

# **Revisiting the Ecosystem Extent Account: Lessons Learned from Germany**

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## **Abstract:**

The ecosystem extent account monitors changes in ecosystem area over time and is the spatial basis of the accounting system. All other accounts – condition, services, assets and thematic – build on this mutually exclusive and exhaustive spatial mapping of areas to ecosystem types. Despite its importance, there is limited technical guidance to implement the extent account laid out in the System of Environmental-Economic Accounting – Ecosystem Accounting (SEEA EA) framework. This paper gives a short overview of the main objectives, the structure and the technical challenges in building a nationwide extent account. We aim to lay out and discuss general guidelines for each step, including a thorough description of semi-automated data handling and geo-data processing that facilitate the integration of future data, updates and revisions. The new ecosystem extent account for Germany, set up by the German Federal Statistical Office, is used as an example. Finally, we discuss which aspects of the SEEA EA framework have been helpful and which areas need more effective guidance to set up the extent account on a national level.

## *Questions for the London Group:*

- *Is there a need to establish further standardized guidelines for the implementation of the extent account (for example in the SEEA EA Guidelines for Biophysical Modelling)?*
- *Is it useful to gather an inventory of case studies to help implement the extent account?*

## *Purpose of submitting work to the London Group:*

- *After the recent adoption of SEEA EA as a statistical standard by the United Nations Statistical Division (UNSD), many new national stakeholders are expected to compile detailed ecosystem (extent) accounts. We believe it is useful to revisit the concepts of the extent account and discuss general but applied guidelines for its implementation as well as to contribute to a broader base of case studies.*

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## 1. Introduction

Ecosystem Accounting is an environmental reporting system designed to capture the complex interactions between humans and the environment. Structured in three main accounts – Extent, Condition and Services – it aims to measure these components in an explicitly geospatial approach. These high-resolution spatial statistics give visibility to the services provided by ecosystems and can function as a localized information basis for political and societal decision-making. The international conceptual framework of Ecosystem Accounting (SEEA EA)<sup>1</sup> is integrated consistently with the System of Environment Economic Accounting (SEEA) and serves as an expansion to the System of National Accounts (SNA).

The ecosystem extent account is the basis for all other main and thematic ecosystem accounts as it provides the classification and geospatial delineation of ecosystems for any given ecosystem accounting area (EAA), typically subnational regions or nation-states. Besides monitoring the extent of different ecosystems over time, it defines the spatial unit of analysis and influences the sets of condition indicators and ecosystem services that will be evaluated for a given ecosystem area. Despite this important role of the extent account in setting up the entire accounting system, there are few guidelines for methods and practical details of its implementation.<sup>2</sup> After the recent adoption of SEEA EA as a statistical standard by the United Nations Statistical Commission, many new national stakeholders can be expected to compile ecosystem accounts, making it even more important to provide a broad base of case studies with practical concepts for extent accounts.

The Guidelines on Biophysical Modelling for Ecosystem Accounting (UNSD, n.d.) are currently under consultation and will provide a decision tree for compilers to help determine the most suitable approach to build an extent account. Here, we are describing the case in which the classification and custom maps are built from scratch, combining processed land cover data and other geo-data sources.<sup>3</sup> We believe it is useful to present this approach step-by-step and, where possible, list general conditions and criteria that facilitate the practical implementation of the extent account.

Producing a high-quality extent account with our chosen approach requires a number of steps. First, we set up a hierarchical ecosystem classification that captures the local context, is clear and easy to navigate and compatible with international typologies. Second, a mutually exclusive and exhaustive mapping from ecological and structural variables to the finest classification level is drawn up. Third, appropriate high-resolution spatial input data from various sources, such as satellite data, public registries and cadastres, aerial observation data and ecological mappings is harmonized and pre-processed. Compilers choose the geospatial structure, i.e. basic spatial (BSU) and minimum mapping (MMU) units. Fourth, a sequential algorithm generates the final geometries and variables of the extent account, applies the classification matrix and aggregates to the accounting output. This approach has the advantage of being feasible and specific to the local context, while providing flexibility to incorporate newly available data sources and produce periodic updates with moderate effort.

This article revisits some of the key challenges in setting up an extent account (Section 2) and provides an in-depth description of each of these steps ranging from classification design (Section 3) to classification application (Section 4). Examples for the case of the implementation of Germany's nationwide extent account, compiled by the German Federal Statistical Office, are presented (Section 5). Finally, our results and suggestions are discussed with regard to the international framework SEEA EA (Section 6).

## 2. Ecosystem Extent Account – Goals and Challenges

The extent account, as laid out in SEEA EA, serves several main purposes, each of which comes with a set of implications and implementation challenges.

- I. The extent account should serve as a common basis of understanding for compilers, users, decision-makers and other stakeholders when referring to different ecosystem types and the measurement scale/observational unit of analysis. This implies that, in order for a national classification of ecosystems to be recognized and functional, it should strike a balance between a feasible and detailed differentiation of ecosystems and a simple and comprehensible representation of the environment. The spatial delineation and classification criteria ought to be transparent and compatible with other ecological concepts and (inter)national typologies, such as land cover data or area statistics. Aggregation in the

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<sup>1</sup> See UNCEEA (2021): SEEA Ecosystem Accounting (SEEA EA): Final draft (as adopted by the UN Statistical Commission in March 2021): [\[https://unstats.un.org/unsd/statcom/52nd-session/documents/BG-3f-SEEA-EA\\_Final\\_draft-E.pdf\]](https://unstats.un.org/unsd/statcom/52nd-session/documents/BG-3f-SEEA-EA_Final_draft-E.pdf)

<sup>2</sup> Currently, SEEA-EA provides general training resources on extent accounts in line with the previous version of the framework (SEEA-EEA). The forthcoming Guidelines on Biophysical Modelling for Ecosystem Accounting (UNSD, n.d.) aim to fill this void. Other guidelines and applications of mapping focus on ecosystem service mapping (Burkhard & Maes 2017, Palomo et al. 2018), mapping at the European level (including country case studies) (EU 2019) and ecosystem accounting at catchment area (Farrell et al. 2021).

