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EU-wide methodology to map and assess ecosystem condition

Towards a common approach consistent with a global statistical standard

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Abstract

The EU Biodiversity Strategy for 2030 calls for developing an EU-wide methodology to map, assess and achieve good condition of ecosystems, so they can deliver benefits to society through the provision of ecosystem services. The EU-wide methodology presented in this report addresses this methodological gap, taking into account the most recent developments on ecosystem condition assessment, such as the global statistical standard on ecosystem accounts.

The EU-wide methodology has adopted the System of Environmental Economic Accounting - Ecosystem Accounting (SEEA EA) as reference framework. The SEEA EA is a spatially-based, integrated framework for organizing biophysical information about ecosystems, adopted as a global statistical standard by the United Nations. The SEEA EA is also the reference framework under the proposal for the amendment of Regulation (EU) No 691/2011 on European environmental economic accounts.

Building on previous work done within the MAES initiative, the EU-wide methodology presents an approach fully aligned with the SEEA EA, to consistently map and assess ecosystem condition in the EU across all ecosystem types. The adoption of the SEEA EA framework offers the flexibility to integrate different data flows, leveraging the use of available EU data, such as data reported by MS under EU legislation and EU geospatial data. The EU-wide methodology presents useful insights to operationalise the SEEA EA at EU level by integrating different EU data streams in a consistent way with this global statistical standard.

The EU-wide methodology proposes comprehensive lists of variables to assess the condition by ecosystem type. The sound application of EU-wide methodology requires the integration of harmonized EU data ensuring spatial and temporal consistency. This poses a major limitation for the integration of data reported by MS under EU legislation related to ecosystem condition, since they are often based on the application of different approaches across MS. In this case, a full integration of MS reported data may be only meaningful at country level.

Moreover, the EU-wide methodology provides recommendations on methods for setting reference levels and thresholds to determine good condition of ecosystems, further discussing related challenges. Defining reference levels and thresholds of good condition appears as an essential, but challenging, task to make ecosystem condition variables comparable and amenable for policy applications.

The implementation of the EU-wide methodology, making use of available data, will provide the scientific knowledge base to support a range of policies and legal instruments. In the future, a consensus should be found between the scientific outcome resulting from the application of the EU-wide methodology and broader knowledge of Member States and relevant stakeholders (i.e. scientific community, NGO's) to better support policy decisions in setting further restoration targets.

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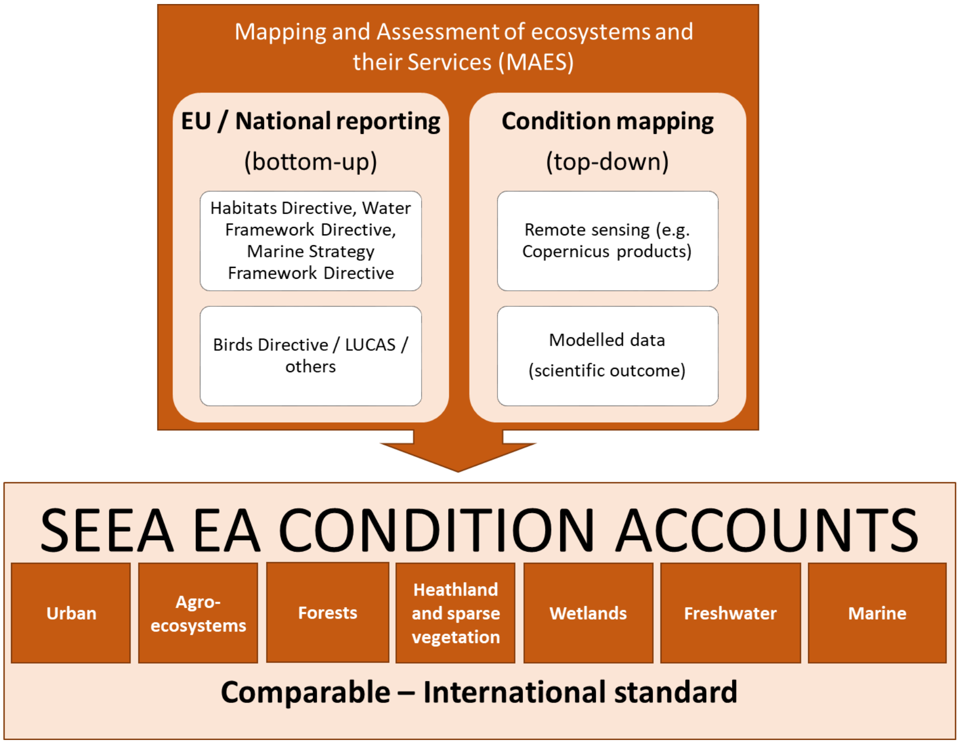
Executive summary

The **EU Biodiversity Strategy for 2030** calls for developing an EU-wide methodology to map, assess and achieve good condition of ecosystems, so they can deliver benefits to society through the provision of ecosystem services. The EU-wide methodology presented in this report addresses this methodological gap, considering the most recent developments on ecosystem condition assessment, such as the global statistical standard on ecosystem accounts.

The EU-wide methodology uses the **System of Environmental Economic Accounting - Ecosystem Accounting (SEEA EA)**[1] as the reference framework. The SEEA EA is a spatially-based, integrated framework for organizing biophysical information about ecosystems, adopted as a global statistical standard by the United Nations. The SEEA EA is also used as the reference framework under the **proposal for a legal module on ecosystem accounts to amend the Regulation (EU) No 691/2011** on European environmental economic accounts[2].

Building on previous work done under analytical framework of Mapping and Assessment of Ecosystems and their Services (MAES), the **EU-wide methodology presents an approach aligned with the global statistical standard on ecosystem accounts (SEEA EA)**, to consistently map and assess ecosystem condition in the EU across all ecosystem types (see figure below).

Potential integration of the EU data flows into the SEEA EA condition accounts by ecosystem type



Source: Own elaboration

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[1] https://seea.un.org/ecosystem-accounting

[2] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2022:329:FIN

The adoption of the SEEA EA, as reference framework to systematically integrate and organise information on ecosystem condition, allows **leveraging the use of data and indicators available at the EU level**. The variables proposed to assess ecosystem condition under the EU-wide methodology are often derived from **EU legislation**, when providing suitable data to inform the assessment. Relevant policies are taken into account for their integration into the SEEA EA framework, including the Nature Directives, the Marine Strategy Framework Directive, the Common Agriculture Policy, the EU Forest Strategy and the EU Pollinators Initiative, among others. In the future, integration of the upcoming proposal for a Soil Health Law is also necessary. The variables of the EU-methodology are also aligned with the indicators suggested in the proposals for a NRL and for a legal module on ecosystem accounts. Likewise, data derived from **EU monitoring programs** such as Land Use and Coverage Area frame Survey (LUCAS) and Copernicus, together with **geospatial data derived from scientific outcome** at pan-European level are also considered.

The EU-wide methodology therefore presents an approach to **operationalise the SEEA EA at the EU level** integrating different EU data stream in a systematic way across ecosystems. The operationalisation of this global statistical standard (SEEA EA) presented by ecosystem type includes (section 4):

1) The proposal of **comprehensive lists of variables to assess the condition by ecosystem type**. The variables selected correspond to six different classes of condition indicators described in the SEEA EA (i.e. physical, chemical, structural, compositional, functional and landscape/seascape) and are based on available data, as well as forthcoming data at multiple spatial scales covering the whole EU territory. In this study, data and knowledge gaps that would need to be filled for a more comprehensive condition assessment are also identified. From the lists of variables proposed, those covering the whole EU territory, with fine spatial resolution, ensuring spatial and temporal consistency, are identified as optimal. This type of data enables a systematic estimation and monitoring, over space and time across the EU of areas that can be considered in good or in degraded condition. Furthermore, optimal data can support the prioritisation of target areas for the implementation of ecosystem restoration measures as well as the identification of effective restoration measures.

Some examples of condition variables proposed in the EU-wide methodology are presented below for ecosystems not sufficiently covered by the Environmental Directives. For these ecosystem types a systematic methodology for the assessment of their condition at the EU level is needed:

- Urban areas (20 variables in total): e.g. imperviousness per inhabitant, air pollutants concentration, tree canopy cover, green space and fragmentation of the green network
- Agroecosystems (26 variables in total): e.g. soil erosion, organic carbon stock in cropland mineral soils, richness of species of the farmland bird indicator, share of landscape features, wild pollinators index and crop diversity
- Forest ecosystems (22 variables in total): e.g. soil organic carbon stock, common forest bird indicator, tree cover density, fire recurrence and forest connectivity.

2) Recommendations of **methods to set reference levels and thresholds to define when an ecosystem is in good condition** based on the selected variables. Defining reference levels and thresholds of good condition is an essential but challenging task to make ecosystem condition variables comparable and suitable for policy applications. There is a need to clearly distinguish different approaches when setting reference levels. Each approach has different implications when it comes to define restoration targets (section 5.4):

- Based on the 'optimal condition': closer to the concept of pristine or intact ecosystems
- Based on 'sustainable thresholds': frequently used for pollutants, based on critical levels or critical loads
- Based on the 'contemporary condition': baseline year in the recent history, frequently used for biodiversity data such as species abundance

Moreover, the **concept of 'good ecosystem condition' is further discussed**, especially for urban ecosystems and agroecosystems (section 1.3). For these **anthropogenic ecosystems**, good ecosystem condition should **guarantee social-ecological resilience** based on the synergies between the ecosystem and requirements of the socio-economic system. Social-ecological resilience should ensure the delivery of a full range of ecosystem services in the long-term, while satisfying societal demand. In this context, definition of reference levels for anthropogenic ecosystems becomes especially challenging.

For some ecosystem types, such as urban ecosystems and wetlands, alternative definitions are available that are more exhaustive and broad, covering some ecosystems already assessed within other ecosystem types. Under these broader definitions, as example, urban ecosystems include forest and agroecosystems in the surrounding of settlements. As for wetlands, in alignment with the Ramsar definition, they also comprise rice fields, wet grasslands and riparian forest, among others. In these cases, to avoid double counting issues, the condition assessment should be considered separately, as a **'thematic' assessment focused on these environmental themes of specific policy relevance.**

The extent of freshwater and marine ecosystems is fully covered by the Water Framework Directive and the Marine Strategy Framework Directive, respectively. These directives follow a similar logic than the SEEA EA framework (i.e. monitor biotic and abiotic parameters of ecosystems, define quantitative reference or threshold values and aggregate indicators to determine condition or status). Therefore, the ecosystem status reported by Member States for these ecosystem types can be considered as equivalent to the concept of ecosystem condition. However, there is still room for a better alignment between the assessment of environmental status under the MSFD and the ecosystem condition assessment under SEEA EA (section 4.6). The **case study for marine ecosystems** shows that the application of the SEEA EA framework incorporates physical condition variables, currently absent in the Marine Strategy Framework Directive. Physical condition variables provide valuable information on the impacts of climate change on the condition of marine ecosystems (e.g. acidification, sea temperature rise).

The sound application of the EU-wide methodology requires the integration of harmonised EU data characterized by spatial and temporal consistency. This poses a major **limitation for the integration of data reported by Member States under EU legislation related to ecosystem condition.** Under the Habitats Directive, there are still knowledge gaps at the EU level about the attributes monitored by Member States for the reporting of habitat condition (i.e. as measured with the 'structure and functions' parameter). Moreover, methods used for the reporting can vary across countries, lacking spatial and/or temporal consistency across the EU (section 5.1). In this context, a full integration of Member State data used for the reporting may be only meaningful for single-country assessments. Member States could further investigate the potential integration and alignment of data collected for the Habitats Directive reporting into the SEEA EA condition accounts. This integration is not meant to replace the current assessment under the Habitats Directive, but to see to what extent available data can inform and supplement the condition assessment based on the global statistical standard. As shown for a case study in Greece, in-situ monitored data for the reporting of habitat condition under the Habitats Directive can be integrated into the SEEA EA framework. In-situ monitored data provide very detailed information on ecosystem condition, which can also be useful for mapping.

The implementation of the EU-wide methodology, making use of available data, will provide the **scientific knowledge base to support a range of policies and legal instruments**. In the future, a consensus should be found between the scientific outcome resulting from the application of the EU-wide methodology and the broader knowledge of Member States and relevant stakeholders (i.e. scientific community, NGO's) to better support policy decisions in view of setting further restoration targets.

Most frequent acronyms

BD – Birds Directive
CAMS – Copernicus Atmosphere Monitoring Services
CAP – Common Agriculture Policy
CAPRI – Common Agricultural Policy Regionalised Impact
CBD – Convention on Biological Diversity
CFP – Common Fisheries Policy
CLC – CORINE Land cover
CMEMS – Copernicus Marine Environment Monitoring Service
EASIN - European Invasive Species Information Network
ECT – Ecosystem condition typology
EEA – European Environment Agency
EMEP – European Monitoring and Evaluation Programme
EMODnet – European Marine Observation and Data Network
ETC – European Topic Centre
GBF – Global Biodiversity Framework
HD – Habitats Directive
HRL – High Resolution Layers
IAS – Invasive Alien Species
IUCN GET – International Union for Conservation of Nature Global Ecosystem Typology
JRC – Joint Research Centre
LUCAS – Land Use and Coverage Area frame Survey
LULUCF – Land Use, Land-Use Change and Forestry
MAES – Mapping and Assessment of Ecosystems and their Services
MS – Member State
MSFD – Marine Strategy Framework Directive
N – Nitrogen
NDVI – Normalised Difference Vegetation Index
NFI – National Forest Inventories
NRL – Nature Restoration Law
P – Phosphorous
SEEA EA – System of Environmental-Economic Accounting Ecosystem Accounting
SER – Society of Ecological Restoration
SET – Socio-ecological-technological system
SWF – Small Woody Features
WISE – Water Information System for Europe
WFD – Water Framework Directive

1 General background

1.1 General policy context

The **EU Biodiversity Strategy for 2030**, in the context of the EU nature restoration plan, call for developing an EU-wide methodology to map, assess and achieve good condition of ecosystems, so they can deliver benefits through ecosystem services they provide, such as climate and water regulation, soil health, pollination and disaster prevention and protection (European Commission, 2020). DG ENV commissioned DG JRC to coordinate the development of the aforementioned methodology, in collaboration with the European Environment Agency (EEA) and the European Topic Centres (ETC). In this context, the objective of this report is to provide an EU-wide methodology to map and assess the condition of all ecosystems in a consistent way across the EU. It is meant to support the proposal for a regulation on nature restoration (the **Nature Restoration Law (NRL)** adopted by the Commission in June 2022[3]) and the implementation of the EU Biodiversity Strategy for 2030 as a whole.

In parallel to the proposal for the NRL, Eurostat has developed a proposal for an **amendment of the Regulation (EU) No 691/2011 on European environmental economic accounts** to include a new module on ecosystem accounts based on the United Nations (UN) System of Environmental-Economic Accounting Ecosystem Accounting (SEEA EA) (United Nations, 2021). The **proposed legal module on ecosystem accounts has been adopted by the Commission in July 2022**[4]. When the amendment is approved by the European Council and Parliament, the SEEA EA will be the reference framework for EU MS to report country-level accounts for ecosystems extent, condition and services on a regular basis. It is an important preliminary step to start conveying biodiversity into socio-economic sectors and greening investment[5] as required under the European Green Deal.

The EU-wide methodology constitutes an upgrade and a formalisation of the MAES methodology[6] in alignment with the SEEA EA. Therefore, this study contributes to the implementation of the EU Biodiversity Strategy for 2030, more concretely in support to the Regulation on nature restoration, but also of the amended Regulation on European environmental-economic accounts. The EU-wide methodology makes the best use of available and forthcoming data at multiple spatial scales covering the whole EU territory, and integrates them into a standardised framework that allows making sound comparisons across ecosystem types. It also identifies which data and knowledge gaps need to be filled for a more comprehensive condition assessment.

The mapping and assessment of ecosystem condition reported over time, as proposed under the EU-wide methodology, may also contribute to a better integration of relevant spatial information in support to building synergies with the revised **Regulation on Land Use Land-Use Changes & Forestry (LULUCF) (EU) 2018/841**. In this sense, the identification of areas in need of restoration may provide valuable information to find win-win solutions between ecosystem restoration measures and the enhancement of carbon sequestration and/or storage, becoming more cost-effective measures.

Moreover, the regular assessment of ecosystem condition may also provide relevant information and indicators in support to the reporting under the **8th Environmental action programme** and **the Sustainable Development Goals (SDGs).** Indeed, indicators used for the assessment of ecosystem condition at EU level can also be used to

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[3] https://environment.ec.europa.eu/publications/nature-restoration-law_en

[4] Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Regulation (EU) No 691/2011 available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2022:329:FIN

[5] The Taxonomy Regulation (EU) 2020/852 to be used by investors and businesses when investing in projects and economic activities that have a substantial positive impact on the climate and the environment,

[6] See MAES https://ec.europa.eu/environment/nature/knowledge/ecosystem_assessment/index_en.htm

monitor some of the objectives proposed worldwide, such as biodiversity restoration and the enhancement of natural capital.

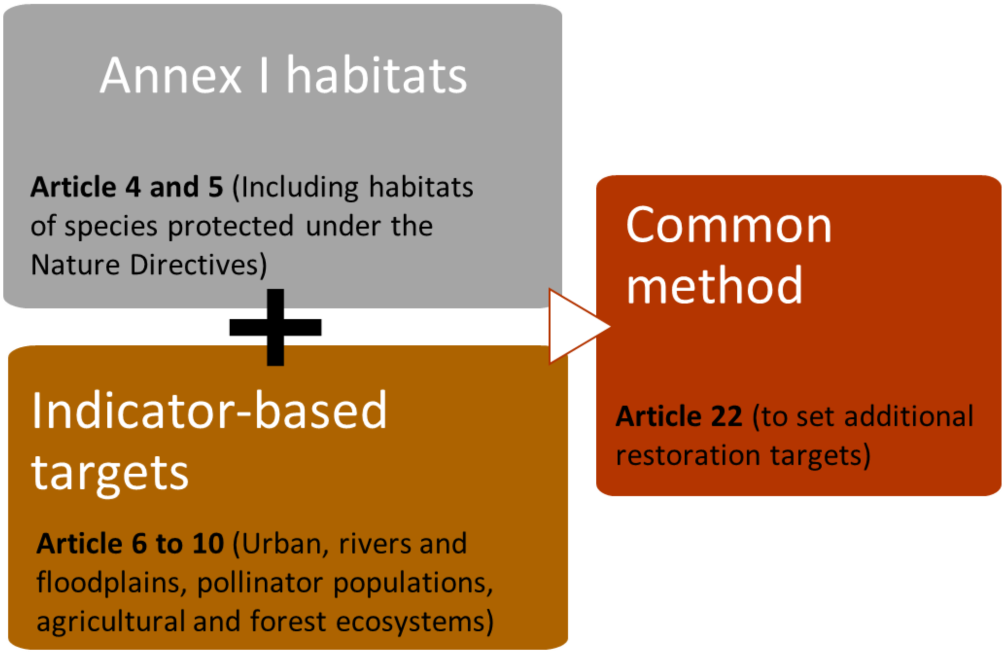
1.2 The Nature Restoration Law

The objective of the proposal for a **Nature Restoration Law** is to contribute to the continuous, long term and sustained recovery of biodiverse and resilient nature across the Union's land and sea areas. More concretely, the specific objective of this proposed Regulation is to **restore degraded ecosystems across the EU to good condition by 2050**, and put them on the path to recovery by 2030.

The proposal for a **NRL is setting restoration targets for habitat types protected under the Habitats Directive (HD),** as well as for habitats of the species protected under the HD and **Birds Directive (BD)** (Figure 1). Restoration measures for terrestrial, coastal, freshwater and marine[7] (Article 4 and 5) ecosystems shall be put in place to improve to good condition areas of habitats of concern and re-establish them when required. MS shall monitor the condition of habitats, and prove that they continuously improve and do not deteriorate.

Beyond habitats protected under the HD and BD, the **NRL proposes indicator-based targets** (Article 6 to 10) to monitor the implementation of restoration measures for ecosystems and species beyond the Nature Directives (HD and BD), i.e. urban ecosystems, rivers and floodplains, pollinator populations, agricultural and forest ecosystems (Figure 1). There, MS will need to prove an increasing trend for a set of specific indicators as required in the legal proposal of the NRL.

Figure 1. Approach to define restoration targets for all ecosystem types under the proposal of a Nature Restoration Law



Source: Own elaboration

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[7] For marine ecosystems, restoration targets will be also defined beyond Annex I habitats of the HD and BD

In addition, **the NRL foresees the development of a common method for assessing the condition of ecosystems not protected under the Nature Directives** (Article 22). A methodology to assess condition for these ecosystems at EU level is not yet fully developed. To cover the current methodological gap, a process is established in the NRL proposal for developing an EU-wide methodology that will allow for a more complete and comprehensive coverage of ecosystems in the long term. At a later stage, **the implementation of the EU-wide methodology, making use of available data, will provide the scientific knowledge base to support the definition of new restoration targets, when required by the NRL**. It will take into account the latest scientific evidence to define good condition of all ecosystems making use of already available data on ecosystem condition such as those derived from pan-European monitoring schemes (e.g. under Forest Europe) or the Copernicus Programme.

1.3 Concept of ecosystem condition

Ecosystem condition is the quality of an ecosystem measured in terms of its abiotic and biotic characteristics (United Nations, 2021).

Ecosystem condition is often assessed by measuring the **similarity (or distance) of a current ecosystem to a reference state**, such as an intact or undisturbed ecosystem, or minimally impacted by people or a historical state (Costanza et al., 1992; Palmer & Febria, 2012). Ecosystem condition is also often combined with measures of ecosystem extent, to provide an overall picture of the quantity (i.e. extent) and quality (i.e. condition) of ecosystems.

Under the SEEA EA, and based on ecological principles, the description of ecosystem condition is strongly rooted in the concept of **ecosystem integrity, which implies an unimpaired condition of being complete or undivided** (Karr, 1993). Ecosystem integrity is defined as the ecosystem's capacity to maintain its characteristic composition, structure, functioning and self-organisation over time within a natural range of variability (Pimentel et al., 2000; United Nations, 2021). Traditionally, the notion of ecosystem integrity as defined above mainly relates to natural ecosystems (i.e. unimpaired condition) (Martin & Proulx, 2020) and therefore, ecosystem condition can be considered as equivalent to the concepts of naturalness and intactness, which are also used to describe the distance of an ecosystem from an (undisturbed) reference state (Anderson, 1991).

Therefore, **good ecosystem condition** will be considered when it presents good physical, chemical, and biological condition, or good physical, chemical and biological quality with self-reproduction or self-restoration capability, in which species composition, ecosystem structure and ecological functions are not impaired (cf. definition of the Taxonomy Regulation (EU) 2020/852[8]).

Since humans have modified or replaced natural ecosystems over large parts of the globe, including the EU, the measurement of ecosystem condition also needs to be suitable for anthropogenic ecosystems, but also for semi-natural ecosystems whose existence fully depends on human activity (e.g. semi-natural grasslands). The **identification of reference states for ecosystems that otherwise would not exist without human**

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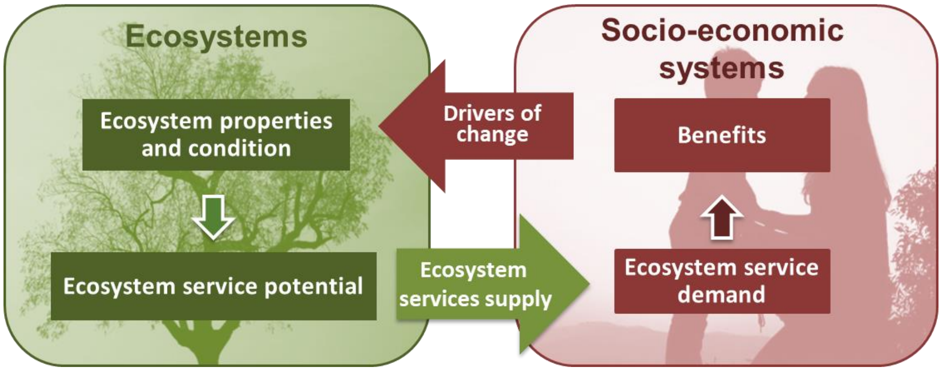
[8] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32020R0852

intervention for their maintenance, cannot be defined as a natural or minimally disturbed state, because these ecosystems, by definition, rely on human action and therefore need to be disturbed. Therefore, the measure of ecosystem integrity (or good ecosystem condition) should not be only oriented towards naturalness (Martin & Proulx, 2020). For instance, in the case of semi-natural grasslands, management (e.g. grazing) plays a key role in the maintenance of the biotic and abiotic characteristics typical of those ecosystems. Therefore, in this case, management measures should be considered as an integral part of these ecosystems, and therefore of their reference state.

For anthropogenic ecosystems, **good condition is expected to bring long-term social-ecological resilience**, which should be considered when identifying reference states for these particular ecosystems. Social-ecological resilience is the capacity to adapt or transform in the face of change in social-ecological systems, particularly unexpected change, in ways that continue to support human well-being (Chapin et al., 2010). By adopting a social-ecological resilience approach, we bring a stronger focus on the interactive feedback between social and ecological systems (Biggs et al., 2015). The conceptual framework presented in Figure 2 shows the relationship between ecosystems and socio-economic systems. Ecosystems provide services to society contributing to human well-being, while socio-economic systems drive changes in ecosystems with positive and/or negative impact on their condition. A good ecosystem condition for anthropogenic ecosystems should ensure an equilibrium between both systems (i.e. positive feedback between them). This implies the maintenance of the composition, structure and function of ecosystems, so they can ensure the delivery of a full range of ecosystem services in the long-term, while satisfying societal demand (at local and global level).

Figure 2. Conceptual framework for EU wide ecosystem assessments



Source: modified from Maes et al. (2013)

Condition of urban ecosystems and agroecosystems are further discussed in section 1.3.1 and 1.3.2, respectively. Although anthropogenic ecosystems are embedded into complex socio-ecological systems, the assessment of their ecosystem condition is focused on the ecological dimension and not on the overall condition of these complex systems.

1.3.1 Condition of urban ecosystems

Urban ecosystems are defined as socio-ecological or socio-ecological-technological systems (SETs), where technological components refer to artificial structures and processes (e.g. buildings and waste generation). Conceptualising urban ecosystems as SETs is consistent with the most recent urban ecology paradigm (McPhearson et al., 2016), which integrates humans and their processes as part of the ecosystem. As such, the definition of ecosystem condition provided by the SEEA EA requires some adjustments for urban ecosystems.

