetation upslope). Carbon sequestration is a peculiar service, because people always benefit from this service, and for this service capacity equals flow (in line with Schröter et al., 2014).

A particular issue with regulating services (but not exclusively for regulating services) is that there can also be a disservice, i.e. services with a negative value, e.g. involving carbon emissions form a degraded

[1] Artificial Intelligence for Ecosystem Services (https://aries.integratedmodelling.org/aries-for-seea-explorer/)

peatland or from living biomass due to fire, or pest and diseases from ecosystems. In some urban contexts, there are also disservices observed related to cultural services, e.g. with vegetation blocking property views. Services with a negative value are difficult to accommodate in an accounting context. (The direction of the flow from disservices can be exactly the opposite to the flow of the service, as in the case of carbon emissions from drained peatlands. The flux of carbon from drained peat is from the ecosystem to the atmosphere, the sequestration of carbon by forests on mineral soil involves a flux from the atmosphere to the ecosystem. Considering these disservices is important in view of their relative economic importance, their importance for policy making (e.g. REDD+) and the potential occurrence of services and related disservices within the same institutional unit (World Bank, 2014).

Cultural services. Cultural services are the experiential and intangible services related to the perceived or actual qualities of ecosystems whose existence and functioning contributes to a range of cultural benefits. Cultural services range from tourism and recreation to spiritual aspects and biodiversity conservation. Similar to the other ecosystem services, the capacity of the service needs to be defined and determined for each specific service individually. For recreation and tourism, it may relate to the amount of tourists that can potentially be accommodated in a specific area as a function of the level of interest in the type of ecosystem involved, the level of access / remoteness, etc. Similar to the regulating services this capacity becomes a flow if there are people benefiting from this capacity.

2.2.9 Ecosystem capacity

In the SEEA EA, ecosystem capacity is the ability of an ecosystem to generate an ecosystem service under current ecosystem condition, management and uses, at the highest yield or use level that does not negatively affect the future supply of the same or other ecosystem services from that ecosystem. In general terms, the capacity of an ecosystem to provide ecosystem services depends on the area covered by an ecosystem (its extent), and the state of the ecosystem (its condition) (SEEA EEA – 6.140). The capacity of the ecosystem asset to continue to generate ecosystem services into the future will change as a function of changes in the condition and extent of the ecosystem asset and in response to changes in the expected flows of ecosystem services (EC et al., 2013). While ecosystem condition may be assessed without considering measures of ecosystem services, the measurement of ecosystem assets in terms of their capacity to generate ecosystem services must involve assessment of ecosystem condition, for instance soil fertility and rainfall influence regrowth of standing stock of timber following timber harvest.

Capacity may be aligned with the concept of sustainable yield, in the case of a single resource (e.g. a fish stock) (SEEA EEA 2.32). The sustainable yield, in turn, is determined by the opening stock of the resource (e.g. the fish stock), the growth rate of the resource (e.g. the increase in fish stock due to replenishment) and the loss of fish due to natural processes (e.g. climate variability). However, in reality, single resource use in ecosystems is very rare, many ecosystems provide a basket of goods and services. Hence, in general the capacity to generate provisioning services can be defined on the basis of the long-term capacity of the ecosystem to supply services based on current land use, management and climate (EC et al., 2013). A comprehensive approach is required to establish the capacity. For instance, in the case of timber production (an activity), using timber stands naturally grown in the forest ecosystem (the service), the capacity of the forest at a given time to sustain timber harvesting in the future is a function of the standing stock of timber and the regenerative capacity of the forest (i.e. the mean annual increment, which is in turn determined by among others the age of the trees, soil fertility, water availability, temperature, fire incidence, and potentially management of the forest).

The supply of individual services is often related. For instance, timber extraction at a maximum sustainable rate (a rate that would not jeopardize future timber harvest) may lead to negative effects on biodiversity conservation or carbon sequestration. This indicates that the extraction rate used as a benchmark for sustainable extraction varies for different types of services and land use, and needs to be defined based on locally relevant conditions. The basic principle should be to analyze capacities for all ecosystem services individually based on current management practices. An important implication is that the value of an asset as included in the Ecosystem Accounts is by no means necessarily equal to the maximum value that can be generated by an ecosystem. In this way trends in ecosystem service supply, use and value reflect the current institutional regime, rather than an optimal type of management.

2.3 Spatial modelling techniques

2.3.1 Tiered approach for biophysical modelling

Ideally, local data is used to produce wall-to-wall maps of ecosystem services for the overall Ecosystem Accounting Area. In practice, often data is lacking for some areas or for some specific indicators. In those cases, spatial interpolation and/or modelling techniques can be used to produce comprehensive maps. A range of datasets including remote sensing images, thematic maps, surveys for specific administrative or ecological units, and point data from specific studies can be used as input for the spatial models or modelling techniques. These datasets need to be spatially defined, i.e. they need to be attributed to a spatially defined reference location using a relevant coordinate system – either in case of point data or in case a map is used. Common to all modeling or interpolation methods is that they are representations of reality and not reality itself, and therefore have uncertainty associated with them. A key practice for spatial modelling in ecosystem accounting is to quantify and report uncertainty so that SEEA will be reputable and sustainable, fostering trust in policy makers and end users.

To accommodate differences in available data, resources, experience and interest between countries, a tiered approach can be used for biophysical modelling of ecosystem services. This approach consists of three tiers of biophysical modelling advancing in spatial detail, computational complexity and accuracy, where tier 1 comprises of freely available tools for ecosystem service models using globally available datasets, tier 2 comprises of biophysical models that use national datasets and tier 3 comprises of biophysical models that are customized to the local context and that use local data. The tier3 biophysical models produce the most accurate estimate. However, the rough estimates from the tier 1 models can be very useful when starting with ecosystem accounting or for modelling the ecosystem services that have a low (policy) relevance in a country. Nota bene, with high resolution satellite imagery becoming available also at global level the distinction between biophysical modeling tiers in terms of global-national-locally available data sets is being dissolved. Moving forward selection criteria for biophysical ES model is likely to focus more in documentation of spatial and temporal accuracy.

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2.3.2 Biophysical ecosystem services modelling tools

In this section a few well known tools to model ecosystem services are presented. More tools can be found via the MAES methods explorer (via page: http://www.maes-explorer.eu/page/99). There are several ecosystem service modelling tools. Recently, the ARIES for SEEA Explorer application has been launched. This is based on one of the most well-known ecosystem service modelling tools; ARIES (ARtificial Intelligence for Ecosystem Services). ARIES contains a range of predefined modules (deterministic and/or probabilistic) that facilitate the spatial modelling of ecological processes, and flows of services. The ARIES for SEEA Explorer has been developed to provide a user-friendly application that can generate ecosystem accounts for any user specified ecosystem accounting area (such as country, region or watershed) using freely available global remote-sensing derived data and models (tier 1). Currently, the Explorer can generate maps and tables for ecosystem extent, ecosystem condition (currently specifically for forest ecosystem types) and a select set of ecosystem services, both in biophysical and monetary units and new models for ecosystem services are still being developed. To accommodate the use for accounting, the Explorer automatically generates a report using the format of a standard scientific publication, containing the account presented in maps and tables, and comprehensive documentation of the methods, the models and the data used. ARIES is built in k.LAB (see: https://integratedmodelling.org/getting-started/). After registration, the k.LAB control center (a dedicated modelling engine) can be downloaded. There are two options for using ARIES; the k.Explorer (that can connect the modelling engine to the internet) can be used to calculate the ecosystem accounts, or the k.LAB modeler can be used to run ecosystem models on a local computer. Agent-based models are used to simulate ecosystem service flows. The k.LAB modeler can be used to add additional data (tier 2) and modify or add ad hoc models (tier 3) to calculate the ecosystem services where existing process models do not exist or are inadequate for local contexts. An interesting feature of ARIES is that it allows using data to analyse the relationships between variables, learning these relationships, and applying results to data-scarce conditions, which is useful where there is insufficient information on for instance, linkages between ecosystem condition and ecosystem capacity. A major advantage of ARIES is that it is freeware, and courses are regularly given. Furthermore, the models use artificial intelligence (AI) to select the best data available to calculate the accounts, this has the advantage that the results are optimized for the accounting area, but a possible disadvantage of AI selecting the best model and data can be that calculating the same account for the same area in consecutive years may not use the same model and data sources. The documentation clearly documents the methods and data used, so this can be checked.

Another widely-used tool to map and analyse ecosystem service flows is InVEST (Integrated Tool to Value Ecosystem Services and their Trade-offs). It is a freely available suite of on open source software models to model specific ecosystem services. The models can be used independently of mapping software, but mapping software (for instance arcGIS or QGIS) is needed to view the output maps. There are several models in InVEST including proxy-based mapping (tier 1) and basic biophysical production equations (tier 2). Tier 3 models are essentially models that the users can add to the overall InVEST application. Specific, predefined models are available to map such ecosystem services as (i) Carbon Storage and Sequestration: Climate Regulation; (ii) Coastal Blue carbon;; (iii) Coastal Vulnerability: Coastal Erosion Protection; (iv) Marine Fish Aquaculture; (v) Fisheries; (vi) Pollinator Abundance: Crop Pollination; (vii) Habitat Quality: Biodiversity; (vii) Scenic Quality; (viii) Recreation and Tourism; (ix) Urban cooling; (x) Urban Flood Risk Mitigation; and (xi) Water Yield: Reservoir Hydropower Production.

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New models are still being developed. Several of the models is InVEST are relatively simple, mostly (though not exclusively) using the Look Up Table approach (see section 2.3.3).

ESTIMAP contains a suite of models to spatially explicitly map ecosystem services at the European scale; currently 8 modules are operational at the European scale: 1) capacity of ecosystems to remove air pollutants, 2) capacity of land cover to prevent soil erosion, 3) capacity of coastal ecosystems to protect against inundation and erosion from waves, storm or sea level rise, 4) capacity for retention of water in the landscape, 5) capacity of ecosystems to sustain pollination activity, 6) habitat quality for breeding common birds, 7) recreational and cultural services, and 8) bird richness of pest-control providers.

2.3.3 Biophysical modelling of ecosystem services

There are a range of spatial modeling tools available in general GIS packages for the modelling of ecosystem services. The simplest is called the 'Look-up Tables' approach. More sophisticated methods allow for extrapolation of data to missing points, as well as more elaborate statistical or process based modeling of services supply. In the lookup tables approach, specific values for an ecosystem service or other variable are attributed to every pixel in a certain class (by a spatial join between a map and a lookup table, or by reclassifying the values in the map to the values in the lookup table), usually a land cover or land use class. The values in the look-up table need to be derived from the scientific literature, for ecosystems that are comparable in terms of 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 (for example 250 tons C/ha) based on studies that analyzed the carbon contents of this forest type in a specific agro-ecological zone. In general, the more homogeneous the class is, the more accurate a LUT approach will be.

Geostatistical interpolation techniques, such as kriging, rely on statistical algorithms to predict the value of un-sampled pixels on the basis of nearby pixels in combination with other characteristics of the pixel. The basic interpolation methods use simple interpolation algorithms, for instance nearest-neighbor interpolation, but there are more sophisticated geostatistical tools that also considers sets of correlated variables. For instance, timber productivity may be related to productivity in nearby pixels, but in a more comprehensive approach it may also be related to factors such as soil fertility or water availability for which spatial maps are available. Critical in applying geostatistics is that a sufficiently large sample size is available, and that samples are representative of the overall spatial variability found.

In addition, there are several statistical approaches for spatial modelling of ecosystem services, capacity and condition, e.g. distribution models. Distribution models are models that treat the geographic distribution of observable objects of a specific type (e.g. species) as a response to a set of supplied predictors (Guisan, Thuiller and Zimmermann 2017). A wide array of statistical modeling techniques exist, such as GLM, Random Forest, MaxEnt, and deep learning methods such as neural networks. . Maxent (Phillips et al., 2006) stands for Maximum Entropy, and is relatively user friendly in the context of ecosystem accounting. MaxEnt has traditionally been used to map habitat for different species. The model predicts the potential of a species or ecosystem attribute 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" (Philips et al., 2006). 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).

