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Review Article

Integrating national and international ecosystem typologies for condition assessments: Principles for typology design and policy alignment

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Abstract

This study presents an overview of the integration of national, European and global ecosystem typologies used in European countries to support ecosystem condition assessments and policy reporting obligations. The aim is to understand the development and integration of ecosystem typologies for assessing ecosystems at national level, both under obligatory EU reporting requirements and beyond, in support of the European Union (EU) implementation of the System of Environmental-Economic Accounting - Ecosystem Accounting (SEEA EA). Based on the review of literature and a comprehensive survey, the progress in ecosystem typologies development, condition assessment and data sources were identified for thirty-one countries (EU27 countries, United Kingdom, Switzerland, Norway and Israel). Additionally, the study provides an overview of European/global ecosystem typologies, habitat classifications and land-cover classification systems, tracing their evolution and highlighting their role in addressing global environmental challenges. National level typologies, constituting around 52% of the typologies identified, were found to be compatible with at least one international typology, such as the European Nature Information System (EUNIS) or the land-cover typology of Coordination of Information on the Environment (CORINE) and the ecosystem typology applied by the EU Mapping and Assessment of Ecosystems and their Services (MAES) initiative. The study discusses principles for designing condition-enabled ecosystem typologies, emphasising the use of ecologically homogeneous classes supported by functional definitions, that are also practical operationalisable at appropriate spatial and temporal scales. It also highlights the crucial role of crosswalks in linking different typologies for international comparability. The integration of national, European/global ecosystem typologies is essential for advancing ecosystem assessment and management efforts, considering their growing relevance in policy- and decision-making within countries and international bodies, such as the United Nations and the EU.

Keywords

ecosystem typologies, ecosystem condition assessment, ecosystem accounting, environmental policy

Introduction

'Ecosystem Typology', in the context of this study, *broadly includes different systems of classification and characterisation of ecosystem types at multiple scales, aiming to record commonly associated habitats, species and other abiotic elements or management aspects*. This includes classification systems developed for habitats, land cover and biotopes - each with distinct purposes and conceptual foundations.

Habitat classifications often focus on biological communities and are species-centric. They describe the environments that support specific organisms or populations. Definitions vary and *habitats* are described as:

1. 'provided by ecosystems for individual species' (Bogaart et al. 2019);
2. 'the place or type of site where an organism or population naturally occurs' (Secretariat of the Convention on Biological Diversity (CBD) 2011);
3. 'a place where plants or animals normally live, characterised primarily by its physical features (topography, plant or animal physiognomy, soil characteristics, climate, water quality etc.) and, secondarily, by the species of plants and animals that live there' (Davies et al. 2004).

These classifications are often grouped in habitat typologies or habitat-based ecosystem typologies, which, while not exactly designed to capture ecological processes, can serve as proxies for ecosystem types in certain contexts.

Land-cover classifications, such as those used in the Coordination of Information on the Environment (CORINE) Land Cover (CLC) dataset, focus on the physical and biological surface characteristics of the Earth, including vegetation, waterbodies and built environments. For example, the EU INSPIRE Directive (European Parliament 2007) defines *land cover* as "the physical and biological cover of the Earth's surface including artificial surfaces, agricultural areas, forests, (semi-) natural areas, wetlands and water bodies”. While Arnold et al. (2023) describe it as a combination of “landscape elements”, such as buildings, trees, roads or waterbodies, along with biophysical characteristics to portray a continuous surface. Although land-cover classifications do not directly represent ecosystems as functional units, they are widely available and spatially detailed, making them a practical starting point for ecosystem classification. In the SEEA EA, land-cover data are often used to disaggregate broad ecosystem types and support spatially explicit assessments of ecosystem extent, condition and ecosystem services (United Nations 2021, Vallecillo et al. 2022).

Biotope is defined as ‘the division of the landscape (a topographic unit) characterised by similar environmental (physical) conditions and a specific assemblage of plant and animal species’ (Dimitrakopoulos and Troumbis 2019). Biotopes focus on species composition and ecological characteristics and are conceptually close to both habitats and ecosystems.

These three classification systems - habitats, land cover and biotopes - are closely related to the concept of ‘ecosystems’ defined as a dynamic complex of plant, animal and micro-organism communities and their non-living environment interacting as a functional unit (United Nations 2021). Due to overlapping features, they may be regarded as “practically synonymous”. Understanding the development of these typologies and how they are used is crucial for assessing ecosystem condition, which refers to the quality of an ecosystem measured in terms of its abiotic and biotic characteristics (United Nations 2021). This understanding also supports biodiversity protection and the sustainable use of natural capital.

European and global ecosystem typologies and classification systems emerged in the last quarter of the 20th century (Fig. 1) as a means to set common habitat definitions for global intergovernmental environmental agreements. The increasing awareness of environmental issues, combined with the availability of digital data and processing capabilities, has supported the development of various habitat-based as well as hybrid land-cover ecosystem typologies, designed to meet environmental assessment and policy needs at national and international levels.

While these systems aim to structure and describe the natural environment, their focus, scope and application differ significantly. Therefore, it is important to distinguish clearly between the related, but distinct concepts, particularly in the context of the System of Environmental Economic Accounting – Ecosystem Accounting (SEEA EA) framework (United Nations 2021). Ecosystem typologies in the SEEA EA are designed to support ecosystem accounting by providing spatially explicit and policy-relevant classifications of ecosystems. These typologies are structured to reflect both ecological characteristics and the capacity to deliver ecosystem services and are typically aligned with land-cover data to ensure spatial consistency (United Nations 2021, Chapter 3).

Ecosystem typologies offer a broader framework for understanding the distribution, condition and trends of ecosystems. In the context of the SEEA EA, *ecosystem types* are considered the main functional units of nature, representing areas where ecosystems share similar ecological characteristics and capacities to deliver ecosystem services (United Nations 2021). These typologies are broader than species-specific habitats – since different species can perform similar ecological functions – and narrower than land-cover types, which may not always reflect functional ecological differences. National-level typologies are generally tailored to reflect the specific ecological contexts of each country, while European/global typologies are designed to allow for regional or global comparisons. Therefore, it is important to understand how international typologies are integrated and adapted at the national level. While distinctions between land cover, habitat and ecosystem typologies are conceptually useful, in practice, they can be seen as complementary approaches to classify ecosystems.

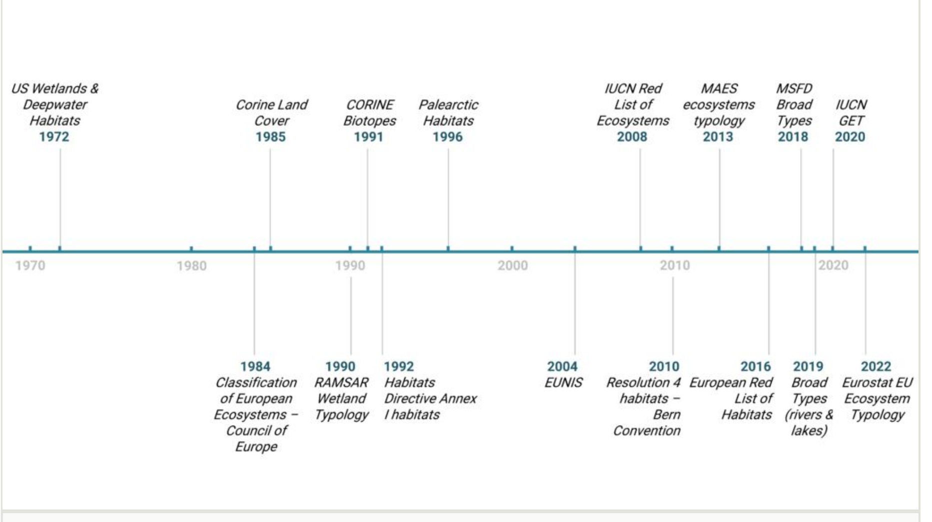


Figure 1.

Simplified and non-exhaustive timeline of ecosystem typology, habitat classifications and land-cover classification development (adapted from Rendon et al. (2023)).

At national level, the diversity in ecological context and policy needs leads to a wide range of typologies. For example, Germany uses detailed classification systems for biotope types, which includes various natural and semi-natural habitat types at Federal State level (Federal Statistical Office (DESTATIS) 2021a). Similarly, France employs a system known as "Zones Naturelles d'Intérêt Écologique, Faunistique et Floristique" (ZNIEFF), which focuses on areas of ecological, faunal and floral importance (Inventaire National du Patrimoine Naturel (INPN) 2016). In Finland, the Finnish Environment Institute (SYKE) has developed a habitat type classification system, which is used for assessing the status of habitats, especially in relation to forest and agricultural lands (SYKE 2019). In contrast, Spain's classification system, called SIOSE (Information System for Land Occupation in Spain), focuses on land-cover and land-use mapping, providing detailed information on various ecosystems within its territory (Spanish National Ecosystem Assessment 2014). Such national systems are often developed in alignment with broader European/global typologies, addressing policy needs such as the EU Habitats Directive (Council of the European Communities 1992), the Mapping and Assessment of Ecosystems and their Services (MAES) (Maes et al. 2013) and European Nature Information System (EUNIS) (European Environment Agency (EEA) 2019).