<sup>3</sup> Other approaches include the use of already existing (global) classifications and mappings, the use of ready-made tools, such as EnSym or ARIES, or the constructions of custom maps from raw aerial or satellite imagery.

- classification as well as spatial aggregation and visualization using ecosystem maps support this common information basis.
- II. The extent account tracks and reports changes in ecosystem extent and composition over time. Therefore, the compilation should be implemented in a time-consistent manner. Methodology, implementation and input data must ensure that the result is an unbiased time-series of extent accounts that tracks ecosystem conversions and changes in biodiversity. This means that the choice of input data is restricted to frequent time-series. The emergence of new and revised datasets of higher quality and resolution may require revisions of past accounts, thus favouring an automated approach for the compilation of extent accounts.
  - III. Besides serving its own purpose of monitoring ecosystem areas, the extent account serves as the spatial basis for condition and service accounts. This additional but crucial feature generates multiple challenges. First, the delineation of ecosystems in the extent account has a direct implication for the set of potential condition indicators and evaluated services. Thus, the decision whether to separate a given area into different ecosystems requires the compiler to think carefully about the consequences regarding the follow-up accounts. Second, the spatial units for the measurement of condition indicators and the modelling of services may affect the delineation of ecosystems, if the compiler wants to ensure that geometries in the extent account align with those most suitable for later purposes. Third, small and linear features, such as rivers, hedgerows, roads and railroads, are essential ecosystems or important structural elements that influence ecosystem services. Compilers may therefore be required to implement additional data processing steps to capture them.

In order to fulfil its intended purposes, the compilation of the extent account requires a careful design and implementation regarding the classification, the input data and the application of the area-to-ecosystem mapping. In particular, implementation challenges arise, when the above objectives contrast with limited computational capacity, lack of practicality, lack of data sources and time.

### 3. Setting up a National Classification

According to SEEA EA, ecosystems are differentiated based on stable abiotic and biotic characteristics, which include soil and lithography, land cover (e.g. vegetation, buildings, hydrology), land use (e.g. building type, agricultural use), topography (e.g. sea level, slope), climate and flora-fauna habitats. This reflects the view that while ecosystems should predominantly be distinguished by their ecological traits, structural components like anthropogenic objects, administrative boundaries, monitoring areas or land use types may be important to match all objectives of the extent account.<sup>4</sup> Similarly, the Convention on Biological Diversity defines an ecosystem as “a dynamic complex of plant, animal and micro-organism communities and their non-living environment interacting as a functional unit” (UN 1992). In practice, the most readily available and used databases that capture some, if not most of these characteristics, are land use and land cover (LULC). By mostly relying on satellite data, such datasets are widely available<sup>5</sup> and constitute a low entry cost. As a result, LULC classifications like the Corine Land Cover (CLC)<sup>6</sup> or FAO Land cover Classification System (LCCS)<sup>7</sup> types are often used directly for the categorization of ecosystems. However, the requirements for an ecosystem typology go beyond simple characteristics of land cover and land use (see Vardon et al. 2020). Other classifications suggested for international reporting are typically designed to capture a broader differentiation of ecosystems to achieve comparability across countries, ecological contexts and different data sources. As noted in SEEA EA, using a national classification that can be aggregated to other typologies may have significant advantages because it can be tailored to a country’s local ecological context, data availability and user base. Bogaart et al. (2019) have summarized the most important design criteria of an ecosystem reference classification: based on ecological principles, mappable, collectively exhaustive, mutually exclusive, practical and linkable. They also provide several guidelines to construct a classification at the national or regional level, on which we build our conceptual basis. To set up a national classification for Germany’s ecosystem accounting, our approach is to refine or modify LULC classes based on a number of simple conditions.<sup>8</sup> Sufficient conditions for an ecosystem class to be distinguished and accounted separately are that

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<sup>4</sup> For a complete list of potential traits and characterization of ecosystems, see Chapter 3.3 and Annex 3.1 of SEEA EA (2021).

<sup>5</sup> For example, Copernicus Global Land Cover Maps [<https://land.copernicus.eu/global/products/lc>], World Terrestrial Ecosystems (Sayre et al. 2020).

<sup>6</sup> Corine Land Cover [<https://land.copernicus.eu/pan-european/corine-land-cover>]

<sup>7</sup> FAO Land Cover Classification System (LCCS) [<http://www.fao.org/land-water/land/land-governance/land-resources-planning-toolbox/category/details/en/c/1036361/>]

<sup>8</sup> This step benefitted significantly from the proposed classification and modification of LULC classes for Germany by Grunewald et al. (2020).

- i) the ecosystem is currently relevant (in size) and existent in Germany's national territory, including the Exclusive Economic Zone (EEZ),
- ii) the possibility that a currently non-existent ecosystem type becomes relevant in the future (e.g. types of irrigated agriculture, semi-arid plantations) and
- iii) the bundle of ecosystem services provided is distinct from any other ecosystem types, thus exhibiting particular ecological relevance, (e.g. hedgerows or riparian forests).

Necessary conditions for a differentiation of ecosystems are that

- i) ecosystem classes and their respective criteria can be distinguished using currently available nationwide datasets at a maximum 3-year reporting frequency,
- ii) mutual exclusiveness (unique mapping) and exhaustiveness of the classification are ensured,
- iii) the resulting classes (the lowest hierarchy level of the classification) are comprehensible for non-expert users and align with already established terminologies and taxonomies.