Next to the ARIES for SEEA explorer the Artificial Intelligence for Ecosystem services project also used an agent-based modelling approach to assess ecosystem services termed "Service Path Attribution Networks" (SPANs) (Bagstad et al., 2013). SPANs are used to map ecosystem service flows, highlighting the spatial connections between source, sink, and use locations. It involves three classes of agents: (1) carrier agents, which represent carrier quanta created at all source locations that move through the network following service-specific movement rules (in case of provisioning benefits this can be pollinators or in case of a preventive benefit this can be floodwater), (2) sink agents, which can reduce the quantity held by carrier agents upon encounter (in case of provisioning benefit this has a detrimental effect on the ecosystem service (for instance it attracts pollinators and less pollinators visit the crop field), in case of a preventive benefit it has a positive effect on the service (less floodwater reach the people), and (3) user agents, which benefit from or are harmed by encounters with the carrier. It has been developed for nine ecosystem services: aesthetic viewsheds, open space proximity, surface water supply, riverine flood regulation, sediment regulation, coastal flood regulation, subsistence fisheries, recreation, and carbon sequestration and storage.

Bayesian network (BN) are used to model ecosystem services, by providing a meta-modeling framework within which to link different driver-pressure-state-response models required to calculate the biophysical logic chain of some ecosystem services (Barton et al.2008;2012). BNs also provide an approach to documenting and integrating expert opinion into biophysical ecosystem service models, alongside other types of knowledge, while accounting for uncertainty (Gret-Regamey et al. 2013). Recently spatial BNs have made it possible to generalize site specific models to landscapes and accounting areas (Landuyt et al.,2015). A potential advantage of spatial BNs for generalizing biophysical ES models is that they offer a way to keep track of joint model uncertainty at the basic spatial unit level predicted by the linked biophysical models. Early applications of AIRIES used Bayesian networks to encode biophysical ES models (https://aries.integratedmodelling.org/publications/). The current AIRIES platform for ecosystem accounting using global datasets and tier 1 biophysical ES models does not use BNs. However, BNs may still be useful for tier 3 applications adapted to local accounting areas, and where accounting for uncertainty is considered important for the accounting application to policy.

Furthermore, based on equations of ecosystem service models in the scientific literature, ecosystem service models can be programmed in Python, R or Matlab. These programs are able to read-in raster files (python also vector files) and perform similar computations as in GIS (like reclassifying land use data based on a LUT), but can also do more advanced computations like calculating the spatial distribution of pollinators or predators based on their source habitat and their foraging distribution patterns.

2.4 Temporal modelling techniques

In SEEA EEA, temporal modelling is required to forecast the capacity of the ecosystem to generate ecosystem services over time. Hence, they are not a substitute for spatial modelling techniques, but they are complementary. 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.). 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.

The modelling approach most consistent with coming to an understanding of flows of ecosystem services is a dynamic systems approach. This approach is based upon the modelling of 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. Dynamic systems models use a set of equations linking ecosystem state, management and flows of services. A dynamic systems model contains state and flow indicators and variables that capture, for instance, the amount of standing biomass (state), the harvest of wood (flow), and the price of wood (time dependent variable). The models runs on the basis of predefined time-increments and requires fully defined initial conditions. The systems approach can contain non-linear dynamic processes, feedback mechanisms and control strategies, and can therefore deal with complex ecosystem dynamics, which are discussed below. 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.

Complex ecosystem dynamics include irreversible and/or non-linear changes in the ecosystem as a response to ecological or human drivers. 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. The needed environmental conditions for the transition from one state into another might also be different depending on the current state. This is known as hysteresis. A well-known example in biology is that the transition from water plants in clear water to turbid water with algae, due to eutrophication, occurs at high N and P levels, but the transition back to clear water with water plants requires much lower N and P levels than the level where the transition to turbid water occurred. 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. These complex dynamics occur in a wide range of ecosystems, and have a major impact on the future flows of ecosystem services. Where possible, pending data and understanding of the ecological processes involved (see for example Seidl et al., 2012; Turner et al., 2021), these aspects should be considered in the Ecosystem Asset Account.

In some cases, spatial and temporal modelling approaches need to be combined. For instance, process based models are generally required to model regulating services such as erosion control, or ground and surface water flows. Erosion, and erosion control is often modelled with the USLE approach (even though its reliability outside of the part of the world was developed (i.e. the US) has proven to be variable). Other examples of process based models are the hydrological models such as SWAT and (CSIRO) SedNet. These models are both temporally and spatially explicit, using a dynamic systems modelling approach integrated in a GIS (for instance using the Python modelling language).

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SWAT is one of the most widely used hydrological models, and uses Hydrological Response Units (HRUs) to model water flows and water stocks, and the processing taking 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 that 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.

Note that a critical aspect of modelling hydrological flows is the resolution of the model, both in space and in time. The required resolution depends upon the study area and the geomorphology of the study area, and the selection of the resolution will also be influenced by the availability of data. In general, to have an ecologically robust modelling of water flows, a spatial resolution of at most 30 meters (corresponding to the global ASTER Digital Elevation Model[2]) is recommendable. A temporal resolution of a day would also be recommendable in order to understand and calibrate water flows over time, including the capacity of ecosystems to store water in support of downstream flood control or dry season water supply. At the level of smaller catchments in the context of urban accounting, hourly temporal resolution may be needed to model landcover contribution to flood risk. Biophysical models for ecosystem accounting must strike a challenging balance between accurate local description and generalization to whole landscapes and annual time units used at aggregate accounting level (municipal, regional, national). Models that use a temporal resolution of months or even years (such as the current InVEST hydrology module) would not generally be adequate to model this service.

3. Modelling for ecosystem accounts

This section presents a general introduction to the different approaches that can be used to biophysically model ecosystem condition, capacity and service flows (the link between ecosystem condition, asset and ecosystem service flow is described in detail in a specific, accompanying report). Note that the ecosystem asset is described in terms of its condition and its capacity to generate ecosystem services. The specific modelling approaches that can be used are a function of the ecosystem, ecosystem services, ecosystem management, data availability, and the environmental and social context involved and always need to be specified based on local conditions.

3.1. Modelling ecosystem extent

Ecosystem extent is the basis for ecosystem accounting. Ecosystem assets (EA, section 2.2.4) are the statistical units for ecosystem accounting. Each ecosystem asset is classified to an ecosystem type.

2 Note that the local accuracy of the global ASTER DEM dataset may vary for different parts of the planet, see also Table 4 of this report.

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The ecosystem accounting area (EAA, section 2.2.7) is the geographical territory for which an ecosystem account is compiled. The EAA therefore determines which ecosystem assets are included in an ecosystem account. The following principles should apply when delineating ecosystem assets: EA should represent ecosystems following the definition of the convention on biological diversity (CBD), it should be possible to map EA to a specific location, the set of EA should be exhaustive, and EA should be mutually exclusive. Ecosystem assets are classified into ecosystem types (ET, section 2.2.5). It is recommended that existing national ecosystem classification schemes be used for ecosystem accounting wherever possible. Generally, such classification schemes involve a large number of ecosystem types and provide detailed descriptions and classes that incorporate specific local ecological knowledge. For the purposes of international reporting and comparison, the SEEA Ecosystem Type reference classification should be applied, reflecting the IUCN GET Ecosystem Functional Groups (EFG). Generally, this level of reporting will have fewer classes than ideal for national level account compilation and hence some aggregation of national classes will be required.

3.2. Modelling ecosystem condition

Ecosystem condition indicators should reflect the main factors influencing the state and functioning of the ecosystem including key ecosystem abiotic and biotic components (water, soil, topography, vegetation, biomass, habitat and species) and reflect processes and provide relevant information with respect to an ecosystem’s composition, structure and function. For example, condition indicators may provide information on nutrient and hydrological cycles in the ecosystem, species composition and productivity of the ecosystem. Indicators should be measurable, scalable, and sensitive to change, i.e. the key processes and components affected by ecosystem change should be reflected in the indicator set. Condition indicators that are comprehensive and comparable and are compiled regularly are of direct policy relevance. It is furthermore useful to include condition indicators that reflect key ecosystem properties that are relevant for the supply of ecosystem services, such as the presence and density of commercial timber species in a forest, or water quality indicators in ecosystems subject to pollution and used for fish production. In addition they may contain other indicators describing ecosystem integrity, intrinsic value, not captured by ES models. It needs to be noted that one condition indicator can be relevant for multiple ecosystem services, and, at the same time, the capacity to supply a specific service will normally depend on multiple condition indicators. Ecosystem condition accounts are designed to complement environmental monitoring systems by integrating data from different monitoring systems, for example concerning biodiversity, water quality and soil properties. However, including indicators that are not measured in other EU monitoring systems enhances the policy relevance.

The SEEA describes a hierarchical typology for organizing data on ecosystem condition characteristics; the ecosystem condition typology (ECT). Condition characteristics can be divided in (A) abiotic ecosystem characteristics, (B) biotic ecosystem characteristics, and (C) landscape level characteristics, like landscape diversity, connectivity or fragmentation. The abiotic ecosystem characteristics (A), can be subdivided in physical state characteristics like soil structure and water availability, and chemical state characteristics like water quality or air pollutant concentration. The biotic ecosystem characteristics (B), can be subdivided in compositional state characteristics like diversity of relevant species groups, structural state characteristics like total biomass or canopy coverage, and functional state characteristics like primary production.

Some studies use condition indicators in combination with reference benchmarks to derive indices of the health of the ecosystem (e.g. Weber, 2007; Weber, 2014). In practical terms, recording ecosystem condition is usually not overly complex, if the required (spatial) datasets are available. Most countries will have information on land cover, and increasingly there are global, regional or national maps of biomass and carbon content that can be used. Chapter 4 lists a number of key datasets that can be downloaded in support of developing Condition accounts in specific countries, with the remark that global datasets (which may have a resolution of, typically, 1 by 1 km) could be a good starting point but may ultimately be bit too coarse for the purpose of ecosystem accounting depending on the spatial variability of the ecosystems in the country (i.e. a coarse resolution may be appropriate to model Canadian forests but not Western European cultural landscapes or urban areas).

Models that are particularly appropriate for modelling ecosystem condition include models that analyze key ecosystem properties or key ecosystem processes. For instance, biomass growth in the ecosystem is usually expressed in terms of Net Primary Production (NPP). NPP indicates the growth of biomass in the ecosystem and is a function of photosynthetic activity and respiration, which, in turn, is influenced by such factors as species composition, temperature, available water, etc. NPP differs between ecosystem as a function of these previous factors, and it may also vary in time, both within the year (NPP may be low during the dry season) and between years (drought). Hence, NPP indicates ecosystem functioning, and is also related to the capacity of the ecosystem to produce biomass (including for example timber for wood production) and carbon sequestration. NPP itself can be measured at a small scale with experiments involving weighing biomass at different points in time, and for large areas it needs to be modelled using remote sensing data. In principle, NPP can be estimated by correlating it to the Normalized Differentiated Vegetation Index (NDVI) that can be derived from remote sensing images. Every ecosystem has a specific correlation between NPP and NDVI which is often available from the literature. In addition, the MODIS website makes NPP estimates based on the MODIS satellite available (for free), see chapter 4, globally, at a resolution of 125 meter.