The integration of national and European/global typologies is a key component for consistent and comprehensive ecosystem assessments, with relevance to policy and decision-making at various levels. Despite the efforts to create interoperable systems, challenges persist in aligning national-level typologies with international frameworks, particularly when adapting to local contexts and specific policy needs. To support this integration, a standardised typology database has been developed within the Ecosystem Assessment Explorer (EASE) tool (Brander et al. 2024) developed in the project 'Science for Evidence-based and Sustainable Decisions about Natural Capital' SELINA (https://project-selina.eu/).

This study aims to present a comprehensive overview of the use and integration of ecosystem typologies in European countries (including the United Kingdom, Switzerland, Norway and Israel). This paper focuses on European and global typologies identified in literature and outlines the results of a survey conducted amongst the partners of SELINA, summarising the ecosystem typologies, relationship with international standards and assessment methods used for ecosystem condition across countries. The survey results are followed by a discussion of the different properties of ecosystem typologies, exploring what makes them more or less suitable for ecosystem condition assessments. This discussion further elaborates on the principles for designing condition-enabled ecosystem typologies and the role of crosswalks in harmonising national and European/ global classification systems.

Materials and Methods

This study was conducted as part of the project SELINA, in particular under Task 3.1 on 'Integrating dataflows to map, assess and test ecosystem types'. Information on ecosystem typologies was collected through two parallel processes, targeting national and European/global typologies, respectively. The national typology survey focused on the evaluation of ecosystem extent and condition at national level and the typologies used for this purpose, while the review of European/global typologies aimed to compile and understand international frameworks used for assessing ecosystems. Additionally, two thematic discussions were held to identify the connections between ecosystem typologies and ecosystem condition assessments. These complementary approaches provided a comprehensive overview of the typologies in use and their integration at different scales.

Survey and data collection

To gather information on national typologies, a structured survey was developed and distributed amongst the project partners in the SELINA consortium in February 2023 (see

Rendon et al. (2023) for details). The primary aim of the survey was to gain insights into the typologies used and the data sources they were built on, as well as to understand how ecosystem condition is evaluated within each country. Responses were provided by scientists and representatives from national authorities involved in national ecosystem assessments or ecosystem accounting efforts. The survey consisted of three primary sections:

Ecosystem Typologies

This section aimed to identify the specific typologies utilised in the countries. Questions covered:

1. the names of the typologies;
2. their spatial/geographical scope (subnational, national or international);
3. compatibility with international classifications (if applicable and specifying which classification systems);
4. existence of linked spatial datasets (ecosystem type maps);
5. key references.

Respondents were asked to specify how the typologies were applied to different ecosystem groups.

Ecosystem condition

This section aimed to capture information on the assessment of ecosystem condition beyond the mandatory assessments required by EU Directives (Habitats Directive (HD), Marine Strategy Framework Directive (MSFD), Water Framework Directive (WFD)). For each ecosystem assessed, respondents provided details on:

1. specific indicators used for assessing ecosystems condition (including defined thresholds or reference levels);
2. methods employed to assess ecosystem condition;
3. software, models or tools used;
4. main reference(s).

Data sources

This section addressed information about data sources used for ecosystem assessments in the respective countries. The following questions were included:

1. name of data sets;
2. data provider;
3. spatial coverage;
4. spatial resolution;
5. temporal resolution;
6. year of first available data;
7. year of latest available data;
8. main reference of data sources.

The data collected from the survey responses, specifically about ecosystem typologies, were analysed and synthesised to compile the information presented in this paper. The responses were consolidated to gain insights into the integration of data flows for ecosystem mapping, evaluation and testing, which, in this context, refers to the application and validation of ecosystem typologies and data integration methods in real-world settings at two SELINA Test Sites (Peters et al. 2025). The main elements of the ecosystem typologies used at national level are summarised in Suppl. material 1, Annex A. Rendon et al. (2023) provides a detailed analysis of the survey results.

Compilation of European/global ecosystem typologies

In parallel with the national survey, a review was conducted to gather information on European/global ecosystem typologies. The review focused on compiling basic information on typology structure and information flows behind them. This is especially important in terms of linking to condition assessments and knowing how this process is undertaken at national level in order to meet EU or global reporting obligations. A database was developed gathering all this information on international ecosystem typologies, which included both those referred to in the national typology survey and additional European/global typologies. The aim of this process was to better understand the role of these typologies in different reporting streams and their links to condition assessments at both national and international level.

The database developed aimed to standardise and organise the collected information on European/global typologies, aligning with the structure of the national survey (Brander et al. 2024). It also facilitated comparisons between national and international typologies in terms of typology structure and crosswalks (correspondences between typologies) and included the information fields:

1. Typology name and type (ecosystem-based, habitat-based, land-cover-based);
2. Structure and hierarchical levels (if applicable);
3. Class labels and codes;
4. Key references for further information.

Additional elements of the database were the existing published ("official") crosswalks (e.g. European Topic Centre on Biological Diversity (ETC/BD) (2015)) showing the relationship between typology classes and the nature of these relationships (where available), allowing classes to undergo a semantic or thematic comparison. This information can also be used as the basis for developing further typologies. The information collected was organised as:

1. source and target typology;
2. crosswalk direction;
3. source and target labels;
4. source and target levels.

This review went beyond the typologies reported by SELINA partners in the national typology survey by providing a broader overview of existing classification systems. Its findings are also intended to support spatial scientists in ecosystem accounting, particularly in assessing ecosystem extent. This was complemented by a parallel exercise focused on crosswalking national and international typologies and mapping ecosystem boundaries.

Thematic discussions

The survey and compilation of the database was followed by structured discussions in break-out groups with the participation of the survey respondents, as well as participants of the SELINA tasks addressing the two main steps of ecosystem condition assessments (i.e. the selection of ecosystem condition variables and the identification of reference levels for these variables). These discussions took place in person at two SELINA workshops (Madrid, 03.10.2023 and Trondheim, 18.06.2024) and their main focus was the identification of the connections between ecosystem typologies and ecosystem condition assessments. In particular, the participants used concrete examples for ecosystem types and assessment contexts, when the two steps of the condition assessment become particularly challenging (or easy), which were then used to identify those aspects of the ecosystem typologies which determine its "suitability" for use in condition assessments/accounting. The lessons from these discussions form the basis of our recommendations.

The ecosystem typologies used in Europe

Survey responses were received from thirty-one distinct countries, comprising the 27 EU countries, the United Kingdom, Switzerland, Norway and Israel. A total of 32 responses were collected, including separate responses from Portugal and The Azores. Most responses provided comprehensive details, offering a broad perspective on the ecosystem typologies and assessment approaches employed amongst participating countries.

From these 32 responses, a total of 42 typologies were identified, including national and European/global
ones. Specifically 24 (52%) have a national scope, 14 (31%) European/global scope and eight (17%) a subnational focus (Fig. 2). This underlines the importance of context-specific typologies for capturing regional ecological nuances, as well as the relevance of international frameworks for broader ecosystem assessments

In the following sections, we present an overview of the main national and European/ global typologies identified in the survey, discussing their use and the commonalities and differences across them. A more detailed overview of the responses received is presented in Rendon et al. (2023).

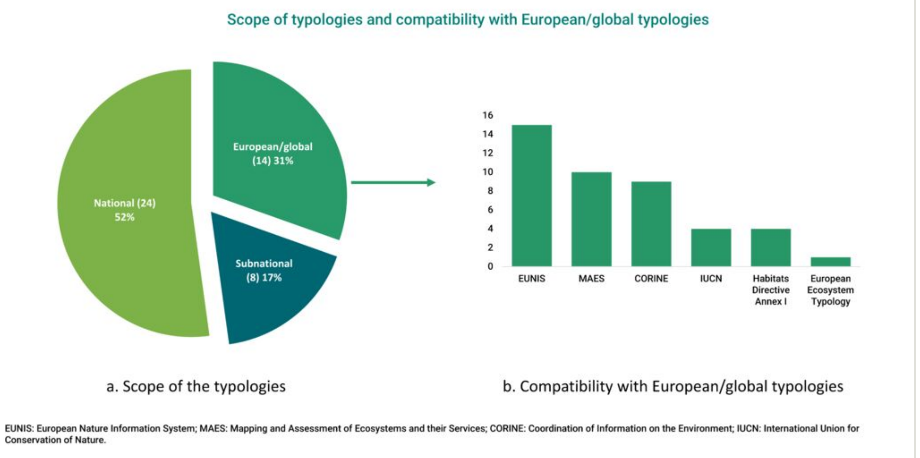


Figure 2.

Scope and compatibility of the ecosystem typologies reported in the survey; the Y axis in Fig. 2b presents the number of respondents (multiple typologies per respondent possible).

National typologies

The national ecosystem typologies reported by respondents varied widely in scope and application. To capture the diversity of typologies in use, respondents were asked to list the ecosystem typologies applied in their country and to classify each as either international, national or subnational. However, no formal definitions of these categories were provided in the survey, which may have led to differences in interpretation. As shown in Fig. 2, the most frequently mentioned category was national (24 mentions), reflecting country-specific systems tailored to national policy and ecological contexts. These typologies are not always comparable across countries.

To better understand how different countries classify ecosystems and utilise ecosystem typologies, we conducted a review and comparative analysis of the national typologies reported in the survey responses. This analysis examines key aspects, including the structural characteristics of the typologies, the data sources and methodologies, their applications and uses (known or potential), their alignment with policy and reporting and the frequency of updates and maintenance. This assessment highlights the diversity of approaches, identifies commonalities and differences across countries and considers the implications for policy and ecosystem management. The results of this analysis are summarised in Suppl. material 1, Annex A.