Once we have identified ecosystem classes that satisfy those conditions for Germany, we are left with 74 national classes, 71 of which are currently non-empty (see Table 1). To support communication and visualization at more aggregated levels, classes are grouped to national ecosystem groups (21), divisions (6) and sections (2) in a hierarchical manner.<sup>9</sup> The nomenclature partially follows the Statistical Classification of Economic Activities in the European Community (NACE) and identifies classes by alphabetical letters and four-digit numerical codes in line with the approach used for statistical classification systems.

The classes are differentiated by land cover and use combinations and additional criteria such as soil type, water body morphology, climatic condition, building volumes, marine habitats and other structural or land use aspects, which address different goals of the extent account. For example, distinguishing alpine and lowland meadows and heathlands by elevation or separating marine waters by distance to shore aligns ecosystems classes with common conceptions of users. Identifying hedgerows and meadow orchards adds particularly relevant ecological corridors and their services. Differentiating rivers by water body morphology or characterizing settlements by building density facilitates the future generation of condition and services accounts.

To ensure comparability and compatibility with international typologies, crosswalks with the International Union for Conservation of Nature Global Ecosystem Typology (IUCN GET) Functional Groups, Mapping and Assessment of Ecosystem Services (MAES) level two types and CLC classes were constructed. These many-to-many class links may use additional criteria not utilized within our national classification.

## 4. Implementing and Applying the Classification

Along with the ecosystem classification, we built up an inventory of 26 classification variables, including their type, source and admissible values. Since the classification is a mutually exclusive and exhaustive mapping from these variables to ecosystem classes, it can be represented by a classification matrix that serves as a function for spatial input data. The mapping (matrix) is unique, which means certain priorities are built in (e.g. once a bog forest is classified, it cannot become a montane forest, even if it is located at high altitude). However, the explicitly spatial dimension of the extent account warrants a stepwise implementation of these priorities. To construct simple geometries in as little steps as necessary, some of the criteria in the classification matrix are already used in prior geo-data processing steps. In other words, the shape of polygons that enter the classification process depends on the order in which different geo-data sources are combined or intersected. For instance, even though our river data contains continuous geospatial objects ranging from riverhead to mouth, we avoid cutting through lake polygons by prioritizing the processing of lake geo-data.

Furthermore, to implement the sequence of GIS-processes needed to generate the final extent account geometries flexibly and efficiently while respecting classification criteria, we aim to carry out as many geo-data pre-processing steps independently from the classification matrix. This section describes our step-by-step procedure from raw input data to the finished extent account products. All processing steps were programmed in Python using tools of the ArcGIS software, examples are presented in Section 5.

### 4.1 Input Data

The first main task of the implementation is to identify, organize and process data sources that can fill the classification variables with information compliant with a number of requirements concerning time-consistency, frequency, resolution and quality.

- i) Data on dynamic variables should be available consistently at a maximum 3-year frequency (the current frequency of Germany's high-resolution LULC data). Data sources that are expected to be mostly stable

<sup>9</sup> Only national ecosystem sections A (terrestrial) and B (marine) are complete and non-empty. Potential Sections C (subterranean areas) and D (upper biosphere) are laid out but currently remain empty, as suggested in SEEA EA.

over a minimum period of 10 years (e.g. location of reefs, soil profiles) are used until revised datasets are published.

- ii) Data for terrestrial ecosystems must be geo-referenced and should respect the MMU (1ha for Germany). This means that any larger objects of relevance must be identified and represented by the input data. Due to the (current) lack of high-resolution satellite data for the seabed, we allow for a higher mapping unit for marine ecosystems.<sup>10</sup> Although some data sources can be selective for specific ecosystems, they must cover all German territory plus the EEZ for the respective purpose.

Table 1: Data Sources for Germany's Ecosystem Extent Account

Description	Source
Land cover and use (incl. soil sealing, vegetation)	Land Cover Model Germany (LBM-DE, Federal Agency for Cartography and Geodesy)
Highlands/Alpine Zones	Landscapes Germany (Federal Agency for Nature Conservation)
Elevation in m	Digital Terrain Model Germany (Federal Agency for Cartography and Geodesy)
Riparian Zone	Copernicus Riparian Zones High Resolution Layer
Bog/peat	Digital Landscape Model Germany (Federal Agency for Cartography and Geodesy)
Bog/peat soil types	Soil Map Germany 1:200.000 (Federal Institute for Geosciences and Natural Resources)
Reefs	EU Habitat Mapping (Federal Agency for Nature Conservation)
Sandbanks	EU Habitat Mapping (Federal Agency for Nature Conservation)
Seagrass and green algae	EU Habitat Mapping (Regional Agencies)
Mussel beds on tidal flats	EU Habitat Mapping (Regional Agencies)
Modified and artificial water bodies	EU Water Framework Directive (Federal Institute of Hydrology)
Coastal water bodies	EU Water Framework Directive (Federal Institute of Hydrology)
EEZ and open sea	Federal Maritime and Hydrographic Agency + EU Water Framework Directive (Federal Institute of Hydrology)
Rivers	Digital Landscape Model Germany (Federal Agency for Cartography and Geodesy) + Water Framework Directive (Federal Institute of Hydrology)
Hedgerows	Digital Landscape Model Germany (Federal Agency for Cartography and Geodesy) + Copernicus Small Woody Features High Resolution Layer
Roads	Digital Landscape Model Germany (Federal Agency for Cartography and Geodesy)
Railroads	Digital Landscape Model Germany (Federal Agency for Cartography and Geodesy)
Dunes	Biotope Mapping (Authorities of the federal states)
Building volumes	2,5D Model LoD1-DE (Federal Agency for Cartography and Geodesy)
Orchards meadows	Biotope Mapping (Authorities of the federal states)

- iii) Data stems from governmental, international organizations or published scientific sources, preferably in raw or minimally processed formats. This excludes, for instance, any data that was referenced subjectively or without transparent criteria.