Urban areas are anthropogenic ecosystems where human intervention and occurrence are a dominant element (Alberti, 2010). Consequently, urban ecosystem condition, and its underpinning concepts of ecosystem integrity, resilience, and health should embed the human dimension, and its social and technological components. Therefore, urban ecosystem condition should include the ecological dimension as well as key aspects of its interaction with the social and technological dimensions.

Urban ecosystems lack an unimpaired reference condition (or undisturbed state) due to their artificial essence. To overcome this limitation, urban ecosystem health and social-ecological resilience might be assessed based on a comparative assessment between independent urban ecosystem assets or their potential scenarios. Concurrently, a healthy urban ecosystem should satisfy societal demand for ecosystem services while guaranteeing the delivery of services in the long term. Furthermore, since urban ecosystem condition is highly influenced by the human component, the concept of good condition may vary over time and across different geographic regions and cultures.

In the case of urban ecosystems, striving for a better condition is not only related to enhancing its long-term supply of ecosystem services, but it should also be balanced with human population demand of ecosystem services from urban ecosystems themselves and outside them up to sustainable levels.

Consequently, since urban ecosystems are human modified by definition, the establishment of reference condition and the definition of good urban ecosystem condition should be further investigated in a later stage with the implementation of the EU-wide methodology.

1.3.2 Condition of agroecosystems

Agroecosystems are ecological systems created by human activity with the primary objective to produce food, feed, fibre and energy, and are true socio-ecological systems. They originate from the interaction between socio-economic and ecological processes with the objective to produce biomass for human use and consumption. It is recognized that the process of agricultural intensification is accompanied by high and increasing environmental costs. This concerns not only the negative impacts on air and water quantity and quality, soil health, and other parts of the ecosystem (plant, fungi and animal species including soil biota and above-ground species), but as well depletion of natural resources. Thus, besides impacting on other ecosystems (e.g. causing chemical and nutrient pollution), intensification processes often lead to degradation of agroecosystems, decrease their resilience to climate change and in the long term jeopardises their capacity to generate biomass and healthy food for human use and consumption.

Based on such awareness, the EU Green Deal and several of its initiatives (e.g. the EU Biodiversity Strategy for 2030, the Farm to Fork Strategy and the Zero Pollution Action Plan) set, among targets for EU agriculture, the improvement of the balance between farming and nature: agricultural production should be achieved non-depleting land, air, soil, water, plant and animal health and welfare, and releasing pressures on biodiversity so to foster its recovery.

The concept of ecosystem condition for agroecosystems should be embedded in these considerations and legislative requirements. The strict definition of ‘good ecosystem condition’ (cf. definition of the Taxonomy Regulation (EU) 2020/852, see above) can only be applied to natural grassland ecosystems. The rest of agroecosystems are not characterised by self-reproduction or self-restoration capability since they are transformed by human action. However, the ecosystem processes and functions on which agricultural production is based, should be characterized by a self-reproduction or self-restoration capability. Therefore, ‘good condition of agroecosystems’ should be intended as a state characterized by a regenerative, non-depleting and non-destructive use of natural resources. Good condition is resulting from sustainable management of biotic and abiotic resources; it supports biodiversity and ecosystem functions, processes and structure. Moreover, a good condition is the foundation for the supply of critical ecosystem services, including food provision, carbon sequestration and soil, water and climate regulation.

1.4 EU initiatives assessing ecosystem condition

1.4.1 Environmental EU legislation related to ecosystems condition

Different concepts related to ecosystem condition are described under some EU environmental directives, assessing diverse aspects of ecosystems and their biodiversity as summarised below.

The Habitats Directive (HD) (Directive 92/43/EEC[9]) was the first law that came into force in the EU in 1992, requiring MS to report on habitat/ecosystem status. In the HD, 'habitat conservation status' is assessed based on a set of **four parameters**: 1) range, 2) area, 3) structure and functions, and 4) future prospects. **Only the parameter 'structure and functions', including typical species, is considered under the HD in terms of habitat condition[10]**, which is defined in the HD as '*the specific structure and functions which are necessary for its long-term maintenance exist and are likely to continue to exist for the foreseeable future*'. The 'structure and functions' parameter is assessed based on the ecosystem area in good or not-good condition, its trends and the presence of typical species. There are different methods to determine the ecosystem area that is in good condition (or not), including surveys or statistical analysis, data interpolations, or expert opinion when data are very limited. In the habitat assessment, in general terms, if 90% of habitat area is considered as in 'good' condition, then the status of 'structure and functions' parameter is 'favourable'. If more than 25% of the habitat area is reported as 'not in good condition', then the 'structure and functions' parameter is 'unfavourable-bad'. For many reported habitats, their condition is 'unknown' and there is currently no method for gap filling when 'unknown' condition is reported.

The reporting of area in good, not-good or unknown condition has been introduced since the latest reporting period (2013-2018) to better identify priorities for restoration. However, each country has developed their own guidance on assessing the condition of habitats at the site/stand level, which leads to a lack of consistency in the way habitat condition is measured across the EU territory. Currently, there is no review available of condition parameters measured across MS, but the Commission is working on these lines to compile relevant information and improve harmonisation among MS for monitoring and assessing habitat condition.

The Water Framework Directive (WFD) (Directive 2000/60/EC[11]), adopted in 2000, defines '**surface water status'** based on two components: 1) '**Chemical status**' to refer to the environmental quality standards for annual average and maximum allowable concentrations of certain chemical substances; 2) '**Ecological status**' referring to the quality of the structure and functioning of aquatic ecosystems. Determination of the ecological status is based on assessment of physico-chemical, hydromorphological and biological quality elements (aquatic assemblages). Ultimately, **surface water status is determined by the poorer status of either the ecological or chemical status**. A monitoring network has been designed to provide a coherent and comprehensive overview of ecological and chemical status within each river basin, permitting the classification of water bodies into **five classes**: bad, poor, moderate, good and high. Definition of good chemical or ecological status is made on the basis of type-specific reference conditions for surface water body types, since the same quality targets cannot be achieved for all types of water bodies (e.g. heavily modified water bodies require different reference conditions). Although there are currently different ecological assessment methods across the EU, an inter-calibration of methods has been carried out to ensure comparability of the ecological status assessment in the EU (e.g. Poikane et al., 2014) and boundary values have been established Commission Decisions (EU) 2007/589 and 2018/229.

In the Marine Strategy Framework Directive (MSFD) (Directive 2008/56/EC[12]), adopted in 2008 and currently under review, the concept used is '**environmental status**' and it is a measure of **ecological diversity, health and productivity of marine waters**. The MSFD and its Decision defining Good Environmental Status foster the

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[9] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:31992L0043

[10] From here onwards, we refer to 'habitat condition' of the HD including the 'structure and functions' parameter and typical species.

[11] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32000L0060

[12] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32008L0056

coherence and re-use of information monitored and reported under other directives, such as the WFD for coastal waters, the HD for some biodiversity elements or the Common Fisheries Policy for commercial fish stocks. It should avoid duplications and ensure consistency of approaches. **Environmental status relies on eleven qualitative descriptors**: 1) biodiversity, 2) non-indigenous species, 3) population of commercially exploited fish and shellfish species, 4) food webs, 5) eutrophication, 6) sea-floor integrity, 7) hydrographical conditions, 8) contaminants, 9) contaminants in fish and seafood for human consumption, 10) marine litter, and 11) energy and underwater noise. These descriptors are common for all countries and are the basis to determine the environmental status of marine waters and for the setting of environmental targets to achieve or maintain good status. However, within each descriptor a set of criteria[13], indicators and methodological standards shall be agreed among all interested parties to ensure consistency and to allow for comparison between marine regions or sub-regions of the extent to which good environmental status is being achieved. Reviews of the criteria and indicators used in all countries were performed to further ensure consistency in the approaches (e.g. Palialexis et al., 2019; Queirós et al., 2016), contributing to Commission Decision (EU) 2017/848 on criteria and methodological standards on the definition of good environmental status.

In conclusion, **there is no single EU-wide methodology to assess ecosystem condition that can be applied in a consistent way to all ecosystem types**. The evolution and gradual adoption of environmental legislations on the protection of nature, freshwater, the marine environment, but also other legislative frameworks related to agriculture, forestry and fishery have resulted in different and tailored assessment frameworks.

1.4.2 EU ecosystem condition assessment under MAES

The EU initiative of **Mapping and Assessment of Ecosystems and their Services (MAES)** was set up in 2011 to **address Action 5 of Target 2 of the EU Biodiversity Strategy to 2020**. An operational framework was developed by the members of the MAES Working Group in collaboration with policymakers and researchers that has been described in a series of MAES reports[14]. MAES set an analytical framework linking ecosystems and biodiversity to people through drivers of change and ecosystem services. The **fifth MAES report presents a typology for pressures and ecosystem condition** (third column of Table 1), showing a selection of indicators per ecosystem type to assess the pressures and condition (Maes et al., 2018). Importantly, **MAES promotes a spatially explicit approach for the mapping and assessment of ecosystem condition** to support the decision-making on setting priorities for ecosystem restoration. However, MAES also acknowledges the need to integrate other complementary indicators to provide a more comprehensive assessment of ecosystem condition.

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[13] Distinctive technical features that are closely linked to qualitative descriptors

[14] https://ec.europa.eu/environment/nature/knowledge/ecosystem_assessment/index_en.htm

Table 1. Key ecosystem attributes – broad types to assist the evaluation of the biotic and abiotic properties and functions of an ecosystem in support to the assessment of ecosystem condition

	SEEA Ecosystem condition typology	Key ecosystem attributes (Society of Ecosystem Restoration)	MAES pressures and ecosystem condition typology
	Not included (can be covered by other classes)	**Absence of threats** (Direct threats to the ecosystem such as overutilization, contamination, or invasive species are absent)	**Pressures** (e.g. habitat conversion and degradation, invasive alien species, pollution)
Group A: **Abiotic ecosystem characteristics**	Class A1. **Physical state characteristics**: physical descriptors of the abiotic components of the ecosystem (e.g. soil structure, water availability)	**Physical conditions** (Environmental conditions, including the physical and chemical conditions of soil and water, and topography, required to sustain the target ecosystem are present)	**Environmental quality** (physical and chemical)
	Class A2. **Chemical state characteristics**: chemical composition of abiotic ecosystem compartments (e.g. soil nutrient levels, water quality, air pollutant concentrations)		
Group B: **Biotic ecosystem characteristics**	Class B1. **Compositional state characteristics**: composition / diversity of ecological communities at a given location and time (e.g. presence/abundance of key species, diversity of relevant species groups)	**Species composition** (Native species characteristic of the appropriate reference ecosystem are present, whereas undesirable species are absent)	**Structural ecosystem attributes** (incl. species diversity and abundance & soil attributes)
	Class B2. **Structural state characteristics**: aggregate properties (e.g. mass, density) of the whole ecosystem or its main biotic components (e.g. total biomass, canopy coverage, annual maximum NDVI)	**Structural diversity** (Appropriate diversity of key structural components, including demographic stages, trophic levels, vegetation strata and spatial habitat diversity are present)	
	Class B3. **Functional state characteristics**: summary statistics (e.g. frequency, intensity) of the biological, chemical, and physical interactions between the main ecosystem compartments (e.g. primary productivity, community age, disturbance frequency)	**Ecosystem function** (Appropriate levels of growth and productivity, nutrient cycling, decomposition, species interactions, and rates of disturbance)	**Functional ecosystem attributes** (incl. soil attributes)
Group C: **Landscape level characteristics**	Class C1. **Landscape and seascape characteristics**: metrics describing mosaics of ecosystem types at coarse (landscape, seascape) spatial scales (e.g. landscape diversity, connectivity, fragmentation)	**External exchanges** (The ecosystem is appropriately integrated into its larger landscape or aquatic context through abiotic and biotic flows and exchanges, facilitated by connectivity)	**Landscape mosaic**

In 2020, the MAES framework was operationalised with the best available data and results were published in the first EU Ecosystem Assessment (Maes et al., 2020a). The EU Ecosystem Assessment covers the total land area of the EU (wall-to-wall) as well as the EU marine regions. It constitutes a knowledge base and data foundation for future assessments and policy developments, in particular with respect to the ecosystem restoration agenda for the current decade (2020-2030).

The EU MAES Ecosystem Assessment presents an in-depth trend analysis of pressures and condition of terrestrial, freshwater and marine ecosystems using a single, comparable methodology based on data gathered at EU level. The year 2010 was used as a policy baseline against which changes in pressures and ecosystem condition were evaluated. The report was a first and necessary step to better describe and understand trends of ecosystems. However, it was highlighted that **subsequent work is needed to define reference conditions** to compare the past, current or future condition of ecosystems and to decide, in a later stage, on threshold values required achieve good condition of ecosystems.

The EU MAES Ecosystem Assessment makes use of a full set of available European datasets to provide a comprehensive assessment of ecosystem condition based on an integration of different data streams: 1) **EU reporting on ecosystem status and habitat condition (EU environmental legislation)**, and 2) **Spatially-explicit data for the condition mapping**. An important property of the MAES initiative is that **geospatial wall-to-wall data, with frequent and regular time series, are preferred for the mapping and assessment**. In this sense, the MAES approach makes frequent use of scientific modelled outputs or Copernicus products, among others. Copernicus is the European Union's Earth observation programme that has been specifically designed to monitor the Earth and its environment in support to sustainable management. Copernicus provides very valuable information for the assessment of ecosystem condition. Although Copernicus products do not represent a very large percentage of the indicators used in the EU MAES ecosystem assessment, data are very valuable in terms of their spatial resolution and coverage, with relatively frequent temporal updates.

2 International standard on ecosystem condition accounts

This section summarises relevant aspects of the System of Environmental Economic Accounting - Ecosystem Accounting (SEEA EA), adopted by the United Nations (UN) Statistical Commission as international standard for ecosystem accounts. The SEEA EA includes a dedicated, generic framework for ecosystem condition accounts where a systematic method is defined to account for the condition of different ecosystem types and changes in their condition over time in a spatially explicit way.

2.1 What is the SEEA EA?

The SEEA EA is a **spatially-based, integrated statistical framework for organizing biophysical information about ecosystems**, tracking changes in ecosystem extent and condition, measuring ecosystem services and possibly valuing ecosystem services and assets to link this information to measures of economic and human activities. It has been developed by a multidisciplinary group of international experts to make visible the contribution of nature to the economy and people, and better record the impacts of economic and other human activity on the environment (United Nations, 2021).

The SEEA EA is a key reference framework also considered in the proposal of headline indicators of the monitoring framework for **the post-2020 Global Biodiversity Framework (GBF)[15] under the Convention on Biological Diversity (CDB)[16]**. Although the short-term focus of the post-2020 GBF in using SEEA EA is on ecosystem extent and services, information gathered for ecosystem condition accounts will also support the reporting to monitor some of the proposed targets and goals.

The SEEA EA has also been used as reference document to include the definition of 'good ecosystem condition' in the **EU Taxonomy Regulation (EU) 2020/852[17]**, which supports the establishment of a framework to facilitate sustainable investment for sustainable economic activities.

The fundamental units of SEEA EA accounts are ecosystem assets, which are spatially contiguous areas that can be considered as internally homogeneous with respect to ecosystem type, condition and service flows. Data on ecosystem assets are summarised in five core accounts (see Annex 1 for further information):

1. **Ecosystem extent accounts** record the total area of each ecosystem, classified according to a well-defined typology within a specified area (ecosystem accounting area). The extent accounts of ecosystem accounting areas (e.g. nation, province, river basin, protected area, etc.) are measured over time by ecosystem type, thus quantifying the changes in extent from one ecosystem type to another over the accounting period.

2. **Ecosystem condition accounts** record the condition of ecosystem assets in terms of selected characteristics at specific points in time. They record the changes of condition over time, and provide valuable information on the integrity (health) of ecosystems.

3. & 4. **Ecosystem services flow accounts** (physical and monetary) record the supply of ecosystem services by ecosystem assets and the use of those services by economic units, including households.

5. **Monetary ecosystem asset accounts** record information on stocks and changes in stocks (additions and reductions) of ecosystem assets. This includes accounting for ecosystem degradation and enhancement.

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[15] https://www.iucn.org/resources/issues-brief/post-2020-global-biodiversity-framework-0

[16] https://www.cbd.int/

[17] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32020R0852

Moreover, the SEEA EA also anticipates a set of accounts that may be appropriate for specific environmental themes, which are known as **thematic accounts**. They are used to better organise data on themes of specific policy relevance (e.g. focus on a more targeted area). Thematic accounts are also relevant for the condition accounts (further details on section 4.1 and 4.4).

2.2 Key concepts to build ecosystem condition accounts under SEEA EA

The SEEA EA provides a generic framework on how countries can report the size and condition of their ecosystems. The guidelines, principles, typologies, and methods developed by the SEEA EA can be used globally, and thus also in the EU. This approach is adopted as reference framework in the ecosystem accounts module amending the Regulation (EU) No 691/2011[18].

The development of ecosystem condition accounts requires first to delineate different ecosystem types, in which ecosystem condition will be measured.

An **ecosystem type** reflects a distinct set of abiotic and biotic components and their interactions. The SEEA EA proposes the **IUCN global ecosystem typology (IUCN GET)** to classify ecosystems (Keith et al., 2020a). The IUCN GET is a hierarchical classification system that, in its upper levels, defines ecosystems by their convergent ecological functions and, in its lower levels, distinguishes ecosystems with contrasting assemblages of species engaged in those functions. It consists of six levels: Level 1 - realms, Level 2 - functional biomes, Level 3 - ecosystem functional groups, Level 4 - biogeographic ecotypes, Level 5 - global ecosystem types and Level 6 - sub-global ecosystem types. The SEEA recommends in general terms the use of Level 3, although for national and subnational accounting, but also for anthropic ecosystems, finer levels of classification will be required. Each ecosystem functional group (level 3) shares common ecological drivers which promote convergence of the biotic traits that characterise the group.

SEEA EA discriminates among ecosystem characteristics, ecosystem condition variables and ecosystem condition indicators:

- **Ecosystem characteristics** refer to the ecosystem properties and its major abiotic and biotic components (water, soil, topography, vegetation, biomass, habitat and species) with examples of characteristics including vegetation type, water quality and soil type;
- **Ecosystem condition variables** are quantitative metrics describing individual characteristics of an ecosystem asset. Ecosystem condition variables are thus ecosystem characteristics that are measured using specific units of measure;
- **Ecosystem condition indicators** are rescaled versions of ecosystem condition variables between 0 and 1. Usually they are rescaled between a lower level that corresponds to ecosystem collapse and an upper level that corresponds to the state of a reference ecosystem.

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[18] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02011R0691-20220220

2.3 How the SEEA EA accounts for ecosystem condition?

The SEEA EA describes a three-step approach to assess ecosystem condition:

- **Step 1: Defining and selecting characteristics and variables of ecosystem condition**. To this end, the SEEA EA technical guidance provides assistance in the form of **an ecosystem condition typology** and criteria to select an appropriate set of ecosystem variables (Czúcz et al., 2021a; Czúcz et al., 2021b). The SEEA EA guidance also contains an indicative list with ecosystem condition variables.

- **Step 2: Defining reference condition and/or reference levels.** A reference condition is the condition against which past, present and future ecosystem condition is compared to in order to measure relative change over time. A reference level is the value of an ecosystem condition variable at the reference condition.

- **Step 3: Defining aggregate indices of ecosystem condition.** Ecosystem condition indices and sub-indices are composite indicators that are aggregated from the combination of individual ecosystem condition indicators.

2.4 SEEA EA ecosystem condition typology

The SEEA ecosystem condition typology (ECT) is a hierarchical typology for organizing data on ecosystem condition characteristics, which may be available at different spatial scales, from plot level in-situ monitoring to data at country or at the EU level. It can be used as a template for variables and indicators selection and provides a structure for aggregation. The ECT also establishes a common language to support increased comparability among different ecosystem condition studies. The SEEA ECT has six classes as listed in Table 1.

SEEA ECT is comparable with other classifications used to assort ecosystem characteristics (Table 1): the key ecosystem attributes of the Society for Ecological Restoration (SER) (Gann et al., 2019) and the MAES hierarchical structure and classification of pressure and condition indicators (5th MAES report, Maes et al. (2018)). The **SER typology describes six key ecosystem attributes** (Table 1) that can be used to describe the reference ecosystem. Together, these six attributes contribute to the overall ecosystem integrity (Gann et al., 2019).

The **MAES classification distinguishes between pressures and condition indicators** for environmental quality (which express the physical and chemical quality of ecosystems) and ecosystem attributes (which express the biological quality of ecosystems in terms of their structure and function) (Table 1). It has been used to structure the ecosystem condition indicators used in the EU ecosystem assessment (Maes et al., 2020a), where also landscape indicators such as the land mosaic have been included.

Pressures under the SEEA EA: although SEEA ECT does not contain a separate class for pressures on ecosystems, the ecosystem condition typology is sufficiently flexible to host variables that report pressures on ecosystems as alternatives for variables that directly measure the condition. For example, air emissions or pesticides use can be reported under chemical state; soil sealing or sea level rise can represent physical state variables; and data on introductions of invasive alien species can be reported under composition state. If there are little data available on state, then measures of pressures on ecosystems can be considered a useful surrogate, as long as the relationship between the two is well understood and justified (Bland et al., 2018). Apart from a different approach to consider pressures, **the SEEA ECT and the SER typology are closely aligned**. **Both classifications consider physical, chemical, compositional, structural and functional characteristics as essential elements for measuring the state of an ecosystem. They also both reckon the importance of how ecosystems are embedded in the land- and seascape and connected to ecosystems of the same or another type**.

2.5 SEEA EA reference condition and reference levels

A **reference condition** is a condition against which past, present and future ecosystem condition is compared to, in order to measure relative changes over time. It represents the condition of an ecosystem that is used for setting the upper reference level ('optimal' endpoint) of ecosystem variables, reflecting high ecological integrity.

A **reference level** is the value of a variable against which it is meaningful to compare past, present or future measured values of the variable (as also required to determine status under the HD, and also WFD and MSFD).

The SEEA EA proposes a list of possible methods for setting reference levels. The list below shows the methods proposed by the SEEA EA (a detailed description of these methods is provided in Annex 3):

1. Identification of reference sites: minimally-disturbed condition ('pristine' ecosystems with no or minimal human disturbance)
2. Modelled condition: for instance potential vegetation models, historical condition[19]
3. Statistical methods based on ambient distribution:
    a. Least-disturbed condition: the currently best available condition of an ecosystem
    b. Best-attainable condition: expected condition of an ecosystem under best possible management practices and attaining a stable socio-ecological state
4. Prescribed reference levels
5. Contemporary condition: making use of a baseline year (recent history)
6. Expert opinion
7. Combination of methods listed above

In the context of the EU-wide methodology, it is also highlighted the need to make a distinction of different types of prescribed reference levels depending on the criteria used to define them:

a. Based on scientific criteria (e.g. critical loads of eutrophication)
b. Based on policy targets/thresholds (e.g. exposure of agricultural areas to ozone at 6 000 μg/m^3)
c. Absolute physical boundaries (e.g. zero nitrogen surplus)

Among the methods listed above, perhaps the most intuitive one is the **identification of reference sites as pristine or minimally-disturbed locations**. The condition found in these areas is then used to define the upper reference level (e.g. high condition score) for each variable to identify which areas are closer to the 'natural state' and therefore present high ecosystem integrity. This approach is especially **suitable for natural ecosystems.** If this method is also applied to semi-natural ecosystems created by human management (e.g. semi-natural grasslands), then, the extensive management contributing to the maintenance of the ecosystem should be considered as an historical integral part of the ecosystem. As such, the required management measures to maintain the biotic and abiotic characteristics typical of those ecosystems have to be also considered when defining their '(semi-) natural state'.

For anthropogenic ecosystems other methods to set reference levels have to be identified that fit better the needs of such particular ecosystems. Possible methods are statistical approaches to identify the best-attainable condition that would be expected under the best possible management practices, or the condition in a baseline year, among others.

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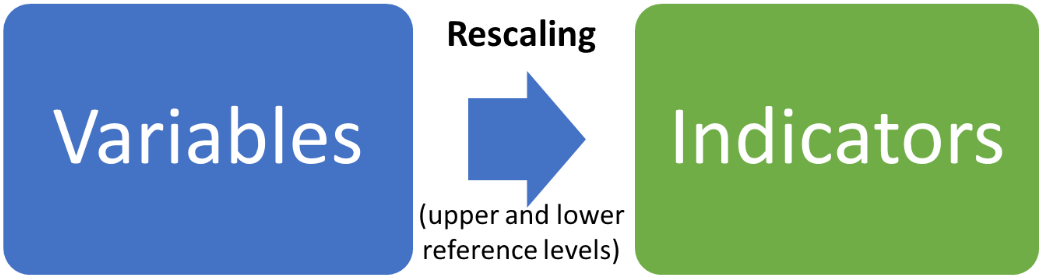
[19] 'Historical condition' has been included as part of the modelled condition due to the lack of data at EU level on historical condition

The strengths and weaknesses of each of these methods to set a reference needs to be defined before a consensus on reference levels can be found (see Annex 5.2 in United Nations (2021) for a detailed description of options for establishing reference conditions). The rationale for selecting the reference condition or levels should be properly described and justified.

Reference levels are usually set as intervals, with high and low values reflecting the limits of the range of a condition variable that can be used in re-scaling (upper and lower reference levels). Upper level may refer to an optimal (or desirable) state (based on the reference condition) and the lower level may refer to a degraded state where ecosystem processes cannot maintain their functions (ecosystem collapse). The value of the reference levels is used to re-scale the variables to derive the condition indicators (Figure 3), using equation 1.

Figure 3. Deriving ecosystem condition indicators from variables



Source: Own elaboration

$$Condition\ indicator = \frac{(\mathrm{V-VL})}{(\mathrm{VH-VL})} \qquad \text{[Equation 1]}$$

Where:

- V is the measured/observed value of the variable,
- VH is the high condition value for the variable (upper reference level),
- VL is the low condition value (lower reference level).

If the value of the variable is larger than or equal to the high condition value, then the indicator takes value of one. If the values of the variable are smaller than or equal to the low condition value, then the indicator takes value of zero. Reference levels are fixed over the whole time series accounted for.