Fig. 3 provides an overview of these results, grouping the typologies by classification type (ecosystems, habitats, land cover, land use and biotopes) and highlighting their structural features as well as their application and uses.

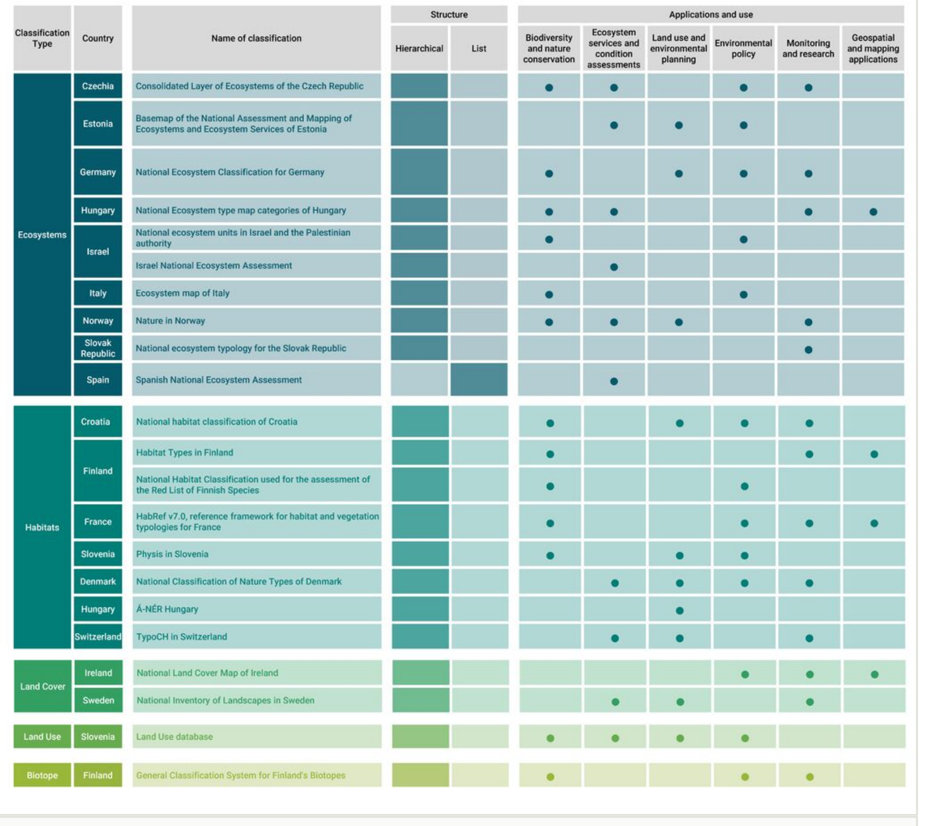


Figure 3.

Overview of national typologies by classification type, structure and application.

Structural characteristics of ecosystem typologies

Across the surveyed countries, two broad types of national ecosystem typologies were reported. The first group includes habitat-based or theoretical typologies such as Hungary's Á-NÉR (Bölöni et al. 2007) and Norwegian Nature Index (NiN) (Halvorsen et al. 2016, Framstad et al. 2022). These are typically high hierarchical, science-driven classification systems that are not tied to a single dataset. Instead, they serve as conceptual frameworks or reference standards for ecosystem classification and are often used in policy, environmental impact assessment and conservation planning. These typologies classify ecosystems across multiple levels, from broad categories (e.g. forests, wetlands, grasslands) to more detailed subtypes, based on ecological variables such as vegetation, hydrology, soil and land use.

The second group includes practical dataset-specific typologies, which are developed for particular applications such as national assessments, monitoring programmes or mapping exercises. These typologies are often linked to specific datasets – sometimes even one-off studies – and may be less hierarchical or more tailored to the structure of the data. Examples include typologies used in forest inventories, waterbody classifications under the WFD (Lyche Solheim et al. 2019) or marine typologies under the MSFD.

Some countries combine their approaches and introduce unique classifications. For instance, Hungary uses a single-level typology (Á-NÉR) structured along two dimensions: vegetation type (defining habitat categories) and naturalness (reflecting habitat quality) (Bölöni et al. 2007). Norway's NiN system is based on three primary axes of natural variation: composition, structure and function (Halvorsen et al. 2016, Framstad et al. 2022)

Other countries emphasise the spatial application of typologies. Czechia employs a four-level hierarchical system integrated with spatial data layers that reflect ecosystem attributes (Nature Conservation Agency of the Czech Republic 2023). Sweden, by contrast, uses a sampling-based approach rather than a continuous national map. In this system, habitat types are assessed, based on their occurrence in sampled plots. While the typology itself is theoretical, the dataset it supports is spatially referenced through sampling (Esseen et al. 2007, Ståhl et al. 2010). Similar sampling-based monitoring systems exists in other countries (e.g. Norway's Area-representative nature monitoring (ANO)) (Framstad and Stabbetorp 2021) and at the EU level (e.g. LUCAS) (EUROSTAT 2017). Unlike most countries, Spain uses a list-based approach rather than a hierarchical structure. The Spanish National Ecosystem Assessment integrates both national and European typologies to identify areas where natural ecosystems are most prominent (Spanish National Ecosystem Assessment 2014).

Data sources and methodologies

Several countries rely on field surveys combined with remote sensing data and national land-cover or land-use databases. These approaches ensure the integration of on-the-ground validation and large-scale spatial analysis. Countries such as Finland, Denmark and Israel further enhance their typologies with ecological and biodiversity inventories, historical records and abiotic environmental variables such as climate, geology and geomorphology (Rotem and Weil 2014, Nygaard et al. 2016, SYKE 2019). Advanced modelling techniques are also used to enhance classification accuracy. Hungary and Switzerland use predictive modelling such as random forest classifiers and ensemble modelling to refine habitat mapping, integrating species distribution models, vegetation indices and Sentinel-2 time-series data (Price et al. 2021, Tanács et al. 2021). In contrast, Norway focuses on species-specific datasets, incorporating species distribution, environmental stress and anthropogenic disturbances to map ecosystems characteristics (Framstad et al. 2022).

Application and use

Ecosystem typologies are widely used across the different countries for creating ecosystem type maps, which are, in turn, used in diverse policy contexts, including spatial planning, biodiversity monitoring and conservation, environmental management and many sectoral policies. Many countries integrate them into conservation strategies, impact assessments, scientific research and ecosystem service assessments.

Some countries leverage ecosystem typologies for specific conservation planning efforts. Finland, for instance, uses them to assess threats to species on the Red List (Hyvärinen et al. 2019), whereas Italy utilises them to compile the national Red List of ecosystems and to guide habitats and species conservation policies at national level (Capotorti et al. 2023). Switzerland and Spain incorporate them in habitat mapping and ecosystem accounting to track biodiversity changes over time (Spanish National Ecosystem Assessment 2014, Huber et al. 2022).

The application of ecosystem typologies extends beyond conservation into policy and decision-making. Germany uses them in national economics and statistical reports (Federal Statistical Office (DESTATIS) 2021b), whereas Ireland integrates them into environmental laws, greenhouse gas emissions tracking and illegal waste detection (Lydon and Smith 2023). Hungary and Slovenia use them for green infrastructure development and spatial planning, with Slovenia further applying them in agricultural policy and land-use compliance (Ministry of Agriculture, Forestry and Food 2022).

EU and international Legal Frameworks

Ecosystem typologies are not only used for ecological classification, but they also play a key role in supporting reporting obligations under multilateral environmental agreements (MEAs) and other policy frameworks. These include the Convention on Biological Diversity (CBD), the Ramsar Convention and the UN Sustainable Development Goals (SDGs). Typologies help structure the information needed for national reporting, monitoring progress towards biodiversity targets and assessing ecosystem condition and extent.

In the EU context, typologies are also applied in support of regional policy instruments, such as the EU Biodiversity Strategy, the WFD and the MSFD - though these are not MEAs in the strict sense. For example, countries such as Croatia, Czechia and Denmark use typologies to report on habitat status under the Habitats Directive and Ramsar commitments. In Estonia and Finland, typologies are embedded in national biodiversity strategies that also address climate adaptation and environmental impact assessments.

While the specific legal and policy instruments vary, a common pattern is the use of ecosystem typologies to organise, standardise and communicate ecosystem information across scales and sectors. This enhances coherence between national monitoring systems and international reporting requirements and supports the integration of ecosystem data into broader sustainability and land-use planning efforts.

Typology updates and maintenance

Unlike datasets or monitoring programmes, ecosystem typologies do not follow fixed reporting cycles. However, they may be updated periodically to reflect advances in ecological knowledge, changes in policy needs or feedback from users. These updates can involve refining classification criteria, adding new ecosystem types or restructuring hierarchical levels.