All input data is projected to *ETRS1989 UTM Zone 32N* and, if necessary, harmonized across regions. This applies for example to some data sources in Germany that are produced by regional authorities of the federal states (*Landesämter*), and can vary in terms of timeliness, definitions and terminology. Table 1 lists the main LULC data as well as additional data sources.<sup>11</sup>

## 4.2 Pre-processing

In many instances, our main database (Germany's land cover model LBM-DE, in the following referred to as 'land cover model' only) can be combined or expanded with additional data sources, independently from the classification process. Generally, pre-processing can be used to lower time and hardware requirements, if

- i) the processing step does not depend on the area of the geometry (pre-processing geometries are not final),
- ii) the procedure on a given geometry is not a function of characteristics of its neighbours

There are three main types of pre-processing steps that can run separately or sequentially and that can be applied to a single ecosystem or multiple ecosystems classes jointly.

<sup>10</sup> Improved biotope mapping and shallow water satellite data is expected to be available in the future.

<sup>11</sup> For more information on these datasets, see BKG (2020): Land Cover Model Germany. [<https://www.bkg.bund.de/DE/Ueber-das-BKG/Geoinformation/Fernerkundung/Landbedeckungsmodell/landbedeckungsmodell.html>], BKG (2019): Digital Landscape Model Germany (Basis-DLM). [<https://gdz.bkg.bund.de/index.php/default/digitale-geodaten/digitale-landschaftsmodelle/digitales-basis-landschaftsmodell-kompakt-basis-dlm-kompakt.html>], BKG (2020): Digital Terrain Model Germany. [<https://www.bkg.bund.de/DE/Produkte-und-Services/Shop-und-Downloads/Digitale-Geodaten/Gelaendemodelle/Deutschland/DGM-Deutschland-cont.html>], BfN (2003): Landscapes Germany. [<https://www.bfn.de/index.php?id=1862>], BGR (2020): Soil Map Germany 1:200.000. [[https://www.bgr.bund.de/DE/Themen/Boden/Informationsgrundlagen/Bodenkundliche\\_Karten\\_Datenbanken/BUEK200/buek200\\_node.html](https://www.bgr.bund.de/DE/Themen/Boden/Informationsgrundlagen/Bodenkundliche_Karten_Datenbanken/BUEK200/buek200_node.html)], UBA (2020): Water Framework Directive Germany. [<https://www.gewaesser-bewertung.de/>], EEA (2020): Riparian Zones. [<https://land.copernicus.eu/local/riparian-zones>], EEA (2019): Resolution Layer Small Woody Features. [<https://land.copernicus.eu/pan-european/high-resolution-layers/small-woody-features>].

Table 2: National Ecosystem Classification for Germany

A01 Settlement areas and transport infrastructure																
A01.1 Settlement areas with high building density			A01.2 Settlement areas with low building density			A01.3 Transport infrastructure				A01.4 Mining area, dumpsites and construction sites			A01.5 Leisure and urban green areas			
A01.11 Residential area with high building density	A01.12 Industrial areas with high building density	A01.13 Commercial areas and public facilities with high building density	A01.21 Residential area with low building density	A01.22 Industrial areas with low building density	A01.23 Commercial areas and public facilities with low building density	A01.31 Roads	A01.32 Railroads	A01.33 Ports	A01.34 Airports	A01.41 Mining areas	A01.42 Dumpsites	A01.43 Construction sites	A01.51 Green urban areas	A01.52 Sport- and leisure areas	A01.59 Other green urban areas	
A02 Agricultural land																
A02.1 Arable land			A02.2 Permanent cropland								A02.3 Pastures		A02.4 Hedgerows			
A02.11 Non-irrigated arable land		A02.19 Other arable land	A02.21 Vineyards		A02.22 Fruit tree and berry plantations		A02.23 Orchard meadows		A02.24 Tree nurseries		A02.29 Other permanent cropland		A02.30 Pastures		A02.40 Hedgerows	
A03 Forests and woodland																
A03.1 Broadleaf forests				A03.2 Coniferous forests				A03.3 Mixed forests				A03.4 Transitional wood- and shrubland				
A03.11 Montane and subalpine broadleaf forests	A03.12 Broadleaf bog forests	A03.13 Riparian forests	A03.19 Other broadleaf forests	A03.21 Montane and subalpine coniferous forests	A03.22 Coniferous bog forests	A03.29 Other coniferous forests	A03.31 Montane and subalpine mixed forests	A03.32 Mixed bog forests	A03.39 Other mixed forests	A03.41 Reforestation	A03.42 Forest glades and forest regeneration	A03.49 Other transitional wood- and shrubland				
A04 Semi-natural areas and wetlands																
A04.1 Natural or extensively used grassland			A04.2 Wetlands						A04.3 Sparsely or non-vegetated areas							
A04.11 Heathland	A04.12 Alpine meadows	A04.19 Other natural or extensively used grassland	A04.21 Marshes	A04.22 Peat bogs with active cutting	A04.23 Natural or renaturalized peatbogs	A04.24 Natural or renaturalized fens	A04.25 Salt marshes	A04.29 Other wetlands	A04.31 Sand or pebble beaches, inhomogeneous coast, Dunes	A04.32 Coastal dunes	A04.33 Inland sand-, soil or rock surfaces	A04.34 Montane erosion areas	A04.35 Natural bare rock	A04.36 Glaciers and perpetual snow	A04.37 Montane and subalpine heath or shrubland	A04.39 Other sparsely or non-vegetated areas
B01 Inland waters																
B01.1 Watercourses								B01.2 Standing bodies of water								
B01.11 Large natural watercourses		B01.12 Large modified watercourses		B01.13 Large artificial watercourses		B01.19 Other, small watercourses		B01.21 Large natural standing bodies of water		B01.22 Large modified standing bodies of water		B01.23 Large artificial standing bodies of water		B01.29 Other small standing bodies of water		
B02 Marine waters																
B02.3 Tidal flats			B02.1 Coastal sea water						B02.2 Open sea							
B02.11 Tidal flats with macrophytes		B02.12 Tidal flats with mussel beds	B02.19 Other tidal flats	B02.21 Coastal sea with macrophytes		B02.22 Coastal reefs	B02.23 Coastal sandbanks	B02.29 Another coastal seabed	B02.31 Open sea with macrophytes		B02.32 Open sea reefs		B02.33 Open sea sandbanks		B02.39 Other seabed at open sea	