If reference levels for the proposed variables are not set, the condition accounts would only provide a 'neutral reporting' showing information about the direction of the change of the condition variable: whether it is increasing or decreasing. However, it would not provide evidence on how far is the current condition from being considered good. The importance of selecting reference levels is also highlighted by the SER as a key principle of ecosystem restoration: 'Principle 3: Ecological restoration practice is informed by native reference ecosystems, while considering environmental change'. Therefore, **defining reference levels is highly needed when setting restoration priorities**.

2.6 SEEA EA aggregation of ecosystem condition indicators

Through the application of Equation 1, ecosystem condition indicators are available at the same dimensionless [0-1] scale, which makes their aggregation technically straightforward. Nevertheless, the **aggregation of indicators into condition indices is optional within the SEEA EA**. The need of providing a final aggregated ecosystem condition index will **depend on the specific policy requirements**. Aggregated condition index can be useful to develop a high-level policy index of ecosystem condition and its changes; whereas looking at individual condition variables and their trends allows identifying the correct actions for improving ecosystem condition. In this sense, the SEEA EA makes a proposal of a hierarchical approach to aggregation reflecting the structure of the typology of the indicator classification. Ultimately, aggregation as suggested by SEEA EA is only possible when variables are rescaled between 0 and 1 (condition indicators).

3 Towards a common EU-wide methodology

3.1 Comparison of EU approaches to assess ecosystem condition

The EU-wide methodology to map and assess ecosystem condition, based on the previous work done under MAES and its EU ecosystem assessment, presents an integrated approach based on different data streams. The different EU data streams previously used under MAES present a series of advantages and disadvantages in terms of consistency across all ecosystem types (Table 2). On the one hand, the EU reporting on ecosystem status (WFD and MSFD) and habitat condition (for Annex I habitats of the HD) represent a bottom-up approach, frequently based on in-situ monitoring at plot level of the condition of specific habitat types, that also makes use of expert judgement (local expert knowledge) and models. On the other hand, the condition mapping at EU level presents a top-down approach, based on mapping at grid cell level for the whole EU covering all broad ecosystem classes at different spatial resolution (from fine resolution ≤ 100 m, to coarse resolution ~50 km).

The setup of the EU ecosystem status (WFD, MSFD) and habitat condition (HD) reporting systems presents some disadvantages such as the difference in the criteria to report on status/condition across ecosystem types depending on the Environmental Directive regulating the assessment. Moreover, in the case of the HD, condition is only assessed for those habitats listed under the Annex I (habitats of Community interest), and therefore condition is unknown for areas beyond these habitats (Table 2). Frequently, bottom-up approaches present data gaps and tend to lack comparability. In contrast, the top-down MAES condition mapping offers a full coverage of the EU territory, while it may only provide a general (broad) picture of ecosystem condition, if only large spatial scale indicators are selected or available. Moreover, not all relevant condition variables are available in a spatially explicit way.

Current EU ecosystem status/habitat condition reporting is derived from a mandatory and periodic assessment based on diverse approaches across MS, which currently does not offer fully comparable time series. Reference levels are frequently set to identify good status of ecosystems, while the condition mapping can offer comparable time-series but without setting reference levels for the definition of good condition (Maes et al., 2020a).

Table 2. Comparison between EU Environmental Directives and MAES data flows used for the mapping of ecosystem condition

EU reporting on ecosystem status (WFD, MSFD) / habitat condition (HD)	MAES condition mapping
Bottom-up approach	Top-down approach
Plot level (ground monitoring and local expert knowledge)	Grid cell level (with different spatial resolutions)
Focus on specific habitats (very detailed)	Focus on broad ecosystem types (grouping of habitats, based on land cover/use data)
Different across ecosystem types (status estimated/measured in different ways)	Harmonised and transparent approach
Under the Habitats Directive, condition is only assessed for Annex I habitats (protected)	Full coverage of the EU territory
Derived from a mandatory assessments (large scale reporting effort of MS), but with data gaps	Multiple data sources used (requires GIS expertise)
Currently not fully comparable time series and diverse approaches across Member States	Comparable time-series and consistent coverage of the EU territory
In some cases, reference levels to define good status/condition are set (mainly in the WFD and MSFD)	No reference levels to determine good condition

3.2 Need to integrate EU data flows related to ecosystem condition

In ecological systems, different properties emerge at different spatial and temporal scales of observation, as well as at different levels of biological organization (De Leo & Levin, 1997). Therefore, for a proper interpretation of ecosystem condition measures, it is essential to consider the spatial and temporal scales at which abiotic and biotic characteristics are measured (Keith et al., 2020b). Therefore, **the assessment of ecosystem condition should ideally be based on the best available information collected at multiple scales and over time**. This information may be derived from existing policies and monitoring programs already in place that may provide relevant information. It may also rely on publicly available data collected at larger spatial scales, such as remotely sensed imagery or modelled data that potentially provide suitable spatial indicators of ecosystem condition over representative periods and covering the whole EU territory. **Spatially explicit indicators are necessary to fulfil the fundamental policy mandate of ecosystem condition assessment**: to enable the comparison of ecosystem condition at different locations in a scientifically robust and transparent way. Ecosystem condition, measured with spatially explicit indicators, can provide an opportunity to map and measure ecosystem restoration (or regeneration) and degradation, in a consistent way across Member States, biogeographical regions and ecosystem types.

Although previous studies on ecosystem condition mainly report at regional level (subnational) (Rendon et al., 2019), integration of different spatial scales is becoming highly encouraged. A need for different types of measurements of ecosystem condition was recognised in the SEEA EEA Technical Recommendations (United Nations, 2017), where both top-down and bottom-up approaches are suggested for measurements across different scales. Moreover, **studies on ecosystem integrity also adopt a multiple scale perspective since many ecosystem characteristics (biotic and abiotic) are scale-dependent** (Carter et al., 2019).

The EU-wide methodology also helps to identify any other relevant EU data flow contributing to improving our knowledge on the condition of ecosystems in the EU. In addition to the above-mentioned EU frameworks to assess ecosystem condition (directives reporting on ecosystem status/habitat condition and the condition mapping), **data derived from other reporting obligations, such as CAP indicators, may also be relevant**. This will contribute to foster the use of reported data by MS. For instance, data reported on species conservation status under the HD and Birds Directive (BD) (Directive 2009/147/EC[20]) can provide relevant information on the composition of ecosystems. Reporting under the National Emission reduction Commitment Directive (NECD Art.9) (Directive (EU) 2016/2284[21]) or Invasive Alien Species regulation (IAS Regulation (EU) No 1143/2014[22]) can also be used to further improve the ecosystem condition assessment. Beyond reporting obligations, data from the Land Use and Coverage Area frame Survey (LUCAS) monitoring programme provides harmonised in-situ data at the EU level on the condition of soils, which are a key component of ecosystems.

In this sense, the **SEEA EA**, as international statistical standard for organizing biophysical information to account for ecosystem condition, offers a **robust and transparent framework allowing for the integration of data measured at multiple spatial scales**, such as those derived from different EU efforts already in place. Figure 4 below illustrates the **integration of available EU data flows into the SEEA EA framework for a consistent assessment of ecosystem condition across all ecosystem types**.

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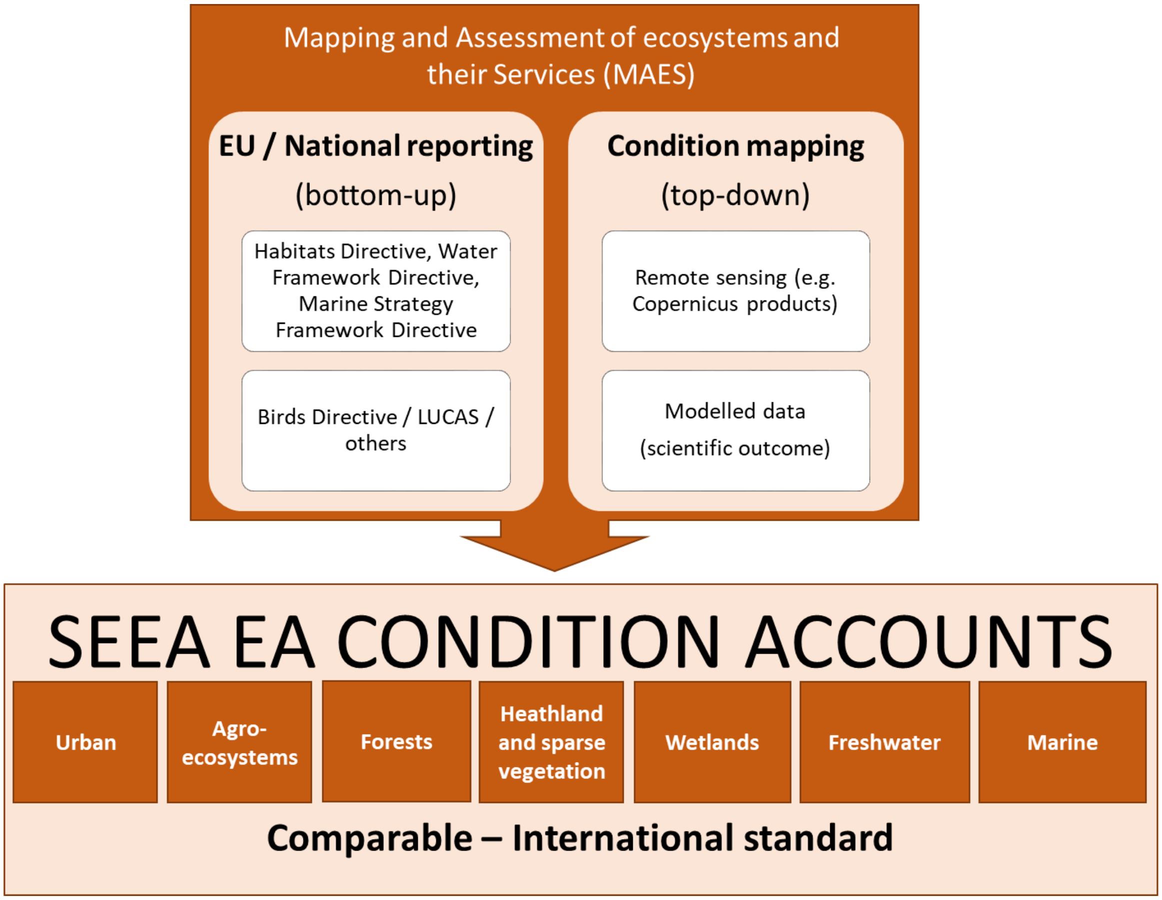
[20] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32009L0147

[21] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2016.344.01.0001.01.ENG&toc=OJ:L:2016:344:TOC

[22] https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1417443504720&uri=CELEX:32014R1143

Figure 4. Potential integration of the EU data flows into the SEEA EA condition accounts



Source: Own elaboration

3.3 Towards an integrated assessment of ecosystem condition

The EU-wide methodology addresses the current methodological gap for the assessment of ecosystem condition in support to the NRL, which explicitly refers to areas not covered under the Nature Directives (see also section 1.2). The condition assessment of Annex I habitats is already regulated by the HD, while for non-Annex I habitats, the application of the EU-wide methodology is foreseen. The implementation of different approaches depending on the habitat type (i.e. Annex I habitat or not) would not allow for a consistent assessment of ecosystem condition. Therefore, the EU-wide methodology recommends an integrated approach applicable to all ecosystem types, making use of different data flows available at the EU level covering the overall extent of ecosystems.

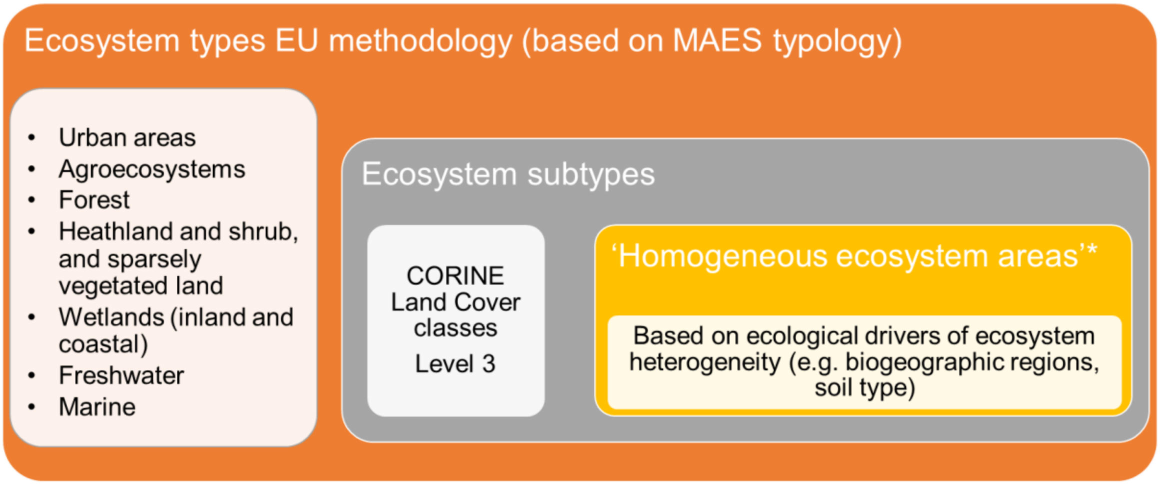
The EU-wide methodology, building on the previous MAES work, provides general recommendations to map and assess condition of the different ecosystem types in the EU, based on the integration of relevant data streams in a consistency with the SEEA EA framework on condition accounts. Moreover, the EU-wide methodology proposes methods for setting reference levels and further discusses the challenges to define them.

The EU-wide methodology is based on the broad MAES ecosystem types, as presented in the EU ecosystem assessment (Maes et al., 2020a):

1. Urban areas
2. Agroecosystems (cropland and grassland)
3. Forest
4. Heathland and shrubland
5. Sparsely vegetated land
6. Wetlands (inland and coastal wetlands)
7. Freshwater (rivers and lakes)
8. Marine ecosystems

This level of aggregation is useful for reporting purposes, but it may be too coarse for a detailed assessment of ecosystem condition, given the large heterogeneity that these broad ecosystem classes present. MAES ecosystem types need to be disaggregated into different **ecosystem subtypes** (Figure 5). Given the importance of the spatial component in the condition assessment under the EU-wide methodology, **CORINE land cover** (CLC) represents the most suitable dataset currently available to disaggregate broad ecosystem classes into land cover classes over time (e.g. Maes et al. (2013), Annex 2). Therefore, CLC data are used as proxies of ecosystem types, although this land cover classification presents important limitations in terms of thematic accuracy. For instance, a better distinction of 'moors and heathland' class would be required since it is considered as one single land cover class, but from an ecological perspective it is very heterogeneous. Nevertheless, beyond CLC there is currently no more detailed mapping of ecosystems (or habitats) for representative time series all over Europe, which is key for the implementation of the EU-wide methodology.

Figure 5. Ecosystem classification for the mapping and assessment of ecosystem condition



*This subdivision might be required to define meaningful reference levels for some condition variables, but not all

Source: Own elaboration

The EU-wide methodology presents the adaptation of the MAES work into the SEEA EA at the EU level for the first two steps of the condition accounts (section 2.3):

Step 1: Selection of ecosystem condition variables

Step 2: Definition of reference condition and/or reference levels

Providing recommendations on potential methods for the aggregation of ecosystem condition variables is not within the scope of the EU-wide methodology (Step 3 of the SEEA EA condition accounts). As mentioned before, it is optional within the SEEA EA and it largely depends on policy needs. Different tests on aggregation schemes were performed when drafting the EU ecosystem assessment, and the most supported approach to be adopted for aggregation was the 'convergence of evidence'[23]. However, further testing might be required in the future to better consider the possible advantages of developing an aggregated index of ecosystem condition.

Step 1. Selection of ecosystem condition variables

This guidance aims at proposing a representative number of **variables to cover each of the different classes of variables** (ECT, also aligned with SER): 1) Physical state, 2) Chemical state, 3) Compositional state, 4) Structural state, 5) Functional state, 6) Land- and seascape.

The selection of key variables was based on the criteria defined in Czúcz et al. (2021b) and integrates data derived from the different data flows described above: EU reporting on ecosystem status/habitat condition, condition mapping, and other EU data sources. Ultimately, variables presented in the EU-wide methodology also ensure the alignment with the current list of indicators proposed under the NRL; however, this list might be subject to changes in the future.

Importantly, the conclusion on ecosystem status/habitat condition as reported under the related EU environmental directives (HD, WFD and MSFD) is an aggregated indicator. As such, it is unsuitable for its direct integration in the SEEA EA framework, in which ecosystem condition variables describe individual characteristics of an ecosystem as represented in the ecosystem condition typology (Table 1). In the EU-wide methodology, it is further explored **to what extent the underlying parameters (variables) used to report the ecosystem status could be integrated into the ECT of the SEEA EA**, as far as they refer to biotic, abiotic or landscape characteristics of ecosystems.

For instance, under the HD, the 'structure and functions' parameter, including typical species, is considered in terms of habitat condition, since it is related to the biotic and abiotic properties and functions of an ecosystem. However, the conclusion of the status of the 'structure and functions' parameter is not a suitable indicator under the SEEA EA, since it is an aggregated indicator that relies on different types of measures, which vary across ecosystem types. For instance, 'structure and functions' of forest habitats may include variables such as species composition, canopy cover, age classes, dead wood, fragmentation, and presence of fire, which could be integrated into the ECT proposed under SEEA EA. **The use of the underpinning variables of the 'structure and functions' parameter would be key to achieve a proper integration of the HD into the SEEA EA**. However, the integration of the HD data remains very challenging given the lack of knowledge on the underpinning indicators used by the MS to report on the 'structure and functions' parameter. The EU-wide methodology presents a **case study of Greece** to illustrate how the integration of the HD data into the SEEA EA framework could potentially work.

The 'structure and functions' parameter, including typical species refers mainly to the biotic classes of ECT (Table 1), although some countries also monitor physical, chemical, and land-seascape characteristics under the HD. In case not all ECT classes are monitored under the HD, complementary variables would be needed to ensure consistency with the SER and ECT typology for the assessment of ecosystem condition.

Although the approach to accounting for ecosystem condition is spatially explicit (United Nations, 2021), the EU-wide methodology distinguishes different types of data depending on their properties:

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[23] Example: https://knowledge.unccd.int/sites/default/files/2018-06/GLO%20English_Ch4.pdf

1) **Optimal data**: when data are **spatially explicit covering the full EU territory, frequently and regularly collected/measured and made available in a timely manner**. This will allow tracking ecosystem condition variables over space and time. Proposed variables should be based on previous work done at EU level to map and assess ecosystem condition (Maes et al., 2020a) and/or other spatially explicit data that may be relevant for this purpose such as Copernicus data. Spatial resolution may significantly vary depending on data sources, from coarse spatial resolution (e.g. grid cells of 50 km) to fine spatial resolution (e.g. 100 m or even lower). These measured variables will provide maps to inform the ecosystem condition assessment, becoming thus useful to quantify the area of a given ecosystem that is considered to be under good condition or degraded.

2) **Modelled data**: some variables are difficult to be obtained for the whole EU territory by direct measurements. In this context, variables are often derived from modelling to provide spatially explicit and regular time series at the EU level. Models rely on assumptions and therefore a different outcome might be obtained when using an alternative model, which makes modelled data less reliable than optimal data. Proxies of ecosystem condition variables derived from models should be based on the most up-to-date scientific knowledge and be accompanied with validations, uncertainty assessments and/or measures of accuracy. In spite of the important limitations of using modelled data, they provide a spatially-explicit approximation very valuable for the overall purpose of the EU-wide methodology.

3) **Complementary data**: there might be other data that are valuable to support the assessment of ecosystem condition even when they do not match some of these criteria: full EU coverage, regular updates, spatially and/or temporally consistency. When such data are used, its source and application conditions (validity, uncertainty) shall be well documented. Data can also be available at coarse spatial resolution or for only sampling points, without full covering the whole EU territory. In this sense, complementary data are also included because they still can be relevant for an ecosystem condition assessment reported only at the EU level (geographically aggregated assessment), or modelling can be proposed to further increase the suitability of the indicator for a more consistent condition assessment or at finer spatial resolution.

4) **Coming soon:** data currently not available but on which there is a project or initiative currently working on it, which will provide useful data on ecosystem condition in the future.

Ultimately, the EU-wide methodology also makes proposals of possible **data gaps** for key variables currently missing and for which there are no plans to be developed in the near future. The data gap can be due to the lack of appropriate input data or to the lack of suitable methods to generate the variable. The importance of a data gap for the assessment of ecosystem condition needs to be justified based on the scientific literature. For instance, there might be some relevant variables on species composition at the European level, for which it is not foreseen initiative to produce the missing data.

Step 2. Definition of reference levels

As mentioned before (section 2.5), the SEEA EA proposes a comprehensive set of methods to identify reference conditions or reference levels for ecosystem condition variables.

Ultimately, the method chosen to identify the reference condition for each ecosystem type will be variable-dependent. There may be some variables of ecosystem condition with already well-defined reference levels, while other variables may require further analysis based on available data to define them. **The EU-wide methodology identifies first if the reference level for each condition variable already exists or not**. In case the reference level can be already defined, the method used for setting it is indicated. In this way, reference condition would be defined as a bottom-up approach based on the a-priori reference levels of a set of ecosystem condition variables. If reference levels are not yet defined, then, recommendation is provided on the possible methods to estimate it according to the SEEA EA (Annex 3).

When setting reference levels by ecosystem type or subtype (Figure 5), each CLC class may still present a considerable variability over the whole EU territory, showing important differences in condition variables that are not attributable to real differences in ecosystem condition, but rather to different environmental settings, such as climate or soil typology. In this context, a finer level of classification would be required to ensure a comparable assessment of ecosystem condition in different locations. A robust and operational solution to produce a more spatially detailed ecosystem classification for the assessment of ecosystem condition would be using the combination of land cover data (i.e. ecosystem subtypes), climate and/or landforms (e.g. mountains, hills, soil types) (United Nations, 2021). The combination of this spatial information is useful to delineate '**homogeneous ecosystem areas**' capturing ecosystem variability across the territory (Figure 5).

The **identification of 'homogeneous ecosystem areas'** is required as a prior step to set reference levels, which allows rescaling the ecosystem variable into a meaningful indicator on ecosystem condition (see section 2.5). Delineation of homogeneous ecosystem areas should be:

- Feasible: in terms of the total number of homogeneous ecosystem areas to work with
- Operational from the mapping point of view: based on spatially explicit ancillary data

The IUCN GET at level 4 proposes a pragmatic top-down sub-division of GET level 3 based on biogeographic ecotypes, as proxies for compositionally distinctive geographic variants that occupy different areas within the distribution of a functional group (Keith et al. 2020). The use of biogeographic ecotypes (or ecoregions) at the EU level would result in a too much detailed classification, recommended under the SEEA EA only for national and sub-national levels, but not for the supranational approach of the EU-wide methodology. Therefore, a more feasible alternative at the EU level following the same logic as the IUCN GET level 4, would be to make use of **biogeographical regions to define 'homogeneous ecosystem areas' of natural and semi-natural terrestrial ecosystems** instead of ecoregions. Biogeographical regions reflect global differences in species distribution due to geographic separation and evolutionary history and, therefore, can be considered a feasible criterion to define 'homogeneous ecosystem areas'. Moreover, this approach would also ensure coherence with the HD, in which the assessments reported by habitat type provide information on the biogeographical region it belongs to and correspondence with MAES ecosystem types to facilitate the aggregation at coarser spatial scale. However, for some ecosystem types presenting high heterogeneity the use of only biogeographical regions may be not sufficient to define 'homogeneous ecosystem areas'; therefore, in these cases, other factors such as soil type might have to be considered.

The criteria of using biogeographical regions in combination with land cover data may be not suitable for **anthropogenic ecosystems such as urban areas and agroecosystems**. In this case, it would be more appropriate to incorporate data on land cover, land use/management and other variables related to the socio-economic system they belong to.

In the case of **freshwater ecosystems**, the criteria to define different typologies to assess condition has been already defined by the WFD. Under this Directive, MS have developed **typologies for lakes and rivers based on ecoregions, but also altitude, catchment size, and geology**, which are most important to explain the natural variability of the biological and supporting abiotic components (e.g. nutrients, transparency, oxygen, flow, structure of the riparian zone). Similarly, **marine ecosystems** are also considered separately by **marine regions** (and sub-regions) as defined in the MSFD.

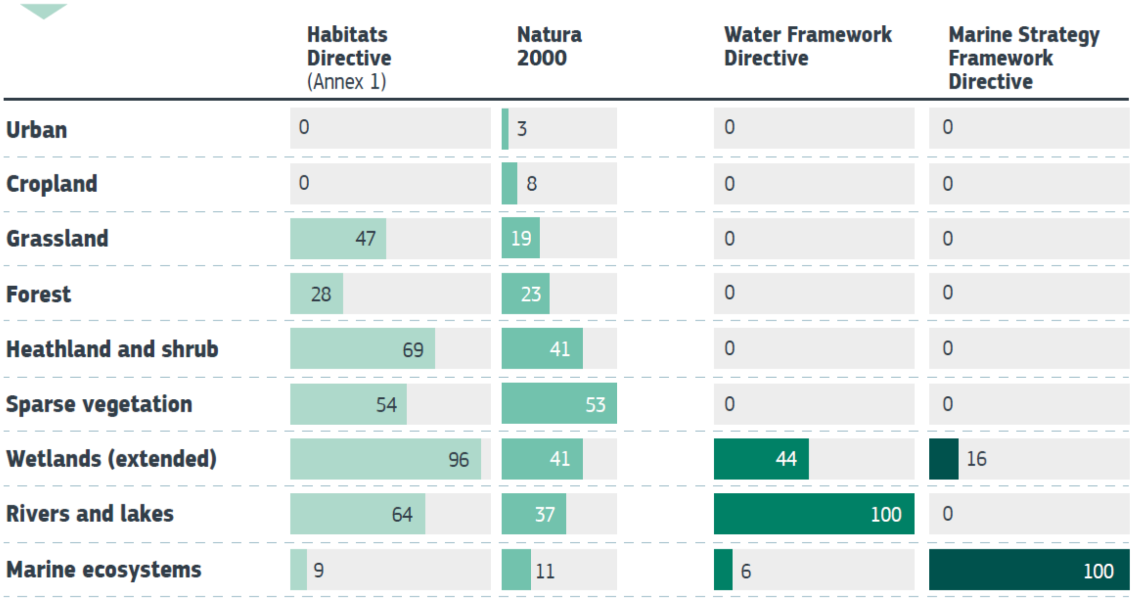
Ultimately, the criterion to define 'homogeneous ecosystem areas' may vary across ecosystem types as discussed in the dedicated sections for each broad ecosystem.