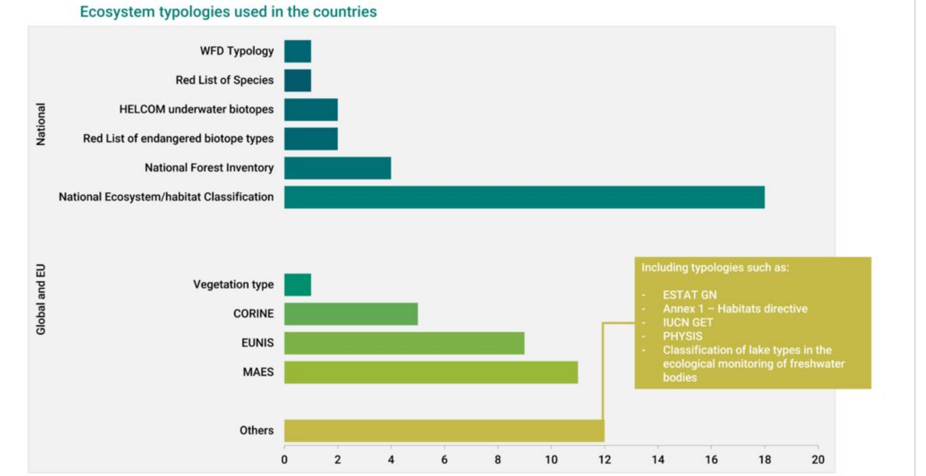
A key aspect of maintaining robust and reusable typologies is the presence of a custodian – an institution responsible for overseeing the typology's development, collecting feedback, coordinating updates and ensuring consistency over time. For example, the NiN is maintained by the Norwegian Environment Agency, while the EUNIS habitat classification is coordinated by the European Environment Agency (EEA) and its thematic centres. In some countries, national environmental agencies or research institutes serve as informal or formal custodians of widely-used typologies. In contrast, project specific or one-off typologies developed for a single assessment or mapping exercise often lack a custodian, which can limit their long-term usability and integration into broader monitoring or policy frameworks.

European and global typologies

European and global typologies, including MAES, EUNIS and CORINE, were also commonly cited, with 13, 10 and six respondents, respectively (Fig. 4). Other less frequently mentioned typologies are the International Union for Conservation of Nature Global Ecosystem Typology (IUCN GET) (Keith et al. 2020) and Habitats Directive Annex I habitat list (2 mentions each). Additional responses included vegetation type, Red List of endangered biotope types, each with varying levels of representation. Other respondents highlighted the utilisation of broader classifications and data sources related to ecosystem assessment, including the European Ecosystem Typology for ecosystem accounting under European Environmental Economic Accounting (Reg. 691/2011) (European Parliament 2011) the Eurostat Guidance Note (ESTAT GN) on ecosystem extent accounts (EUROSTAT 2023) and Land Use, Land Use Change and Forestry (LULUCF).

The selection of European and global typologies was primarily guided by the results of the national level survey. Thus, mainly those typologies were included in the review which were also frequently referred to or incorporated in some way at national level. The MAES Ecosystem typology (Maes et al. 2013), EUNIS habitat classification (European Environment Agency (EEA) 2019) and CLC (European Environment Agency (EEA) 2021) were the ones most frequently referenced by respondents.

European and global typologies are developed and used for harmonising sectoral policies and environmental reporting across countries. As environmental problems are global, effective policy responses also need international coordination. The MAES Ecosystem typology was developed in response to underpinning the delivery of the EU Biodiversity Strategy 2020 for mapping and assessing ecosystems and their services on national territory (Target 2, Action 5 of BDS 2020, European Commission (2011)). An EU-wide ecosystem assessment process was undertaken to harmonise information on ecosystem condition, biodiversity and the capacity of these ecosystems to provide ecosystem services.



WFD: Water Framework Directive; HELCOM: Helsinki Commission; CORINE: Coordination of Information on the Environment; EUNIS: European Nature Information System; MAES: Mapping and Assessment of Ecosystems and their Services; ESTAT GN: Eurostat Guidance Note on Ecosystem Typologies; IUCN GET: International Union for Conservation of Nature Global Ecosystem Typology, PHYSIS: Habitat classification system.

Figure 4.

National and European/global ecosystem typologies reported by the respondents. The X-axis indicates the number of mentions, with multiple typologies possible by country. Note: Some entries (e.g. Red List of endangered biotope types) are not ecosystem typologies per se. The Red List of ecosystems is an assessment protocol that can be applied to any internally consistent classification system. Sector-specific typologies (e.g. forest inventories, WFD, MSFD) are often tailored to individual ecosystem types and may vary by country.

The mapping of MAES ecosystem types is based on EUNIS 2012 level 2 habitat types along with data from CLC as the main spatial reference. However, in practice, the mapping is primarily based on CLC with additional data sources, such as Copernicus high resolution layers, imperviousness information, data from Habitats Directive Article 17 reporting and Natura 2000. MAES was the most frequently reported ecosystem typology described in the survey as 'taken up' at national level. Several survey responses that indicated the use of the MAES framework also mentioned its application in ecosystem condition assessments, thus reflecting its practical relevance and the growing importance of ecosystem condition assessment. Beyond the national survey, Vári et al. (2024) also looked at the format of uptake of MAES for the assessment of different ecosystem types through national projects to meet obligations under EU Biodiversity Strategy 2020. While some countries used the MAES typology for the purpose of fulfilling their reporting obligations, several planned to expand on it with follow-up projects, based on needs identified in the first MAES implementation. Other countries further used the MAES assessment to establish longer-term monitoring projects, thereby supporting ecosystem condition assessment in practice.

The uptake of CLC can be linked to prioritising the spatial delineation of ecosystem extents. It is based on an information system of recording land-cover and land-use data under the Copernicus Land Monitoring Service (CLMS). While originally established as a tool to provide information for environmental policy in relation to land cover, based on extracting information from high resolution satellite images, it is increasingly used to link biodiversity and spatial data for ecosystem accounting purposes. It is also a requirement of the SEEA EA reference framework, adopted by the EU for ecosystem accounting regulation (European Commission 2022), to ensure spatial integrity of ecosystem accounts. Spatial data most commonly used to compile an ecosystem extent account provides an underlying infrastructure for the measurement of ecosystem condition and for the measurement and modelling of many ecosystem services (United Nations 2021). While the national survey showed a strong reliance on the use of national data sources for assessments, the inclusion of CLC and other CLMS is not surprising in terms of being freely available with the potential to fill gaps where national data are not available.

The EUNIS habitat classification system is a comprehensive cascading typology covering the whole of the European land and sea area, which is largely based on classifying natural habitats with traditional phytosociology for terrestrial ecosystems. It can describe broad habitat groups, habitats grouped as mosaics or complete and smaller scale habitats occupying as small an area as 1 m^2. This habitat classification system was the most frequently referenced ecosystem typology as ‘compatible’ with national typologies, along with CLC. While it does not have a spatial component and does not distinguish specifically some level 1 ecosystem groups as distinguished under other typologies (e.g. croplands), the hierarchical framework allows the addition of localised habitat classes at lower levels, making it an ideal framework for categorising natural habitats.

Relationships between EUNIS habitat and other habitat classifications are an important component of the classification. These enable users of national classifications to relate their data to the international level and provide linkages to habitat systems in use in legislation (Moss 2008). The ‘National Inventory of Landscapes in Sweden’ (Ståhl et al. 2010), for instance, is designed to allow compatibility with EUNIS and other land-cover schemes. The Bulgarian assessment programmes for different ecosystem types, for example with heathland and shrub ecosystems (e.g. Velev et al. (2017)), largely adopt the MAES structure and use EUNIS level 2 as the base for the mapping assessment approach.

Beyond their uptake at national level, MAES, CLC and EUNIS form the basis of several other ecosystem products and processes; ecosystem maps, ecosystem typologies and use in specific reporting processes. The Map of European Ecosystem Types first developed in 2006 aimed to combine spatially explicit land-cover information (CORINE) with non-spatially explicit referenced habitat information (EUNIS) (Weiss and Banko 2018) as input to the MAES analytical framework. The European Ecosystem Typology for Accounting developed for the ecosystem extent accounting module is based on MAES, EUNIS and CLC classes and is developed for the purpose of ecosystem condition and services monitoring and reporting (EUROSTAT 2023).

According to survey responses, some countries reported using the IUCN GET to support their ecosystem assessments. This typology was developed to address the growing risk of ecosystem collapse and to support global conservation efforts. It provides a hierarchical classification system that organises ecosystems, based on their functional traits, ecological processes and species assemblages, enabling consistent assessment and reporting across regions and scales (Keith et al. 2020).

An overview of the main European and global typologies allows a better understanding on how and why they were adopted and where commonalities exist between them. Annex B (Suppl. material 2) lists the main typologies and summarises information on scope and coverage, structural characteristics, data sources and methodologies, applications and use, integration in policy and reporting and updates and maintenance.

Scope and coverage

The extent of ecosystem typology is either regional, for example, Baltic Sea area (Baltic Marine Environment Protection Commission - HELCOM) only or European, for example, EU27+UK,or pan-European. In the example of European typologies, these can refer to EU27 only or pan-European, the latter referring to EU27 and countries in the European Environment Information and Observation Network (EIONET). An example of this is EUNIS which covers Turkey (Anatolian Region), for instance. The labels in this field are exactly provided in the main reference (e.g. EU27 or EU27+UK).

Structural characteristics of ecosystem typologies

Some typologies reported are habitat-based typologies where habitats are defined by vegetation structure or species composition. Amongst these, certain systems – such as the Annex I list of habitats under the EU Habitats Directive – serve as policy-driven lists of habitats identified for protection. While these lists are valuable, they are not typologies in the strict sense, as they are not designed to be exhaustive or mutually exclusive – two fundamental principles of classification systems as defined by the Organisation for Economic Co-operation and Development (OECD) standards (Organisation for Economic Co-operation and Development (OECD) 2008).