First, some ecosystem classes require building up completely new geometries that differ widely from the land cover classification in the land cover model. Often this includes linear features like roads, railroads, rivers and hedgerows that may be smaller than the land cover data's MMU. Due to their importance in fragmenting the landscape and as ecosystems in their own right, these linear objects can be transformed to area objects using additional data on their local average width. Other areas that require this step are the open sea and EEZ ecosystems. Since the land cover model does not cover them, we use administrative boundaries, units of the EU water framework directive (WFD), reef and sandbank monitoring as well as information on wind parks and shipping lanes to build new geometries.

Second, we identify ecosystem classes, which are only partly represented by the existing geometries in the land cover model, e.g. a forest in a riparian zone may be part of a larger polygon of broadleaf forest in the land cover model. Such areas are cut out using additional data sources. This means original geometries may be sub-divided, but their outer borders are preserved. If an intersection of data sources leads to areas smaller than 1ha, they are resolved using majority rules.

Third, the addition of further data to existing, new or modified geometries in the land cover model using zonal statistics or spatial joins without changing their shape completes the pre-processing steps. It is important to note, that if this step is violating the pre-processing conditions, then it is excluded from pre-processing. One admissible example is the spatial join between lakes in the land cover model and water body morphology based on the WFD. An inadmissible pre-processing step would be the calculation of the mean elevation of a polygon, an operation that is clearly dependent on the final geometry area.

### 4.3 Applying the Classification

The actual classification algorithm is launched with the land cover model as input data. To handle the volume of operations, each region and the EEZ are classified separately. In order to apply different classifiers, each handling one or a group of several similar ecosystem classes, one at a time in pre-specified order, the input data is updated constantly and passed on. In the following, we call this updated input data the working file. Figure 1 shows the structure of the classification algorithm. Each classifier works as follows:

- i) Before including the pre-processed data in the working file, it is clipped to the current state of the working file. This guarantees that areas that have been classified before will not be dealt with again. Thus, the spatial dimension of priorities in the classification matrix is implemented. For example, if a previous classifier cut out an area of riparian forest, it cannot be a candidate for bog forest, even though it is part of the pre-processing file.
- ii) If there are geo-data processing steps that were inadmissible for pre-processing, they are now run to enhance the updated geometries. These steps are carried out on relevant data only. For example, in order to separate montane forests from other forests, elevation data plays an important role. Hence, we consider the mean elevation of the polygons in question. As the number of input polygons of the pre-processing step might be huge, we run this computation on-the-fly for all polygons with forest as land cover that have not been classified earlier. Thus, we increase the fitness of the elevation data to the polygons.
- iii) In order to minimize the volume of data handled at a time, a premature classification step takes place in accordance with the spatial dimension of priorities in the classification matrix.
- iv) The working file is updated. For this purpose, areas that have been classified in the prior classifier step are erased from the working file.

Once all classifiers have been applied, data remaining in the working file is classified based on the classification matrix.

### 4.4 Post-processing

Post-processing is used to 'clean up' and aggregate the extent account database. Among others, the following steps help to refine the final product.

- i) Control the completeness and exhaustiveness of the classification, repair geometries and clean up small splitter polygons (<0,01 ha),
- ii) Log the classification data source of each polygon to ensure transparency and traceability of the classification
- iii) Implement a quality control procedure, for instance, by drawing a random sample of extent account polygons and attempt to validate the ecosystem class using aerial photography or other representative samples and studies
- iv) Aggregate at different administrative and classification levels to create the final data outputs, i.e. accounts and maps

For the example of the German extent account, we log all pre-processing and classification steps separately to be able to track the exact sources that lead to the classification of a particular polygon.

Given that clipping of pre-processed data with the working file may produce large numbers of very small splitter polygons, we dissolve these areas. For this step, we unify such areas with the best-fitting adjacent polygon according to a pre-defined cost matrix.



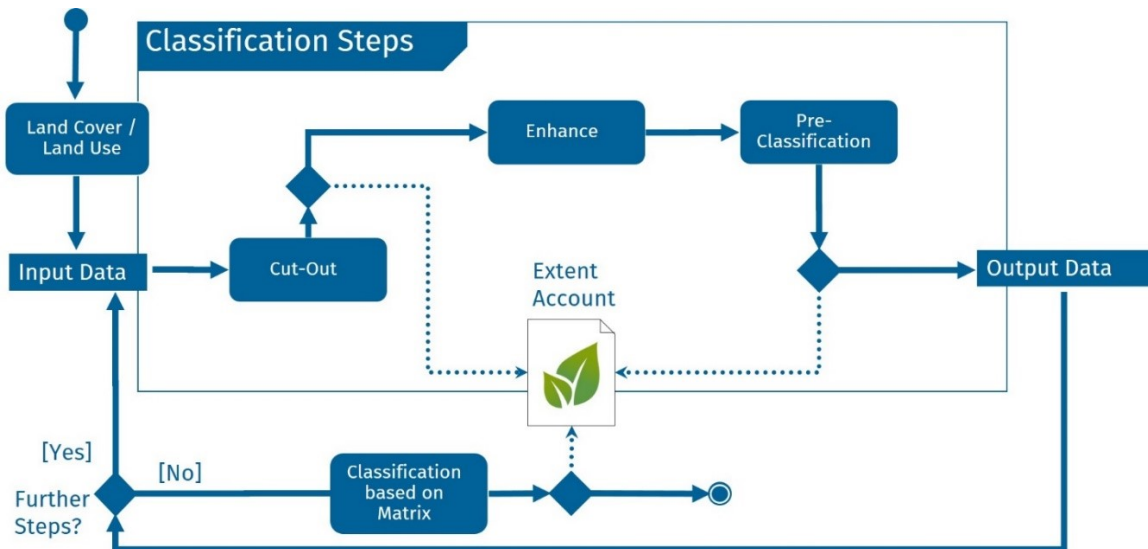


Figure 1: Iterative classification procedure (4.3 Applying the Classification)