3.4 The case for rivers and lakes and marine ecosystems

Water ecosystems, including rivers, lakes and marine ecosystems, differently from terrestrial ecosystems, have their whole extent fully covered by environmental laws, the WFD and MSFD, respectively (Figure 6).

Figure 6. The relative share of ecosystems covered by the Habitats Directive, the Water Framework Directive and the Marine Strategy

Percent area under legal designation of EU directives and the Natura 2000 network (% area)



	Habitats Directive (Annex 1)	**Natura 2000**	**Water Framework Directive**	**Marine Strategy Framework Directive**
Urban	0	3	0	0
Cropland	0	8	0	0
Grassland	47	19	0	0
Forest	28	23	0	0
Heathland and shrub	69	41	0	0
Sparse vegetation	54	53	0	0
Wetlands (extended)	96	41	44	16
Rivers and lakes	64	37	100	0
Marine ecosystems	9	11	6	100

For wetlands, the extended layer is considered for this analysis. Annex 1 habitat are habitats listed under Annex 1 of the Habitats directive. Natura 2000 is the nature protection network established under the Habitats Directive.

Source: Maes et al. (2021b)

The WFD and MSFD apply methodological frameworks that broadly follow the same steps proposed under the SEEA EA to account for ecosystem condition (section 2.3):

1) Monitor biotic and abiotic parameters of ecosystems,

2) Define quantitative reference or threshold values,

3) Aggregate indicators and determine status of water bodies and marine areas.

In this sense, the WFD and MSFD provide a fully developed methodology for the assessment of ecosystem status that is being applied in a consistent way over the whole area of freshwater and marine regions in the EU, and therefore considered distinctly from terrestrial ecosystems.

The **ecosystem status provided by the WFD and MSFD** for freshwater and marine ecosystems, respectively, is considered in this document as **equivalent to the concept of ecosystem condition**.

Although in general terms, the methodologies in place under the WFD and MSFD seem compatible with the ecosystem condition accounts (SEEA EA), the potential integration of the data used to report on status under these Directives with the SEEA standard should be further tested. In this sense, the EU-wide methodology illustrates, **as case study, to what extent the assessment of environmental status under the MSFD is consistent with the ecosystem condition assessment under SEEA EA**.

Another water-related ecosystem, wetlands, is practically covered under legal designation by the HD (Figure 6), showing also important overlaps with the WFD and the MSFD. This legal overlap in the reporting of status for wetlands makes the possibility of developing a consistent assessment of wetlands still more challenging. In this context, an integration of the current approaches already in place would be encouraged in the long term, however a deep review of current directives on this regard is not foreseen. Importantly, the directive with the largest coverage of wetland ecosystems is the HD (Figure 6), but the reporting on habitat condition of the HD is not fully transparent, and underpinning data for the assessment of the habitat condition is unknown at EU level (see Step 1 in section 3.3 for further details on the limitations of the use of the HD).

The EU-wide methodology does not attempt to substitute any existing method to define the 'environmental status' or 'habitat condition' as provided by the EU legislation. Instead, it aims to assess to what extent, underpinning parameters/variables/data required to assess environmental status and habitat condition can be integrated together with other data flows to assess ecosystem condition, following the international standard of the SEEA EA.

4 Integrated condition assessment by ecosystem type

This section provides methodological guidance to map and assess the condition of EU ecosystems. Subsections below are dedicated to different ecosystem types, covering the entire EU land and seascape with no overlap or gap. However, as described above (section 3.4) rivers and lakes and marine ecosystems are considered slightly differently from terrestrial ecosystems.

Each subsection presents a definition of the target ecosystem and an extensive **list of variables to assess condition at EU level** based on the ecosystem condition typology of the SEEA EA. Allocation of the variables to the different classes (e.g. physical, chemical, structural, compositional) is not necessarily univocal and very often some variables may fit into more than one class. Although the allocation of a variable into a given class or another will not have a strong impact on a potential aggregated condition index, differences among ECT classes should be further refined to make these classes mutually exclusive. In this sense, practical examples showing variables allocated to different classes as shown in this report could be used as reference to better set the limits between ECT classes.

For each variable, there is also a **documented justification of its relevance for the condition assessment**, that shows how the variables included are related to degradation or to improvement of ecosystem condition (i.e. directional meaning, Czúcz et al. (2021b)). Variables are described independently for each ecosystem type, although they may be common for some of them (but not all). This may imply some repetition of the information provided but, in this way, potential readers interested in only a given ecosystem type may find all the relevant information in the same section.

The lists of condition variables by ecosystem type provide a **comprehensive overview of different options available to map and assess ecosystem condition**. Ultimately, the suitability of each variable for the condition assessment will depend on the specific purpose of such assessment. If the focus of the condition assessment is on mapping degraded areas, then, only geospatial data should be selected. The adoption of an EU approach, as presented in this report, would be relevant to identifying restoration hotspots at continental scale. Ultimately, prioritization for the implementation of local restoration measures would also require local knowledge and data to better account for habitat heterogeneity at local scale. However, the application of the EU-wide methodology, based on the SEEA EA, using more detailed national or regional data is also feasible.

If the ecosystem condition assessment is focused on analysing changes for the whole EU, then, all variables reporting time series, even those with just one value for the EU, would be chosen. Tables included below for each ecosystem type summarise the main properties relevant for this type of variables selection: spatial and temporal resolution, describing also some of the possible limitations of their use (by showing the type of data). The implementation of the EU-wide methodology in practice should be based on a careful selection of these variables matching the characteristics required for specific purposes.

Methodological support and recommendations are also provided on the **methods to be used for setting reference levels**, required for the ecosystem condition assessment**.** Very often, a finer ecosystem classification is needed to better define reference levels (Figure 5) and, in this case, possible criteria to identify and delineate ‘homogeneous ecosystem areas’ are also described. Lastly, there is also an **overall conclusion for each ecosystem type**.

4.1 Urban areas

4.1.1 Definition and delineation of urban areas

An **urban area is a built-human settlement characterised by high population density**, artificial environments and a concentration of organised human activities. From an ecosystem condition perspective, urban areas can be defined in several ways and analysed at different geographical levels. They can be defined strictly considering the densely built-up land where people live, i.e., ‘settlements and other artificial surfaces’. They can also be understood from a broader perspective, which includes the densely built artificial zones and their surroundings. This latter perspective corresponds to a definition of urban ecosystems, where built-up areas are just one of the components of urban ecosystems, together with other ecosystem types such as agroecosystems, forests and freshwater ecosystems (Maes et al., 2020a).

In this context, two complementary approaches to assess ecosystem condition can be adopted (similarly to wetlands):

1. **General approach**: provides information about the condition of only ‘**settlements and other artificial surfaces’**[24] (previously named ‘urban’ under the MAES classification, Maes et al. (2013)). This approach provides an analysis of condition of highly artificial land, omitting overlaps with other ecosystem types. However, it will not provide a complete picture of the overall condition of the urban ecosystem in which those highly artificial surfaces are embedded.

2. **Thematic approach**: the focus is on **urban ecosystems** defined as cities and the surrounding socio-ecological systems where most people live (Maes et al., 2020a; Maes et al., 2016). This approach will provide a more detailed and specific information about the condition of urban areas, including their hinterland or local area of influence. Under this definition, urban ecosystems correspond to a mosaic of anthropogenic, natural, and semi-natural land covers surrounding highly artificialized and densely populated areas that allows capturing the complex interactions between artificial areas and other ecosystem types. Urban ecosystems represent mainly human habitats, but they usually include significant areas of habitat for synanthropic species (Maes et al., 2013). These systems are structurally complex and highly heterogeneous fine-scale spatial mosaics formed by diverse types of patches, which may be recognised in fine-scale land cover and land use classifications (Keith et al., 2020a).

   This thematic assessment is also consistent with the SEEA EA. Thematic accounts are useful to provide additional detail on a focus area, especially when alternative classifications are provided. In this case, the focus area includes cities, towns, suburbs and their surroundings.

The general and thematic approaches may present different sets of variables to assess the condition of urban areas. Therefore, when presenting the list of variables it will be also specified if the variable is suitable only for the general, the thematic or both approaches.

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[24] The term ‘settlements and other artificial areas’ has been adopted as alternative to the term ‘urban ecosystems’ of the MAES ecosystem classification to ensure consistency with: a) the definition of ‘urban ecosystems’ that include cities, towns, suburbs and their surroundings, and b) the definition used in the ecosystem accounting module amending Regulation EU 691/2011 on European Environmental Accounts.

The importance of the reporting units for urban systems

To facilitate monitoring and successful implementation of policies, the minimum reporting unit (i.e., the minimum spatial unit used to report on variables) for 'settlements and other artificial areas' and 'urban ecosystems' should correspond with the administrative unit in charge of urban policies. Therefore, an adequate definition of the reporting unit becomes a crucial element.

Reporting units for urban areas may vary depending on the policy focus. Both, the proposed amendment of the Regulation on European environmental economic accounts and the proposal for a NRL make use of local administrative units (LAU) (e.g. considered as cities and/or towns and suburbs) as reporting units for the assessment of urban areas, in which the thematic approach has to be adopted.

4.1.2 Variables to assess the condition of urban areas at EU level

Variables identified to map and assess the condition of urban areas are presented in Table 3, showing as well for which approach (general and/or thematic, section 4.1.1) these variables can be applied. Many of the variables included were previously used in different assessments of the condition of urban ecosystems (Maes et al., 2020b; Maes et al., 2019). The description and justification of the variables selected to assess the condition of urban areas is included below.

Relevance of physical state variables

Imperviousness per inhabitant: Imperviousness is a well-known variable of ecosystem degradation, since it seals the soil and limits functions such as the infiltration of water. It has also been widely demonstrated its direct relationship with an increase of land surface temperature, and consequently, intensification of urban heat island effect, especially during warm months (Marando et al., 2022). Imperviousness is a consequence of the expansion of built-up areas, which are needed to provide houses and infrastructure to people. For this reason, the suggested variable measures the level of imperviousness in relation to the population size (impervious area per capita). Imperviousness data is derived from reliable and accurate remote sensing imagery (High Resolution Layers of Copernicus product), covering the whole EU with comparable time series. Population data used to estimate imperviousness per capita is derived from the GEOSTAT 1x1 km population grid provided by Eurostat, providing also spatially accurate and reliable data to be used consistently at EU level.

Waste generated per inhabitant: Waste generation is related to the rate of urbanization, the population density, the types, and patterns of consumption, household revenue, size, and lifestyles (Maes et al., 2020a). Monitoring or estimating changes in material consumption would provide a better understanding of the amount of resources demanded by inhabitants in urban ecosystems, and therefore the environmental pressure generated by them on the condition of ecosystems on which they are dependent. The indicator is measured per inhabitant to better acknowledge unit of demand (citizen), to ensure a fair comparison among urban ecosystems of different sizes (population) and facilitate definition of reference levels broadly applicable to urban ecosystems independently of their size. This variable can be disaggregated by category of waste, material or waste treatment, which might provide relevant additional details. Detailed definition of this indicator (e.g. specific categories of waste considered) and specific datasets to be used should be further defined during in a future stage. Currently, data at EU level are only available per country, which is a too coarse spatial resolution for a detailed urban assessment. Data disaggregated by local administrative unit (LAU) would be required instead.

Table 3. Variables for the condition assessment of urban areas

Ecosystem Condition Typology	Urban approach	Variable	Units	Source of the variable at EU level	Temporal series available	Spatial Resolution	Type[1]
A1. Physical state	General & Thematic	Imperviousness per inhabitant	ha/inhabitant	Copernicus HRL Land + GEOSTAT Pop. Grid (or GHSL pop)	2006-2012-2018 (1975-1990-2000-2015)	1 km (250 m)	Optimal
		Waste generated per inhabitant	kg waste/ inhabitant	Eurostat (e.g. env_wasmun[2])	2000-2020 (annual data collection)	Country	Complementary (very coarse spatial scale)
	Thematic	Normalised Difference Moisture Index (NDMI)	Dimensionless	LANDSAT	1982 to date (freq. 16 days)	30 m	Optimal
		Noise pollution exposure	Inhabitants	Urban agglomerations (Environmental Noise Directive)	2012-2017 (every 5 years)	Urban agglomeration	Complementary (not full EU coverage, no consistent reporting unit, large scale assessment)
A2. Chemical state	General & Thematic	Air pollutants concentration (NO_2, PMx, O_3, SO_2, CO)	$\mu g/m^3$	EMEP	2000-2018 (from EMEP modelled data updated)	0.1°	Optimal / Modelled
				CAMS	2018 (CAMS expected to be updated regularly)	0.1°	
				Annual AQ statistics from European Environment Agency	2003-2022 (Annual AQ Statistics)	Ground monitoring points	
		Soil organic carbon stock	kg C/ha	Biogeochemical models and soil monitoring databases	-	-	Data gap
		Heavy metals in soil	$\mu g/g$	Soil monitoring databases (e.g. LUCAS)	-	-	Data gap

Ecosystem Condition Typology	Urban approach	Variable	Units	Source of the variable at EU level	Temporal series available	Spatial Resolution	Type[1]
B1. Compositional state	Thematic	Autochthonous woody vegetation species (or functional trait) richness	Number of species (traits)	-	-	-	Data gap
		Urban bird species richness	Number of species	-	-	-	Data gap
		Pressure by invasive alien species on urban ecosystems	Dimensionless	JRC-EASIN	No	10 km	Complementary (currently no time series)
B2. Structural state	General & Thematic	Greenness - annual max NDVI	Dimensionless	LANDSAT	1982 to date (freq. 16 days)	30 m	Optimal
		Tree canopy cover	%	HRL Land	2012-2015-2018	10 m	Optimal
		Green spaces and/or green spaces per inhabitant	% or ha/inhabitant	LANDSAT	1982 to date (freq. 16 days)	30 m	Optimal
				CORINE++	2018 (not available yet)	10 m	Coming soon
		Semi-natural and natural riparian land cover	%	Riparian Zones Copernicus & Copernicus HRL Land	2012-2018	0.5 ha & 10 m	Optimal
B3. Functional state	Thematic	Plant evapotranspiration	mm d-1	PML V2 model	2002-2020	500 m	Modelled
		Wild pollinators indicator	Dimensionless	STING/SPRING projects	2024	EU (finer resolution to be decided)	Coming soon
C1. Landscape and seascape	General &Thematic	Integrity of the green network	%	Copernicus HRL Land	2006-2012-2018	10 m	Optimal
		Fragmentation of the green network	%	Copernicus HRL Land	2006-2012-2018	10 m	Coming soon

Ecosystem Condition Typology	Urban approach	Variable	Units	Source of the variable at EU level	Temporal series available	Spatial Resolution	Type[1]
		Riparian fragmentation	meters	Riparian Zones Copernicus Land & Copernicus HRL Land	2012-2018	0.5 ha & 10 m	Coming soon
	Thematic	Patch richness or Shannon diversity index of land cover type	Dimensionless	CLC (or CLC+, about to be available)	1990-2000 - 2006-2012-2018 (2018)	100 m (10 m)	Optimal

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[1] Type: Optimal (EU map and temporal series), modelled (maps are a modelled outcome), complementary (when data match at least one of these criteria: no full EU coverage, no time series, not spatially or temporally consistent, require modelling-point data, very coarse spatial resolution, coming soon (data that are currently not available but there is a project or initiative currently working on it), data gap (key variables currently missing for which there are no plans to be developed).

[2] The code included for illustrative purposes can be used to calculate municipal waste generated per capita. There are other examples of waste datasets related to specific other categories, materials, treatments and management operations that could be useful to calculate this variable. Further analysis might identify necessary calculation by specific waste-related categories and need of using a different dataset than the one referred as an example.

Normalised Difference Moisture Index (NDMI): Vegetation functional status can be influenced by natural factors (e.g. drought), or human activities (e.g. urban green management or air pollution). Functional status of vegetation is strongly linked to water availability. A higher water availability is usually related to a higher ecosystem function, and to an enhanced capability to provide ecosystem services. Remote sensing indices that estimate the water content in tree canopies, such as NDMI (Normalised Difference Moisture Index), or other plant/soil water content indices, are widely used and can detect early or ongoing water stress in vegetation, therefore indicating a worsening or an improvement of the functional status of vegetation. NDMI is derived from Near Infra-Red and Short-Wave Infra-Red satellite bands and can be easily calculated from Landsat images at no cost.

Noise pollution exposure: Noise pollution negatively influences human activities (e.g. learning) and human health (Hammer et al. 2014). It also negatively influences fauna physiology, behaviour, and reproduction, including those species already present in urban or peri-urban areas (Newport et al., 2014). In the case, of urban ecosystems both aspects are relevant, since humans are the species for excellence inhabiting this ecosystem and fauna is already highly pressured in urban ecosystems and surrounding ecosystems (which could be also impacted by noise from urban areas). In this sense, monitoring noise pollution provides valuable data to understand urban ecosystem condition, including the one of humans inhabiting this ecosystem. However, there is not consistent available noise monitoring data and yet the possibility to model it in a consistent way for the entire EU (with the aim to inform policy making). The only available dataset updated every five years is the large-scale assessment data reported at agglomeration level as a response to the Environmental Noise Directive. This variable cannot be disaggregated by ecosystem asset (ecosystem subtypes) within urban ecosystems.

Relevance of chemical state variables

Air pollutants concentration (NO_2, PM_{10}, $PM_{2.5}$, O_3, SO_2, CO): To maintain urban ecosystem health, it is essential to keep air pollution levels as low as possible. The five pollutants used in the European Air Quality Index are here proposed. Carbon monoxide (CO) is also added to these five pollutants since it is considered in other air quality indexes (e.g. air quality index developed by the United Stated Environmental Protection Agency), and therefore its monitoring is also recommended. High levels of air pollution are still a main cause of premature human death and chronic illness negatively influencing human quality of life. High levels of air pollution also contribute to damage the health of terrestrial plants, which is observable as an increased defoliation, poorer crown condition (in woody plants), higher probability of insect damage. Air pollution also causes the reduction of terrestrial plant species richness, including lichens and mosses, since those resistant to high levels of air pollution are more advantaged (Bignal et al., 2007). Data on air pollutant concentration can be derived from EMEP and CAMS products at 0.1°, which could be later downscaled to 1x1 km resolution using ground-monitoring station data provided in the annual air quality statistics repository of the European Environment Agency. The air quality database contains validated air quality monitoring information for more than 30 participating countries throughout Europe. Every year countries report air quality measurements for a set of pollutants at a representative selection. Data are validated, sources are reputable and provide reliable data continuously updated over time. The monitoring of air pollution at 1 km resolution provides spatially accurate data to be used consistently at EU level.

Soil organic carbon stock: Soil organic carbon, among other processes, influences soil structure and availability of energy and matter for soil microorganisms and macroinvertebrates, as well as organic bound nutrients in the soil (Billings et al., 2021). It indirectly influences net productivity of land plants since they are dependent on the presence of nutrients, macroinvertebrates and soil microorganisms that through a cascade of processes make nutrients bioavailable for plants and mobilise those along the soil profile. In addition, soils with higher levels of organic carbon provide increased resilience to extremes of weather (i.e. droughts, floods). Consequently, soil organic carbon has a relevant role in the functioning of terrestrial ecosystems, including urban ecosystems, and the derived ecosystem services. In this context, it is well understood that soils with low organic carbon stocks struggle to provide a balance of ecosystem services. Currently, in the case of urban ecosystems there is a gap regarding soil data, since monitoring schemes are not systematically developed, while remote sensing products do not have the necessary spatial resolution or spectral characteristics to capture soil condition. Moreover, biogeochemical models on soil organic flows (e.g. RothC) are being developed to inform the dynamics of other ecosystems but are difficult to be used for policy purposes since results are difficult to be validated due to the use of theoretical carbon pools instead of real monitorable pools. Finally, soil carbon stocks are expressed for a reference depth of soil. IPCC Guidelines measure carbon stocks to a default depth of 30 cm.

Heavy metals in soils (As, Cd, Cr, Cu, Hg, Pb, Mn, Sb, Co, Ni, Zn): While low levels of heavy metals are required in the form of micro-nutrients for good ecosystem functioning, high levels are of concern. Heavy metals cannot be easily degraded and are sometimes difficult to be stabilised or to be modified to reduce the associated risks. Moreover, heavy metals tend to bio-accumulate in many trophic chains, with a long-term risk for the local biota and humans (Briffa et al., 2020). In the case of urban ecosystems, heavy metals are of special concern because they are a consequence of past and present commercial and industrial activities and transport. Currently, as explained in soil organic carbon for urban ecosystems there is a gap regarding soil data.

Relevance of compositional state variables

Autochthonous woody vegetation species (or functional trait) richness: It represents the amount of native tree or shrub species (or their functional traits) present in an area. Species (or trait) richness is positively correlated to ecosystem health and function (Tilman, 1997). Higher levels of species richness are linked to higher ecosystem stability and resilience. EU-Forest Dataset (JRC) and local urban tree inventories are suitable sources of information on the amount and distribution of native tree species. It is necessary to carefully evaluate the spatial resolution of the analysis, as the relation between richness and ecosystem function is scale dependent.

Urban bird species richness: Presence of specific species of birds and their richness has already been used as a variable informing about good ecological condition of urban areas (Morelli et al., 2021). In this sense, a condition variable measuring urban bird species richness among a predefined set in European urban areas might be useful to inform on ecological condition for animal biodiversity in a broad sense. Additionally, there are already pilot studies relating species richness in urban areas to positive effects on human mental health (Methorst et al., 2021). Beyond species richness, other indicators are currently being tested in pilot studies for urban areas to provide biodiversity indicators more robustly related to the condition of ecosystems (Zulian et al., 2022b). This issue is further discussed in Box 3 (section 5.1).

Pressure by invasive alien species on urban ecosystems: The pressure by IAS on ecosystems has a potential negative effect on their condition due to the increased threat (Pyšek et al., 2020). Pressure by IAS can be measured as the cumulative pressure exerted by IAS based on the sum of their occurrence in an area, weighted by the extent of the ecosystem(s) potentially affected. This cumulative pressure indicator was developed for the EU ecosystem assessment (Maes et al., 2020a) using species records from the baseline distribution of IAS of Union concern available on the European Invasive Species Information Network (https://easin.jrc.ec.europa.eu/easin/Documentation/Baseline). It will be possible to infer trends in relation to the baseline of IAS when the EU MS second reporting under the IAS Regulation becomes available in 2025.

Relevance of structural state variables

Greenness – annual max NDVI: Greenness is defined as the amount of vegetation present in urbanised areas. This variable has been used to identify urban green areas and changes in vegetation cover (Zulian et al., 2022a). Specifically, change in vegetation cover is used as 'structural ecosystem attribute' to analyse urban ecosystem condition. Gradual and abrupt changes in greenness are used as a proxy of an improvement or worsening of the amount of vegetation cover in urban areas. In particular, based on the direction and intensity of the change, it is possible to discriminate between gradual changes, likely due to vegetation growth, land degradation, or drought as well as other factors, and abrupt changes, usually induced by land use change or shifts in urban green space management, as well as extreme events such as fires or climatic conditions. Greenness is estimated calculating the highest value of NDVI of the year, therefore is always indicative of the maximum vegetation growth (influenced by intra-annual phenological variations).

Tree canopy cover: 'Urban tree canopy cover' means the total area of trees in an urban area, calculated based on the Tree Cover Density data, as provided for by the Copernicus Land Monitoring Service, representing the 'vertical projection of tree crowns to a horizontal earth's surface. Trees and other woody plants along streets and in public squares and car parks as well as private gardens contribute to biodiversity and provide habitat for wildlife and supporting pollination. The link between the abundance of tree canopy cover and several ecosystem services (such as air temperature mitigation, runoff prevention and air quality regulation) is well established in literature. An increase in tree canopy cover is indicative of an improvement of ecosystem condition, whereas a decrease can be indicative of ecosystem degradation (for natural or anthropogenic causes). High quality Copernicus satellite data is already available going back to 2000 and will be available every three years at high-resolution scale at 10m^2 level of detail. This data can very easily be set over urban areas and it is available online.

Green spaces per total urban area and/or green spaces per inhabitant: 'Urban green space' is the proportion of existing green infrastructure in an urban area. Urban green spaces can generate a substantial range of social, environmental and economic benefits for urban citizens, whilst also providing protection against the effects of climate change. Urban green space is defined as the ensemble of the following categories of the CLC Classification: 'green urban areas', 'broad-leaved forests', 'coniferous forests', 'mixed forests', 'natural grasslands', 'moors and heathlands', 'transitional woodland-shrubs' and 'sparsely vegetated areas'. As urban green spaces are the basic building blocks of urban ecosystems, measuring and monitoring variations in % of the total urban area represents the fundamental variable of urban ecosystem condition, and it is linked to it with a direct relationship. CLC maps are updated every six years, providing data validated by MS.

Semi-natural and natural riparian land cover: Riparian zones are transitional environments (ecotones) that provide a wide range of services and functions, such as air and water filtration, flood control and habitat maintenance. Riparian zones are key components of the green-blue infrastructure, and exert an essential role in sustaining biodiversity and ecosystem integrity, as well as in minimizing pressures (Clerici et al., 2014). Nevertheless, riparian zones are also highly vulnerable and susceptible to anthropic pressure and are easily degraded, involving alterations in the hydrologic regimes and species composition. Due to the multitude of benefits that semi-natural and natural riparian land covers deliver to humans and the urban ecosystem as a whole, and their linkage with overall ecosystem health, their presence can be considered as directly correlated with urban ecosystem condition. In terms of resolution, riparian zones Copernicus Land & Copernicus HRL Land offer reputable data at an adequate temporal (every 6 years) and spatial resolution (0.5 ha and 10 m) for the entire EU.

Relevance of functional state variables

Plant evapotranspiration: It is the amount of water evaporated from the soil and vegetation in a given amount of time. It is a proxy of water status and reflects vegetation physiological status. In case of vegetation stress, the rate of gas exchange between the plant and the atmosphere usually decreases as a result of a reduction of water availability or an impairment of photosynthetic rate, or as a change in climatic and environmental conditions (Fusaro et al., 2015). It can be derived from models such as the PML_V2 Penman Monteith Leuning model (Zhang et al., 2019), available at 500 m spatial resolution every 8 days. However, it is uncertain how often it will be updated in the upcoming years.

Wild pollinators indicator: Pollinators ensure healthy ecosystem functioning and maintain biodiversity of terrestrial ecosystems, providing very valuable information on the functional state of ecosystems and thus, on their condition. See section 5.2.1 for further details on how insect pollinator monitoring can inform the assessment of ecosystem condition.