In addition to vegetation-related condition indicators such as standing biomass, NPP (as described above) and species composition (expressed, for example, the number of species, the biomass of dominant species, or the relative cover of different species), there will generally be condition indicators related to soils. Important indicators are the organic matter content of the topsoil indicating soil fertility, the acidity of the soil, the groundwater level, or the infiltration capacity (expressed through the indicator k_{sat}, that can be measured with field experiments and that indicates how fast water infiltrates the soil as a function of the presence of pores). A starting point for such analysis are the national soil maps, if available, and alternatively the global soil maps that may be available on the internet (for the latter, see Chapter 4). Most soil condition indicators are strongly linked to soil type, and the soil type (and metadata showing soil physical properties) can be derived from such maps. In many cases existing national soil maps have insufficient spatial and classification resolution to be useful for e.g. runoff modeling, in which case a soil sampling programme is needed designed to meet the needs of the ES models.

The Water Framework Directive monitors many aspects of aquatic ecosystem condition. Aggregated indicators like ecological quality, chemical quality and biological quality can give an overall view on the state of aquatic ecosystems. These are composed of several indicators, like N or P concentration or pH, that are of interest in relation to eutrophication and acidification of ecosystems.

3.2.1 Including biodiversity in the ecosystem accounts

In the widely used definition of the Rio Conference, biodiversity includes ecosystem, species and genetic diversity. Biodiversity is both important in terms of supporting the supply of various other ecosystem services, and as a service in itself (Mace et al., 2010). The first aspect is very relevant as part of ecosystem condition: ecosystems with a largely intact biodiversity may be more resilient to change and potentially more productive compared to degraded ecosystems. Hence, it is useful to include some aspects of biodiversity in the condition account (as further discussed below). Second, some aspects of biodiversity are a final service in itself: people may appreciate and value the presence of intact biodiversity, as indicated by the presence of protected areas in most countries of the planet. People may come to these parks for recreation, they may support tourism industry, and there may be other services provided by parks (such as watershed regulation or wood production), but an essential component of most parks is also the protection of rare, threatened and/or endemic species regardless of the use of these species. This latter aspect of biodiversity is what is meant with biodiversity also being a final ecosystem service. This aspect may be very difficult if not impossible to capture in a monetary value, and it may also not feature in the ecosystem services account, given that it does not necessarily involve a flow from the ecosystem to people (it is the presence rather than the use that may be appreciated by people). Hence, biodiversity is one of the four thematic accounts that can be produced next to the core accounts.

There is a wide array of primary data on ecosystems, species and genes that is used to support the measurement and assessment of biodiversity. The focus of biodiversity assessments may be regional, national or global in scale, or may consider individual species or ecosystem types. Work on assessing biodiversity is the focus of a range of global and national measurement initiatives and assessment frameworks including the IUCN Red List of Threatened Species, Red List of Ecosystems, Key Biodiversity Areas; the Intergovernmental Science-policy Platform on Biodiversity and Ecosystem Services (IPBES); the Biodiversity Indicators Partnership; and the Global Biodiversity Information Facility. The GEOBON Essential Biodiversity Variables approach, while not providing assessments or data in itself, provides an organizing framework for observations. Given this rich and long standing body of information, accounting for biodiversity is not intended to replace or duplicate existing initiatives in biodiversity assessment.

3.2.2 Measuring biodiversity as part of condition

It is clear that biodiversity is an important element of ecosystem condition, specifically those elements of biodiversity that are required to sustain the functioning of the overall ecosystem (e.g. keystone species), the resilience of the ecosystem (e.g. diversity within functional groups), or the supply of specific services (e.g. flowers harvested for ornamental use or plants sampled for plant breeding). A specific issue is to what degree biodiversity contributes to ecosystem resilience. Resilience is defined the ability of a system to absorb disturbance without shifting to a qualitatively different structural and functional state (Holling, 1973). The rivet hypothesis states that all species contribute to the maintenance of the functioning of the ecosystem. The functional redundancy hypothesis proposes that a limited number of species (i.e. keystone species) are responsible for the maintenance of the functioning of the ecosystem. An intermediate view suggests that both species diversity and functional diversity are important, but that the diversity of species within each functional guild is the most important factor in maintaining ecosystem resilience. In this sense, biodiversity can be seen as providing insurance capital for securing the functioning of the ecosystem (Barbier et al., 1994).

The degree to which biodiversity indicators relevant for ecosystem functioning and resilience can be included in the account will in practice depend upon both the ecological understanding of the ecosystem (are key functional relationships known and have they been quantified?) as well as the availability of data (on the occurrence and distribution of species key to ecosystem functioning). In reality, it may well be that, in particular in the initial phases of ecosystem accounting, there will be relatively few areas where this information is available with sufficient detail to include them in the accounts. Nevertheless, this aspect is highly important from both a conceptual perspective and, in view of declining biodiversity world-wide, also from a management perspective. Ecosystem accounting will be useful in this context by testing to what degree these aspects can be included in the accounts, and by identifying areas where further scientific efforts or data collection are required.

3.2.3 Measuring biodiversity as part of a biodiversity account

The biodiversity account requires a flexible approach to record information that is relevant for conservation including such aspects as the presence of rare and endemic species, species important for ecosystem quality or functioning, habitat condition, etc. Biodiversity accounting builds upon an extensive literature on biodiversity indicators (Vačkář et al., 2012). Three general approaches to analyze biodiversity have been widely applied, involving indices based on status (such as the IUCN Red List categories), on species surveys (reflecting species richness or abundance), and based on ecosystem type modelling (including indices reflecting the presence of natural and/or relatively undisturbed ecosystems such as the Mean Species Abundance, see Alkemade et al., 2009). It therefore requires access to biodiversity surveys specifying occurrence and/or abundance of species followed by the spatial modelling (e.g. using MaxEnt as described above to get the spatial distribution of the species), or observations (including remote sensing observation) of habitat quality. For the latter indicators such as intactness, fragmentation, or condition relative to natural ecosystems, where such a comparison can be made (i.e. the latter approach is more applicable in the US or Australia compared to Europe).

3.3. Modelling ecosystem service flows

To model provisioning services, the basic data needed is the amount of products gathered or harvested in a specific ecosystem or Land cover ecosystem unit (LCEU) in a specific time unit. If data is available for a specific area, e.g. a municipality, it needs to be decided if it is necessary to also have a spatial representation of the data. If so, the data needs to be downscaled, which involves distributing the annual amount of products to the specific units in which the product is harvested or collected. This becomes a lot easier if there a specific surveys or studies that spatially connect harvests to a specific ecosystem, in this case these points can be used to calibrate the downscaling process using a LUT approach, geostatistical interpolation or MaxEnt as described above. Next to specific surveys, NPP estimates based on the MODIS satellite, can be used to calibrate the downscaling process for provisioning services based on plant biomass like crop production. For all provisioning services, the contribution of the ecosystem needs to be combined with other inputs in order to produce a tangible benefit. Therefore, remaining challenge, is to quantify the contribution of the ecosystem to the service.

For regulating services, data on the flow is often not available, but needs to be modelled. For instance, to model the service air purification, spatial data on particulate matter can be combined with models that estimate the capture of particular matter by vegetation. For some cultural services, data may be available, for instance overnight stays in accommodations close to nature areas, while for others the physical flow may be impossible to assess, for instance the presence of species (as mentioned before regarding the thematic biodiversity account).

Based on the above, some first practical guidance on how ecosystem services can be modelled in an accounting context is provided in table 1 below. However, in reality there are very large differences between ecosystems, ecosystem uses and thereby services provided, socio-economic context and data availability. Therefore the specific models always need to be fine-tuned to the specific context. It is important, in this context, to consider (peer reviewed) papers that have analyzed similar ecosystem services in similar contexts to get guidance on specification equations that can be used to model services. For instance, carbon sequestration can be modelled based on NPP minus Ecosystem respiration, with NPP available from MODIS images (free) at different resolutions. Soil respiration data specific for the ecosystems involved needs to be found in the literature. For provisioning services, there is often statistical data available on the flow of the benefits In the case of timber harvesting, for example, the quantity of timber that is harvested may be available from logging companies. If these data are available for some concessions and not for others, spatial interpolation may be carried out to obtain an indication of timber logged in un-sampled conditions (see Sumarga and Hein, 2014 for an example).

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Service	Potential indicator	Description
Carbon storage	Ton of carbon (or carbon-dioxide) per hectare or square kilometer.	Carbon storage includes storage in vegetation (above ground, root, dead wood, and litter carbon) and soil carbon. Soil carbon may be low compared to vegetation carbon, as in some types of poor fertility tropical forest soils, or it may be by far the largest component of total carbon storage, as in peatland soils in deep peat (World Bank, 2014). Above ground carbon can be measured with radar remote sensing, but the measurement of below-ground carbon with optical techniques is generally not possible. Instead, for this part of the carbon stock, soil sampling and interpolation of data points is required. Carbon maps are increasingly available for different parts of the world (see also Ch. 4).
Carbon sequestration	Ton of carbon (or carbon-dioxide) sequestered per year, per hectare or per square kilometer.	Carbon sequestration can be related to net ecosystem productivity (NEP), i.e. the difference between net primary productivity (NPP) and soil respiration. NPP can be derived from the Normalized Difference Vegetation Index (NDVI) that can be measured with remote sensing images. However care needs to be taken that the relation between NDVI and NPP is well established for the ecosystems involved, and that accuracy levels are calculated based on sample points. It is often difficult to find credible values for the spatially very variable soil respiration rate, which depends on bacterial and fungi activity which are in turn guided by the local availability of organic matter (e.g. fallen leaves), temperature, moisture, etc.
Maintaining rainfall patterns	mm water evapotranspiration per hectare per year, mm rainfall generated per hectare per year.	Rainfall patterns depend on vegetation patterns at large scales. For instance, it has been estimated that maintaining rainfall patterns in the Amazon at current levels requires maintaining at least some 30% of the forest cover in the basin. Reductions in rainfall in the Western Sahel and the Murray Basin in Australia have also been correlated to past losses of forest cover. This is a significant ecosystem service, however the value of individual pixels is difficult to establish since it requires understanding large scale, complex climatological patterns, large scale analyses of potential damage costs, and interpolations of values generated at large scales to individual pixels with detailed climate-biosphere models.
Water regulation	- water storage capacity in the ecosystem in m3 per hectare (or in mm); - difference between rainfall and evapo-transpiration in m3/ha/year	Water regulation includes several different aspects, including (i) flood control; (ii) maintaining dry season flows; and (iii) water quality control – e.g. by trapping sediments and reducing siltation rates). Temporal, i.e. inter-annual and intra-annual, variation is particularly important for this service. Modelling this service is often data-intensive and also analytically complex. SWAT is a model often used to model this kind of flows, however extensions of the SWAT model are needed to link land use to water flows, see also Ch.4.
Surface water modelling; Flood protection	Surface water modelling can be deployed to analyze reductions in flood risk, expressed either as reduction in probability of occurrence, reduction in average duration of the flood, or reduction in water level depending on context	Flood protection depends on linear elements in the landscape that act as a buffer against high water levels (e.g. a mangrove, dune or riparian system). Modelling this service requires modelling flood patterns and the influence of the vegetation. It may not always be needed to model flood protection in physical terms in order to understand the monetary value of the service - in particular in those areas where it is certain that natural systems, if lost, would be replaced by artificial ones (e.g. a dyke), as would be the case in most of the Netherlands, for instance. In this case, valuation may be done on the basis of a replacement cost approach that does not require understanding the physical service in full.

Erosion and sedimentation control	difference between sediment run-off and sediment deposition in ton/ha/year	There is relatively much experience with modelling this service. Erosion models can be integrated in a catchment hydrological models (such as SWAT or CSIRO SedNet, both freeware) to predict sediment rates. In SWAT, a watershed is divided into Hydrological Response Units (HRUs), representing homogeneous land use, management, and soil characteristics. Erosion rates need to be estimated for each HRU, for instance on the basis of the MUSLE or RUSLE erosion models or alternatively SWAT landscape can be used which includes grid based land cover units.
Water purification	Amount of excess nitrogen and or phosphorous removed in the ecosystem	Various hydrological models, including SWAT include modules that allow estimating the nutrient loads in rivers as a function of streamflow, discharge, temperature, etc. Nitrogen is broken down by bacterial activity, phosphorous is typically removed in ecosystems by binding to the soil particles. Modelling these processes in SWAT requires large datasets, preferably with daily time-steps, of nutrient concentrations in various sampling stations along the river course. Simulation in SWAT using predefined modules allows calculating the nutrient concentrations in other parts of the river.