In contrast, other systems, such as the EUNIS habitat classification, aim to provide a comprehensive hierarchical framework that can accommodate all habitat types across Europe, independent of specific policy mandates. Additionally, land-cover/land-use typologies – such as CORINE Land Cover - are developed with spatial delineation in mind. Recent efforts, such as the development of the European Ecosystem Typology for ecosystem accounting, reflect a trend towards integrating ecosystem-based information with land-cover/use systems. This integration supports more robust mapping and delineation, which, in turn, enhances our ability to assess the condition of ecosystems and their services.

Data sources and methodologies

Data sources and methodologies are a key aspect of typology development, as they reveal both the scientific foundation and the interoperability or each system. For instance, the MAES typology was developed to align with EUNIS and CLC, ensuring consistency across ecosystem and land-cover classifications. CLC itself is based on harmonised earth observation-based contributions from participating countries, offering high-resolution, pan-European land-cover data. EUNIS draws on biological data from the European Vegetation Archive (EVA) and the Waterbodies in Europe – Integrative Systems to assess Ecological Status and Recovery (WISER) database, integrating phytosociological and ecological information. At the global level, the IUCN GET was developed through extensive expert consultation and peer review, ensuring conceptual consistency and scalability across realms and biomes. These examples illustrate how typologies are often built upon one another, forming a network of interoperable systems that support both national and international reporting.

Application and use

The application and use of typologies often extends beyond their original purpose. The Annex I list of habitats under the EU Habitats Directive, for example, is used for reporting conservation status and underpins the Natura 2000 network. CLC supports the Common Agricultural Policy (CAP) and environmental monitoring, while also feeding into typology development such as the European Ecosystem Typology for Accounting (European Commission 2022). EUNIS is used for reporting under the Bern and Barcelona conventions and serve as a foundation for national typologies and the European Typology for Accounting. The LULUCF typology supports greenhouse gas accounting under the United Nations Framework Convention on Climate Change (UNFCCC) and is linked to the Nature Restoration Regulation (European Union 2024) and the EU Biodiversity Strategy 2030 (European Commission 2020). These interconnections demonstrate the flexibility of typologies and how they can be adapted and reused across policy domains, reducing duplication and enhancing coherence.

EU and international Legal Frameworks

Ecosystem typologies are often embedded in or aligned with regulatory frameworks. Annex I is mandated under the EU Habitats Directive. CLC aligns with the INSPIRE Directive and supports multiple EU policies. EUNIS is referenced in the MSFD and the Nature Restoration Regulation. LULUCF is governed by Regulation (EU) 2018/841 (European Parliament 2018). The European Ecosystem Typology is used under the SEEA EA framework for environmental economic accounting. This regulatory alignment ensures that typologies are not only scientifically sound, but also policy-relevant and legally grounded.

Typology updates and maintenance

The updates and maintenance of the typologies vary depending on their regulatory role and institutional support. Annex I habitats are reported every six years. LULUCF data are updated annually. The European Ecosystem Typology for Accounting is planned for a three-yearly reporting. EUNIS has been under revision since 2012, with updates based on new ecological data. HELCOM HUB is updated through periodic Red List assessments, such as those conducted in 2013 and the 2022-2024 cycle. Understanding these timelines is essential for aligning ecosystem condition assessments with reporting obligations and ensuring data consistency over time.

An outcome of this review is the development of a standardised typology database within the SELINA Ecosystem Assessment Explorer (EASE) tool (Brander et al. 2024), which consolidates key information on national and European/global ecosystem typologies in a user-friendly format. This tool enhances transparency, comparability and accessibility of ecosystem classification systems across Europe.

Compatibility of national typologies with European and global typologies

We asked respondents to indicate whether the national or subnational typologies used in their countries were compatible with established international frameworks. In this context, EUNIS and CORINE were the most frequently acknowledged international typologies, with 13 respondents each confirming compatibility. The MAES typology also showed a high level of compatibility, with 10 mentions. Other international frameworks, such as IUCN GET and the Habitats Directive, Annex I were also noted, but less frequently.

International typologies often serve as points of reference when national level typologies are designed, especially in newly-established typologies where compatibility with international policies (reporting use) and established national systems are both desirable. The typology underlying the Ecosystem Map of Hungary, for instance, combines the categories of the MAES and EUNIS systems with the Hungarian Á-NÉR system in a hierarchical classification (Tanács et al. 2021). Another example is the ecosystem map of Italy. Capotorti et al. (2023) provide a review of the first version of this map that was produced for the national MAES assessment in 2016, based on CLC and was updated and improved in 2023.

Fig. 2 provides an overview of the compatibility between national typologies and international frameworks, emphasising the diversity in how countries approach ecosystem classification. The findings highlight variations in the degree of alignment and integration, reflecting the unique methodologies and perspectives adopted by different countries.

Overview of ecosystem condition assessment efforts

Understanding the condition of ecosystems is essential for informed environmental policy and sustainable management. This section provides an overview of ecosystem condition assessment efforts across Europe, highlighting initiatives that extend beyond the requirements of EU Directives. Drawing on survey responses from various countries, it explores the scope, methodologies and data sources used to evaluate ecosystem condition, providing insights into the diverse approaches within the SELINA consortium.

Beyond the EU obligations: Additional assessment of ecosystem condition

The survey enquired about ecosystem condition assessments conducted beyond the obligatory evaluations mandated by EU Directives (e.g, Habitats Directive, MSFD, WFD). A notable 64% of respondents confirmed that such ecosystem condition assessments had been undertaken, while 14% indicated they had not and 21% of the respondents were uncertain (Fig. 5). This variation demonstrates the differing levels of commitment and capacity amongst countries for advancing ecosystem condition assessments.

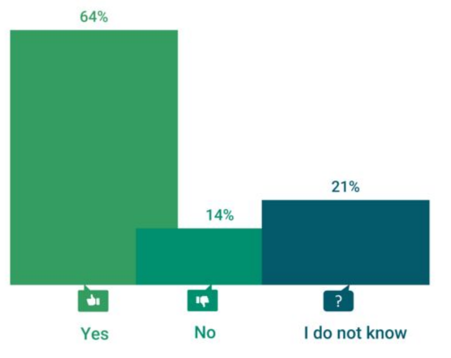


Figure 5.

Ecosystem condition assessed by countries beyond the mandatory EU Directives.

Respondents reported assessing ecosystem condition across a wide range of ecosystem types. The most frequently assessed were woodland and forest ecosystems (mentioned 25 times), followed by croplands (15 mentions), grasslands (14 mentions) and urban ecosystems (11 mentions). Freshwater ecosystems, including rivers and lakes, were also commonly assessed, each receiving 14 mentions. Marine ecosystems — such as coastal areas, shelf ecosystems and the open ocean — were mentioned less consistently, but were still included in several assessments. It is important to note that this question referred to ecosystem types in general, not to specific typologies and respondents could list multiple ecosystems for which condition assessments had been conducted.

Fig. 6 illustrates the variety of ecosystem types evaluated, highlighting the broad scope of assessment efforts across countries. The detailed breakdown provides insights into the ecosystem types most commonly prioritised in condition assessments.

Approaches used in different countries

The methods used for assessing ecosystem condition across the EU varied considerably and were often influenced by both the ecosystem type and the availability of resources. Respondents were asked to report the methods used for each ecosystem type individually, allowing for multiple responses per country. The most commonly reported approach was the use of comprehensive surveys or statistically robust estimates, selected in 61% of cases (Fig. 7), indicating a strong preference for systematic data collection and analysis where feasible. In contrast, extrapolation from limited data (26%) and reliance on expert opinion (10%) were more frequently used in contexts where data availability was constrained. A small proportion of responses (3%) noted that no assessment was possible due to insufficient or unavailable data. These findings reflect the practical realities of ecosystem monitoring, where methodological choices are shaped not only by national capacity, but also by the characteristics and data availability of specific ecosystem types.

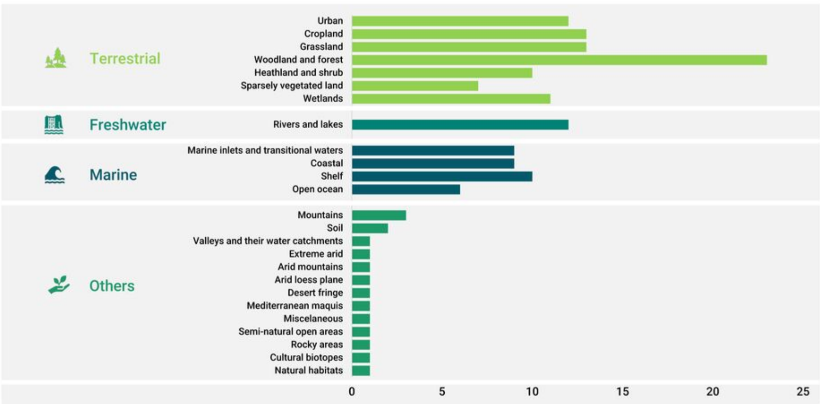


Figure 6.

Ecosystem condition assessments per ecosystem type in the EU.

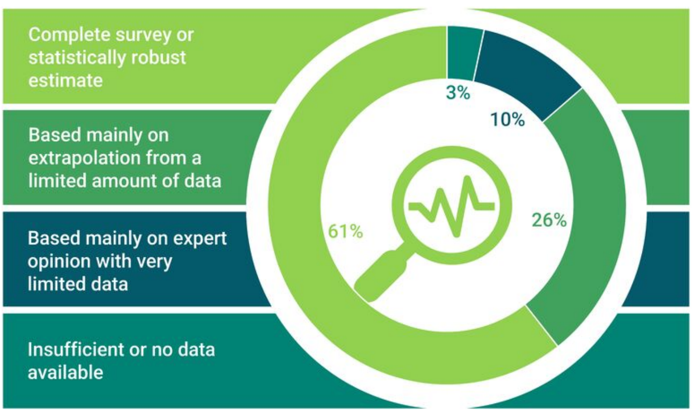


Figure 7.