Relevance of landscape characteristics

Integrity (coherence) of the green network: Integrity is defined as the degree of connectedness of all green areas in a given space and time (Vogt, 2021), and it can be regarded as an additional metric to measure ecosystem connectivity, whose relationship with condition is well established (Correa Ayram et al., 2016). It describes the status of a given network of green areas. The increase in integrity is a measure of the success of a restoration scenario (i.e. increase in size, consistency, and number of green areas patches). An increase in integrity is indicative of an increase in condition (higher coherence, connectivity), whereas a decrease will be indicative of a worse condition (fragmentation, deterioration). The quantitative variable values and their change (before/after) are also usually applied to serve compelling arguments to define and defend the most cost-efficient restoration scenarios. Moreover, it is critical to quantify temporal progress towards policy goals and the final overall success of a restoration project. Integrity is calculated using urban green spaces as input data (CLC classification).

Fragmentation of the green network at Fixed Observation Scale: Landscape fragmentation is usually defined as the splitting of a habitat or ecosystem asset into smaller pieces. In landscape ecology, it is commonly accepted that landscape fragmentation can be assimilated to the inverse of structural connectivity, i.e., the degree to which a landscape mosaic does or does not facilitate the movement of species among patches. In this case, it is also assumed that fragmentation represents the inverse of structural connectivity. With Frag-FOS the level of structural connectivity of the network of natural and semi-natural vegetation patches (e.g. linear features, small woody patches and large forested areas) in urban areas can be measured. Since fragmentation/connectivity depends on the scale- of observation, a suitable, fixed observation scale must be chosen to capture and quantify the degree of connectivity. Consequently, the analysis scheme FOS (Fragmentation at Fixed Observation Scale), measuring fragmentation in five categories from highly fragmented to little fragmented is proposed. Fragmentation values can be measured at the patch level. The methodology is based on geometric principles only; as such, it can be applied to any natural and semi-natural vegetation raster maps, independent of spatial resolution. In contrast to many existing fragmentation schemes, the outlined methodology provides a normalised index quantifying fragmentation within the range of 0-100 %. This metric can be measured via the freeware Guidos Toolbox (Vogt et al., 2022).

Riparian fragmentation: As previously described for the ‘semi-natural and natural riparian land cover’ variable, riparian zones exert key functions and provide essential services. However, not only their presence and abundance are indicative of good ecosystem condition, but also their connectivity. High levels of lateral and longitudinal semi-natural and natural riparian land covers regulate the changes in matter, energy and biota (Fernandes et al., 2016). Euclidean Nearest Neighbour of semi-natural and natural riparian land covers informs about the distance to the nearest patch of the same land cover class or group of them (Babí Almenar et al., 2019). This variable will help to monitor changes in the structural connectivity of the semi-natural and natural riparian land covers in a simple and cost-efficient form. In terms of input data, the same sources of the variable ‘semi-natural and natural riparian land cover’ can be used, from where distances between patches can be calculated.

Patch richness or Shannon Diversity Index (SHDI) of land cover types: Natural and semi-natural land cover richness (heterogeneity) and its proportion (amount) in the total extent of an ecosystem accounting area inform about the capacity of a system to contribute to species richness and their abundance (Silva et al., 2015). It is also expected that higher levels of natural and semi-natural land cover diversity would contribute to maintain a more diverse set of ecological processes and functions and therefore a more diverse set of derived ecosystem services. Moreover, high levels of land cover richness or diversity are associated with a general positive human (visual) perception of the surrounding landscape (independently of cultural legacy) and might contribute to the supply of cultural services such as outdoor recreation activities. The above attributes together with the easiness to measure diversity (SHDI) or richness of land cover and communicate it to policy makers made this variable suitable to monitor landscape characteristics contributing to urban ecosystem condition. In terms of resolution, there is available spatial data generated by reputable sources (Copernicus Land Project) at an adequate temporal (every 6 years) and spatial resolution (100 to 10 m) for the entire EU.

4.1.3 Definition of reference levels for urban areas

The definition of ‘homogeneous ecosystem areas’ is a preliminary step to the definition of reference levels. For both approaches, general and thematic, the urban areas in the European territory must be classified into **clusters to identify different groups of ‘homogeneous urban areas’** and make them operational to define meaningful reference levels within each of these areas.

Groups should be homogeneous in relation to climatic, biophysical and socio-economic characteristics or attributes. Differentiation should be based on the following characteristics:

- size in terms of population (based on the degree of urbanisation[25] and the OECD urban population by city size[26]);
- climatic classes (e.g. Köppen-Geiger climate classification);
- dominant land cover composition (e.g. using the Land Mosaic approach (Vogt & Riitters, 2017));
- structure of built-up areas, i.e., dispersion vs compactness[27] (e.g. modelled using the Fragmentation of Open Spaces approach)

The final sub-division would require practical testing to ensure consistency across the European territory.

For the thematic approach, where interrelations between artificial components and the broader mosaic is assessed in detail, urban ecosystems should be split internally in sub-classes. This subdivision could be done making use of land cover classes (e.g. CLC) that help to represent the sub-systems of homogeneous character that compose urban ecosystems.

Reference levels for the assessment of ecosystem condition are already established for only three variables: noise pollution exposure, air pollutants concentration and heavy metals in soil. In this three cases, reference levels are defined according to the **prescribed reference levels as defined by law, in which scientific evidence is also considered (Table 4).** The Environmental Noise Directive, in alignment with the World Health Organization, defines threshold for noise pollution exposure, The Air Quality Directive dictates legal thresholds for air pollutants concentrations that are currently under revision. In the case of heavy metals in soil, screening values are defined at MS level, however there are currently no harmonised EU standard (Carlon et al, 2007). EU standards for heavy metals in soil are currently being discussed in the context of the up-coming ‘Soil Health Law’ (see discussion on section 5.2.3 for further information). For all the other variables proposed, except the wild pollinators indicator, **combination of methods to identify reference levels** would be required including a **modelled reference condition, statistical approaches based on ambient distribution, and expert opinion**.

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[25] https://ec.europa.eu/eurostat/web/degree-of-urbanisation/background

[26] See OECD cities classification: https://data.oecd.org/popregion/urban-population-by-city-size.htm#:~:text=their%20administrative%20boundaries.-,Urban%20areas%20in%20OECD%20countries%20are%20classified%20as%3A%20large%20metropolitan,areas%20if%20their%20population%20is

[27] Historically, urban areas in Europe have been developed in a more or less compact form as a consequence of the environmental and socio-cultural factors influencing their evolution. Therefore, besides contemporary urban sprawl, by legacy there are urban areas more or less compact, what influences their ecological functioning. Reason why it is important to characterise cities based on their default compactness since it could influence reference levels for condition attributes.

Table 4. Methods for setting reference levels of condition variables for urban areas

Reference levels		Variable	Values
Existing reference levels	Prescribed levels (legal thresholds aligned with scientific evidence)	Noise pollution exposure	Environmental Noise Directive
		Air pollutants concentration	Air Quality Directive
		Heavy metals in soil	At country level: Carlon et al. 2007 (no EU standard)
Reference levels to be defined	Combination of methods (modelled reference condition, statistical approaches based on ambient distribution, expert opinion)	All other variables for urban areas	To be defined
	To be defined when indicator available	Wild pollinators indicator	To be defined

Carlon et al. (2007) Derivation methods of soil screening values in Europe. A review and evaluation of national procedures towards harmonisation - EUR 22805-EN, European Commission, Joint Research Centre, Ispra.

4.1.4 Conclusions

In the case of urban ecosystems, there are **many variables that can be calculated by making use of remote sensing products**, their inventories, and derived models, at an adequate temporal and spatial resolution. Therefore, the availability of optimal data permits a robust estimation of the condition of urban areas. In fact, physical, chemical and structural state classes are already well represented.

For biotic variables (compositional and functional classes), in the case of urban ecosystems there are **major gaps in terms of detailed biotic characterization**. There is no tradition of monitoring and inventorying flora and fauna in these contexts in a systematic and consistent way in the EU. Furthermore, major data gaps are also detected for monitoring soil variables influencing ecosystem condition (i.e. soil organic carbon, heavy metals concentration in soil). As a result, those condition classes remain incomplete and knowledge can be expected to be gathered only for woody plants, since they are not mobile species and are large enough to be potentially mapped through remote sensing products. Despite this gap, the interest in urban biodiversity and urban ecosystems is increasing. It is demonstrated by the latest initiatives and projects in the European Commission, such as the project BiodiverCities (Maes et al., 2021a). This project aimed at promoting the deployment of urban green infrastructures, enhancing the condition of urban ecosystems and providing benefits for people and nature. There is also an emergent interest in soil monitoring in the EU Soil Strategy and the proposed Soil Health Law, which includes urban soils. Linked to this emerging interest, in the medium/long term, it is expected that monitoring/inventorying advances permit a more complete representation of those condition classes.

Moving from variables to indicators, supported by **the definition of reference levels, is still very challenging in the case of urban ecosystems**. First, it will require clustering individual ecosystems in consistent groups in the EU. However, different to other ecosystems, scholars have not agreed yet on this type of clustering for urban ecosystems. In fact, research on classification of urban ecosystems (from a socio-ecological perspective) is still in its infancy. Therefore, much more work is required before defining an adequate clustering of urban ecosystems at the EU, and their associated reference levels.

4.2 Agroecosystems

4.2.1 Definition and delineation of agroecosystems

Agroecosystems are communities of plants and animals interacting with their physical, chemical, and biological environments that have been modified by people to produce food, feed, fibres, energy and other products for human consumption and processing (Maes et al., 2018).

Agroecosystems are classified into cropland and grassland ecosystems. Cropland includes land area under temporary and permanent cultivation, land temporarily fallow, horticultural and domestic habitats. Grasslands are areas covered by grass-dominated vegetation (including tall forbs, mosses and lichens), which include pastures, meadows, semi-natural and natural grasslands. High-diversity landscape features on agricultural land, including buffer strips, hedges, non-productive trees, terrace walls and ponds are considered an integral and important part of agroecosystems. In the CLC nomenclature, all ten level-3 classes 2.x.x except class 2.3.1 'Pastures' identify the area for cropland, while classes 2.3.1 'Pastures' and 3.2.1 'Natural grassland' identify the area for grasslands.

The Utilised Agricultural Area (UAA) is defined as 'total area taken up by arable land, permanent grassland, permanent crops and kitchen gardens used by the holding, regardless of the type of tenure or of whether it is used as a part of common land'[28]. The UAA provides a stricter quantification of the extent of agroecosystems, since it quantifies the area directly used by agricultural holdings.

On the other hand, it should also be stressed that farming or 'agriculture' as socio-ecological system goes far beyond the area frame based on CLC classes or UAA, since land cover not always coincides with land use (e.g. grazing can occur in forest, heathland and shrub ecosystems as well). Moreover, some landscape features may be accounted as part of the UAA.

4.2.2 Variables to assess the condition of agroecosystems at EU level

The selection of variables for condition assessment of agroecosystems is based on previous work done under the EU ecosystem assessment (Maes et al., 2020a), indicators selected for the NRL, and impact indicators suggested for the assessment of the performance of the Common Agricultural Policy (CAP). The CAP 2023-2027 presents a framework for identifying specific needs at Member State level. It also requires achieving concrete results with ambitious environmental objectives, which makes the CAP strategic plans a potentially effective tool to implement restoration actions in European agroecosystems.

The common framework for the monitoring and evaluation of the results is presented in the Regulation establishing the CAP strategic plans (EU Regulation 2021/2115[29]), and it is based on impact, result, output and context indicators.

Table 5 presents the variables for the assessment of agroecosystem condition. In order to provide a cross-policy platform to optimise measures for agroecosystems restoration, some of the variables, such as soil organic carbon, gross nutrient balance, risk and use of pesticides, farmland bird indicator, totally or partially coincide in the concept and/or definition with impact indicators for the assessment of the performance of the CAP. For variables such as pollinators, crop diversity and share of landscape features, the definition and especially the protocol for calculating the CAP indicators are under development and an alignment in the methodologies may be necessary once they are finalised. Table 5 also shows the type of data stream from which the different variables can be obtained (i.e. mapping or EU/MS reporting).

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[28] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Utilised_agricultural_area_(UAA)

[29] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32021R2115

Table 5. Variables for the assessment of agroecosystem condition

Ecosystem Condition Typology	Data stream[1]	Variable	Units	Source of the variable at EU level	Temporal series available	Spatial resolution	Type[2]
A1. Physical state	Mapping	Soil erosion by water	ton/ha/year	ESDAC modelling	2010, 2016, 2020	100 m	Modelled
A2. Chemical state	Mapping	Exceedance of critical loads for acidification	eq/ha/year	EMEP	2000, 2005, 2010, 2016, 2020	0.5° longitude; 0.25° latitude	Modelled
		Exceedance of critical loads for eutrophication	eq/ha/year	EMEP	2000, 2005, 2010, 2016, 2020	0.5° longitude; 0.25° latitude	Modelled
		Pesticides residues in soils[3]	µg/g	JRC modelling	2016	1 km	Modelled
		Pesticide use[3]	kg/year	JRC modelling	2016	1 km	Modelled
	EU/MS reporting, Mapping	Nitrogen balance	kg/ha	Eurostat [AEI_PR_GNB] / CAPRI	2010-2017	1 km	Modelled
		Organic carbon stock in cropland mineral soils	kg C/ha	LUCAS / JRC	2009, 2015, 2018	Sampling points / 1 km	Complementary / Modelled
		Heavy metals in soils	µg/g	LUCAS / JRC	2009 (2018 coming soon)	Sampling points / 500 m	Complementary / Modelled
	EU/MS reporting	Harmonised pesticide risk indicators[3]	Dimensionless	European Commission	Yearly 2011-2019	EU, MS	Complementary (very coarse spatial resolution)
B1. Compositional state	Mapping	Richness of species of the farmland bird indicator	Number of species	EBBA2/PECMBS	No	10 km	Complementary (no time series)
		Soil biodiversity	Not applicable	LUCAS / JRC modelling	2018, 2022	1 000 m	Coming soon
		Pressure by invasive alien species on agroecosystems	Dimensionless	JRC-EASIN	No	10 km	Complementary (currently no time series)

Ecosystem Condition Typology	Data stream[1]	Variable	Units	Source of the variable at EU level	Temporal series available	Spatial resolution	Type[2]
		Crop genetic diversity	Not applicable	Not applicable	Not applicable	Not applicable	Data gap
	EU/MS reporting	Grassland butterfly indicator	Dimensionless	ABLE	Since 1990	EU	Complementary (very coarse spatial resolution)
		Common farmland bird indicator	Dimensionless	Pan-European Common Bird Monitoring Scheme (PECBMS)	Annual, 1980 to 2021 or 1990 to 2021	Country	Complementary (very coarse spatial resolution)
		Percentage of farmland species with good population status	Percentage (%)	Art.17 HD	Reporting periods:2001-2006; 2007-2012; 2013-2018	MS per biogeographical region	Complementary (very coarse spatial resolution)
		Farmland species richness of conservation concern (no birds)	Number of species	Art.17 HD (for all species except birds)	Reporting periods:2001-2006; 2007-2012; 2013-2018	10 km	Complementary (no spatially or temporally consistent)
		Richness of key plant species (for grasslands and cropland)	Number of key species or key species groups	LUCAS (only grassland) / EMBAL	2022-2023	MS	Complementary (very coarse spatial resolution)
B2. Structural state	Mapping	Share of small woody features	Percentage (%)	Copernicus	2015,2018	1 km	Optimal
	EU/MS Reporting	Share of landscape features	Percentage (%)	LUCAS, JRC / CAP I.21	2022	>NUTS2	Coming soon
B3. Functional state	Mapping	Loss of productivity due to drought	%, area of drought impact (km^2); or normalised vegetation productivity anomalies (standard deviation)	Remote sensing (MODIS)	2000-2019, to be updated until 2021, annual	500 m	Optimal

Ecosystem Condition Typology	Data stream[1]	Variable	Units	Source of the variable at EU level	Temporal series available	Spatial resolution	Type[2]
		Exposure of agricultural area to ozone	$\mu g/m^3$ or ppb	Air Quality e-reporting database (former AirBase) station data, EMEP dispersion model	1996-2019	500 m map from point (station) data	Modelled
	EU/MS reporting, Mapping	Share of fallow land	Percentage (%)	Eurostat [EF_LAC_GREENFAL]	2013, 2016	NUTS2	Complementary (coarse spatial resolution)
				Eurostat / CAPRI	2010-2018	1 km	Modelled
	EU/MS reporting	Wild pollinators indicator	Dimensionless	STING/SPRING projects	2024	EU (finer resolution to be decided)	Coming soon
C1. Landscape and seascape	Mapping	Crop diversity	Dimensionless	Sentinel 1 crop map	2018 - updates planned on a 3 years cycle	1 km	Complementary (currently no time series)
		Connectivity of small woody features	Not applicable	Not applicable	Input data available for 2015 and 2018	Not applicable	Data gap

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[1] EU/MS Reporting (Reported data by MS or EU monitoring), Mapping (spatial data)

[2] Type: Optimal (EU map and temporal series), modelled (maps are a modelled outcome), complementary (when data match at least one of these criteria: no full EU coverage, no time series, not spatially or temporally consistent, require modelling-point data, very coarse spatial resolution, coming soon (data that are currently not available but there is a project or initiative currently working on it), data gap (key variables currently missing for which there are no plans to be developed).

[3] Different types of variables related to pesticides have been included due to the different nature of the data, while pesticides residues in soils is a modelled output that refers only to soil, pesticides use includes a broader scope of pesticides (beyond soil) as proxy of pesticide content, and harmonised risk indicators are not available below the national level. The suitability of each variable will ultimately depend on the purpose of the application of the methodology.

The description and justification of the variables selected to assess condition of agroecosystems are included below.

Relevance of physical state variables

Soil erosion by water: Soil erosion by water is one of the major threats to soils in the European Union, with a negative impact on ecosystem services, crop production, drinking water quality, biodiversity and carbon stocks. Pressure indicators expressed as flows are not fully SEEA EA compliant. However, soil erosion in the framework of the EU-wide methodology is used as a surrogate of relevant condition variables such as soil depth, for which there is currently no information. Moreover, the relationship between soil erosion and ecosystem condition is very consistent and well understood. Since the inclusion of soil erosion is one of the eight threats listed in the European Commission's Soil Thematic Strategy, an approach to monitor soil erosion has been identified. This is based on the application of the Revised Universal Soil Loss Equation (RUSLE) model (Panagos et al., 2015), as the result of modelling input factors (rainfall erosivity, soil erodibility, cover management, topography, support practices) using available datasets at European scale. The modelling approach has been scientifically validated and is the main model used to assess erosion in MS. The first estimation of soil loss for the reference year 2010 was followed by an update for 2016. Taking into account the scientific soundness of the approach, maps have been produced at 100 m spatial resolution. The 2020 update for soil erosion will be developed by JRC and it is expected to integrating data from the farm accountancy data network (FADN) for 2020.

Relevance of chemical state variables

Exceedance of critical loads for acidification and eutrophication: The critical load concept is defined as 'a quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge' (Nilsson, 1988).

Nitrogen and sulphur emissions and depositions can lead to eutrophication and acidification of ecosystems. When these pollutants exceed certain levels, they affect the ecological condition of ecosystems (Hettelingh et al., 2017; Tsyro et al., 2018). Exceedance of nitrogen and sulphur are the consequence of elevated concentration and deposition of these pollutants, which are mostly produced by human activities. Modelled maps at a coarse horizontal resolution of 0.5° longitude and 0.25° latitude of exceedances of critical loads are provided by the co-operative programme for monitoring and evaluation of the long-range transmission of air pollutants in Europe (European Monitoring and Evaluation Programme - EMEP). The maps cover the EU territory and are available for 2000, 2005, 2010, 2016 and 2020.

Pesticides residues in soils: Diffuse pollution by active ingredients of plant protection products is a major soil threat. In particular, it is proven that some pesticides have a high soil persistence, resulting in toxicity to non-target species. Such diffuse pollution impacts soil functions and soil biodiversity, and through off-site transport can impair sink ecosystems functioning (Silva et al., 2019). JRC is currently finalising an assessment of residues in cropland soils across the EU based on analysis of approximately 3 000 samples collected during the 2018 LUCAS Survey.

Pesticide use: Pesticides have a direct effect on the state of ecosystems, due to their intrinsic properties, pesticides can in fact be harmful to non-target organisms (European Commission, 2022), either through direct exposure or through reduction in food and habitat availability (Hallmann et al., 2014; Kennedy et al., 2013). In absence of data on the presence of residues in the environment[30], total pesticides emissions provide a proxy for pesticides effects on biodiversity beyond target organisms. As described in Galimberti et al. (2020), a database with a first

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[30] https://www.insignia-bee.eu/

disaggregation exercise of pesticide (sales or use) data of about 150 substances is available for the year 2016, at 1 km resolution.

Nitrogen balance: The gross (or agricultural) nitrogen balance describes the difference between all nitrogen inputs and outputs on agricultural land. Nitrogen is the main element of many fertilisers used in agricultural production. A positive balance or surplus therefore reflects inputs that are in excess of crop and forage needs, and may result in diffuse pollution through, for example, the loss of nutrients to water bodies, leading to decreased water quality and increased eutrophication. Surplus nitrogen can also be lost to air as ammonia and other greenhouse gases. High nitrogen losses from agricultural land to the environment therefore have a significant negative impact on biodiversity and ecosystems, and have the potential to cause problems for human health (EEA, 2021).

The balance includes data from multiple sources such as consumption of fertilisers, livestock population, crop production and areas of various types of crops. The geospatial layer is derived from the disaggregation of CAPRI data (Leip et al., 2008) and is available in a yearly time series 2010-2017. The use of CAPRI data is proposed to further explore how spatially explicit data holding sufficient spatial resolution could inform the ecosystem condition mapping and assessment. If CAPRI data are proven to be relevant for this purpose, then, a regular production of these data needs to be guaranteed. In particular, procedures and input data to calculate N balance at NUTS2 level and disaggregation routines are constantly under improvement on the basis of new data and information availability.

Organic carbon stock in cropland mineral soils: Human pressure on soil is threatening vital ecosystem services, such as food and fibre production, and the soil ability to sequester carbon, thus mitigating the emissions of greenhouse gases, is at risk (Lal, 2004). Recognizing the importance of soil organic carbon (SOC) for sustaining soil quality, food production and resilience against weather extremes, the European Commission considers the decline of SOC in soils as one of the main threats for soil degradation in its Thematic Strategy for Soil Protection[31]. At the same time, depleted organic carbon levels, particularly in agroecosystems, provide an opportunity for increased carbon sequestration through adequate management practices. Importantly, the goal of the exercise is to restore the condition of the agroecosystem and selected practices should not be detrimental to biodiversity. There are available LUCAS campaigns (2009 - 2015 - 2018). In addition, soil organic carbon (SOC) stock at pan-European level at 1 km resolution was obtained by applying CENTURY model, based on soil, climate, land use and management data (Lugato et al., 2014). Model results were validated with LUCAS 2009 data on top-soil SOC and EIONET-SOIL data. JRC is further improving the modelling of SOC in cropland to provide output at 100 m resolution.

Heavy metals in soils (As, Cd, Cr, Cu, Hg, Pb, Mn, Sb, Co, Ni, Zn): Several anthropogenic activities, such as expanding industrial areas causing disposal of heavy metal wastes, excessive use of fertilisers and pesticides, irrigation with wastewater, and atmospheric deposition, drive the uncontrolled accumulation of heavy metals in soils. These pollutants are dangerous because, despite organic contaminants are normally subject to oxidation by microbial action, most metals are not characterised by the same degradation level and persist in many soils for a very long time. Agroecosystems are severely affected by the presence of heavy metals in soils as the latter might generate food and ground water unsafety, and increase food insecurity due to a reduction of land potentially usable for production.

The soil sampling campaign realised during the LUCAS survey of 2009, 2012, and 2018 included the analysis for the detection of heavy metals. The JRC makes available the first modelled results (500 m resolution) of copper distribution in European Union topsoils. More detailed maps on heavy metals and soil contaminants will become available soon (https://esdac.jrc.ec.europa.eu/themes/soil-contamination).

Harmonised pesticide risk indicators: The Harmonised Risk Indicators[32] (HRI1, HRI2) show the risks associated with the use of pesticides since 2011 under Directive 2009/128/EC. HRI1 measures the use and risk of pesticides,

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[31] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52006DC0231

[32] https://ec.europa.eu/food/plants/pesticides/sustainable-use-pesticides/harmonised-risk-indicators/trends-eu_en

based on the sales of pesticide active substances (AS) reported to the Commission by Member States, including low risk AS and candidates for substitution. It is calculated by multiplying these quantities by a weighting factor linked to each of the four AS risk groups. HRI2 is based on the number of emergency authorisations granted. It is calculated by multiplying the number of emergency authorisations granted by a weighting factor, as in HRI1. Harmonised Risk Indicators are relevant for assessing condition of agroecosystems, but due to their coarse geographical reporting unit, the indicators cannot be used for high-resolution ecosystem condition assessments.

Relevance of compositional state variables

Richness of species of the farmland bird indicator: One of the main objectives of the second European Breeding Bird Atlas (EBBA2) is to provide maps showing bird occurrence at a 10 km resolution for as many of the European breeding bird species as possible (Keller et al., 2020). With almost 120 000 10x10 km cells across Europe, it would be practically impossible to carry out comprehensive surveys in each spatial unit. Consequently, the only feasible approach to achieve this goal is modelling the probability of bird occurrence by means of: i) gathering a sample of standardised bird occurrence data; ii) using these data to model the relationships between bird occurrence and the environment (40 predictor variables e.g. habitat, climate); and iii) projecting these relationships across the whole set of 10x10 km cells in Europe.

The layer on richness of species composing the farmland bird indicator is based on the distribution of the 39 species composing the farmland bird indicator and represents the number of species in each 10x10 km cell, as surveyed in the 2014-2017 period. The European Breeding Birds Atlas is not going to be updated on a regular basis. Regular updates on geospatial distribution of species occurrence can be derived from data collected by the Pan-European Common Bird Monitoring Scheme. However, this option needs to be tested.

As alternative to the EBBA2 data, available to the JRC for farmland birds, bird distribution data at 10x10 km from Art. 12 of the BD, reported every 6 years, could be potentially of use, as suggested for other ecosystem types. The limitations of species richness as condition indicators are further discussed in Box 3 (section 5.1).