In a final step, we derive aggregated accounting tables by intersecting the classification results with subdivisions of the study area, for example a subdivision into municipalities (*Verwaltungsgemeinschaften*), regions (*Bundesländer*) or the North and Baltic Sea.<sup>12</sup> Additionally, two mapping solutions are provided. First, an interactive online map at the municipality level allows the user to view maps at division and group level as well as accounting tables at the class level. Second, raster maps with 100x100m cells (compatible with the European Union's INSPIRE format) show ecosystem classes separately for each group.

#### 4.5 Time-series

The creation of an extent account series allows tracking changes in ecosystem composition and area over time. Once extent accounts for two or multiple time periods are generated using a consistent methodology and input data, any observed changes in the accounts represent real ecosystem conversions. By intersecting the spatial extent, such changes can be tracked separately for each polygon.

Classifying ecosystem conversions into anthropogenic or natural and to appraisal or degradation is a complex task that may require additional information on land management, ownership as well as weather and climate. For instance, to judge whether a change from coniferous forest to sparsely vegetated areas is a result of logging (anthropogenic) or windthrow (natural), we would need geo-coded data on land use/management (extraction of timber) and extreme weather events (storms). Furthermore, there is not a clear-cut and formal definition to distinguish between these conversion categories for some ecosystems. Some that are defined may be confusing to users, such as deeming long-run consequences of climate change 'natural', e.g. desertification. For the German extent account, the classification of conversions is therefore currently under development and not part of the published output.

### 5. Implementation Examples

#### 5.1 Watercourses

The challenge with capturing watercourses for the ecosystem extent account lies in the combination of different data sources and the interconnectedness of river systems, which requires selecting and processing rivers based on their catchment area and width and linking them via a water body index number (*Gewässerkennzahl*). Additionally, since most geo-data on watercourses comes in linear features, processing steps to build up, connect and dissolve polygon features need to be implemented. For the pre-processing and classification of other linear objects, such as roads and railroads, where different data sources are combined to characterize and buffer linear objects above a specific size cut-off, we follow a similar methodology to the river example.

<sup>12</sup> Since Germany has multiple special border arrangements, such as condominiums with Luxemburg (rivers Our, Sauer and Moselle), Austria and Switzerland (Lake Constance) and the Netherlands (Ems-Dollart estuary), these areas can be captured separately to avoid double counting at the international level.

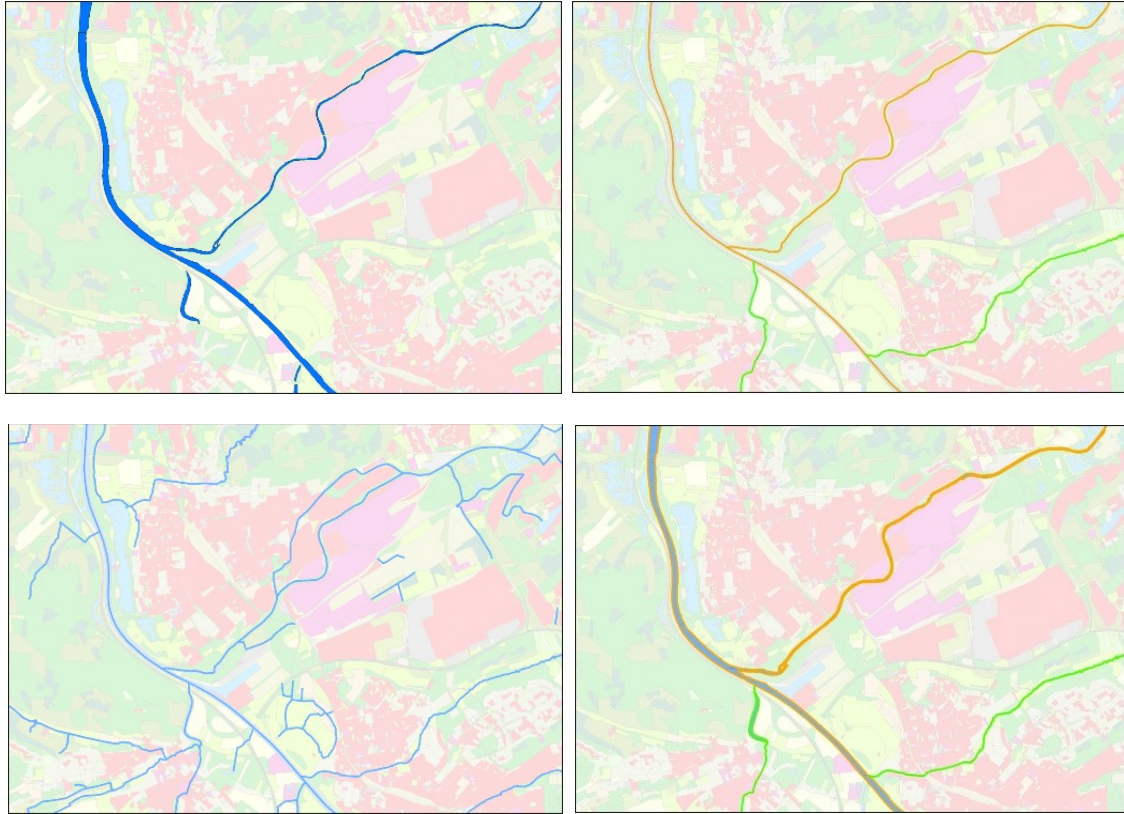


Figure 2a: Areas with land cover 'watercourse' in the land cover model (top left). Figure 2b: Watercourses in the WFD dataset: green: 'natural', orange: 'modified' (top right). Figure 2c: Watercourses as linear objects in the digital landscape model (bottom left). Figure 2d: Final selection of watercourses in the Ecosystem Extent Account: 'large, natural' (green) and 'large, modified' (orange) (bottom right) (Sources: LBM-DE, WFD, Basis DLM, own calculation)