3.4. Modelling ecosystem capacity

A crucial component of the ecosystem asset concept is the capacity of the ecosystem to generate ecosystem services. Capacity can be related to the yield that would, at the current ecosystem condition, not lead to degradation of the ecosystem. This has also been labelled the sustainable yield (e.g. Tietenberg, 2000). For example, in the case of commercial timber harvesting, the capacity would equal the mean annual increment of commercial timber species. The capacity needs to be assessed under current management (in which case actual timber harvest patterns may reduce the capacity of the ecosystem to generate other forest products), with capacity potentially changing over time due to changes in ecosystem condition. For provisioning services, the actual ecosystem use may be lower, equal to, or higher than the capacity (in the latter case the ecosystem can be expected to be subject to degradation). For regulating and cultural services, the capacity reflects the functioning of the ecosystem, and a flow of an ecosystem service (as recorded in the production account) occurs if there are people benefiting from this service (for instance because there are people living in the zone where flood risks are reduced due to ecosystem functioning) (cf. Schröter et al., 2014; Bagstad et al., 2014; Villa et al., 2014).

In order to understand the monetary value of the asset, expressed as Net Present Value (in line with the SEE CF), it is necessary to establish the expected flow of ecosystem services. Modelling the ecosystem asset requires forecasting the flow of ecosystem services in the future as a function of changes in ecosystem condition. This involves the integration of temporal models (as described above) in the GIS. In case harvests are below the sustainable use levels of the ecosystem, and in case there is no other degradation of the ecosystem as expressed through a change in ecosystem condition, the flow of services may be assumed to be constant making it relatively easy to understand future flows and the ecosystem asset. In case of degradation, future flows may be lower than present flows of ecosystem services, and temporal modelling is needed to understand how the flow of the service may decrease.

Note that degradation will generally be reflected in both the Ecosystem condition (e.g. a decline in soil fertility) and Ecosystem Asset (e.g. a decline in capacity to support crop production). As yet, there is

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relatively little experience with modelling ecosystem degradation in an accounting context, no examples have been found in an elaborate literature survey. However, there are examples in the ecological literature of how specific condition indicators can be linked to ecosystem services. For instance, there is ample experience with modelling the effects of soil degradation on crop production, with linking water scarcity to the production of (irrigated) crops and modelling rangeland productivity to rainfall variation and soil degradation (see e.g. Hein 2010).

4. Modelling approaches and examples

4.1 Flowchart for identifying biophysical modelling approaches

The basic steps in biophysical modelling are synthesized in Figure 1 below. Biophysical modelling follows onto the definition of the scope of the accounts, in terms of area included in the account, ecosystem services potentially to be included and condition aspects relevant for the ecosystem involved (e.g. because these condition aspects are subject to change or are related to ecosystem degradation in the area of interest). Subsequently, building upon the explanation provided in Chapter 2 of this guideline,

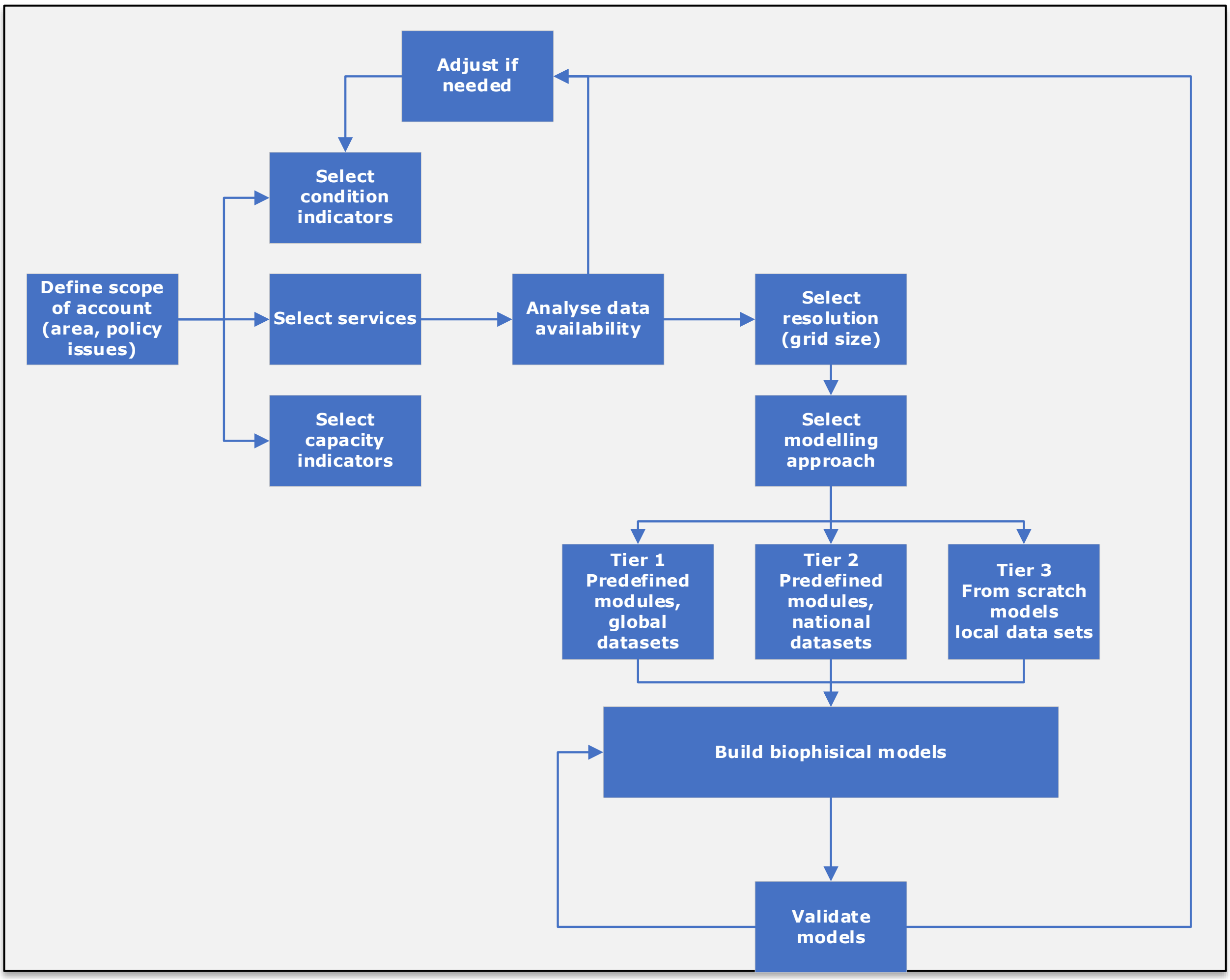

Figure 1. Conceptual flow chart for developing biophysical models in the context of ecosystem accounting.

appropriate indicators have to be selected for the relevant condition aspects, for ecosystem services flows, and for ecosystem assets. This is an iterative process that goes hand in hand with analyzing the availability of data. If national or local data is lacking on a specific service, for instance, it needs to be decided if additional data will be collected (with implications for time and finances required), or if the service will be excluded from the (first version of) the accounts, or alternatively whether a tier 1model will be used as a rough approximation. The availability of data and the indicators selected determine the feasible resolution, which may vary from 2.5 by 2.5 meter (as in CBS and WUR, 2021), to 100 by 100 meter up to potentially even larger areas in case of low data availability and relatively homogeneous ecosystems (e.g. Canadian boreal forests). Next, the modelling approach needs to be selected, either involving (i) the use of predefined modules form Aries or InVEST or potentially other programs (Aries and Invest are the models most compatible with ecosystem accounting, but even their applicability varies per service types, as specified in Section 3.1. above); or (ii) the development of ecosystem accounting models for specific condition, capacity and services in a GIS environment (e.g. ArcGIS or QGIS in case a freeware program is preferred), or a programming language like python or R. Developing models gives more flexibility and may be better aligned with existing expertise in the agency developing the account, but requires more effort for development of the models. Guidance on the development of the models itself is provided in Chapter 3 above. Following construction of the models, validation is required, either by requesting an assessment by expert (expert-judgment) and/or by validating the model with additional datasets. Some spatial modelling techniques (e.g. kriging and species distribution modeling), as explained in Chapter 3, can provide a validation of model outputs with regards to the spatial accuracy of the model. The validation should lead to lessons and insights that can be used to improve the model, either through changing the indicators used, as a basis for collecting more data, or by enhancing the models themselves (e.g. updating the equations used to model specific ecosystem processes).

4.2 Trade-offs, scope versus depth and use of global datasets

This section describes a number of key considerations that may emerge during the development of biophysical models for ecosystem accounting purposes.

Criteria for selecting a modelling approach. There are several criteria for selecting a biophysical model for ecosystem accounting, including accuracy, required resolution, data requirements, and modelling expertise required. Often, accuracy and required resolution are not easy to estimate upfront, however some leads can be given. For instance, for regulating services, a sufficient temporal and spatial resolution is required, preferably time steps of one day (as in SWAT) for a hydrological model and a spatial resolution of 30 to 50 meters in order to analyze topography including altitude differences. In practice, data availability will be a main driver for selecting the modelling approach. If relatively little data are available, or when a service is considered an important ecosystem service at EU level, but has a very low policy relevance in a member state, a module from Aries or InVEST can be selected, because these modules have simplified processes and include for some services some general data that can be used in the absence of location specific data. Furthermore, when more ecosystem services are included, also ecosystem services that are expected to have a marginal contribution, the sum of all ecosystem services, when aggregated in ecosystem accounts, prove substantial and consequential

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policy support. It may be worthwhile to test the ecosystem accounting approach on a sub-national scale (e.g. municipality, a province or watershed) pilot to test various models prior to scaling up. In case a long-term perspective is envisaged, with the flexibility to include ecosystem across a country, and sufficient resources are available, from-scratch model development in GIS or in python or R may be the preferred approach, because this has greater flexibility, doesn't require the transfer of large datasets over the internet (as with ARIES), and because in many countries there are national experts with ArcGIS, QGIS or programming expertise.

In terms of scope versus depth, it is important that there is minimum degree of accuracy in the ecosystem accounts. Given the uncertainties in the biophysical modelling (e.g. with regards to modelling flows of ecosystem services or extrapolating ecosystem condition from sampled points to un-sampled points), it may be a challenge, with current state of ecosystem accounting, to reach an accuracy high enough for policy purposes. Hence, it may be preferable, to start with a relatively small (e.g. 1 to 5) set of ecosystem services where the degree of confidence that it can be modelled high enough relative to rate of ecosystem change and the policy purpose of the accounts. Policy relevance is also an important consideration in selecting an initial set of services for the first phase of the accounts, in order to maintain policy interests and release funding for ecosystem accounting. Potential services for which there is relatively ample modelling experience include most provisioning services, carbon sequestration, water regulation (although this service requires more modelling work compared to carbon sequestration) and erosion/sedimentation control (this service is prone to high degrees of uncertainty and would preferably be included only if data for calibration of erosion and sedimentation rates is available) or crop pollination (similar to water regulation this intermediate service requires more modelling work).

Use of deterministic versus probabilistic models. In statistics for national accounts, there is often a certain reluctance to use probabilistic models given that SNA statistics is about recording historical patterns rather than estimating potential patterns, e.g. of ecosystem use. There are two sides to this choice, when the goal is to align the ecosystem accounts as much as possible with the national accounting approach, a deterministic approach to biophysical modelling is preferred. However, probabilistic models have the advantage that information can be inferred whether found trends are statistically significant, and can provide information on which data should be collected to further improve the models to be a relevant decision support tool.