Types of methods used to assess ecosystem condition across surveyed countries.

Data sources for condition assessments

The survey highlighted a strong reliance on national data sources, with 89% of the sources cited being national. These sources mainly come from environmental agencies, research centres, forest monitoring programmes and statistical offices, reflecting the extensive network involved in data collection. International data sources accounted for 21% of the total, highlighting their complementary role in transboundary assessments or in cases where national data were unavailable. Sources at the European level included outputs from the European Environment Agency (EEA), the Copernicus programme and the Joint Research Centre (JRC). Fig. 8 provides a breakdown of the data sources used for ecosystem condition assessments, emphasising the collaborative and interdisciplinary nature of these efforts within the SELINA consortium.

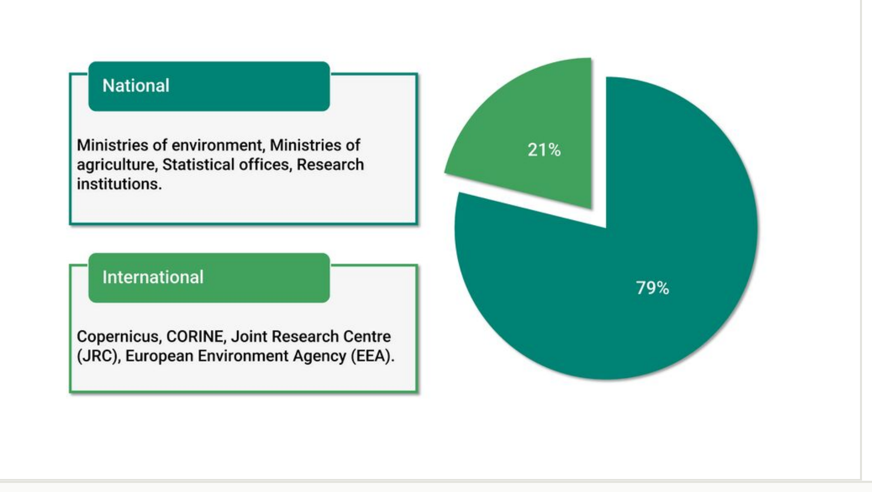


Figure 8.

Data sources for ecosystem condition assessments.

Designing ecosystem typologies for condition accounting

The survey on national typologies revealed a broad diversity of ecosystem typologies being actively used in various policy contexts. Several of the ecosystem typologies mentioned were designed with some type of ecosystem condition/status assessments/ accounting in mind. For example the MAES typology was designed to support the EU MAES assessment (Maes et al. 2020). On the other hand, the “waterbody” typologies developed in the diverse national WFD implementations (e.g. Norwegian Environment Agency (NEA) (2018)) were primarily designed as the main reporting units for the ecological status of freshwater or coastal ecosystems under the WFD.

To uncover which characteristics of these typologies (or any ecosystem typology) make them more (or less) suitable for assessing ecosystem condition, we relied on the outcomes of the thematic discussions in SELINA (see thermatic discussions in the materials and methods section), inspired by the results of the survey. These discussions resulted in a number of concrete points regarding what to aim for and what to avoid in ecosystem typologies, from the perspective of ecosystem condition accounting (Table 1). In the next part of this section, we place these points presenting them in a more comprehensive theoretical context, discussing what they mean for the design of ecosystem typologies. Then we discuss the importance and role of crosswalks in linking the different ecosystem typologies to each other and establishing connections between the individual ecosystem type categories of the different systems.

Table 1.

Main considerations for condition-enabled ecosystem typologies identified in the SELINA WP3 thematic discussions.

Consideration	Description
Considerations for individual ETs	
Fine-scale elements	Very fine-scale land-cover elements (e.g. different types of buildings, roads, trees, hedgerows or forest clearings) should preferably not be used as ecosystem (sub)types (one possible exception is streams and rivers). The frequency (or pattern) of these fine-scale elements can, on the other hand, be considered as condition variables for the embedding ecosystem type.
Miscellaneous categories	Ecosystem typologies should avoid "miscellaneous" classes, where highly different "leftover" categories are grouped together (it is very challenging to identify meaningful condition variables for such a heterogeneous ecosystem type class).
Crop types	Crop types (in particular annual ones, such as "wheat" or "corn") should not be used as ecosystem types or subtypes (this would lead to lots of spurious ecosystem type conversions in the resulting extent accounts). Different management regimes (e.g. arable fields, permanent crops, paddy systems) are much more suitable to be used as subtypes of “croplands”.
Transient types	Transient states of ecosystems (e.g. burnt forest, clearcut forest, abandoned area) should not be used as ecosystem types (this would also lead to lots of ambiguous ecosystem type conversions).
Greenhouses	Large areas densely covered with greenhouses are functionally similar to industrial/ commercial areas (they share the same characteristics as industrial areas), so they should belong there (and assigning them to the same ET class as arable fields or grasslands makes the selection of condition variables and reference levels almost impossible).
Considerations for ET hierarchies:	
Same condition variables	The lower levels of an ecosystem type hierarchy should not differ from their parent ecosystem type in their characteristics (list of condition variables).
Different reference levels	The different hierarchical levels can, however, differ in their reference levels (and the “homogeneity of reference levels” can, in fact, be a useful design principle for hierarchical ecosystem typologies).

Principles for designing condition-enabled ecosystem typologies

As a starting point, all classifications applied in official statistics need to meet two fundamental Aristotelian principles: the set of classes needs to be *exhaustive* and *mutually exclusive* (Organisation for Economic Co-operation and Development (OECD)

2008). Exhaustiveness and mutual exclusivity are also basic principles underlying wall-to-wall categorical maps, where each pixel (location) needs to be characterised with exactly one ecosystem type, without gaps or overlaps, so the requirements of accounting and those of valid geospatial layers coincide.

Beyond these elementary considerations, typologies need to meet several further requirements in order to be fit-for-purpose for ecosystem condition accounting (see Box 1 in Fig. 9 below for a summary of these principles). SEEA EA defines ecosystem types as the main "functional units" of the ecosystems (cf. SEEA EA: 2.6), which also implies that, in a “condition-enabled” ecosystem typology, the main “classes” of an ecosystem typology should reflect the dominant (socio)ecological processes. Ecosystem type categories need to be as ecologically homogeneous as possible, since the selection of condition variables requires *shared characteristics*, i.e. that all instances (“assets”) of the same ecosystem type would be characterisable with the same set of variables and the “ecological meaning” of these variables would not change drastically between the instances. Additionally, the concept of reference condition and reference levels (SEEA EA: 5.62; Czúcz et al. (2025)) also demands ecological homogeneity: for heterogeneous ETs (combining “apples” with “oranges”), meaningful references can become unachievable (what is meaningful for the “apples” will not make sense for the “oranges”). This need for ecological/functional homogeneity also implies that, in condition-enabled typologies, ecological functioning (interactions with physical environment, biophysical properties) should have priority over the economic role (often recorded as land use).

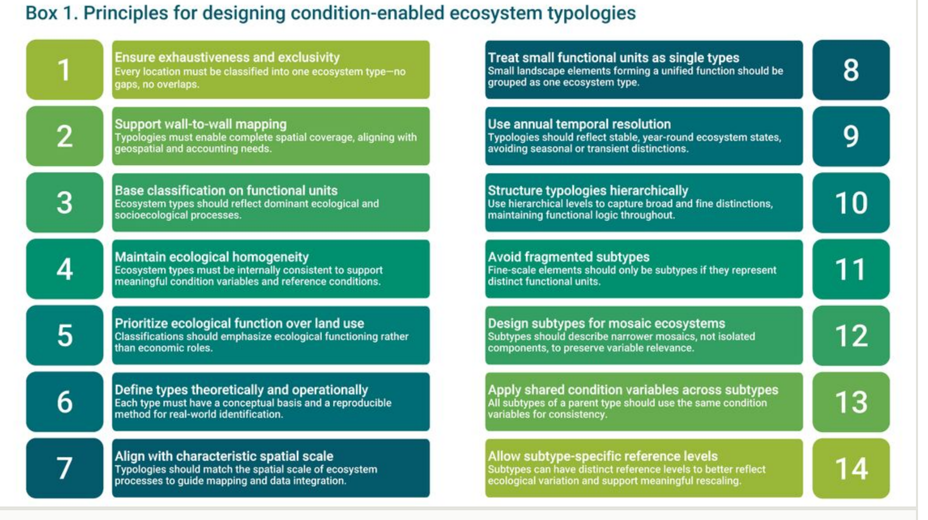


Figure 9.

Box 1. Principles for designing condition-enabled ecosystem typologies.

In addition to the theoretical requirements discussed so far, an ecosystem typology that is useful in condition assessments also needs to be practically implementable. Accordingly, beyond the theoretical considerations linking each class to a particular set of (socio)ecological processes, there should also be a (relatively) objective and reproducible method for assigning a concrete ecosystem type to each "piece" of a real-world landscape and the two should be aligned. In other words, each ecosystem type category needs two types of definition: a theoretical one (linked to ecological theory and functioning) and an "operational definition" (the ecosystem type to concrete observable, measurable properties of the ecosystem). Additionally, this has strong implications on the "scale" of the ecosystem typologies.