In the national ecosystem classification for Germany, four classes are reserved for watercourses: 'Large natural watercourses', 'large modified watercourses', 'large artificial watercourses' and 'other, small watercourses'. Similar to a MMU for areas, we set a size cut-off for rivers to a catchment area of 10 km<sup>2</sup>. This coincides with the set of rivers captured in the EU WFD, which provides data on the morphology of water bodies. If smaller watercourses are present in our land cover model dataset, they enter the 'other, small watercourses' class. There is also scope to capture smaller watercourses, which are ecologically relevant, with polygon-specific measures of count, length, density and fragmentation in the condition account without explicitly capturing them as spatial objects.

We combine land cover data for rivers from the land cover model (width larger 15m, see Figure 2a) and the digital landscape model (polygons for rivers wider than 12m, linear objects with width estimates for rivers with width smaller than 12m, see Figure 2c) with information on water body morphology in the EU WFD (see Figure 2b).

In the pre-processing steps, watercourses covered by the EU WFD are matched with linear objects from the digital landscape model via official water body index numbers. This results in a match of 12.383 indexed watercourses with a total length of 145.943 km. We then match rivers, or their respective subsections, with a water body morphology attribute ('natural', 'modified', 'artificial'). Finally, the watercourses are buffered with their reported average width and dissolved to polygons based on their water body index number (Figure 2d).

Classifying watercourses, we start with erasing regions that have already been classified from the pre-processed data. This includes lakes due to a higher priority in the classifier list. As a result, water bodies are clearly separated where rivers flow into lakes.

## 5.2 Settlement Areas

Urban ecosystems are very different from their rural counterparts in terms of both service supply and demand. They may therefore be differentiated and considered in particular detail in the extent account (Wang et al. 2019). Anthropogenic land cover and objects like buildings are highly relevant for ecosystem accounting because they often heavily influence the condition and the demand for services of surrounding ecosystems. For instance, soil sealing and structural volume affect local climate (e.g. heat islands), water absorption and biodiversity.





Figure 3a: Low (white) and high (black) soil sealing residential areas in the land cover model, City of Bonn (top left). Figure 3b: Low (light) and high (dark) population settlement areas, City of Bonn (top right). Figure 3c: Building footprints in the 3D building model for Germany, City of Bonn (bottom left). Figure 3d: Low (white) and high (black) building density settlement areas in the extent account, City of Bonn (bottom right) (Sources: LBM-DE, Schug et al. (2021), LoD1-DE (BKG), own calculation)

In the land cover model, the main criteria to introduce some measure of continuous urbanity/settlement density is soil sealing and land use. Figure 3a shows this distinction between continuous and non-continuous urban fabric for residential areas for the city of Bonn. However, using this one-dimensional measure, we would group together areas in the town centre with low-rise sub-urban apartments. Clearly, settlement areas also indicate where people, the ‘consumers’ of ecosystem services, live and are highly correlated with various measures of urbanity. Figure 3b shows low and high population density areas. In contrast to soil sealing, high-rise residential areas may lead to high population density in relatively green areas, suggesting that a multi-dimensional approach is needed. Since our classification relies on stable characteristics, we decided to circumvent the use of population estimates and to classify settlements areas based on their structural traits instead, using information on soil sealing, height and footprint (Figures 3c and 3d). Population counts, disaggregated to high-resolution cells, are recorded in the extent account ancillary data.

LULC data allows us to distinguish between residential, industrial and commercial/public settlement areas, a differentiation with important implications with regard to ecosystem service demand in and around these areas. In addition, we harvest information from a 3D building model for Germany (LoD1-DE/BKG), in particular footprint and height, to model building volumes (pre-processing steps).

In the classification steps, settlement areas are characterized as low or high density based on soil sealing and the building volumes (dissolved to the respective land cover geometries). Soil sealing below 90 percent is automatically categorized as low density. All remaining polygons with normalized building volume (*Baumassenzahl*) above (below) a threshold of 4.8 were classified to high (low) density settlement areas, which is in line with how Germany’s federal land utilization ordinance (*Baunutzungsverordnung*) differentiates building areas.<sup>13</sup>

<sup>13</sup> Note that this classification step depends on the final geometry areas in the working file and is therefore inadmissible for pre-processing.

### 5.3 Marine Waters

In line with SEEA EA's recommendations to delineate marine ecosystems within the continental shelf based on the seabed surface, our classification distinguishes different ecosystems based on the seabed, such as 'macrophytes', 'mussel beds', 'reefs', 'sandbanks' and 'other seabed'. Additionally, we implement a structural differentiation based on the distance to shore.