Soil biodiversity: Soil biodiversity is, by definition, the variety of life belowground, where the abundance and diversity of soil-dwelling flora and fauna is greater than aboveground organisms by orders of magnitude. In fact, a teaspoon of soil (about one gram) typically contains one billion bacterial cells (corresponding to about ten thousands different bacterial genomes), up to one million individual fungi, about one million cells of protists and several hundred of nematodes. Soil biodiversity is highly important, as it allows the provision of fundamental ecosystem services, such as nutrient cycling functioning and regulation of water flow and storage, and maintenance of soil structure, and goods such as food and fibre production.

Soil samples collected during the 2018 LUCAS survey provided the baseline for soil biodiversity data. This allows the creation of the first European scale soil biodiversity map, at 1 000 m spatial resolution (Smith et al., 2021). This approach provides spatially-explicit estimates of uncertainty that should be taken into account when using the modelled outcome. A microbial biomass layer is currently available and additional products are in development (by end 2022). A second time stamp is under way as part of the LUCAS 2022 survey.

Pressure by invasive alien species on agroecosystems: The pressure by IAS on ecosystems has a potential negative effect on their condition due to the increased threat (Pyšek et al., 2020). Pressure by IAS can be measured as the cumulative pressure exerted by IAS based on the sum of their occurrence in an area, weighted by the extent of the ecosystem(s) potentially affected. This cumulative pressure indicator was developed for the EU ecosystem assessment (Maes et al., 2020a) using species records from the baseline distribution of IAS of Union concern available on the European Invasive Species Information Network (https://easin.jrc.ec.europa.eu/easin/Documentation/Baseline). It will be possible to infer trends in relation to the baseline of IAS when the EU MS second reporting under the IAS Regulation becomes available in 2025.

Crop genetic diversity: Genetic resources include domesticated and related wild species of plants, animals, forest trees, fungi, invertebrates, and microorganisms, and their genetic diversity—including cultivars, breeds, populations, individuals, and genes. They are an important part of biodiversity, providing the raw materials on which humankind relies for food, nutrition and livelihood security, supporting the bioeconomy. The vast range of traits expressed in genetic resources, and their adaptive capacity, are essential for enhancing the resilience of agricultural production systems (GEnRes Bridge Project[33]). Though the erosion of genetic resources and loss of genetic diversity is recognised (FAO, 2019), a genetic resources monitoring system is not yet in place.

Grassland butterfly indicator: The EU grassland butterfly indicator is one of the few indicators of the status of biodiversity in the European Union. It is an abundance indicator based on data recording the population trends of 17 butterfly species in 16 EU countries (Van Swaay et al., 2019). The EU indices for the 17 species were combined by taking the geometric mean of the indices. This indicator is a unified measure of biodiversity following the bird indicators as described in Gregory et al. (2005), by averaging indices of species rather than abundances in order to give each species an equal weight in the resulting indicator. When positive and negative changes of indices are in balance, then their mean would be expected to remain stable. If more species decline than increase, the mean should go down and vice versa. Thus, the indicator is considered a measure of biodiversity change.

The indicator is calculated yearly and improved as the number of surveyed transects increases or Countries join the monitoring system. The Assessing Butterflies in Europe project (ABLE), the European Butterfly Monitoring Scheme (eBMS), the EU Pollinators Monitoring Scheme (EU-PoMS) and the Strengthening Pollinator Recovery through INdicators and monitorinG (SPRING)[34] project are four main initiatives extending and improving the monitoring schemes, so that each individual EU Member State will be able to produce a national indicator.

Due to its coarse reporting unit, the indicator cannot be used for high-resolution ecosystem condition assessments. In the medium term, when the number of surveys transect will reach a statistically significant number, it will be possible to geospatialise the information on each individual species, following the example of Polce et al. (2018).

Common farmland bird indicator: The Farmland Bird Indicator (FBI) is intended as proxy to assess the biodiversity status of agricultural landscapes in Europe. The FBI is developed at the pan-European level making use of the Common Bird Monitoring Scheme (PECBMS[35]). It is a composite indicator that measures the rate of change in the relative abundance of 39 common bird species at selected sites. The selected species are dependent on farmland for feeding and nesting and are not able to thrive in other habitats. Population trends are derived from the counts of individual bird species at census sites and modelled as such through time. The indicator is available at the EU level, and at national level (except for Malta). It is worth noting that the national monitoring schemes have been set in place in different years but all have been running for at least ten years. The indicator is available as well for four European macro-regions (North, Central and East, West, and South). Due to its coarse reporting unit, it cannot be used for high-resolution ecosystem condition assessments.

Percentage of farmland species with good population status (see Box 1 on indicator species by ecosystem type): Population size of different (non-bird) species is assessed against a 'favourable reference population' (FRP) under the Article 17 of the HD to report the status of population size. A favourable reference population is the population in a given biogeographical region considered the minimum necessary to ensure the long-term viability of the species (DG Environment, 2017). Thus, larger percentage of agricultural species with good population status (i.e. population size is less than 5% below the FRP) ensures the species maintenance in the long term, hence contributing to the ecosystems' integrity (De Leo & Levin, 1997). Population data reported under the HD currently presents limitations in terms of spatial resolution. Each population assessment per species is done per country and biogeographical region. It can potentially be mapped at 10 km resolution making use of occurrence polygons also

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[33] http://www.genresbridge.eu/

[34] See section 5.2.1 for further information on the EU-PoMS and SPRING

[35] https://pecbms.info/

reported for each species. An important caveat is that the reporting for different time periods are not fully comparable to assess changes over time.

Box 1. Indicator species for the assessment of ecosystem condition by ecosystem type

The assessment of ecosystem condition comprises compositional state characteristics that include information related to species composition. The condition assessment performed separately for each ecosystem type requires a careful selection of species closely related to the condition of each ecosystem type to develop robust condition variables (i.e. higher values are related to better condition). The selection of indicator species for condition to monitor ecosystem integrity has been broadly discussed in the literature (see Carignan and Villard (2002)) and a robust selection of indicator species for condition remains still very challenging (Siddig et al., 2016). At the EU level, there is well-accepted lists of common birds associated to forest and to farmland ecosystems, for which population data are used as indicators for the condition of these ecosystem types. In spite of the widespread use of the farmland and forest common bird indicators, lists of species associated to different ecosystem types are only defined for these two ecosystem types. Identification of indicator species for other ecosystem types would be also required.

The identification of species-ecosystem association is far from being an easy task, especially for mobile species. Frequently, species are associated to different ecosystem types, moreover the association may change during the annual cycle (e.g. spring, winter), and, importantly, the species-ecosystem association varies geographically.

Recommendations for species data of the Habitats and Birds Directives

Identification of indicator species to build condition indicators is beyond the purpose of the EU-wide methodology. However, in the absence of official lists of indicator species some recommendations are provided to select a potential set of indicator species based on available data for each ecosystem type. However, further testing would be required for their consolidation.

In this sense, species under conservation concern included in the HD and BD may be selected as indicator species because they present relatively narrow ecological niches, being more sensitive to changes in the environment and therefore, becoming better indicators of ecosystem condition. Moreover, this group of species also present specific policy interest with concrete restoration targets defined under the Nature Restoration Law.

For species listed under the Habitats and Birds Directives, a work done in 2015 provides a species-habitat-MAES ecosystem association* by biogeographical region that can help in identifying potential species as indicator for condition by ecosystem type. Based on this information, indicator species for condition could be selected as those with just a single preferred ecosystem across all biogeographical regions, to ensure a strong association between the species and the targeted ecosystem. The indicator species selected can then be used to develop variables for each ecosystem type in relation to species components.

The dataset with species-ecosystem association is currently under review by the European Environment Agency and will be available in quarter four of 2022. This review includes only all species from the Habitats Directive (non-bird species).

*Available at https://www.eea.europa.eu/data-and-maps/data/linkages-of-species-and-habitat & https://www.eea.europa.eu/data-and-maps/data/article-12-database-birds-directive-2009-147-ec/article-12-data/csv-files/at_download/file

Farmland species richness of conservation concern (Art. 17 HD, no birds): see Box 3 on the use of species richness as indicator of ecosystem integrity for further information. Available data at EU level for species of conservation concern (except birds) are derived from Article 17 reporting of the HD. This variable, although not directly reported under the HD, can be easily calculated with the polygons used for reporting species occurrence. Data are based on a reference grid of 10 km spatial resolution, but the reporting is done by biogeographical region and country, which usually is a spatial resolution too coarse for an ecosystem condition mapping. These data currently present important spatial gaps and no fully comparable time series.

Richness of key plant species: plant species richness in **grasslands** is an indicator of ecological value, since species richness declines as intensification increases (Plantureux et al., 2005). In the frame of the LUCAS grassland module, a time and cost-efficient solution for monitoring plant diversity in grasslands was identified in a proxy, consisting in monitoring a restricted number of key species (Sutcliffe et al., 2019) in a 20 m transect for 20 000 LUCAS grassland points. An identical protocol is part of the European Monitoring of Biodiversity in Agricultural Landscapes survey (EMBAL). Results from both surveys can be used to derive an indicator reflecting vegetation diversity, based on a concept applied in defining agri-environmental measures for flower rich meadows (e.g. Fleury et al. (2015)). A list of 12 key species or key species groups has been drafted, describing EU grasslands in each of the 10 grassland regions in which the EU has been divided. Both LUCAS and EMBAL 2022-2023 campaigns are aiming to provide the indicator at MS level.

Richness of key plant species in **cropland**: similarly to key species identified for grasslands, in the frame of the EMBAL survey a list of key species or species group was identified as indicators of the ecological value of croplands, recorded along 20 m transects positioned in 500 m plots. The indicator is relevant for assessing condition of agroecosystems, but due to its coarse geographical reporting unit (at the MS level), it cannot be used for mapping ecosystem condition.

Relevance of structural state variables

Share of landscape features and of small woody features: Agricultural landscape features (LF) are small elements of non-productive semi-natural vegetation embedded in agricultural landscapes. This definition includes several elements of agricultural landscapes, such as hedges, ponds, ditches, trees in line or in-group, field margins, terraces, dry-stone or earth walls, etc. These elements have important functions, such as windbreaks and erosion protection, and maintenance of agricultural biodiversity and ecosystem services in the European agricultural landscapes.

The most comprehensive and consistent geospatial database of landscape features in Europe is currently the Copernicus Small Woody Feature (SWF) layer (validation study by the EEA currently ongoing), but it only includes woody landscape features (e.g. hedges, trees in line), which amounts to ~30% of all the elements classified as landscape features. The SWF layer was produced for the reference year 2015, with an update for 2018, at 5 m spatial resolution. In the framework of condition assessment for agroecosystems, the layer will be resampled at 1 km spatial resolution.

Another major upcoming EU data source on landscape features is the LUCAS LF module (Czúcz et al., 2022). This module will provide a statistically representative estimation for the share of all LF types at a NUTS2 level, which can be further refined using Copernicus SWF, and further spatial datasets. A regression estimator based on Copernicus SWF and LUCAS LF will be able to provide a statistical estimation of landscape features at a relatively fine spatial level, combining the positive sides of the two datasets. This estimator will also serve as the basis for the CAP impact indicator I.21.

Following the target of the EU Biodiversity Strategy for 2030 to bring back at least 10% of agricultural area under high-diversity landscape features, a wider discussion on harmonisation of the definition, identification, mapping, and areal estimate of landscape features in EU policies is ongoing (Czúcz et al., 2022). An improvement of both indicators may also become possible and necessary once this discussion is finalised.

Through the EMBAL survey, data on the ecological quality of landscape features is collected and can be used to complement the information.

Relevance of functional state variables

Loss of productivity due to drought: Between 2000 and 2019, the EEA-39 region was affected by severe droughts with an annual productivity loss of 3% in impacted areas. Croplands in particular marked a 4% decrease, with peaks of 61% of affected croplands in Portugal[36]. A loss in productivity is linked to a change in the functional state of the ecosystem, which has impaired abilities to deliver a range of ecosystem services, to support biodiversity and a decreased adaptation to climate change.

EEA data cover the period 2000-2019 and include the long-term linear trend (%) at 500 m resolution.

Exposure of agricultural area to ozone: Ground level ozone is one of the most prominent air pollution problems in Europe, mainly due to its effects on human health, crops and natural ecosystems. When absorbed by plants, it damages plant cells, impairing their ability to grow and reproduce, and leading to reduced agricultural crop yields, decreased forest growth, and reduced biodiversity (Mills et al., 2011). Given the importance of ozone for the condition of agroecosystems, this pressure is included as proxy of a more suitable condition variable such as yield loss due to ozone exposure. This variable shows the exposure of areas covered with vegetation (crops and forests) to ground-level ozone. Yearly maps at 500 m resolution are provided by the European Environment Agency for the period 1996-2019.

Share of fallow land: Fallow land is all arable land either included in the crop rotation system or maintained as described in Annex II of Council Regulation No 1306/2013, whether worked or not, but which will not be harvested for the duration of a crop year. The essential characteristic of fallow land is that it is left to recover, normally for the whole of a crop year. Fallow land was established to allow the recovery of soil (especially soil organic matter levels), in order to enhance its productivity capacity and to control the pests population (Kozak & Pudełko, 2021). Besides the increase of soil chemical properties levels, major improvements in the soil structure, topsoil water storing capacity, and nutrient availability were observed in the long period (Nielsen & Calderon, 2011).

The share of fallow land at 1 km scale is based on the disaggregation of CAPRI yearly data at European level for the period 2010-2018. New 10 m resolution data derived from Copernicus should become available in the short term.

Wild pollinators indicator: Pollinators ensure healthy ecosystem functioning and maintain biodiversity of terrestrial ecosystems, providing very valuable information on the functional state of ecosystems and thus, on their condition. See section 5.2.1 for further details on how insect pollinator monitoring can inform the assessment of ecosystem condition.

Relevance of landscape characteristics

Crop diversity ('true diversity')**:** Crop diversity is resulting from agricultural practices that incorporate several farming techniques, such as crop rotation, cover cropping, intercropping and cultivar mixtures. As several studies have pointed out, agricultural production based on crop diversity increases significantly its sustainability compared to monoculture (Vandermeer, 1990). For example, yield increase achieved through mixed cropping, pest reduction without the use of pesticides, increase of soil fertility and reduction of the airborne pests and pathogens are among the main advantages from an increase in crop diversity (He et al., 2019). In the framework of agroecosystem restoration, a 10m resolution European crop map (d'Andrimont et al., 2021) derived from Sentinel-1 and LUCAS Copernicus in-situ data (reference year 2018) was used to calculate the crop diversity based on Shannon's entropy at 1 km spatial grid (Merlos & Hijmans, 2020).

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[36] https://www.eea.europa.eu/ims/drought-impact-on-ecosystems-in-europe#:~:text=During%20the%20period%202000%2D2019,an%20annual%20average%20of%204%25

Connectivity of small woody features: The flow of organisms, materials, energy and information across landscapes is a pivotal function that needs to be guaranteed, to support gene flow, migration, re-colonization and more in general species movement between habitat patches (Correa Ayram et al., 2016). Landscape connectivity is a broad concept that needs to be broken down into its structural or functional aspects to be described through data and indicators. Examples are available in Estreguil et al. (2016). Some further discussion is needed about connectivity aspects that should be highlighted and translated into a geospatial indicator to support the assessment of agroecosystem condition.

4.2.3 Definition of reference levels for agroecosystems

About half of the condition variables proposed for agroecosystems present already defined reference levels, mainly based on the different types of prescribed levels, including scientific criteria, and/or aligned with legal targets or thresholds and absolute physical boundaries (Table 6). The use of absolute physical boundaries corresponds with a situation in which reference levels are defined according to an 'optimal condition' or 'desired state'. For instance, a state in which there is no nitrogen surplus, no pesticides residues in soil and no loss of productivity due to drought. The definition of these reference levels does not imply they should be used as potential policy targets in the future, but as levels to inform the assessment of the agroecosystems condition as the distance to this 'optimal condition'.

The use of prescribed levels is also found to be the most adequate method to set reference levels when these are not available (e.g. pesticide use, share of small woody features). The use of prescribed levels defined under policy targets strengthen the coherence of the condition assessment with current policies such as the EU Biodiversity Strategy for 2030, the CAP and the Farm to Fork Strategy. Although this method is not strongly recommended by the SEEA EA, the use of policy targets as reference levels can be justified due to the socio-ecologic nature of agroecosystems, its important productive role and the fact that policy targets are the result of consultations and agreements among many stakeholders. Meeting important targets such as a significant decrease of pesticide use requires the effort of several actors, and an adequate amount of time, but the application of policy targets might fail in achieving a real good condition from an ecological perspective. For instance, the pesticides reduction by 50%, presented in the proposal of a new Regulation on the Sustainable use of pesticides[37], might be not enough to avoid the impact of pesticides on ecosystems. Therefore, the use of reference levels based on policy targets should be reviewed in the future, if the impact on the ecosystem persists. Since this would imply a recalculation of the resulting indicators, changing reference levels should be done in exceptional cases. The alignment of indicators and reference levels with upcoming policies such as the Soil Health Law should also be considered in the future (see section 5.2.3).

In case of prescribed levels based on targets defined at EU or MS level, the definition of 'homogeneous ecosystem areas' may become necessary to spatially distribute the contribution of different areas towards reaching the target. Only in the case of SOC, the concept of 'homogeneous ecosystem areas' is already considered when setting different values depending on the soil type, environmental conditions and land use (de Brogniez et al., 2015).

Statistical approaches based on ambient distributions, combined with expert opinion, are only proposed for farmland species richness and crop diversity (Table 6). Setting reference levels for biodiversity is extremely complex (see also section 5.3).

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[37] https://ec.europa.eu/food/plants/pesticides/sustainable-use-pesticides_en

Table 6. Methods for setting reference levels of variables for agroecosystems

Reference levels		Variable	Values
Existing reference levels	Prescribed levels (scientific evidence)	Soil erosion by water	2 ton/ha (Panagos et al., 2015)
		Exceedance of critical loads for acidification/eutrophication	Zero exceedance (based on critical loads) (Hettelingh et al., 2017)
		Organic carbon stock in cropland mineral soils	Varies according to soil type, environmental conditions and land use – general acceptance that less than 20 g OC/kg affects supply of ecosystem services (de Brogniez et al., 2015)
	Prescribed level (aligned to legal targets)	Exposure of agricultural area to ozone	Long term target 6 000 (μg/m^3)
		Percentage of farmland species with good population status	All species with good conservation status of population size (aligned with the NRL)
	Prescribed levels (legal thresholds aligned with scientific evidence)	Heavy metals in soils	At country level: Carlon et al. 2007 (no EU standard)
	Other prescribed levels (absolute physical boundaries)	Nitrogen balance	No surplus
		Pesticides residues in soils	No residues in soils
		Loss of productivity due to drought	No loss of productivity
	Contemporary condition	Grassland butterfly indicator, common farmland bird indicator	100%: value of the indicator for the reference year
Reference levels to be defined	Prescribed level (legal target)	Pesticide use, harmonised pesticide risk indicators	In line with the 50% reduction target
		Share of landscape features and of small woody features, share of fallow land	Contribution to policy target under discussion
	Combination of methods	Richness of species of the farmland bird indicator, farmland species richness of conservation concern, crop diversity	Statistical approaches based on ambient distributions, scientific criteria, modelled and/or contemporary condition
		Pressure by invasive alien species on agroecosystems	Expert opinion / contemporary condition
	To be defined when indicator available	Wild pollinators indicator, soil biodiversity, crop genetic diversity, connectivity of small woody features	To be defined

Carlon et al. (2007) Derivation methods of soil screening values in Europe. A review and evaluation of national procedures towards harmonisation - EUR 22805-EN, European Commission, Joint Research Centre, Ispra

de Brogniez et al. (2015) A map of the topsoil organic carbon content of Europe generated by a generalised additive model. European Journal of Soil Science, 66, 121–134

Hettelingh et al. (2017) European critical loads: database, biodiversity and ecosystems at risk: CCE Final Report 2017. RIVM, Coordination Centre for Effects, Bilthoven, Netherlands

Panagos et al. (2015) The new assessment of soil loss by water erosion in Europe. Environmental Science & Policy, 54, 438-447

In the case of agroecosystems, reference levels for farmland species richness and crop diversity could be based on a delineation of ‘homogeneous ecosystem areas’ in agricultural land, in which the potential achievable within each zone is identified and set as reference level. The definition of ‘homogeneous ecosystem areas’ should be based on cropping systems and/or grassland areas, including information on intensity of management and environmental characteristics such as altitude and climate. The maximum number of species in an ‘homogeneous ecosystem area’ under a specific management type and sharing similar landscape characteristics (e.g. rice fields in Northern Italy) can be assumed to be the potential condition for that area, and therefore used as reference level. Another option is to use past surveys or modelling results to calculate reference levels e.g. lost richness and set thus a recovery potential.

4.2.4 Conclusions

There are multiple difficulties in assessing the condition of agroecosystems. The most important is that they are modified ecosystems characterised by a high variability throughout the EU, originated by complex interactions between societal demand, economic drivers, environmental potential and limits and historical developments. For such reasons, the process to identify reference sites against which to compare the values of ecosystem condition variables found in other locations is very complex, if not impossible. Setting individual reference levels for each of the identified variables is an effective solution, which guarantees the achievement of a regenerative functioning of agroecosystems. Importantly, when taking up this solution, trade-offs among indicators should be carefully considered.

Overall, 26 variables are identified to describe condition of agroecosystems, covering all the six SEEA EA state categories. Ultimately, the suitability of each variable for the condition assessment will depend on the specific purpose of the application of the EU-wide methodology (e.g. mapping or assessment at EU aggregated level). Of these 26 variables, 15 are available, even if as proxies (derived from modelling), as geospatial layers covering the entire EU territory over time.

In the process of selecting condition variables, crop production was not considered because it highly depends on human inputs and therefore, it is largely unrelated to the ecosystem condition. Note that the ecosystem condition assessment is focused only on the ecological dimension of the social-ecological complexity of agroecosystems. Moreover, some pressures such as soil erosion and exposure to ozone were considered as essential to be included in the condition assessment. Although they are not SEEA EA compliant, they were considered here due to the lack of better data capturing the impact of these pressures on ecosystem condition.

4.3 Forest ecosystems

4.3.1 Definition and delineation of forest ecosystems

The notion of forest ecosystems evokes the combination of structural, compositional and functional features present in forested areas. In forest ecosystems, trees are higher than 5 m with a canopy closure of 30% at least, along with transitional woodland-shrubland. This notion is associated with the definitions used in CLC, which has proven appropriate for mapping forest ecosystems at EU level (Maes et al., 2013). The MAES forest ecosystems classification includes four CLC categories: broad-leaved forest, coniferous forest, mixed forest and transitional woodland-shrub. Note that transitional woodland-shrub is considered part of forest ecosystems because it may represent forest degradation, regeneration, recolonization or natural succession, which are processes normally associated with forest ecosystems.

4.3.2 Variables to assess forest condition at EU level

Variables identified to assess the condition of forest ecosystems are presented in Table 7. This table also shows the type of data stream from which the different variables can be obtained (i.e. mapping or EU/MS reporting). The selection of variables for forest ecosystems was based on the general criteria (see section 3.3), but also on the indicators proposed under the EU Forest Strategy for 2030 with the aim to strengthen the linkage between forest management and monitoring systems already in place (Box 2). The Forest Strategy proposes enhancing forest management practices that preserve and restore biodiversity and forest condition, taking into consideration the great diversity of forest ecosystems and species, but also considering habitat types, biogeographical regions and forest types. Management practices that support biodiversity and improve forest ecosystem condition are essential, for instance practices that enhance functional diversity, mixed-species forest, uneven-aged forest and deadwood. Therefore, these traits may suggest indicators that should be considered for tracking progress in forest restoration.