While ecosystem typologies do not (typically) have a well-defined spatial resolution, they can still commonly be linked to a characteristic spatial scale at which the ecosystem type categories are defined (and recognisable). For example, a typology that distinguishes trees, grass surfaces, roads and buildings operates at a much finer characteristic scale than one that distinguishes "dense urban fabric" and "urban park". For condition-enabled ecosystem typologies, the characteristic scale at which the ecosystem types are defined should correspond to the characteristic scale of their dominant (socio)ecological processes (sensu Urban et al. (1987)). This characteristic scale can then have a powerful role in the implementation of the ecosystem types in data products (e.g. in the form of mapping rules, for example, minimum mapping units: MMUs) and condition accounts can offer a better way to bring the really small (sub-MMU) elements of the landscape into ecosystem accounts (Payet et al. 2013). In other words, *small surface "elements*" that form a single functional unit (such as streets, gardens and buildings) should also *form a single ecosystem type*, no matter how conspicuous (easy to distinguish) they are and the "internal" patterns and frequencies of these elements (within the ecosystem type) should be addressed in the context of ecosystem condition accounts.

In addition to the characteristic spatial scale discussed above, ecosystem accounting also prescribes a multiannual temporal scale, which also has implications on the meaningfulness of possible ecosystem type categories. Most ecosystems, as well as economic activities have a clear *annual cycle*, which is also respected in accounting as a basic temporal unit (SEEA EA: 2.69). Accordingly, it does not make sense to distinguish sub-annual (e.g. seasonal) "aspects" of the same ecosystem as different ecosystem types (e.g. distinguish the "bare soil" phase and the "crop" phase of an arable cropland as two different ecosystem type categories). This consideration is also in line with ecological theory (functional units are expected to have a considerable resilience and stability) and accounting principles (the stability of ecosystem types is the best way to ensure that *type conversions* always indicate *fundamental permanent changes* - thus delegating the tracking of gradual changes and transient processes to *condition accounts*). In other words, transient phases caused by human management or natural disturbance regimes (e.g. a clearcut or freshly burnt area) should not be recorded as a different ecosystem type, only if it is permanently transformed into something else (e.g. urban sprawl).

Finally, there is an additional set of considerations relevant for hierarchical ecosystem typologies. A hierarchical structure can bring some flexibility (scalability) into the "thematic resolution" (granularity) of ecosystem typologies, which can also be very useful in an ecosystem accounting context. In such typologies, the *top level* (level 1) of the hierarchy should correspond to the main functional differences across (possible) ecosystem types, while ecosystem “subtypes” at lower levels (level 2 or level 3) can be used to delineate finer differences in ecological or land-use processes. Nevertheless, distinctions at all levels of the hierarchy should reflect *functional* differences and the same spatial (and temporal) scales should apply throughout the entire hierarchy. This implies that fine-scale (“sub-MMU”) landscape elements should not be used as ecosystem type categories, even at lower hierarchical levels. One possible exception from this rule is (small) *rivers and streams*, which constitute a (socio)ecologically distinct functional unit with a clearly distinct set of characteristics, even if these habitats are often smaller than the MMUs typically applied in spatial datasets and mapping projects (at least in one dimension).

On the other hand, for an ecosystem type naturally consisting of a mosaic of different fine-scale elements (such as buildings and other “grey” (sealed) and “green” surfaces), the use of these fine scale elements as subtypes can be problematic, as the characteristics (condition variables) that make sense for the mosaic may not make sense for its individual components. In such cases, ecosystem subtypes should also describe the *same mosaic* as the “parent” ecosystem type category, just in a “narrower sense”, resulting in smaller, more homogeneous categories (like “continuous urban fabric” or “urban greenspace” in the EU Ecosystem Typology (EUROSTAT 2024a), which are all defined themselves, too, as mosaics of “grey”, “green” and even “blue” surfaces although in different relative proportions). This simple principle can guarantee that ecosystem characteristics (condition variables) selected at level 1 (which is the main level of selecting condition variables) would also be meaningful and applicable at the lower hierarchical levels.

While the same set of condition variables should apply to *all subtypes* of the same high-level ecosystem type class, the same is not true about *reference levels*. In fact, ecosystem subtypes, if selected wisely, can be a powerful “tool” for making the selection of reference levels and the subsequent rescaling of condition variables both efficient and meaningful (Czúcz et al. 2025). To achieve this, ecosystem subtypes need to identify those groups amongst the diverse occurrences amongst all occurrences of an ecosystem type class, which would look “reasonably similar” in an ideal/natural state (~ reference condition, which is expected to be the natural state for natural ecosystem types; cf. SEEA EA: 5.70). However, this principle can also be useful for designing hierarchical typologies also in semi-natural or anthropogenic ecosystems: if the two instances of a broad ecosystem assume different types of reference (= ”optimal”) states, then they should probably not belong to the same ecosystem subtype.

The role of crosswalks

An ecosystem typology, no matter how well it is designed, is never standing alone. Ecosystems and their main characteristics do not change abruptly at the boundaries of countries or datasets, so it can be expected that the ecosystem types used to describe them would also show some “continuity” across regions, countries and datasets. This is particularly true for typologies designed for use in accounting, because international comparability is one of the most fundamental goals and principles for accounting. However, accounting also has a traditional tool for establishing this expected continuity across different regional or national domains: crosswalks.

Accordingly, crosswalks have a crucial role for ecosystem typologies in establishing reliable connections between the different datasets and national approaches. Major international typologies, such as MAES, CLC and EUNIS, which were also predominantly mentioned in the responses to our survey (the ecosystem typologies used in Europe section), the EU Ecosystem Typology or the IUCN GET typology highlighted by SEEA EA as a "standard" at the global level, can have a particularly important role in this respect. Crosswalking diverse regional datasets/typologies to such central/standard typologies can be an efficient way for establishing an overall coherence across the different ecosystem type classifications applied in the different contexts. Anchoring regional typologies to well-established major ones can also be an efficient way to concretise the definitions of the ecosystem types and this can also open up additional data sources (or even "ready-made" condition variables) for the local context.

In a local context, it is often both feasible and desirable to recognise finer, more subtle distinctions between ecosystem types than what is achievable at a broader (European or global) scale. In an ideal case, the additional refinement required by the local context can be "nested under" the broader categories of a suitable European/global typology, thus reducing the new local/regional typology to an additional extra hierarchical level of the international one. This completely nested relationship (each category of the finer typology is unambiguously connected to a single category of the broader one, in *one-to-one* or *many-to-one* relationships) has many ideal properties, but it is rarely achievable. Nevertheless, it is still important for local/regional typologies to avoid *one-to-many* or *many-to-many* relationships, especially to key typologies used in international accounting systems, because such links will make it difficult to translate the fine-scale results into those shared/international categories. Nevertheless, ecosystem extent and condition accounting are still in an early phase of their implementation and, in this early phase, it still makes sense to explore diverse approaches, to avoid potentially harmful lock-ins in poorly-chosen and strictly-enforced standards. This exploratory approach is also reflected in the relatively flexible guidelines provided by SEEA EA and EUROSTAT about the practical implementation of ecosystem typologies.

A further major consideration for crosswalks is that they should reflect *valid* equivalences between the ecosystem (sub)types of the two typologies compared. Superficial similarities in "ecosystem type names" or short descriptions are not suitable grounds for connecting two ecosystem type categories to each other in a crosswalk. It is always the "content" of the categories that should be decisive. The semantics of ecosystem typologies are often burdened with terminological confusions, for example, if (seemingly) identical labels are used in a different meaning ("jingle" fallacies) or when the same meaning (content) is described under different labels ("jangle" fallacies; see for example, Littell (2018)). Such mismatches are very difficult to spot without a careful analysis of the definitions. Nevertheless, hidden mismatches in crosswalks may lead to serious and difficult-to-detect biases in downstream ecosystem extent and condition accounts. This risk can only be mitigated with carefully validated crosswalks across mutually harmonised typologies.

Policy implications and recommendations

Understanding the diversity of typologies, their scope and structure and how they are used to assess ecosystem condition, allows policy-makers to make informed decisions to promote the sustainability of ecosystems and human well-being. Understanding the role of national and European/global ecosystem typologies at national level is essential for advancing ecosystem assessment and management efforts.

The national typology survey shows both a clear uptake in European/global typologies at national level and a wide use of country-specific typologies. National ecosystem or habitat typologies are likely developed to meet specific reporting needs at national level, ensuring that country-specific habitats are accounted for and, therefore, have a system of surveying, data collection and mapping behind them, often with the input of national experts. These are clearly more informative of the state of ecosystems (extent or condition) on a local level.

Extent accounts present policy-relevant information on changes in ecosystem extent and they are the basis for the compilation of ecosystem condition and ecosystem services accounts (EUROSTAT 2024b). There is clearly a need for a standard approach for translating detailed local level information into a European/global system for condition assessment and reporting. While crosswalks offer a practical solution for linking diverse national typologies to European/global frameworks, harmonisation remains essential for ensuring consistency, comparability and interoperability across countries. The harmonisation of national and European/global ecosystems typologies ensures the full optimisation of the detailed information available on ecosystems and their habitats at national level feeding into the process of EU ecosystem assessment. It also ensures a standardised, wall-to-wall mapping of ecosystem condition across Europe.