Criteria for analyzing appropriateness of data. In many cases, the ecosystem accountant will find that the amount of data is low compared to the specific purposes and policy applications of ecosystem accounting, and that data on specific parts of ecosystem condition or ecosystem use is missing, or only partially available. In the beginning of ecosystem accounting, the luxury of choosing between different datasets usually doesn't apply since all data available would be needed to develop the accounts. However, when ecosystem accounting is repeated, it needs to be considered what would improve the accuracy of the ecosystem accounts for policy the most, improving input data or improving the models. Accounting the associated uncertainties could be used to assess what would be the best investment to improve the accounts.

Use of global datasets, and combining local and global datasets. For ecosystem accounting, in particular in the test phase, the general rule would be that the more accurate and the higher the resolution of the data, the better. In a test phase, the accuracy of different resolutions could be compared in order to select the optimal resolution for a country given computing power available, technical expertise available, and the size and level of detail of the datasets. Hence, the choice between using national or global datasets depends upon the accuracy and resolution of the dataset, generally national datasets will be more accurate and with finer resolution than global datasets so their use if preferable, where they are available. However, the temporal resolution of remote sensing data is often greater and the spatial scale is improving. Where national datasets are not available, global datasets may be used as substitute, as described in the next section.

4.3. Global datasets on ecosystem services analysis

There are several databases providing information on ecosystem services and their values, both spatial and non-spatial (Table 3) as well as a number of global tools that provide information on the methods that can be used to map, model or value ecosystem services (presented in Table 4).

4.4. Global datasets on ecosystem components

Table 5 describes some of the key datasets with a global cover that are relevant for ecosystem accounting, subdivided into datasets covering remote sensing data, land cover and vegetation, soils and water. Note that these datasets are usually derived from remote sensing data in combination with other datasets. The table only lists datasets that can be downloaded free of charge, with commercial datasets usually available at higher resolution, but requiring payment for specific geographical areas.

Table 3. Global ecosystem services databases

Dataset	Author	Description	Scale	Link
Pilot Analysis of Global Ecosystems (PAGE): Agro-ecosystems	World Resources Institute (WRI), IFPRI	The study identifies linkages between crop production systems and environmental services such as food, soil resources, water, biodiversity, and carbon cycling	9 geospatial datasets providing a detailed spatial perspective on agroecosystems and agroecosystem services, see Annex 1.	https://www.ifpri.org/publication/pilot-analysis-global-ecosystems
Ecosystem Services Valuation Database	Foundation for Sustainable Development (FSD), Wageningen	Database containing information on valuation studies carried out across the planet (value estimates, authors of studies, general description of methodology used).	Non-spatial.	https://www.esvd.net/

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Table 4. Databases with methods for ecosystem service assessment

Dataset	Author	Description	Link
Values Database	Deutsche Gesellschaft für internationale Zusammenarbeit (GIZ) GmbH; Helmholtz-Zentrum für Umweltforschung (UFZ) GmbH	Database with detailed description of modelling methods and valuation approaches	http://www.aboutvalues.net/method_database/
Ecosystemvaluation.org	University of Maryland	Database with information on and examples of valuation methods	www.ecosystemvaluation.org

Note that the resolution of the Sentinel satellites is finer than the Landsat images, and an additional advantage is that the satellites provide both radar and optical images. Of the 6 Sentinel satellites, Sentinel 1 (Radar) and Sentinel 2 (Optical) are the most relevant for Ecosystem Accounting. Note also that remote sensing data provides information on the observable properties of ecosystems. Some of this information can be linked to ecosystem uses (i.e. ecosystem service flows), such as information on deforestation patens or land use change. Other observable information can be linked to Ecosystem assets (such as standing biomass or Net Primary Production). The specific linkage of remote sensing data to ecosystem service flow or asset modelling always needs to be determined for the specific ecology and uses of the area involved. Using remote sensing images to compile ecosystem accounts is relevant for modeling land cover and ecosystem services such as crop production, carbon sequestration (through fine resolution NPP mapping) and erosion control (e.g. by modelling vegetation cover of the soil). Given that data volumes are large this means that larger data storage and processing facilities will be needed to deal with the information generated.

Many of the datasets mentioned in table 5 and other derived products are also available in google earth engine (see: https://developers.google.com/earth-engine/datasets/)

Table 5. Global datasets

Dataset	Author	Description	Scale	Link
Remote sensing data				
MODIS imagery dataset	NASA Earth Observation System (EOS)	Views the entire surface of the Earth every one to two days, imagery can be downloaded from website.	Its detectors measure 36 spectral bands between 0.405 and 14.385 µm, and it acquires data at three spatial resolutions -- 250m, 500m, and 1,000m.	https://lpdaac.usgs.gov/products

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Landsat dataset	NASA	Multispectral data of the Earth's surface on a global basis, from several operational Landsat satellites (plus historical images form earlier Landsat satellites).	Depending on satellite and band, for Landsat 8 has 11 bands with a resolution of 30 by 30 meter for 8 out of these 11 bands.	http://landsat.gsfc.nasa.gov/
Sentinel	European Space Agency	■Sentinel-1 is a polar-orbiting, all-weather, day-and-night radar imaging mission for land and ocean services. ■Sentinel-2 is a polar-orbiting, multispectral high-resolution imaging mission for land monitoring to provide, for example, imagery of vegetation, soil and water cover, inland waterways and coastal areas. ■Sentinel-3 can be used to monitor ocean and land color and ocean and land surface temperature	■Sentinel-1 Wide-swath mode at 240 km and 5×20 m resolution Wave-mode images of 20×20 km and 20×5 m resolution (at 100 km intervals) Strip map mode at 80 km swath and 5×5 m resolution Extra wide-swath mode of 400 km and 20×40 m resolution ■Sentinel-2 has a 10 m, 20 m, and 60 m spatial resolution (in the VNIR to SWIR spectral range)	https://scihub.copernicus.eu/
Land cover and vegetation				
Global Index of Vegetation-Plot Databases (GIVD)		Metadatabase providing an overview of existing vegetation data worldwide, the metadatabase facilitates the use of these data by other scientists.		www.givd.info
The Global Land Cover Map	EU Joint Research Centre	The map illustrates the distribution of surface materials or "land cover" over the entire globe. This map helps to show the major ecological systems that exist such as forests, grasslands, and cultivated areas.	100 m resolution	https://land.copernicus.eu/global/products/lc
ESA WorldCover	ESA	WorldCover provides a new baseline global land cover product for	10 m resolution	https://esa-worldcover.org/en

		2020 based on Sentinel-1 and 2 data		
MODIS NPP dataset	NASA Earth Observation System (EOS)	Continuous estimates of Gross/Net Primary Production (GPP/NPP) across Earth's entire vegetated land surface. Useful for natural resource and land management, global carbon cycle analysis, ecosystem status assessment, and environmental change monitoring.	500m resolution	http://www.ntsg.umt.edu/project/mod17
Global Forest Change 2000–2012	University of Maryland	Results from time-series analysis of 654,178 Landsat 7 ETM+ images in characterizing global forest extent and change from 2000 through 2012. For additional information about these results, please see the associated journal article (Hansen et al., Science 2013). This dataset is updated yearly and can also be found at google earth engine	1 km resolution (note that the maps sometimes classifies plantations such as palm oil plantations as forests)	http://www.earthenginepartners.appspot.com/science-2013-global-forest/download.html
Global Forest Resources Assessment 2020 (also available for 1990, 2000, 2005, 2010, 2015)	FAO	Comprehensive assessment of forests and forestry examining the current status and recent trends for about 90 variables covering the extent, condition, uses and values of forests and other wooded land,	Not spatial, information is presented in tables per country. The reliability and accuracy of the tables varies per country.	http://www.fao.org/forest-resources-assessment/en/
Soils and terrain				
SoilGrid	ISRIC Wageningen	Dominant soil types according to FAO/ISRIC soil classification	1 km grid, global.	https://www.isric.org/explore/soilgrids
NASA Digital Elevation Map	NASA	DEM and water body coverage and detection	30 meter resolution	https://earthdata.nasa.gov/esds/competitive-programs/measures/nasadem https://developers.google.com/earth-

				engine/datasets/catalog/NASA_NASADEM_HGT_001
Water				
Global Precipitation measurement	NASA, JAXA	Observations of rain and snow worldwide every 30 minutes	Global, from 65° north latitude (e.g., the Arctic Circle) to 65° south latitude.	http://www.nasa.gov/mission_pages/GPM/main/ https://gpm.nasa.gov/

4.5 Example using tier 1 to 3 models for crop pollination

In this section an example of the use of biophysical models for crop pollination in the Netherlands will be given. For this example, the crop pollination model in the ARIES (Tier 1, use of an AI ecosystem services model with data that is available online), the crop pollination model in InVEST with local data (Tier 2, use of a standard model with data supplied by the user) and a crop pollination model adjusted for local use and written in python (Tier 3) are compared.

4.5.1. Tier 1: calculating crop pollination with globally available data in ARIES for SEEA Explorer

The model crop provisioning: pollination contribution is one of the four ecosystem services models that is currently available in the ARIES for SEEA Explorer. Pollination services are the ecosystem contributions by wild pollinators to the fertilization of crops. Landscape suitability for pollinators is based on land cover data, lookup tables for nesting sites and floral resources (Lonsdorf et al. 2009, Zulian et al. 2014), and climate data (temperature and solar radiation) (Martinez-Lopez et al. 2019). Following Vallecillo et al. (2018), demand for pollination is defined as the area of pollinator-dependent crops, and supply is modelled as a dimensionless index indicating habitat suitability for pollinators (0 to 1) with high values classified as > 0.3, moderate values from 0.2 to 0.3, low values as 0.1 to 0.2, and minimal value considered as < 0.1. Based on Vallecillo et al. (2018) pollination demand of a crop is considered to be met in areas with moderate to high pollinator habitat suitability. The biophysical value of crop pollination is calculated as crop yield multiplied by the pollination dependency ratio for each crop. The initial ARIES pollination model focusses on eleven pollinator-dependent crops with high pollination dependency ratios (i.e., > 0.5; Klein et al. 2007): apple, avocado, cocoa, cucumber, mango, melon, peach, pear, plum, pumpkin, watermelon. For spatial location of crops, data from Monfreda et al. (2008) is used, this data sets depicts the area (harvested) and yield of 175 distinct crops of the world circa the year 2000, where available this is replaced by national data. This land use data sets were created by combining national, state, and county level census statistics with a recently updated global data set of croplands on a 5 minute by 5 minute (~10 km by 10 km) latitude/longitude grid (http://www.earthstat.org/harvested-area-yield-175-crops/). To account for changes in crop production over time, ARIES adjusts cell-level production values upward or downward based on yearly changes in crop production from FAOSTAT (2020). In ARIES, tabular national statistical data requires spatialization and aggregation through spatial modelling. For time series of crop provisioning, ARIES assumes crop extent to be constant (based on spatial data for the reference year), with only crop yield (tons produced per hectare) to change over time. For the Netherlands, after downloading the k.LAB center (see section 2.3.2) and registration at the k.Hub (https://integratedmodelling.org/hub) the ARIES for SEEA Explorer can be accessed. Administrator rights are not needed to install ARIES. In the

ARIES for SEEA Explorer, the first step is to set the boundaries of the accounting area and the spatial resolution of the calculation and the year or years of interest. For the Netherlands the default resolution is about 1200 m, but calculations can also be done at 100m resolution (based on the Corine Land Cover, however this considerable increases the computation time. The output of ARIES for SEEA consists of a table with crop pollination in tons and a document with the methods, results (tables, figures and maps) and references. For the Netherlands in 2018 at 100m resolution the production in tons is estimated at:

	Cucumber	Melon	Pear	Plum	Apple	Pumpkin	Peach
Production (tons)	2,116,186,336	15,698,655	1,73,328,8212	26,816,942	1,19,153,5931	19,340,1746	1,763

The biophysical volume of crop production was extracted from the FAOSTAT database, and is expressed in tonnes of production (Production quantity) (http://www.fao.org/faostat/en/#data). Landscape suitability for pollinators is calculated by linking the Corine Land Cover map of 2012 for Europe with a lookup table that considers nesting suitability and flower resources for all land cover types. (https://land.copernicus.eu/pan-european/corine-land-cover/clc-2012). Based on (referenced) data availability online, the ARIES for SEEA model selects the most suitable dataset to calculate the pollination service. The Explorer is a typical Tier 1 tool; it is not possible to add user data, maps or lookup tables or adjust the model. In the Explorer it is possible to view the model that has been used, including the look-up tables and model relationships. Adjusting the input data and the model is possible when running the model in the k.LAB modeler (see section 2.3.2), however to modify the models specific knowledge on k.LAB is required.