Table 7. Variables for the assessment of forest ecosystem condition

Ecosystem Condition Typology	Data stream[1]	Variable	Units	Source of the variable at EU level	Temporal series available	Spatial resolution	Type[2]
A1. Physical state	Mapping	Normalised difference water index (NDWI)	Dimensionless	MODIS	2000-2022	30 m	Optimal
A2. Chemical state	Mapping	Exceedance of critical loads for acidification	eq/ha/year	EMEP	2000, 2005, 2010, 2016, 2020	0.5° longitude; 0.25° latitude	Modelled
		Exceedance of critical loads for eutrophication	mol nitrogen eq/ha/year	EMEP	2000, 2005, 2010, 2016, 2020	0.5° longitude; 0.25° latitude	Modelled
	EU/MS reporting	Soil organic carbon stock	kg C/ha	LUCAS	2009, 2015, 2018	Sampling points	Complementary
				UNFCCC (Greenhouse Gas Inventories, LULUCF sector)	Annual from 1990	Country	Complementary (very coarse spatial resolution)
	EU/MS reporting, Mapping	Heavy metals in soils	µg/g	LUCAS / JRC	2009 (2018 coming soon)	Sampling points / JRC 500 m	Complementary / Modelled
B1. Compositional state	EU/MS reporting, Mapping	Pressure by invasive alien species on forest	Dimensionless	JRC-EASIN	No	10 km	Complementary (currently no time series)
		Richness of threatened forest birds	Number of species	Art. 12 Birds Directive / JRC	Art.12-Reporting periods: 2008-2012; 2013-2018 / JRC- 2000, 2006, 2012, 2018	10 km	Complementary (no spatially or temporally consistent) / Modelled
	EU/MS reporting	Percentage of forest species with good population status	Percentage (%)	Art. 17 Habitats Directive	Reporting periods: 2001-2006; 2007-2012; 2013-2018	MS per biogeographical region	Complementary (very coarse spatial resolution)
		Forest species richness of conservation concern (no birds)	Number of species	Art. 17 Habitats Directive	Reporting periods: 2001-2006; 2007-2012; 2013-2018	10 km	Complementary (no spatially or temporally consistent)

Ecosystem Condition Typology	Data stream[1]	Variable	Units	Source of the variable at EU level	Temporal series available	Spatial resolution	Type[2]
		Diversity of tree species	Forest area (or share of forest area) classified by number of tree species	Forest Europe /UNECE/FAO	1990, 2000, 2005, 2010, 2015	Admin units/ Country	Complementary (not spatially consistent)
		Common forest bird indicator	Dimensionless	Pan-European Common Bird Monitoring Scheme (PECBMS)	Annual, 1980 to 2021 or 1990 to 2021	Country	Complementary (very coarse spatial resolution)
B2. Structural state	Mapping	Forest biomass	Mg/ha	JRC	No (2010)	100 m	Complementary (currently no time series)
		Tree cover density	Percentage (%)	Copernicus	2012, 2015, 2018	100 m	Optimal
	EU/MS reporting	Growing stock	m^3/ha	Forest Europe/UNECE/FAO	1990, 2000, 2005, 2010, 2015, 2016*, 2017*, 2018*, 2019*, 2020 (*modelled by JRC)	Administrative units: country (occasionally NUTS2, NUTS3)	Complementary (very coarse spatial resolution)
		Deadwood (total, including standing and lying)	m^3/ha	Forest Europe/UNECE/FAO	1990, 2000, 2005, 2010, 2015	Administrative units: country (occasionally NUTS2, NUTS3)	Complementary (very coarse spatial resolution)
B3. Functional state	Mapping	NDVI (photosynthetic activity)	Dimensionless	Copernicus	2014 to 2020 at 300 m; 1999 to 2020 at 1 km	300 m; 1 km	Optimal
		Fire recurrence	Burnt area (ha/year); burnt area density (ha/km^2/year)	Copernicus, EFFIS	Copernicus since 2014; EFFIS since 2003	250 m-300 m	Optimal
	EU/MS reporting	Tree crown defoliation	Percentage (%)	ICP Forests	1990 to 2021	Plot level data	Complementary (not spatially consistent)

Ecosystem Condition Typology	Data stream[1]	Variable	Units	Source of the variable at EU level	Temporal series available	Spatial resolution	Type[2]
		Wild pollinators indicator	Dimensionless	STING/SPRING projects	2024	EU (finer resolution to be decided)	Coming soon
C1. Landscape and seascape	Mapping	Forest connectivity (Forest area density)	Percentage (%)	JRC (CLC, GUIDOS toolbox)	1990, 2000, 2006, 2012, 2018	100 m	Optimal
		Landscape naturalness	Percentage (%) of natural area	JRC (CLC, GUIDOS toolbox)	1990, 2000, 2006, 2012, 2018	100 m	Optimal
	EU/MS reporting	Percentage of uneven aged forest (age structure)	Percentage (%) of uneven aged forest	Forest Europe/UNECE/FAO	1990, 2000, 2005, 2010, 2015	Administrative units: country (occasionally NUTS2, NUTS3)	Complementary (very coarse spatial resolution)

[1] EU/MS Reporting (Reported data by MS or EU monitoring), Mapping (spatial data)

[2] Type: Optimal (EU map and temporal series), modelled (maps are a modelled outcome), complementary (when data match at least one of these criteria: no full EU coverage, no time series, not spatially or temporally consistent, require modelling-point data, very coarse spatial resolution, coming soon (data that are currently not available but there is a project or initiative currently working on it), data gap (key variables currently missing for which there are no plans to be developed).

Box 2. The EU Forest Strategy for 2030

The EU Forest Strategy for 2030 builds on the EU Biodiversity Strategy for 2030 and will contribute to achieving the EU's biodiversity objectives. According to the Forest Strategy, for reaching the EU's biodiversity objectives, larger, healthier and more diverse forest ecosystems than the current ones are necessary. The Strategy includes measures for strengthening forest protection and restoration, and enhancing sustainable forest management. Likewise, the objective of improving forest monitoring is one of the aims closely related with the scope of this document.

The Forest Strategy paved the way for an ambitious system aimed to improve data collection and monitoring of EU forests. Today information on forest ecosystems condition is patchy. Currently no comprehensive reporting requirement exists and current initiatives have a voluntary character. Robust and comprehensive wall-to-wall indicators of forest condition are scarce, and major challenges remain regarding the use of remote sensing data together with ground-based data, for instance lack of interoperability, lack of common definitions, limited long and comparable high-resolution time-series and limitations of standard forest products from Copernicus.

The description and justification of the variables selected to assess forest condition are included below.

Relevance of physical state variables

Normalised difference water index (NDWI): The NDWI is sensitive to changes in liquid water content of vegetation canopies. It is an index known to be strongly related to the water content of plants. Thus, the NDWI is a good proxy for plant water stress, which in turn can have impacts on plant development and growth (Gao, 1996; Sankey et al., 2021). NDWI is dimensionless and varies between -1 to +1 depending on plant leaf water content. High values of NDWI correspond to high vegetation water content and to high vegetation fraction cover, and vice-versa. Therefore, NDWI decreases with low vegetation water content. Long term effects of water stress on trees can lead to tree defoliation and mortality. NDWI and NDWI anomalies can provide information both on the spatial distribution of the vegetation water stress and its temporal evolution over long time periods. The NDWI is a MODIS remote sensing-derived global product available since 2000 until now as part of the Google Earth Engine Data Catalogue and is provided at a spatial resolution of 500 m. Consequently, the data set is appropriate for calculating time-series of the index. Note, however, that using remotely sensed imagery at higher spatial resolution[38] as input for creating the index, would in turn deliver a higher resolution NDWI dataset.

Relevance of chemical state variables

Exceedance of critical loads for acidification and eutrophication: Nitrogen and sulphur emissions and depositions can lead to eutrophication and acidification of ecosystems. When these pollutants exceeds certain levels, i.e. 'critical load', they affect the ecological condition of ecosystems (Hettelingh et al., 2017; Tsyro et al., 2018). Exceedance of nitrogen and sulphur are the consequence of elevated concentration and deposition of these pollutants, which are mostly produced by human activities. Modelled maps at a coarse horizontal resolution of 0.5° longitude and 0.25° latitude of exceedances of critical loads are provided by EMEP[39]. The maps cover the EU territory and are available for the years 2000, 2005, 2010, 2016 and 2020.

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[38] https://scihub.copernicus.eu/

[39] https://www.emep.int/

Soil organic carbon stock: Chemical properties of the forest topsoil play a key role supporting forest functions and the provision of forest ecosystem services. For example, soil organic carbon (SOC) is key in the nutrient cycle and carbon cycle of forest ecosystems. Therefore, SOC is an important element contributing to enhance the role of forest as carbon sinks. Furthermore, SOC affects forest growth and the forest water cycle, i.e. buffering, regulating and filtering of water (Pan et al., 2011; Rumpel & Kögel-Knabner, 2011).

Unlike croplands, consideration must be given to the carbon content of the litter layer overlying forest top soils. Depending on the tree species and environmental conditions, it may be difficult to accurately define in the field where the mineral soil surface starts as organisms mix highly decomposed organic matter into the upper layers of the mineral matrix. LUCAS data on SOC stocks in forests are available for 2012, 2015 and 2018 (very soon). Approximately 8 000 samples are being collected as part of the 2022 survey, which has been adapted for woodland points to include a sample of the litter layer and increased awareness of the junction between the soil and overlying organic surface horizon. It is expected that these extra elements will reduce the variability of SOC values, as significant changes in concentrations between surveys sometimes reflects inconsistencies in the application of sampling techniques.

Heavy metals in soils (As, Cd, Cr, Cu, Hg, Pb, Mn, Sb, Co, Ni, Zn): While low levels of heavy metals are required in the form of micro-nutrients for good ecosystem functioning, high levels of heavy are of special concern. Heavy metals cannot be easily degraded and are sometimes difficult to be stabilised or to be modified to reduce the associated risk. Moreover, they tend to bio-accumulate in many trophic chains, presenting a long term risk for the local biota and humans (Briffa et al., 2020). Heavy metals are of concern in forest ecosystems because they are a common type of soil pollutant consequence of past and present commercial and industrial activities. LUCAS data on metal content in forest soils are available for 2009 (limited trend data from 2018 soon). Discussions are ongoing regarding further analysis on samples collected during 2022 and on the development of risk indicators (i.e. beyond concentrations). The JRC makes available the first interpolated results (500 m resolution) of copper distribution in European Union topsoils. More detailed maps on heavy metals and soil contaminants will become available soon (https://esdac.jrc.ec.europa.eu/themes/soil-contamination).

Relevance of compositional state variables

Pressure by invasive alien species on forest: The pressure by IAS on ecosystems has a potential negative effect on their condition due to the increased threat (Pyšek et al., 2020). Pressure by IAS can be measured as the cumulative pressure exerted by IAS based on the sum of their occurrence in an area, weighted by the extent of the ecosystem(s) potentially affected. This cumulative pressure indicator was developed for the EU ecosystem assessment (Maes et al., 2020a) using species records from the baseline distribution of IAS of Union concern available on the European Invasive Species Information Network (https://easin.jrc.ec.europa.eu/easin/Documentation/Baseline). It will be possible to infer trends in relation to the baseline of IAS when the EU MS second reporting under the IAS Regulation becomes available in 2025.

Richness of threatened forest birds: see also description of forest species richness above. In this case, data available at the EU level (derived from Articles 12 reporting of the BD) present important spatial gaps since not all countries reported bird distributions, and time series are not fully comparable. For this reason, modelling can be applied to provide a consistent spatio-temporal assessment of the forest suitability to host threatened forest birds (ongoing JRC work in collaboration with the University Rey Juan Carlos, manuscript in preparation (Maes et al., 2022)).

Percentage of forest species with good population status (see Box 1 on indicator species): Population size of different (non-bird) species is assessed against a ‘favourable reference population’ (FRP) under the Article 17 of the HD to report status of population size. A favourable reference population is the population in a given biogeographical region considered the minimum necessary to ensure the long-term viability of the species (DG Environment, 2017). Thus, larger percentage of forest species with good population status (i.e. population size is less than 5% below the FRP) ensures the species maintenance in the long term, hence contributing to the ecosystems' integrity (De Leo & Levin, 1997). Population data reported under the HD currently presents limitations in terms of spatial resolution. Each population assessment per species is done per country and biogeographical region. It can potentially be mapped at 10 km resolution making use of occurrence polygons also reported for each species. An important caveat is that the reporting for different time periods are not fully comparable to assess changes over time.

Forest species richness of conservation concern (Art. 17 HD, no birds): see Box 3 on the use of species richness as indicator of ecosystem integrity for further information. Data available at EU level for species of conservation concern (except birds) are derived from Article 17 reporting of the HD. This variable, although not directly reported under the HD, can be certainly calculated with the polygons used for reporting species occurrence. Data are based on a reference grid of 10 km spatial resolution, but the reporting is done by biogeographical region and country, which usually is a spatial resolution too coarse for an ecosystem condition mapping. These data currently present important spatial gaps and no straightforward comparable time series.

Alternatively, and similarly to agroecosystems, richness of the species included in the common forests bird indicator could potentially also be used as indicator of forest condition (Vallecillo et al., 2016).

Diversity of tree species: The composition of tree species in a forest, i.e. the number of tree species, is affected both by natural factors and by human activity, specifically past and present forestry, and legacies of past land uses. Forest composed of several trees species are often more biodiverse, resilient and functionally diverse than mono-species forests (Forest Europe, 2020; Gamfeldt et al., 2013). This indicator is provided by the FOREST EUROPE, UNECE and FAO initiative (Forest Europe, 2020) using data reported by participating countries. The indicator is reported at country level and is available for the following years: 1990, 2000, 2005, 2010 and 2015. The spatial unit of reporting at country level restricts the usability of this indicator for the assessment of forest ecosystems condition at higher spatial resolution.

Common forest bird indicator: This indicator measures the abundance of common forest birds across their European ranges over time. It is an indicator created from observational data of bird species characteristic of forest habitats in Europe, developed at the pan-European level making use of the Common Bird Monitoring Scheme (PECBMS[40]). The indicator is considered a proxy for biodiversity at large spatial and temporal scales (Gregory et al., 2019; Gregory et al., 2005). This indicator is produced at the European (including 29 countries[41]) and at the EU level, covering the period 1980-2021. The indicator is also provided disaggregated at four macro-European regions, i.e. North, Central and East, West and South. However, the coarse spatial unit of reporting (country level) restricts their usability for high-resolution ecosystem condition assessments.

Relevance of structural state variables

Forest biomass: Forest biomass is the total biomass of living vegetation, both woody and herbaceous in forest. Forest biomass information is often split into aboveground and belowground. Aboveground biomass includes stems, stumps, branches, bark, seeds and foliage. Belowground biomass includes live roots. Similarly as growing stock, forest biomass is a key feature of forest ecosystems. Natural forest and forest with old-growth characteristics contains large amount of biomass, which is often associated with forest functions and biodiversity (Cardinale et al., 2007). An indicator (map) of forest biomass is provided by the JRC (Avitabile et al., 2020)[42]. The map describes above ground forest biomass density at 100 m resolution for the year 2010 matching harmonised reference

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[40] https://pecbms.info/

[41] There is an increasing number of countries reporting over time. Further information on how to alleviate this effect can be found in https://pecbms.info/european-wild-bird-indicators-2021-update/

[42] http://data.europa.eu/89h/d1fdf7aa-df33-49af-b7d5-40d226ec0da3

statistics at national and sub-national level in terms of forest area, biomass density and biomass stock. An updated version of the map is currently in preparation.

Tree cover density: The amount and density of trees in forest is a fundamental trait of ecosystem structure, which underpin, among other processes, biogeochemical processes, habitat for biodiversity, productivity and carbon storage. An understanding of the extent and density of forest trees is necessary for monitoring the condition of forest ecosystems and assess the role of sustainable forest management. A decrease in tree cover density can be the result of natural and/or man-made pressures. While an increase in tree cover density is the result of e.g. planting or natural regeneration. Changes in tree cover density were associated with forest loss and gain, which in turn affects forest structure and condition (Dantas de Paula et al., 2016; Hansen et al., 2013; Miles et al., 2006). Tree cover density is defined as the 'vertical projection of tree crowns to a horizontal earth's surface'. This indicator measures the proportional (percent) forest crown coverage per grid cell at very high resolution of 10 m to 20 m using satellite data. The indicator is produced as part of the Copernicus' High Resolution Layers for 2012, 2015 and 2018. The maps representing the indicator cover the whole EU territory.

Growing stock: Growing stock represents the living tree component of the standing volume of forest. Therefore, this indicator refers to the volume of all living trees over bark and includes all trees with a minimum diameter of 10 cm at breast height. Standing volume excludes branches, twigs and foliage. Growing stock is a fundamental indicator of forest inventories and is also considered a proxy for biodiversity[43]. An increase of growing stock relative to forest area is an indication of a more dense forest. This indicator provides useful information of the potential of forest functions, services and biodiversity. Changes in growing stock are the result of the difference between forest growth and removals, either through human activities or through tree mortality due to natural disturbances (Forest Europe, 2020). This indicator is reported at country level and is available for the years 1990, 2000, 2005, 2010, 2015 and 2020. The spatial unit of reporting at country level restricts the usability of this indicator for the assessment of forest ecosystems condition at high spatial resolution.

Deadwood: Deadwood is all the non-living woody biomass of various sizes either standing or lying on the forest ground. It is a key component of forest ecosystems because provides microhabitats for a wide array of animal and plant species, fungi, moss and lichens. In addition, deadwood plays an important role in nutrient cycles, influences positively soil formation and reduces soil erosion. Furthermore, deadwood is a carbon pool contributing to climate change mitigation (Bauhus et al., 2009; Paillet et al., 2015). This indicator is provided by the Forest Europe, UNECE and FAO initiative using data reported by participating countries. The indicator is reported at country level and is available for the years 1990, 2000, 2005, 2010 and 2015. However, the coarse spatial unit of reporting at country level restricts their usability for the assessment of forest ecosystems condition at high spatial resolution.

Relevance of functional state variables

Normalised difference vegetation index – NDVI (photosynthetic activity): Phenological metrics such as the normalised difference vegetation index (NDVI) provide information on the status of the Earth's vegetative cover and its development over time. In general, NDVI is associated to the amount of carbon fixed by plants through the process of photosynthesis. The monitoring of vegetation productivity typically relies on the multi-temporal and thematic evaluation of long-term time series of remotely-sensed vegetation indices such as NDVI or FAPAR, computed from continuous spectral measurements of photosynthetic activity. These indices are highly correlated with photosynthetic capacity and primary production, which in turn are associated to processes of land degradation and recovery. A persistent decline in vegetation productivity points to the long-term worsening of condition and a decreased productive capacity of the ecosystem (Sommer et al., 2017). The indicator is produced as part of the

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[43] https://www.eea.europa.eu/data-and-maps/indicators/forest-growing-stock-increment-and-fellings-3/

Copernicus' Global Land Service. It measures the NDVI at grid cell level at a spatial resolution of 300 m (series 2014 to 2020) and 1 km (series 1999 to 2020). The maps representing the indicator cover the whole EU territory.

Fire recurrence: Fires are common in Mediterranean and circum-Mediterranean ecosystems where fire has been occurring for long time before the human era. Therefore, some forest ecosystems are thought to be adapted to fire events within the limits of historical occurrence. However, changes in fire occurrence can result in ecosystem degradation if plants and communities cannot adapt to new fire regimes (Turco et al., 2018; Westerling et al., 2006). Analyses of wildfires occurring in Europe in the last 30 years indicate an increase in the length of the fire season (San-Miguel-Ayanz et al., 2022). Nevertheless, improved management and fire prevention actions contributed to mitigate fire occurrence. Data on fire occurrence in Europe is provided by EFFIS (burnt area maps since 2003) and Copernicus (burnt area product since 2014) at a spatial resolution of 250 m and 300 m, respectively.

Tree crown defoliation: Tree crown defoliation is a parameter of tree vitality, which can be affected by a number of human and natural factors (abiotic and biotic). Therefore, defoliation is an important natural bioindicator useful as a measure of forest ecosystem condition. Defoliation can occur, for example, when trees are exposed to insect infestations, fungi, deposition of pollutants, abiotic factors such as heat and drought, frost, wind, snow/ice, or human activities (Michel et al., 2018). The defoliation survey implemented by International Co-operative Programme on assessment and monitoring of air pollution effects on forests (ICP Forests) in 2017 assessed 5,496 plots in 26 European countries, including 101,779 trees (Michel et al., 2018). Despite the key importance of this indicator for describing the condition of forest ecosystems, a seamless data set (map) of defoliation covering the whole EU is not within the objectives of the ICP Forests. This is because the information surveyed and provided by this organization is at plot level. An ecosystem condition assessment following a territorial approach at high spatial resolution would require continuous wall-to-wall maps of the variables considered. Therefore, further efforts would be necessary on this indicator for providing the necessary data for such a high spatial resolution assessment.

Wild pollinators indicator: pollinators ensure healthy ecosystem functioning and maintain biodiversity of terrestrial ecosystems, providing very valuable information on the functional state of ecosystems and thus, on their condition. See section 5.2.1 for further details on how insect pollinator monitoring can inform the assessment of ecosystem condition.

Relevance of landscape characteristics

Forest connectivity (forest area density): Forest connectivity quantifies the degree of spatial intactness of forest cover. The higher the connectivity, the more thriving the forest ecosystem. Forest connectivity can be seen as the opposite of forest fragmentation, i.e. highly connected ≈ little fragmented and vice-versa. Forest connectivity is a key forest trait influencing biodiversity, forest functions and services. Forest fragmentation may lead to the isolation and loss of species and gene pools, degraded habitat quality and a reduction in the forest's ability to sustain the natural processes necessary to maintain ecosystem condition. The methodological concept of this indicator measures Forest Area Density (FAD) in percent at local (grid-cell) level. FAD is then grouped into five categories, showing varying degrees of connectivity/fragmentation within forest patches (Vogt et al., 2019b). The indicator is provided by the JRC[44] and is used in forest monitoring initiatives such as Forest Europe (Vogt et al., 2019b) and FAO (Vogt et al., 2019a).

Landscape naturalness: This indicator derived from the Landscape Mosaic (LM) metric describes landscape composition or the degree of landscape heterogeneity. The LM is based on land cover maps (e.g. CLC). The terrestrial land cover categories are aggregated into three main land cover types, that is, agriculture, natural and developed. Then, relative proportions of these three types are measured for each cell via a moving window algorithm using a

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[44] https://data.jrc.ec.europa.eu/dataset/b28156f8-a8d3-4f26-b15f-902774650e19

fixed neighbourhood area. Based on this, each grid cell is classified in one naturalness class (Maes et al., 2020a; Riitters et al., 2020). This indicator is developed by the JRC and the available dates depend on the land cover maps used for its implementation[45].

Percentage of uneven-aged forest (age structure): This indicator describes the age-class structure of forest available for wood supply (FAWS). FAWS are 'forests where any environmental, social or economic restrictions do not have a significant impact on the current or potential supply of wood. These restrictions can be established by legal rules, managerial/owner's decisions or because of other reasons.' (Forest Europe, 2015). FAWS represent about 85% of forest in the EU, and according to Forest Europe (2020) even aged forest represent more than 70% of Europe's FAWS. Therefore, uneven-aged forests cover barely 30% of the FAWS area. This indicator is important for understanding the ecological condition of forest ecosystems because provides insights regarding the provision of essential ecosystem services and biodiversity. Which are in general more favourable in uneven-aged forest and in old even-aged forests compared to young even-aged forests (Dănescu et al., 2016; Forest Europe, 2020). This indicator is maintained by the Forest Europe, UNECE and FAO initiative using data reported by participating countries. The indicator is reported at country level and is available for the following years: 1990, 2000, 2005, 2010 and 2015. However, the coarse spatial unit of reporting at country level restricts their usability for the assessment of forest ecosystems condition at high spatial resolution.

4.3.3 Definition of reference levels for forests

As mentioned in section 3.3, the **definition of 'homogeneous ecosystem areas'** is required as a previous step to set reference levels, which allows thus rescaling ecosystem variables into meaningful indicators on ecosystem condition. Accordingly, forest ecosystems can be split into sub-types by integrating data on: 1) Forest type according by CLC (i.e. broad-leaved, coniferous, mixed and transitional woodland-shrub) and 2) Biogeographical regions (EEA). This approach defines about 44 'homogeneous ecosystem areas' for forest across the EU.

With this mapping approach to identify 'homogeneous forest areas' we ensure a better alignment of the mapped forest classes with the IUCN global ecosystem typology - GET (recommended by the SEEA EA, see section 2.2). IUCN's GET typology classifies forest types in different ecosystem functional groups[46] (e.g. temperate, boreal, oceanic cool), following an equivalent criteria to classify forest using biogeographical regions. The approach proposed provides a more detailed division of forest ecosystems, but still maintains the attributes necessary to be aligned, and compared with data reported under the HD, which are also reported by biogeographical region.

The method suggested to define reference levels for forest ecosystems depends on the target variable. For some variables there are already defined reference levels (Table 8). For example, in the case of the exceedance of critical loads for acidification and eutrophication, reference levels are defined by the critical loads that have been scientifically estimated (scientific prescribed level). In this case, the reference level corresponding to the maximum integrity would be zero exceedance. Similarly, the common forest bird indicator is a variable that has been already calculated by adopting a reference baseline year (contemporary condition), which commonly is 1990[47]. For those variables with already defined reference levels, there is usually no need to make use of the delineation of 'homogeneous ecosystem areas'.

For those condition variables for which there are no pre-defined reference levels, one of the recommended approaches for EU forest ecosystems is using the values of the variables found in reference forest sites (Table 8). Undisturbed primary and old growth forests are considered appropriate reference sites. Values of the variables found on these areas can be used as reference condition within each 'homogeneous ecosystem area' (i.e. forest

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[45] https://ies-ows.jrc.ec.europa.eu/gtb/GTB/psheets/GTB-Pattern-LM.pdf

[46] A group of related ecosystems within a biome that share common ecological drivers, which in turn promote similar biotic traits that characterise the group. Derived from the top-down by subdivision of biomes

[47] https://ec.europa.eu/eurostat/cache/metadata/en/t2020_rn130_esmsip2.htm

subtype by biogeographic region). In case of lack of primary and old-growth forest in specific ‘homogeneous ecosystem areas’, a second option would be using values of the variables found in undisturbed protected forest (i.e. IUCN categories Ia, Ib and II). Thus, assuming that undisturbed forest under highest protection levels are ecosystems in good condition.

Table 8. Methods for setting reference levels of condition variables for forest

Reference levels		Variable	Reference value
Existing reference levels	Prescribed levels (scientific evidence)	Exceedance of critical loads for acidification/eutrophication	Zero exceedance (Hettelingh et al., 2017)
	Prescribed level (aligned to legal targets)	Percentage of forest species with good population status	100%: all species in good population status
	Prescribed levels (legal thresholds aligned with scientific evidence)	Heavy metals in soils	At country level: Carlon et al. 2007 (no EU standard)
	Contemporary condition	Common forest bird indicator	100%: value of the indicator for the reference year (e.g. 1990)
Reference levels to be defined	Reference forest sites	NDWI, stock of organic carbon in forest land, richness of threatened forest birds, forest biomass, tree cover density, NDVI, connectivity, landscape naturalness	Data driven
	Combination of methods	Diversity of tree species, growing stock, deadwood, tree crown defoliation, fire recurrence, percentage of uneven aged forest (age structure)	Scientific evidence / expert opinion / statistical analysis
		Pressure by invasive alien species on forest ecosystems	Expert opinion / contemporary condition
	To be defined when indicator available	Wild pollinators indicator	To be defined

Carlon et al. (2007) Derivation methods of soil screening values in Europe. A review and evaluation of national procedures towards harmonisation - EUR 22805-EN, European Commission, Joint Research Centre, Ispra

Hettelingh et al. (2017) European critical loads: database, biodiversity and ecosystems at risk: CCE Final Report 2017. RIVM, Coordination Centre for Effects, Bilthoven, Netherlands

However, the use of reference forest sites is only recommended for some geospatial variables, while for others such as fire recurrence, a combination of methods would be more appropriate (Table 8).

Another example is ‘pressure by invasive alien species’ for which a reference level of zero would not be feasible anymore in forest ecosystems. Complete eradication of invasive forest species is not effectively achievable at EU level. In this case, the method to determine reference levels would be based on EU baseline distributions of IAS for a point in the past combined with expert opinion.

In the case of variables available at regional or national scale such as diversity of tree species and growing stock, a combination of methods should be applied.

4.3.4 Conclusions

Remote sensing-derived indicators represent most of the optimal indicators identified. They provide wall-to-wall data for several parameters such as for example land cover, which is used for calculating forest connectivity and landscape metrics, but also indices of plant physiology and stress (i.e. functional) such as NDVI or structural metrics such as tree cover density. They represent promising options for a periodic monitoring of forest ecosystems condition. Nevertheless, challenges related to the use of remote sensing integrated with ground data for calibration and validation should be taken into consideration. A good example of integration of remote sensing data with ground measurements is the JRC's study on the biomass of European forests (Avitabile et al., 2020). This study describes the methodologies used for harmonising and comparing data from different sources, and proposes an improved biomass map consistent with forest inventory data and national statistics.