At European level, the development of a system of extent accounting, based on the global accounting standard (SEEA EA), highlights the need for spatial delineation of ecosystem extents. The European Ecosystem Typology for Accounting has a hierarchical structure that aligns level 2 with and bases level 3 classes on the EUNIS classification system. This is advantageous due to the existing crosswalks between EUNIS and multiple European/global typologies, including CLC, but also between EUNIS and several national typologies, as seen from the national typology survey (Rendon et al. 2023). Crosswalking ecosystem classes to geospatial data can support the analysis of trends in environmental phenomena, when regularly reported. Under the updated environmental accounts regulation, ecosystem extents will be reported every 3 years.

Adopting a standard approach to extent delineation and accounting can contribute towards harmonising multiple reporting streams that aim to assess some aspect of condition. The streamlining of reporting under, for example, the WFD, the EU Habitats

Directive or the MSFD, has long-been sought. However, due to different reporting requirements, different approaches to assessing condition or lack of temporal alignment, results in this being a complicated process.

One of the key challenges that arises from the comparative analysis of ecosystem typologies across different countries is the diversity in classification approaches. Some countries adopt different hierarchical structures and spatial mapping techniques, whereas others use list-based methods. While this reflects national ecological variations, greater harmonisation and crosswalks would facilitate cross-border comparisons and data interoperability. A standardised yet adaptable framework, aligned with European/ global classification systems, such as the IUCN GET or the European Ecosystem Typology for Accounting, can enhance consistency while allowing for national adaptations.

The variation in data sources and methods further highlights the need for greater integration of remote sensing, field surveys and predictive modelling. Some countries already incorporate advanced techniques, such as machine learning and species distribution models, whereas others rely on traditional fieldwork. Encouraging the adoption of modern geospatial techniques and fostering knowledge exchange on best practices would improve the accuracy and efficiency of ecosystem classification. An EU-wide initiative to establish common data standards and methodologies, aligned with the existing reporting obligations, could strengthen comparability and ensure that classifications are robust and scientifically sound.

Ecosystem typologies play a crucial role in policy applications, yet their integration into decision-making varies significantly. While some countries actively use them in land-use planning, environmental impact assessments and conservation strategies, others have yet to fully incorporate them into their regulatory frameworks. Policy-makers could work towards embedding ecosystem classifications into national biodiversity strategies, economic assessments and climate adaptation policies. Examples from countries such as Germany and Ireland show how typologies can provide information for economic and environmental reporting, setting a precedent for broader implementation across Europe.

Stronger international collaboration is necessary to address the differences in classification structures, methodologies and reporting practices. A coordinated approach for ecosystem typology research and data sharing could improve standardisation. Joint initiatives and collaborative assessments of ecosystem condition and services would enhance data consistency and improve conservation outcomes. Governments and international bodies should consider that ecosystem typologies serve as effective tools for biodiversity conservation, environmental planning and sustainable development.

Gaps and future research needs:

- **Aligning of national reporting**: Irregular reporting frequency and lack of a structured update cycle at national level was identified as a barrier to data availability for wider EU policy reporting. While some countries, for example, Germany and Sweden, follow structured update cycles, others conduct assessments on an ad-hoc basis depending on data availability and policy needs. Implementing clearer reporting mechanisms, with an established update frequency would ensure more reliable long-term monitoring, alignment with the availability of free EU data products (e.g. CLMS) and also aligning with EU policy reporting requirements. Reporting under different policies may also take place by multiple national agencies or federal states, which could prove a barrier to effective communication where needed. Improving national frameworks is, of course, rooted in financial support; however, policy incentives could encourage regular assessments, particularly in countries where reporting is inconsistent. Reliable and timely data are essential for tracking changes in ecosystem condition and to provide information for evidence-based decision-making.

- **Streamlining EU level reporting**: As with the point above on alignment at national level, it would be beneficial to further streamline at European level. Several EU reporting obligations require the monitoring and assessment of ecosystem condition and reporting on similar concepts, for example, reference values or ecosystem condition, but with methodologies developed to meet their own specific policy needs and staggered timelines. Streamlining of reporting can be beneficial where there are synergies between condition parameters and may reduce the burden at national level. It could also better facilitate an EU-wide assessment. Examples of elements are the streamlining of reporting frequency or to connect the needs of national level reporting to the EU-level framework (i.e. identification of data sources to fill gaps in data for wall-to-wall EU mapping). In this context, the design of ecosystem typologies plays a foundational role. Typologies used for condition accounting should be ecologically homogeneous and reflect dominant (socio)ecological processes. They must also be stable over time, avoiding the use of transient states (e.g. burnt or harvested areas) as separate ecosystem types unless they represent a permanent transformation. Such design principles ensure that condition variables and reference levels remain meaningful and comparable across reporting cycles.

- **Harmonisation of ecosystem typology use and development of structured crosswalks**: This initiative has shown the need for harmonisation of ecosystem typologies developed for and used at national, EU and global scale. Several policy frameworks require the reporting on similar elements of ecosystem condition, using different typology frameworks. A standardised process to crosswalk national typologies with EU or global typologies would increase the uptake of European or global frameworks. This could result in multiple benefits at national level, for example, reduction in reporting burden or increased resources for on-the-ground monitoring. However, crosswalks must be based on the actual content and ecological meaning of ecosystem types, not just on label similarity. Superficial matches can lead to semantic mismatches – so-called “jingle” and “jangle” fallacies – which risk introducing biases into condition accounts. Future initiatives should concentrate on developing crosswalks between national and European/global typologies, as well as more recent geospatial data sources with a higher resolution and frequency of update, to facilitate further integration at national level.

- **Improving the knowledge base**: While openly available Earth Observation (EO) data are continuously improving both in terms of temporal and spatial resolution, this process is underpinned by having access to *in-situ* data; biodiversity or habitat mapping. There is an increasing need for observed data through monitoring and surveying to train data models and develop policy-relevant data products for both extent and condition mapping. Equally important is ensuring that ecosystem typologies themselves are operationally defined and scalable. Each ecosystem type should have both theoretical definition – linked to ecological function – and an operational definition – based on observable, mappable features. This dual approach supports the integration of remote sensing and field data and ensures that typologies are both scientifically robust and practically implementable.

- **Improving the knowledge chain**: There is a need to better communicate and promote the suite of data products available to countries to facilitate monitoring and reporting of ecosystem condition nationally. While the national typology survey has raised the issue of data and information gaps for condition assessments, SELINA has shown how the use of open EO data products can be taken up at national level to improve mapping where *in-situ* data are not available and create wall-to-wall ecosystem extent (Rendon et al. 2023). Improving the knowledge chain can facilitate the standardisation of methodologies feeding the EU-wide ecosystem condition assessments.

- **Defining fit-for-purpose typologies**: To support robust condition accounting, ecosystem typologies must balance theoretical soundness with practical applicability. This involves ensuring that classifications are both mutually exclusive and exhaustive, so that every area is uniquely and comprehensively categorised. The structure of the typology should be aligned with ecological functions rather than land use, emphasising the dominant (socio)ecological processes that define ecosystem types. To maintain consistency and avoid confusion, crop types, miscellaneous groupings or transient states – such as recently harvested or disturbed areas – should not be treated as distinct ecosystem types. Instead, typologies should be organised hierarchically, allowing for consistent condition variables across levels, while enabling the use of different reference levels where appropriate. These principles provide a strong foundation for developing typologies that are ecologically meaningful, operationally feasible and capable of supporting reliable ecosystem condition assessments across diverse contexts.

Conclusion

The results highlight the important linkages between national and European/global ecosystem typologies for comprehensive ecosystem assessment and management. The compatibility between national and European/global typologies is hugely significant and this indicates the need for standardised methodologies, compatible with European/global frameworks, to be developed to facilitate comparison of ecosystem data and derive wall-to-wall information on condition assessments for all ecosystem types. Such methodologies should ensure that typologies are ecologically homogeneous, reflect dominant (socio)ecological processes and are structured hierarchically to support consistent condition variables and scalable reference levels.

It is acknowledged that a better understanding of data flows and data sources to facilitate the crosswalking process is a requirement for a more accurate and systematic delineation of ecosystem extents for accounting as a precursor to assessing ecosystem condition. Crosswalks between typologies should be based on the actual content and ecological meaning of ecosystem types, avoiding semantic mismatches. Future steps should focus on developing a standardised methodology to enable comprehensive crosswalking and ecosystem extent delineation and a framework within which to aid with this. A methodology to demonstrate this is proposed in Rendon et al. (2023) and has been tested on two SELINA Test Sites (Peters et al. 2025).

This work provides a basis for further integration of national and European/global ecosystem typologies, which can greatly improve the accuracy and reliability of assessment methods for ecosystem condition. By embedding these design principles into typology development and crosswalk implementation, future efforts can ensure that ecosystem condition accounts are both scientifically robust and operationally feasible.

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Conflicts of interest

The authors have declared that no competing interests exist.
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Supplementary materials

Suppl. material 1: Annex A doi

Authors: Rendon, P., Watson, M., Czúcz, B., Ruf, K., Kleeschulte, S., Santos-Martín, F.
Data type: Description of ecosystem typologies
Brief description: The table summarises the main elements of some national ecosystem typologies used in Europe.
Download file (85.97 kb)

Suppl. material 2: Annex B doi

Authors: Rendon, P., Watson, M., Czúcz, B., Ruf, K., Kleeschulte, S., Santos-Martín, F.
Data type: Description of ecosystem typologies
Brief description: The table summarises the main elements of some European and global ecosystem typologies.
Download file (81.91 kb)