ARIES Pollination references:

FAOSTAT. 2020. FAOSTAT Food and Agriculture Data. Accessed October 13, 2020 from: http://www.fao.org/faostat/en/.

Joglekar A.K.B., et al. 2019. Pixelating crop production: Consequences of methodological choices. PLoS ONE 14(2):e0212281.

Klein, A.M., et al. 2007. Importance of pollinators in changing landscapes for world crops. Proceedings of the Royal Society of London B Biological Sciences 274 (1608):303–313.

Lonsdorf, E., et al. 2009. Modelling pollination services across agricultural landscapes. Annals of Botany 103 (9):1589–1600.

Martinez-Lopez et al. 2019. Towards globally customizable ecosystem service models. Science of the Total Environment 650(2):2325-2336.

Monfreda, C., et al. 2008. Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. Global Biogeochemical Cycles 22 (1):GB1022.

Vallecillo, S., et al. 2018. Ecosystem services accounting: Part I - Outdoor recreation and crop pollination, EUR 29024 EN; Publications Office of the European Union, Luxembourg, doi: 10.2760/619793, JRC110321.

Zulian, G., et al. 2014. ESTIMAP: a GIS-based model to map ecosystem services in the European Union. Annals of Botany 4:1–7.

4.5.2 Tier 2: calculating crop pollination using adjusted datasets, implemented in InVEST

The pollination model in InVEST is based on Lonsdorf et al. (2009). It uses a lookup approach to calculate landscape suitability (used as pollinator source map) for pollinators where availability of nesting substrates and floral resources are assigned to land use land cover (LULC) classes based on their ability to provide these resources. The pollination model uses the nest supply index to estimate the pollinators visiting crop fields. It assumes that nearby parcels contribute more pollinators than those farther away. Furthermore, the model weights bee visitation by the floral quality of the parcel to reflect the central place foraging behavior that bees are known to follow. A seasonal effect on the quality of floral resources can be taken into account. The distances pollinators typically fly affect both their persistence and the level of service they deliver to farms. The model can be run for multiple bee species/guilds, for each species/guild information on nesting preferences, foraging activity per season, typical foraging distance and relative abundance is included. Typical flight distances can be supplied from quantitative field estimates (e.g., Roubik and Aluja 1983), proxies such as body size (Greenleaf et al. 2007), or from expert opinion. When data is scarce the model can also be used for pollinators in general. Furthermore, it is possible to correct for the contribution of honeybees in the model.

The InVEST models can be downloaded at https://naturalcapitalproject.stanford.edu/software/invest. Here the user guides for each model and sample data sets can be found. Administrator rights are needed to install InVEST on a PC or laptop. By running the executable, all InVEST models are installed. During the installation it is optional to store the sample data sets. The sample datasets are useful to explore how the input data (e.g. the LULC raster map, the farm vector map and the lookup tables for landscape suitability and pollinator guilds) should be structured. InVEST is flexible in the number of nesting preferences long as the column names in the LUT for landscape suitability exactly match the column names in the LUT for bee species/guilds. In the sample data set, two nesting preferences are distinguished, ground nesting and nesting in cavities. The seasons of interest can also be adjusted. Here the names for the seasons should also exactly match in the lookup tables and the seasons given in the farm shape file containing the information about the crop fields. To run the model a lookup table for the pollinator guilds is required. Furthermore, the model requires a raster containing the land use/land cover classes combined with a lookup table that links the classes to the landscape suitability for floral resources and nesting. These lookup tables and land use map is used to calculate pollinator abundance in the landscape. A vector map containing crop fields is optional, but necessary when the aim is to estimate the contribution of wild pollinators to crop yield. This vector map should contain the following fields: *crop_type* (string): Name of or code for the crop grown on that polygon. *half_sat* (floating point): The half saturation coefficient for the crop grown on that farm. This is the value of the wild pollinator abundance index that results in 50% of pollinator-dependent crop yield being attained. The pollinator dependent crop yield (range [0.0 – 1.0]) is calculated as: pollinator-dependent_crop_yield=p_abund(1-half_sat)/(half_sat(1-2p_abund)+p_abund), where p_abund is the average pollinator abundance in the crop field. *season* (string): the season in which the crop is pollinated. *fr_[SEASON]* (floating point value in the range [0.0, 1.0]): The floral resources available at this farm for the given season. *n_[SUBSTRATE]* (floating point value in the range [0.0, 1.0]): The nesting substrate suitability for the farm for the given substrate. *p_dep* (floating point value in the range [0.0, 1.0]): The proportion of crop dependent on pollinators. *p_managed* (floating point value in the range [0.0, 1.0]): The proportion of pollination required on the farm provided by managed pollinators. Per crop field, a value between 0 (no honey bees) and 1 (pollination demand completely met by honey bees) should be given. Wild pollinators contribute only to the remaining pollination demand. The given SEASON and SUBSTRATE should exactly match a SEASON or SUBSTRATE provided in the guilds table. More information about the input data structure can be found at: https://storage.googleapis.com/releases.naturalcapitalproject.org/invest-userguide/latest/croppollination.html

The output of the model consists of a set of raster maps (tif files).

Pollinator supply – this is an indicator of where pollinators originate from the landscape, this is based on the available nesting sites at a location and the floral resources (i.e., food) in surrounding area. Pollinator abundance – this indicates where pollinators are active on the landscape. Pollinator abundance depends on the floral resources that attract pollinators to a location, and the supply of pollinators that can access that location. Pollinator yield – this indicates the potential contribution of on-farm pollinator abundance to pollinator-dependent crop yield. When a vector map with crop fields is provided (this is an optional input map), for that map the total yield per crop field, *y_tot*, the mean pollinator abundance, *p_abund*, the pollinator dependent crop yield, *pdep_y_w* and the contribution of the wild pollinators to the crop yield, *y_wild* is calculated and stored in a vector map named farm_results. Each of these values are floating points in the range [0.0, 1.0]. Furthermore, more details from the intermediate steps of the model is stored in a separate intermediate output folder.

The InVEST pollination model was capable to run a simulation at the national scale of the Netherlands at a 10m resolution (i.e. with raster files with 27,000 columns and 32,000 rows and a vector file with almost 17,500 crop fields with pollination dependent crops). To make the results comparable with the user-defined model, the simulation included one season and one "average" bee species, with the same mean dispersal distance as in the user-defined model also the half_sat value was set at 0.1, and this approaches the relationship that is used in the user-defined model the best. The InVEST pollination model run for about 10 hours to complete the simulation. In InVEST it is not directly possible to link this contribution of wild pollinators to actual yield in ton/ha or euro/ha but further calculations can be done in a program like QGIS or ArcGIS, or in R or python.

Invest pollination references:

Greenleaf, SS, NM Williams, R. Winfree, and C. Kremen. 2007. Bee foraging ranges and their relationship to body size. Oecologia 153: 589-596

Lonsdorf, E., C. Kremen, T. Ricketts, R. Winfree, N. Williams, and SS Greenleaf. 2009. Modelling pollination services across agricultural landscapes. Annals of Botany 1: 12.

Roubik, DW, and M. Aluja. 1983. Flight ranges of Melipona and Trigona in tropical forest. Journal of the Kansas Entomological Society 56: 217-222.

4.5.3 Tier 3: calculating crop pollination with a user-defined model

The crop pollination model for the Netherlands (CBS and WUR Netherlands Ecosystem Accounts) is also based on Lonsdorf et al. (2009). It uses a lookup approach to assign crop dependance on pollination to crop types and estimate pollinator abundance based on the ability of different ecosystem

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types to provide nesting habitat and floral resources for pollinators. Similar to the InVEST model, typical flight distance of pollinators is taken into account to calculate relative visitation of the crop fields, where crop fields close to pollinator source habitats receive more pollinators than crop fields further away. The model first calculates the percentage avoided production loss, based on the visitation of the fields by pollinators and the extent to which crop production depends on pollination. This is assessed for a user defined set of crops in the Netherlands that depend on pollination, for one season and one pollinator guild (i.e. based on the mean for a large set of pollinators). The model is adapted to take the crop production map calculated for the Netherlands as an input for the avoided production loss in ton crop per hectare. The monetary service is calculated in avoided production loss in euro per hectare based on the annual yield statistics for apple, pear, oil seed rape and beans as reported by Statistics Netherlands, and for the other crops the standard yield per crop as reported by Wageningen Economic Research, commissioned by Ministry of Agriculture, Nature and Food Quality. Yield is combined with the crop parcel map via a lookup table approach. The pollination model for the Netherlands is programmed in python and runs independently from GIS software.

The pollination model developed for the Netherlands produces maps with avoided production loss in percentage in the fields, and the contribution of ecosystems to the avoided production loss in ton/ha or euro/ha, where the avoided production loss is allocated to the ecosystem types that contributed pollination. Furthermore it produces tables with the mean contribution to avoided production loss and total contribution per ecosystem type to the avoided production loss in biophysical and monetary units. For the Netherlands it calculates contribution of ecosystem types to crop production on a 10m resolution. The pollination model in python completed the simulation in less than two hours.

Comparison

The InVEST model and the user defined model use the same input. The InVEST model is more flexible in linking properties to the crop fields as a vector map with all crop fields is input for the model, while the python model uses a raster file as input for the crops, therefore all fields with the same crop have the same properties. The potential pollination in the crop fields is the main output for the InVEST model. The python model also produces the potential pollination and also links this to yield in ton or euro per hectare and allocates the avoided production loss to the ecosystems in the surrounding landscape. Both models are able to run the simulation for the Netherlands at a 10m resolution, however the python model was faster.

The pollinator abundance in the crop fields and the pollination potential in the crop fields are only available in maps. For comparison with the InVEST model, de mean value per crop type was calculated using zonal statistics in ArcGIS (see Table 6).

Generally, the percentage abundance/visitation of the pollinators is lower in the user defined model. The InVEST model incorporates a stronger attraction of locations with flower resources than areas with less flowers or without flower resources, this preferences is not incorporated in the python model. The value of the pollination potential also differs between the models, however the spatial pattern in lower and higher values (as a result of the surrounding landscape) is similar for both models (Figure 2).

Table 6. Comparison between output from the InVEST pollination model and the user-defined pollination model for s subset of the crops in the Netherlands in 2018 with the highest pollination dependence. The values in the InVEST model range between 0.0 – 1.0 and of the user-defined python model range between 0.0 -100.0.