Figure 4: Ecosystem classes in the North Sea (East Frisian Islands) (Sources: LBM-DE, BfN, BfG, National Park Wattenmeer, NLWKN; own calculation)

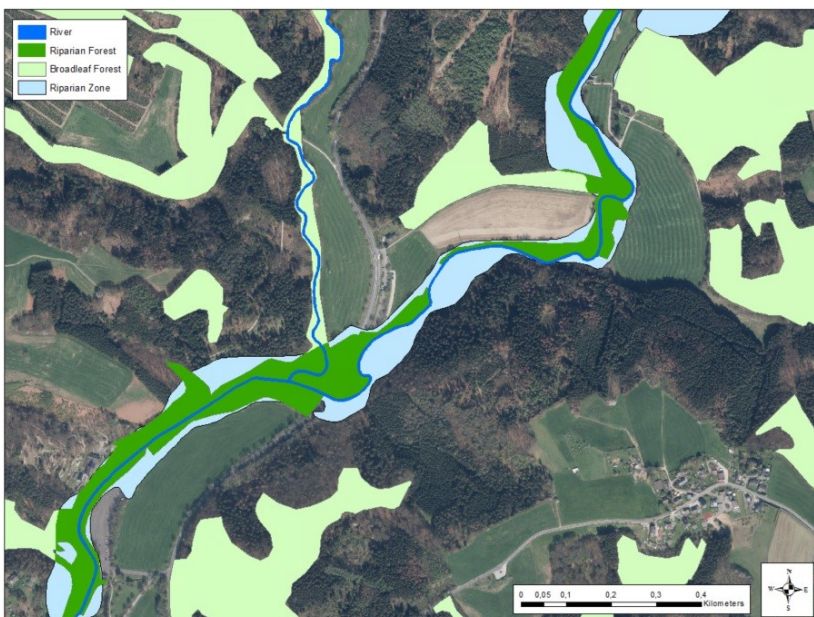
The marine waters ecosystem section also requires additional data sources besides land cover and use for classification. Satellite-based land cover data is not able to cover marine ecosystems well beyond the coastal zones and ecosystem accounting aims to cover even the EEZ, often left out in administrative data sources. It is therefore necessary to build up our own geometries for marine waters.

To do so, we divide them into three zones that are fed from different data sources: coastal areas (within 1 nautical mile from the shoreline), open waters (1-12 nautical miles

from shore) and the EEZ. Close to the coast, the land cover model is very accurate in depicting intertidal flats and we simply add geo-coded information on sandbanks and reefs (mappings for the EU Habitats Directive), mussel habitats (from field surveys), seagrass and green algae (largest yearly extension from aerial footage). Since our inland water mappings are based on the measurement areas of the WFD, we adjust the border between inland and marine waters in the estuaries accordingly. The processing algorithm takes changes in the shoreline over time into account. In open waters, we divide areas using extensions of the WFD areas. The EEZ is constructed using international border geometries for the North and Baltic Sea. Sandbank and reef data are added to both open waters and EEZ. In order to locate anthropogenic influences, we also integrate geometries for wind parks and buffered sea lines.

### 5.4 Broadleaf Forests

The classification of broadleaf forests is an example, where several sequential steps determine the final ecosystem class. Our classification matrix specifies a priority ordering for the four possible classes: 'riparian forests', 'broadleaf bog forests', 'montane and subalpine forests' and 'other broadleaf forests'.



In pre-processing, we intersect broadleaf forest land cover polygons with the 'actual riparian zones' layer (Copernicus Riparian Zones) and with bog areas from the digital landscape model (Basis-DLM) and save the overlapping polygons after dissolving areas smaller than our MMU (1ha). The classification steps use the working file polygons with broadleaf forest land cover and no recorded or timber production land use (candidates) to cut out the respective pre-processed areas for riparian and bog forests.

Figure 5: Classifying riparian forests using riparian zones and land cover data (Sources: LBM-DE, Copernicus Riparian Zones High Resolution Layer, Basis-DLM; own calculation)

We then apply zonal statistics to record elevation measures to the remaining polygons and check if they fall into low mountain/highland areas (*Mittelgebirge*) or the Alps. Based on the landscape and the mean elevation, we use cut-offs at 600 and 900 meters above sea level to differentiate between montane and subalpine broadleaf forests (Leuschner & Ellenberg 2017) and other broadleaf forests. Other polygons with broadleaf forest land cover, but anthropogenic use (for example, adjacent to transport infrastructure) or in settlement areas (*Ortslage*) and partial soil sealing (>15%) are classified to the respective classes, e.g. urban green spaces or port areas.

## 6. Conclusion

The objectives of the extent account are clearly stated in the SEEA EA framework and require compilers to think carefully about the classification and its implementation processes. SEEA EA provides a detailed description of how the classification should combine local context, international reporting standards and available data sources and how the spatial delineation of ecosystem types should be forward-looking to best serve the follow-up accounts for condition and services.

However, compilers may benefit from additional guidance regarding the technical implementation of extent accounts, especially when the extent account is not based on an existent (global) LULC classification and dataset. Teams with limited resources may find it useful to have a growing number of case studies from different contexts at their disposal that lay out the conceptual basis and the technical details.

Implementation guidelines should help to efficiently implement a given classification using as many of the available local data sources as possible by suggesting methods for pre-processing and combining different datasets. This includes guidance on how to unify the area-to-ecosystem mapping and the spatial delineation of ecosystem assets in a single sequential process structure. Additionally, technical advice should focus on automated ways of geo-data processing to facilitate the integration of new and updated data (revisions) and the production of time-series.

There are also elements of the extent account that the SEEA EA touches upon, but that are currently likely to be infeasible for many compilers, including our extent account for Germany. Further research and standardized guidelines in these areas are warranted.

- i) Ecosystem conversion classifications (appraisal, degradation, natural, anthropogenic) are not clearly defined and lack examples of implementation to identify methods and necessary data.
- ii) Categorization by economic use or ownership type requires a high-resolution spatial matching between the extent account and ownership or International Standard Industrial Classification (ISIC) types, which is often either unavailable or under special privacy protection.

A well-defined and standardized technical implementation handbook for ecosystem (extent) accounts can help compilers to maximally exploit the local context and data sources while keeping an internationally comparable and compatible structure.



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