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Crop type	Area	Dependence	InVEST		User-defined python model	
	(ha)		Abundance (mean)	Pollination* (mean)	Abundance (mean, %)	Pollination (mean, %)
Pumpkin	748	0.95	0.41	0.83	22.4	92.5
Courgette	305	0.95	0.45	0.87	19.6	91.6
Pumpkin	41	0.95	0.31	0.75	25.3	100.0
Melon	0	0.95	0.26	0.76	17.4	85.9
Pear	9285	0.65	0.36	0.79	16.4	78.4
Apple	6211	0.65	0.39	0.82	14.3	68.6
Blue berry	932	0.65	0.46	0.88	14.7	69.9
Pear, new	584	0.65	0.36	0.80	16.9	80.6
Sweet cherry	532	0.65	0.44	0.86	20.4	93.4
Apple, new	325	0.65	0.40	0.83	11.7	58.3
Plum	261	0.65	0.44	0.86	20.0	88.9
Sour cherry	246	0.65	0.37	0.83	21.3	93.1
Raspberries	228	0.65	0.49	0.89	18.0	81.0
Black berries	39	0.65	0.49	0.89	19.3	89.5
Stone fruits	18	0.65	0.45	0.87	15.0	72.0
Pickle	5	0.65	0.55	0.92	21.7	95.0
Cucumber	0	0.65	0.54	0.90	20.4	93.7

*pollination is the mean potential contribution to pollinator dependent crop yield

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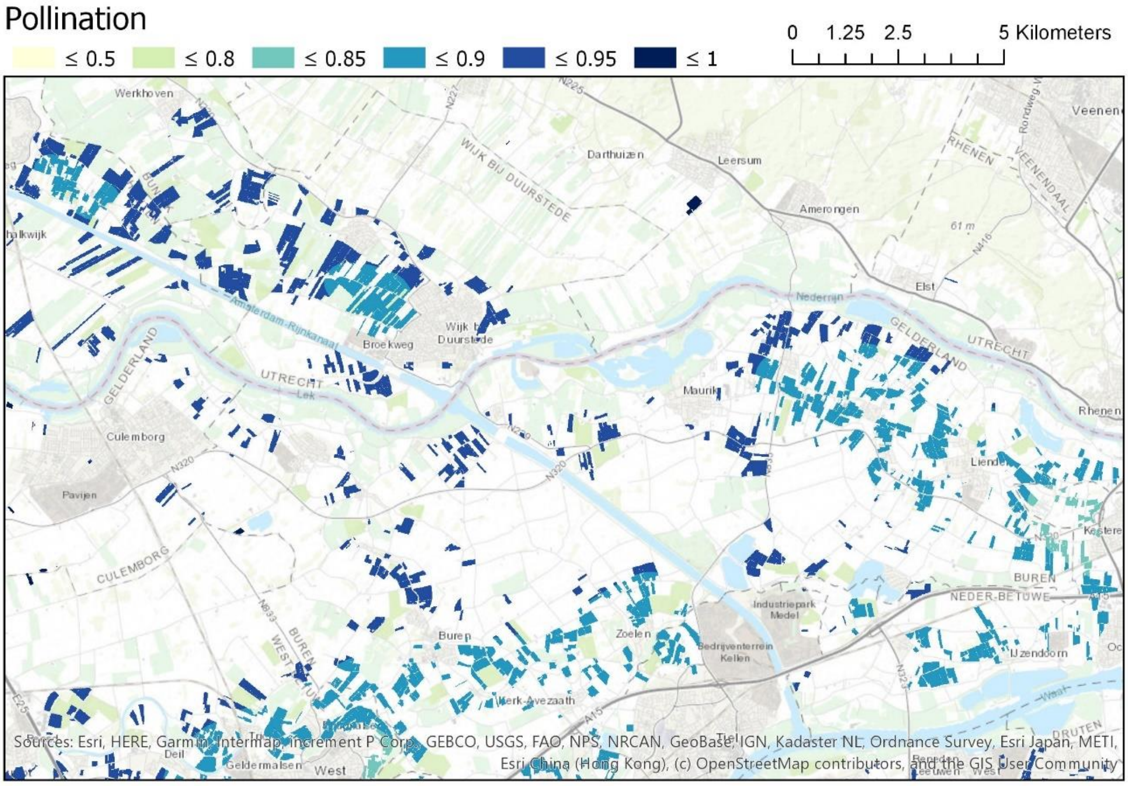

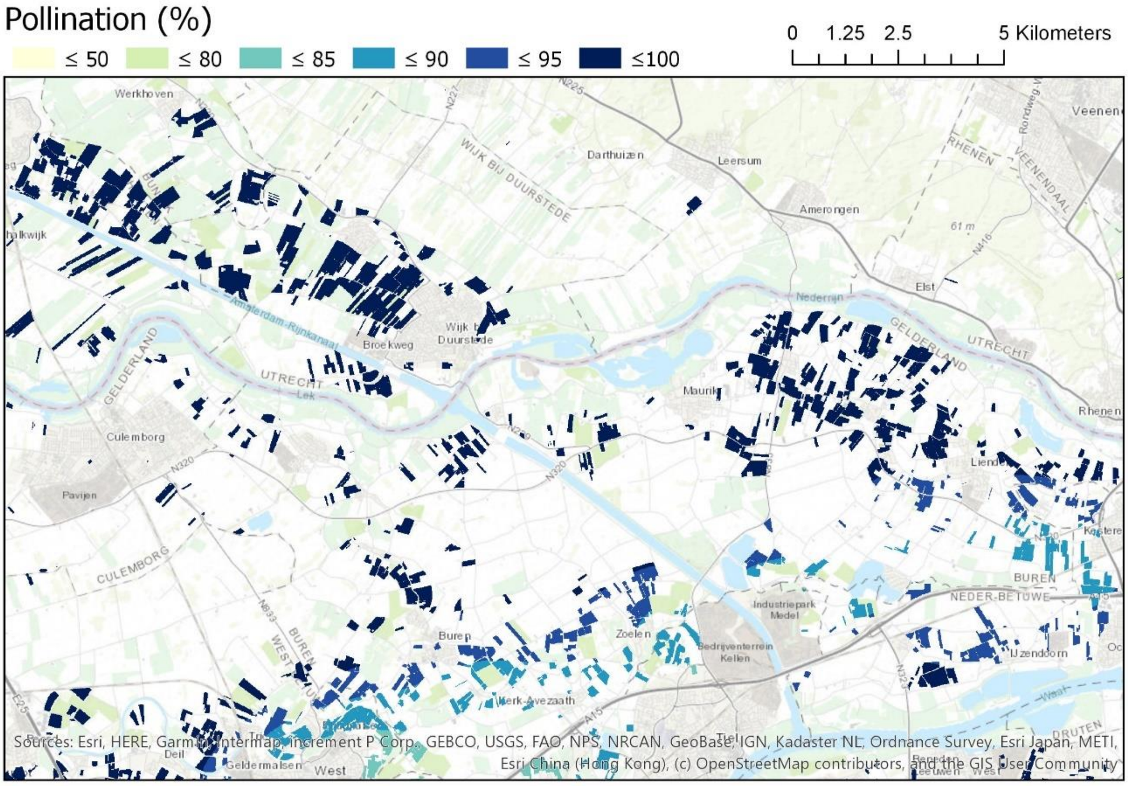

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Figure 2. Potential pollination of orchards and crop fields in one of the main fruit producing regions in the Netherlands as calculated by the InVEST model, using national datasets (range 0.0 – 1.0) and by the user-defined python model, using national datasets (range 0.0 -100.0).

4.6 Additional examples

4.6.1 Calculating stormwater run-off and retention for urban ecosystem accounts

The case study (Barton et al. 2021) illustrates a custom-built biophysical model using local high resolution data to address needs for biophysical modelling of ~~stromwater~~ stormwater run-off in an urban context. For this work a bespoke hydrological estimation method was devised that addresses the whole built area of a city, capable of differentiating the relative stormwater production at property level, while not requiring long hydrological time series for calibration. Sælthun et al. (2020) developed a model for stormwater runoff estimation at property level. The valuation purpose of the biophysical modelling was to estimate property-level contributions to municipal stormwater treatment costs, as a basis for computing cost-savings from increased used of nature-based solutions on property. The model can be applied to urban ecosystem accounting of stormwater retention and cost savings of current land use relative to a reference level landcover from which the ecosystem service is defined (Figure 3). The so-called "REO" model for urban runoff aims to be simple enough for implementation in a GIS environment based on easily accessible landcover maps while being able to differentiate the relative annual stormwater production of a property (m^3/yr). It also computes event run-off (l/s) for 2, 20 and 200 year default rain events. The model requires a number of input datasets that are defined at either the property or city level. City level input layers include the annual rainfall amount, repeat interval of rainfall event, and coefficients used in model functions. Property level layers include basic land cover, low-impact development (LID) measures, property slope and distance to the closest water treatment plant. We used the land cover data to define percentage coverage of roof, permeable surfaces (both covered and uncovered by trees), and impermeable surfaces (both covered and uncovered by trees) for each property (Fig. 3). LiDAR data was used to calculate property-level slope. The Euclidean distance for each property to the nearest water treatment plant was calculated for each property. LID measures included in the model were green roofs, rain beds, terrain sinks, wadis, and partially open surfaces (Fig. 3).

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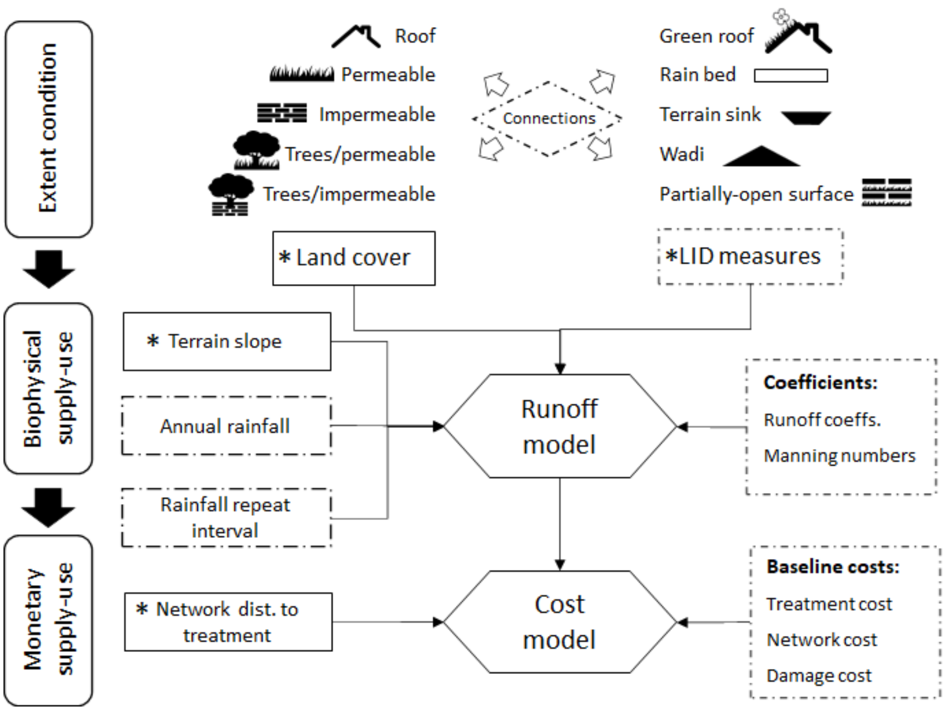

Figure 3. Framework for the stormwater runoff ecosystem service accounting and web application.

The ecosystem accounting steps are indicated on the left of Figure 3 with corresponding data and models on the right. Input data for the runoff and cost models are categorised into those that users can (dashed border) and cannot (solid border) manipulate in the web application. Model inputs with asterisks are those that are defined at the property level, whereas those without are set at city level. LID: low-impact development. Figure 4-5 show screenshots from the online application simulating property level stormwater fees as described in the methodology framework in Figure 3.

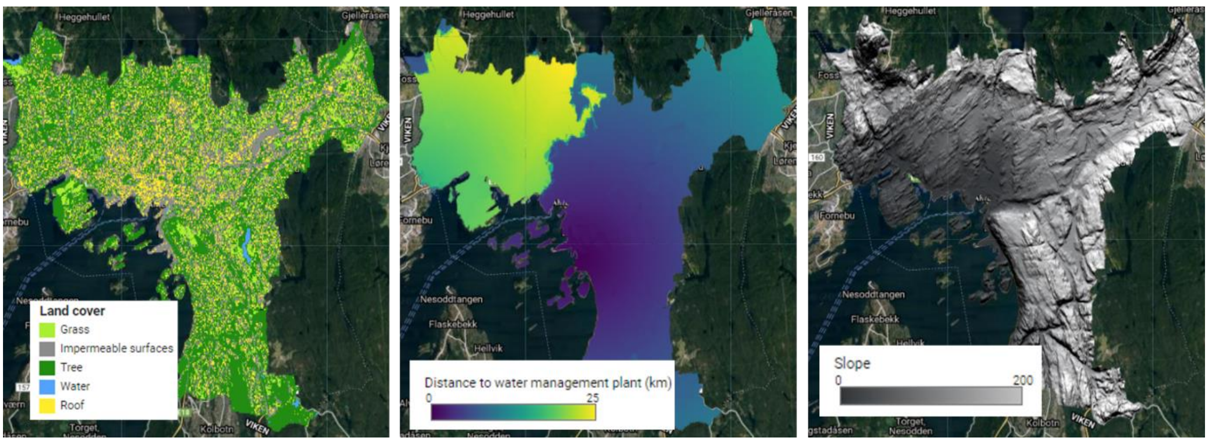

Figure 4. Maps showing the spatial inputs to the runoff model for the Oslo built zone. Land cover (left), distance to water treatment plant (middle) and terrain slope (right).

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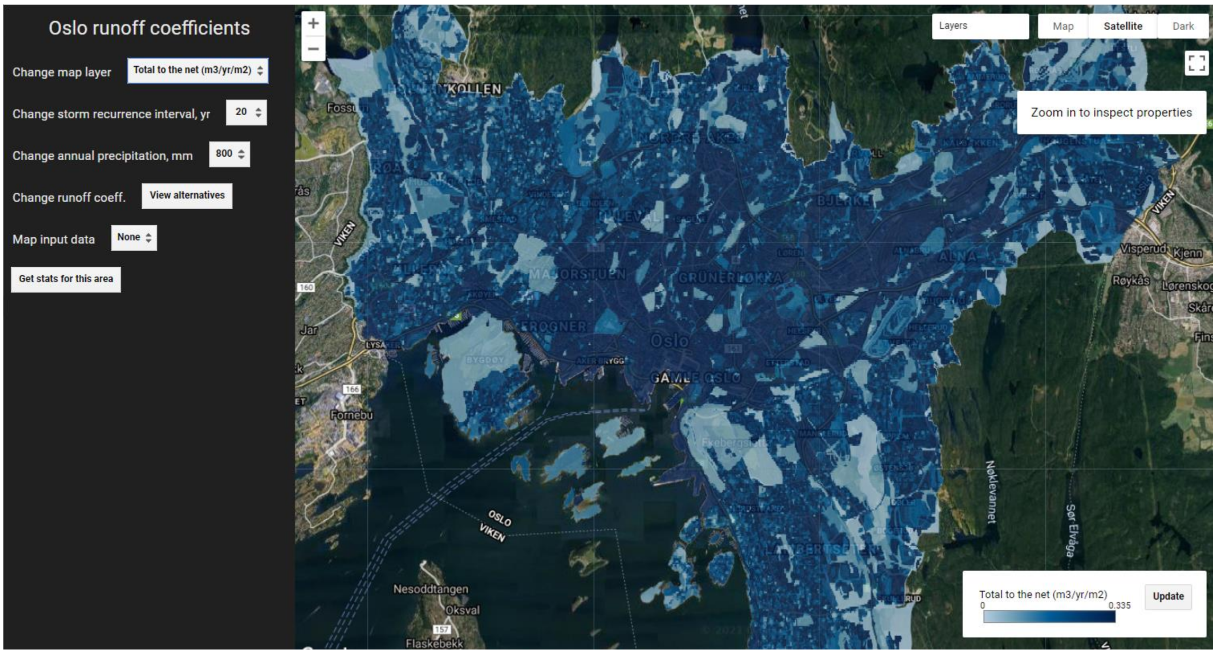

Figure 5. Screenshot from the online web application for calculating property-level runoff estimates.

Biophysical modeling of stormwater retention services in an urban setting and for the purpose of computing stormwater retention using a replacement cost approach is a 'special case'. It assumes that private stormwater runoff in the built zone is subject to a polluter pays principle, requiring properties to pay for or mitigate own stormwater run-off above some regulatory benchmark defining property rights to generate run-off. If property owners have a right to make all private land built/impermeable within an urban land use context, then property owners should be paid for stormwater retention services by the municipality. The modelling approach can be used in both cases by redefining the reference situation from which the service is calculated.

Case references

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4.6.2 Modelling flood regulation for ecosystem accounting in mountain watersheds in Bulgaria

The accounting of flood regulation is based on the assumption that specific ecosystems can reduce the extent and intensity of floods, thus reducing the risk of damage to build environments. The ecosystems

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which provide the flood control functions (ES supply) are located at a particular distance from the demand areas. The spatial relationship between them is conceptualized by the Service Providing Areas (SPA) and the Service Benefiting Areas (SBA). The assessment of ES supply is based on the results of biophysical modelling by the GIS-based AGWA tool which utilizes the KINEROS (Kinematic Runoff and Erosion model) hydrologic model. The results are in the form of flood regulation supply capacity maps presented in six categories ranging from 0 (no relevant capacity) to 5 (very high relevant capacity). In order to define the SPA, the upper three categories from the assessment scale are selected. The SBAs are defined in a similar way by selecting the areas with medium to very high demand from the map of ES demand. The results for SPA represent the ES potential for the case study area which is given in the accounting table, while the results for SDA represent the ES demand (Hristova et al., 2020). The actual flow of flood regulation is calculated as a ratio between ES demand and ES potential and it represents the area of SPA which corresponds to the demand for flood regulation represented by SDA.

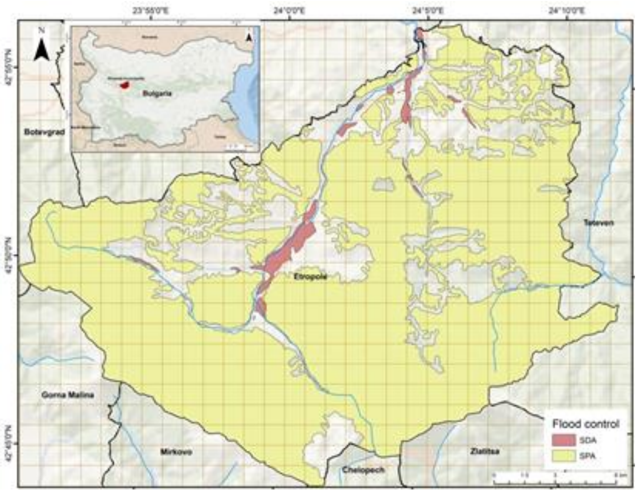

Figure 6. The Service Providing Areas (SPA) and the Service Demanding Areas (SDA) in Malki Iskar watershed within the frame of Etropole municipality delineated using the KINEROS model results.

Case references

Hristova, D., Nedkov, S., Katsarski, N., 2021. Modelling flood regulation ecosystem services in support of ecosystem accounting in Bulgaria. In: La Notte A., Grammatikopoulou I., Grunewald K., Barton D.N., Ekinci B (Eds.), Ecosystem and ecosystem services accounts: time for applications. EUR 30588 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-30142-4, doi: 10.2760/01033, JRC123667

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4.6.3 Natural soil fertility of cropland and grassland in Germany

The case study included grasslands and croplands that are under agricultural use or were converted to a different use, in the years 2012, 2015 and 2018. The Müncheberger Soil Quality Rating (SQR) was used as a physical measure. The SQR classifies a site according to its productivity when used as cropland or grassland, the scale was calibrated with the help of winter wheat and winter rye yields. Agricultural land rent for soils with a specific SQR, calculated via regression. The physical evaluation based upon the SQR raster and the LBM-DE (Digital Land Cover Model of Germany) data resulted in an average SQR value of 57.9 for all agricultural land (totalling 18,379,565 ha) in Germany in 2012. As also lower-quality grasslands where considered, this value is somewhat below the average SQR value of 61.6 from the original SQR dataset. The resulting distribution of soil quality is presented in Figure 7, indicating the relatively large differentiation of natural factors that influence the ecosystem service for crop and grass production. The economic agricultural potential for Germany, assessed in terms of lease income, in 2012 was 3,493,439,872 Euro. The assessment also revealed, that the loss of lease income between 2012 and 2018 due to conversion of agricultural areas into building areas, transportation areas and construction sites was in total 12,677,964 Euros, thus 2,112,994 Euros per year.

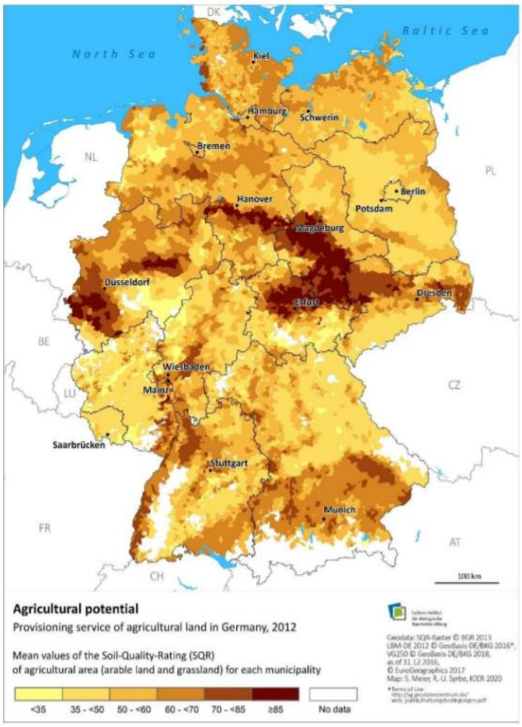

Figure 7: Mean SQR values for German municipalities. Data derived from the Soil Quality Raster (BGR 2013a) and the German land cover model LBM-DE for the time period 2012 (BKG 2016a); the municipality boundaries refer to 2015 (BKG 2016b).

Case reference

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Appendix 1 Reference list of selected ecosystem services SEEA-EA

Table A1 Reference list of selected ecosystem services SEEA-EA (table 6.3, UN, 2021)

Ecosystem service	
Provisioning services	
Biomass provisioning services	Crop provisioning services
	Grazed biomass provisioning services
	Livestock provisioning services
	Aquaculture provisioning services
	Wood provisioning services
	Wild fish and other natural aquatic biomass provisioning services
	Wild animals, plants and other biomass provisioning services
Genetic material services	
Water supply	
Other provisioning services	
Regulating and maintenance services	
Global climate regulation services	
Rainfall pattern regulation services (at subcontinental scale)	
Local (micro and meso) climate regulation services	
Air filtration services	
Soil quality regulation services	
Soil and sediment retention services	Soil erosion control services
	Landslide mitigation services
Solid waste remediation services	
Water purification services (water quality regulation)	Retention and breakdown of nutrients
	Retention and breakdown of other pollutants
Water flow regulation services	Baseline flow maintenance services
	Peak flow mitigation services
Flood control services	Coastal protection services
	River flood mitigation services
Storm mitigation services	
Noise attenuation services	
Pollination services	
Biological control services	Pest control services

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	Disease control services
Nursery population and habitat maintenance services	
Other regulating and maintenance services	
Cultural services	
Recreation related services	
Visual amenity services	
Education, scientific and research services	
Spiritual, artistic and symbolic services	
Other cultural services	
Flows related to non-use values	
Ecosystem and species appreciation	