Modelled data such as the indicators on the exceedance of critical loads provides **useful information to assess ecosystem condition**. These indicators are available as grid wall-to-wall maps for several periods. Therefore, they are considered appropriate for assessing ecosystem condition following a territorial approach. Nevertheless, some characteristics of the modelled data should be taken into consideration, for instance, model validation using ground-based data, model uncertainty, assumptions adopted for model implementation. This information is useful for assessing the consistency of modelled data to convey information on forest condition.

There are significant limitations regarding forest variables, actually only six out of 22 variables were considered optimal. Most limitations are related with coarse spatial unit of reporting, which in some cases is country level. Variables at such coarse spatial level pose challenges for the assessment and monitoring of forest condition. The difficulties are caused by the unknown distribution of the measured parameter at the landscape level. In addition, this makes it problematic to define references levels reconciling local data with the information provided by the variable at country level. In some other cases, the limiting factor is the lack of comparable and consistent time series. For instance, compositional and chemical state show no optimal variables, confirming the **limited availability of highly resolved metrics for biota**.

National Forest Inventories (NFI) represent comprehensive forest monitoring systems. They provide valuable forest information useful for a wide range of forest related policies and reporting streams such as FAO's Global Forest Resource Assessment and Forest Europe. However, data from most NFIs lack the spatial resolution, and in some cases the temporal resolution, needed for a territorial-based ecosystem condition assessment. In addition, issues regarding data harmonisation and common definitions persist (Nabuurs et al., 2019).

When reference levels are not already defined, they can be calculated based on a selection of reference forest sites for variables presenting spatially-explicit and accurate geospatial layers. The **reference forest sites are assumed to be in good ecological condition**. This would require ancillary data for a set of forest reference sites. One option is using primary and old-growth forests as reference sites assuming they are in good condition. Nevertheless, one limitation is that the geographical distribution of primary and old-growth forests in the EU is uneven and scarce (Barredo et al., 2021). Indeed, these forests are absent or very limited in many European sub-regions and further alternatives to set reference forest sites need to be considered. For instance, one option is using protected forest areas exhibiting good ecological condition as reference sites.

The Commission is working for putting forward a legislative proposal for a new EU Framework for Forest Monitoring and Strategic Plans[48] as a measure for alleviating data deficiencies on forest (EU Forest Strategy to 2030[49], Box 2). This will establish an EU-wide integrated forest monitoring system, using remote sensing technologies and

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[48] https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/13396-EU-forests-new-EU-Framework-for-Forest-Monitoring-and-Strategic-Plans_en

[49] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021DC0572

geospatial data integrated with ground-based monitoring. The system will improve forest information across the EU and provide more comprehensive data for assessing and monitoring forest condition.

4.4 Heathland and shrub, and sparsely vegetated land

4.4.1 Definition and delineation of ecosystems

Heathland and shrub

‘Heathland and shrub’ ecosystems are dominated by small woody plants (e.g. heaths or sclerophyllous shrubs), often in combination with herbs and scattered trees and sometimes with a large contingent of mosses, liverworts and lichens. They are distributed across all the biogeographical regions of Europe, from Mediterranean to Boreal regions and from lowlands to high altitudes. This MAES ecosystem type correspond to ‘moors and heathlands’ and ‘sclerophyllous vegetation’ in CLC (Annex 2).

Sparsely vegetated land

‘Sparsely vegetated land’ are all unvegetated or sparsely vegetated habitats (naturally unvegetated areas). Often these ecosystems have extreme natural conditions that might support particular species. They are mainly shaped by geological or climatological processes and include the following CLC classes: beaches, dunes and sand plains; bare rocks; sparsely vegetated areas; burnt areas; glaciers and perpetual snow. ‘Sparsely vegetated lands’ occur throughout the whole Europe and can be associated or interlinked in some mountain or coastal areas.

4.4.2 Variables to assess the condition at EU level of ‘heathland and shrub’ and ‘sparsely vegetated land’

Variables identified to assess the condition of ‘heathland and shrub’ and ‘sparsely vegetated land’ are presented in Table 9. This table also shows for which ecosystem type the variables apply and the type of data stream from which the different variables can be obtained (i.e. mapping or EU/MS reporting).

Both ‘heathland and shrub’ and ‘sparsely vegetated land’ include very heterogeneous CLC classes and variables might be applicable only to certain land cover types. For instance, in the case of beaches, dunes and sandy shores, as well as bare rocks, variables of productivity are not meaningful, but they can be applied in the case of other sparsely vegetated areas.

Table 9. Variables for the condition assessment of 'heathland and shrub' & 'sparsely vegetated land' ecosystems

Ecosystem Condition Typology	Data stream[1]	Ecosystem type	Variable	Units	Source of the variable at EU level	Temporal series available	Spatial resolution	Type[2]
A1. Physical state	Mapping	Heathland & sparsely vegetated land	Soil moisture deficit during the vegetation growing season	Dimensionless	EEA	2000-2019	500 m	Optimal
		Heathland & sparsely vegetated land	Soil water index (Surface soil moisture)	Percentage (%)	Copernicus	2015-2022	1 km	Optimal
		Sparsely vegetated land (only beaches)	Sea level anomaly	meters or %	CMEMS	1993-2019	25°	Optimal
A2. Chemical State	Mapping	Heathland & sparsely vegetated land	Soil organic carbon stock	tonne/ha	LUCAS	2009, 2015, 2018	Sampling points	Complementary
		Heathland & sparsely vegetated land	Exposure to ozone	µg/m^3.hour	EEA	2004-2019	500 m	Modelled
		Heathland and shrub	P and N content in soils	mg/kg (P); g/kg (N)	LUCAS	2009/2012/2015	Sampling points	Complementary / Modelled
		Heathland & sparsely vegetated land	Exceedance of critical loads for eutrophication	mol nitrogen eq/ ha/year	EMEP	2000, 2005, 2010, 2016, 2020	0.5° longitude; 0.25° latitude	Modelled
		Heathland & sparsely vegetated land	Exceedance of critical loads for acidification	eq/ha year	EMEP	2000, 2005, 2010, 2016, 2020	0.5° longitude; 0.25° latitude	Modelled
	EU/MS reporting, Mapping	Heathland & sparsely vegetated land	Heavy metals in soil	µg/g	LUCAS / JRC	2009 (2018 coming soon)	Sampling points, JRC 500 m	Complementary / Modelled
	Mapping	Heathland & sparsely vegetated land	Pressure by invasive alien species on 'heathland and shrub'	Dimensionless	JRC-EASIN	No	10 km	Complementary (currently no time series)

Ecosystem Condition Typology	Data stream[1]	Ecosystem type	Variable	Units	Source of the variable at EU level	Temporal series available	Spatial resolution	Type[2]
			and 'sparsely vegetated land'					
B1. Compositional state	EU/MS reporting	Heathland & sparsely vegetated land	Percentage of 'heathland' & 'sparsely vegetated land' species with good population status	Percentage (%)	Article 17 Habitats Directive	Reporting periods:2001-2006; 2007-2012; 2013-2018	MS per biogeographical region	Complementary (very coarse spatial resolution)
		Heathland & sparsely vegetated land	Species richness for 'heathland' & 'sparsely vegetated land'	Number of species	Art. 12 Birds Directive, Art. 17 Habitats Directive	Reporting periods of the HD and BD	10 km	Complementary (no spatially or temporally consistent)
		Heathland & sparsely vegetated land	Percentage of 'heathland' & 'sparsely vegetated land' birds with increasing or stable population trends (short term)	Percentage (%)	Art. 12 Birds Directive	Reporting periods: 2008-2012; 2013-2018; (2019-2024)	Country	Complementary (very coarse spatial resolution)
B2. Structural state	Mapping	Heathland & sparsely vegetated land	Fraction of green vegetation cover (Fcover)	Percentage (%)	Copernicus	2014-2022	300 m	Optimal
		Heathland & sparsely vegetated land	Tree cover density	Percentage (%)	Copernicus	2012, 2015, 2018	100 m	Optimal
		Heathland and shrub	Small woody features	Density of SWF (percentage aggregated from 5 m resolution data)	Copernicus	2015, 2018	100 m	Optimal
	Mapping	Heathland and shrub	Dry matter productivity	kg/ha/day	Copernicus	2014-2022	300 m	Optimal

Ecosystem Condition Typology	**Data stream**[1]	**Ecosystem type**	**Variable**	**Units**	**Source of the variable at EU level**	**Temporal series available**	**Spatial resolution**	**Type**[2]
B3. Functional state		Heathland and shrub	Aboveground vegetation productivity	Dimensionless	EEA	2000-2016	500 m	Optimal
		Heathland & sparsely vegetated land	Burnt area / fire overall recurrence	ha / fire frequency	Copernicus, EFFIS	Copernicus since 2014; EFFIS since 2003	250 m, 300 m	Optimal
	EU/MS reporting	Heathland and shrub	Wild pollinators indicator	Dimensionless	STING/SPRING projects	2024	NUTS0 (finer resolution to be decided)	Complementary (coming soon)
C1. Landscape and seascape	Mapping	Heathland & sparsely vegetated land	Landscape naturalness	Percentage (%) of natural area	JRC (Crone land cover, GUIDOS toolbox)	1990, 2000, 2006, 2012, 2018	100 m	Optimal
		Heathland & sparsely vegetated land	Fragmentation	Percentage / Mesh density	JRC / EEA	2000, 2006, 2012, 2018	1 km	Optimal

[1] EU/MS reporting (Reported data by MS or EU monitoring), Mapping (spatial data)

[2] Type: Optimal (EU map and temporal series), modelled (maps are a modelled outcome), complementary (when data match at least one of these criteria: no full EU coverage, no time series, not spatially or temporally consistent, require modelling-point data, very coarse spatial resolution, coming soon (data that are currently not available but there is a project or initiative currently working on it), data gap (key variables currently missing for which there are no plans to be developed).

The description and justification of the variables selected to assess condition of 'heathland and shrub' and 'sparsely vegetated land' is included below.

Relevance of physical state variables

Soil moisture deficit during the vegetation growing season: This indicator shows the annual deviation in average soil moisture content of each 500 m grid cell in the long term (1995-2019). Negative soil moisture anomalies indicate that the annual average availability of soil moisture to plants drops to such a level that it has the potential to affect terrestrial vegetation and, hence, cause persistent changes in ecosystem condition. This is especially of concern for moors, which largely depend on soil water. Negative long-term averages and negative trends in the annual data indicate increasing pressures on vegetation and ecosystems, and thus represent a climatic driver that should be considered in EU nature restoration plans. Data on soil moisture during the vegetation growing season is a key variable to monitoring the condition of 'heathland and shrub' and some ecosystems sub-types (CLC classes) of 'sparsely vegetated land' such as burnt- and sparsely vegetated areas. The indicator is computed on a yearly basis (vegetative growing season), it is available for a long time period (1995–2019) for the whole EEA39 region and it has a satisfactory spatial resolution (500 m x 500 m).

Soil water index-SWI (surface soil moisture): Changes in soil moisture have a serious impact on productivity and ecosystem health. Soil water index is complementary to the soil water deficit during the vegetation growing season. The Soil water index is calculated from a fusion of Surface Soil Moisture (SSM) observations from Sentinel-1 C-band SAR and Metop ASCAT sensors. A quality assessment was done for the data between 2015 and 2019, and concluded that the SWI 1 km product is in 'pre-operational' stage.

Sea level anomaly: Mean sea level evolution has a direct impact on coastal areas (beaches and dunes) and is a crucial index of climate change since it reflects both the amount of heat added in the ocean and the mass loss due to land ice melt. Higher anomaly in the sea level is indicative of a worse ecosystem condition due to the major physical impacts such as erosion of beaches, inundation of deltas as well as flooding and loss of habitats (Smyth & Elliot, 2016a). Reported sea level rise effects are expected to diminish coastal ecosystems available to nesting species by removing habitat and inundating nests during incubation (Von Holle et al., 2019). For this reason, the variable suggested measures the level of sea level rise and data are derived from remote sensing and observed data (Copernicus product), providing accurate and reliable data, covering the EU marine regions with comparable time series.

Relevance of chemical state variables

Soil organic carbon stock: Soil organic carbon, among other processes, influences soil structure and availability of energy (matter) for soil microorganisms and macroinvertebrates, as well as organic bound nutrients in the soil (Billings et al., 2021). Having low levels of soil organic carbon is important for the functioning of some types of heathland and shrub and sparsely vegetated land. Data are derived from sampling points (used to model continuous maps) and are available for 2009, 2015 and 2018. However, adequate sampling sites could be an issue.

Exposure to ozone: Although this is primarily a pressure indicator, it has been included in this list of condition indicators as a proxy for the ozone damage on vegetation (which is currently missing), hence an indirect measure of how heathland and shrubland are affected by this pollutant. Air polluted with ground-level ozone is a serious cause for concern in Europe, not only because of its harmful effects on human health but also because of its damaging effects on vegetation, leading to reduced crop yields and forest growth and loss of biodiversity[50]. The

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[50] https://www.eea.europa.eu/ims/exposure-of-europes-ecosystems-to-ozone#footnote-CM5Q67PW

AOT40 maps have been created by combining measurement data from the rural background stations combined with the results of the EMEP dispersion model, altitude field and surface solar radiation in a linear regression model, followed by the interpolation of its residuals by ordinary Kriging. However, considering the latest scientific knowledge concerning vegetation ozone exposure, it should be noted that, at present, ozone impacts on vegetation are better modelled by fluxes of ozone into stomatal openings of vegetation.

Phosphorous (P) and Nitrogen (N) content in soil / exceedance of critical loads for eutrophication: Ecosystems adapted to low N conditions such as Calluna-heathlands are especially sensitive to enhanced atmospheric N deposition that affects many aspects of ecosystem functioning, such as nutrient cycling. Species richness decreases with increasing N deposition for all vegetation types, especially in heathland and shrub. The increase in atmospheric N depositions affects community structure and composition in heathlands by also enhancing grass species over shrubs. The plant-community changes observed with higher N availability may also serve as indicators for negative effects on soil biota (Fagúndez, 2012). In contrast, low level of P content in soil, or a decrease of P content, may be more an issue (Vogels et al., 2013). The removal of above-ground biomass by mowing and/or grazing in heathlands has indeed an effect on the nutrient budgets, by removal of nitrogen and phosphorus from plant biomass. The effects of these management types on nitrogen budgets are lower than the effects on phosphorus budget, and in the long term, management practices aimed at nutrient removal alone will thus lead to a decrease in phosphorus availability relative to nitrogen. N and P content should therefore be low within heathlands, and the degradation of the ecosystem should be linked to an increase in N content, but to a decrease in P content. Modelled maps at a coarse horizontal resolution of 0.5° longitude and 0.25° latitude of exceedances of critical loads are provided by EMEP. The maps cover the EU territory and are available for the years 2000, 2005, 2010, 2016 and 2020.

Exceedance of critical loads for acidification: The acidification of ecosystems is caused by the atmospheric input of sulphur and nitrogen-containing air pollution, leading to negative effects in ecosystems. The input results in a decline of the pH value and the loss of nutrients, and long-term acid stress results in a reduced vitality of the plants and in an increased susceptibility to natural stress factors. Still, acidification of the soil has been shown to diminish the number of species in heathlands. When the pH falls below 5, particularly endangered species will disappear first, as most dominant heathland species (*Molinia caerulea* and *Deschampsia flexuosa*) have a lower pH optimum than the endangered species (Roem et al., 2002).

Heavy metals in soil (As, Cd, Cr, Cu, Hg, Pb, Mn, Sb, Co, Ni, Zn): The increase of heavy metals concentration in soils due to increasing anthropogenic influences such as mining, agricultural process, and combustion of fossil fuels among others is a cause of concern. The high concentration of these metals in soil is toxic not only to plants and animals but also to microorganisms that play an indispensable role in soil and aid the sustenance of natural cycles (Inobeme, 2021). Mapping concentrations of eight critical heavy metals (arsenic, cadmium, chromium, copper, mercury, nickel, lead and zinc) using the 1 588 georeferenced topsoil samples from the FOREGS Geochemical database are available for the year 2008. In 2021, the JRC made available the first pan-European high-resolution Mercury dataset and analyses the reasons for Hg distribution. Finally, the LUCAS topsoil samples (21 682 data records) have been analysed for heavy metals. The JRC makes available the first modelled results (500 m resolution) of copper distribution in European Union topsoils. More detailed maps on heavy metals and soil contaminants will become available soon (https://esdac.jrc.ec.europa.eu/themes/soil-contamination).

Relevance of compositional state variables

Pressure by invasive alien species on 'heathland and shrub' and 'sparsely vegetated land': The pressure by IAS on ecosystems has a potential negative effect on their condition due to the increased threat (Pyšek et al., 2020). Pressure by IAS can be measured as the cumulative pressure exerted by IAS based on the sum of their occurrence in an area, weighted by the extent of the ecosystem(s) potentially affected. This cumulative pressure indicator was developed for the EU ecosystem assessment (Maes et al., 2020a) using species records from the baseline distribution of IAS of Union concern available on the European Invasive Species Information Network (https://easin.jrc.ec.europa.eu/easin/Documentation/Baseline). It will be possible to infer trends in relation to the baseline of IAS when the EU MS second reporting under the IAS Regulation becomes available in 2025.

Percentage of 'heathland' & 'sparsely vegetated land' species with good population status (see Box 1 on indicator species): Population size of different (non-bird) species is assessed against a 'favourable reference population' (FRP) under the Article 17 of the HD to report status of population size. A favourable reference population is the population in a given biogeographical region considered the minimum necessary to ensure the long-term viability of the species (DG Environment, 2017). Thus, larger percentage of species (strongly associated with 'heathland and shrub' and 'sparsely vegetated land') with good population status (i.e. population size is less than 5% below the FRP) ensures the species maintenance in the long term, hence contributing to the ecosystems' integrity (De Leo & Levin, 1997). Population data reported under the HD currently presents limitations in terms of spatial resolution. Each population assessment per species is done per country and biogeographical region. It can potentially be mapped at 10 km resolution making use of occurrence polygons also reported for each species. An important caveat is that the reporting for different time periods are not fully comparable to assess changes over time.

Species richness for 'heathland' and 'sparsely vegetated land': see Box 3 on the use of species richness as indicator of ecosystem integrity for further information. Existing data at EU level are derived from the reporting of Article 12 of the BD and Article 17 of the HD. Available data of Art. 12 reporting of the BD present important spatial gaps (not all countries are currently reporting bird distributions) and time series reported are not fully comparable. In this sense, statistical modelling could potentially be applied to overcome data limitations, as described for forest ecosystems. Available data at EU level for species of conservation concern (except birds) are derived from Article 17 reporting of the HD. This variable, although not directly reported under the HD, can be easily calculated with the polygons used for reporting species occurrence. Data are based on a reference grid of 10 km spatial resolution, but the reporting is done by biogeographical region and country, which usually is a spatial resolution too coarse for an ecosystem condition mapping. These data currently present important spatial gaps and no straightforward comparable time series.

Percentage of 'heathland' & 'sparsely vegetated land' birds with increasing or stable population trends (short term) (Box 1 on indicator species): Larger percentage of bird species with increasing or stable population trends is related to a better ecosystem condition (Turner et al., 2007). Ultimately some species might be more indicative than others depending on their level of specialization (Morelli et al., 2020). Although the use of trend indicators is not encouraged under the SEEA EA, in the case of the BD data, short-term population trends (last 12 years) was the most suitable indicator for the integration in the SEEA. Bird population data reported under Article 12 of the BD do not provide comparison of the population size against a 'favourable reference population' (as done under the HD; see the variable 'Percentage of heathland and shrubland species with good population status), which would be a more SEEA EA compliant indicator. The main limitation of this data is the coarse spatial resolution (only available at country level).

Relevance of structural state variables

Fraction of green vegetation cover (FCover): FCover corresponds to the fraction of ground covered by green vegetation, and is a very good candidate for the replacement of classical vegetation indices for the monitoring of ecosystems. Its temporal evolution can be very useful for environmental applications, especially the land cover changes like fire scar extent, which is relevant for heathland ecosystems. It is also a good indicator to monitor the change in the start of the growing season, and as such impact of Climate change, as the time series can be used for year to year comparison of vegetation status. According to the results of quality assessment exercises, the Sentinel-3/OLCI Collection 300m FCOVER version 1.1 products are in 'pre-operational' stage, while the PROBA-V Collection 300m FCOVER version 1.0 products are in 'operational' stage. (https://land.copernicus.eu/global/products/fcover).

Tree cover density: The word heathland is used to name a treeless area covered by mixed graminoid shrublands, where typically the vegetation cover is >70% and mostly less than 1-m tall heath. Sclerophyllous dry heath lies with or without a low and open canopy of sclerophyll trees. Tree Cover Density product consists of the status layers showing the level of tree cover density in a range from 0-100%, available for the 2012, 2015 and 2018 reference years, and a change product showing increase or decrease of tree cover mask in 2012 - 2015 & 2015 - 2018. Tree encroachment is one of the primary conservation issues in *Calluna* heathlands, a priority habitat in Europe. Improving understanding of the ecological factors that trigger transitions to woodlands is key to developing strategies for heathlands management (Ascoli & Bovio, 2010). Tree cover density data are derived from remote sensing (Copernicus product), providing accurate and reliable data, covering the whole EU with comparable time series.

Small Woody Features (SWF): Higher SWF values (percentages) are better for biodiversity. Reference value are not specified yet, and ETCs are currently studying the share of SWF in agricultural landscapes. The work is on-going and rather complex, as landscapes per se can be characterised by different landscape features (or even their absence). SWF data are spatial data (Copernicus HRL) of 10 m resolution, but there is no time series as the 2015 and 2018 versions are based on different data specifications (the 2018 version includes more features than the one from 2015). Still, the next comparable update should be for the reference year 2021.

Relevance of functional state variables

Dry matter productivity / Above-ground vegetation productivity: Heathlands and shrublands have low to moderate productivity, which is limited by resources and natural disturbances regimes. Reference value should therefore be low. Global warming is leading to an increase in primary production, decomposition, and nutrient cycling and to an increased nutrient availability in heathlands over Europe, which may negatively affect the oligotrophic nature of those ecosystems, and a shift to grasslands as a result of warming is possible in the upland heathland (Wessel et al., 2004).

Dry Matter Productivity (DMP) represents the overall growth rate or dry biomass increase of the vegetation, and is directly related to ecosystem Net Primary Productivity (NPP). However, the available units are customised for agro-statistical purposes (kg/ha/day). Similarly, the Gross Dry Matter Productivity (GDMP) is equivalent to Gross Primary Productivity (GPP). The main difference between DMP and GDMP lies in the inclusion of the autotrophic respiration. By comparison of current DMP or GDMP estimate with long-term average and/or previous periods, it is possible to detect the anomalies in vegetation growth which are useful for early warning purposes. By accumulating DMP or GDMP information over time (e.g. from the start of the growing season onwards), it is possible to identify zones of high or low productivity, useful for the monitoring of pasture areas.

Burnt area / fire overall recurrence: The climate, soils and shrub vegetation promote summer canopy fires at decadal to multi-decadal intervals, especially for Sclerophyllous dry heaths. Therefore, positive feedbacks between fire and vegetation are important in maintaining the ecosystem, preventing a long-term transition to grasslands and forests (Keith et al., 2020a). However, too frequent wildfires also reduce the solid carbon content and can promote soil erosion. The Burnt Area products map burn scars, surfaces which have been sufficiently affected by fire to display significant changes in the vegetation cover (destruction of dry material, reduction or loss of green material) and in the ground surface (temporarily darker because of ash). Moreover, they give temporal information on the fire season. The maps of Burnt Area are recognised as an Essential Climate Variable (ECV) by the Global Climate Observing System (GCOS).

Wild pollinators indicator: pollinators ensure healthy ecosystem functioning and maintain biodiversity of terrestrial ecosystems, providing very valuable information on the functional state of ecosystems and thus, on their condition. See section 5.2.1 for further details on how insect pollinator monitoring can inform the assessment of ecosystem condition.

Relevance of landscape characteristics

Landscape naturalness: The indicator derived from the Landscape Mosaic (LM) metric describes landscape composition or the degree of landscape heterogeneity. The LM is based on land cover maps (e.g. CLC). The terrestrial land cover categories are aggregated into three main land cover types, that is, agriculture, natural and developed. Then, relative proportions of these three types are then measured for each cell via a moving window algorithm using a fixed neighbourhood area. Based on this, each grid cell is classified in one naturalness class (Maes et al., 2020a; Riitters et al., 2020). This indicator is developed by the JRC and the available dates depend on the land cover maps used for its implementation[51].

Fragmentation/connectivity: the fragmentation indicator Effective Mesh Density is available at the EEA. An alternative variable is the connectivity indicator is developed by the JRC (see description of forest). Fragmentation (or the opposite connectivity) are important variables to describe the condition of heathland and shrub and sparsely vegetated land to allow species movements and habitat shifts in response to climate change (climate change adaptation) (Fagúndez, 2013). Both indicators depend on reference land cover maps such as CLC.

4.4.3 Definition of reference levels

The **definition of 'homogeneous ecosystem areas'** is required as a previous step to set reference levels, which allows thus rescaling the ecosystem variable into a meaningful indicator on ecosystem condition.

'Moors and heathlands' and 'sclerophyllous vegetation' are used to map **'heathland and shrub'** based on CLC data. These CLC classes (ecosystem subtypes) include high level of heterogeneity (from wet heath, arctic moors, mosses and lichens, to 'maquis' and abandoned olive groves), that makes necessary to better define 'homogeneous ecosystem areas' to set robust reference levels. In this sense, availability of more detailed habitat/ ecosystem mapping covering the whole EU extent over time would be highly needed (Box 4).

In the absence of better data, 'homogeneous ecosystem areas' for heathland and shrub could be delineated by making use of the EU biogeographical regions. In the case of 'moors and heathland', it would also be important to consider the presence of peatland[52], since it is a key ecosystem characteristic determining major differences across ecosystems in relation to their intrinsic properties. For instance, soil water index, but also productivity will show very different values depending whether it is located in a peatland or not. This would help in better discriminating 'homogeneous ecosystem areas' in combination with the biographic regions (Alpine, Atlantic, Boreal, Continental, Macaronesia and Mediterranean). Further work would be required to better align the definition of 'homogeneous ecosystem areas' with IUCN Global Ecosystem Typology and EUNIS classification.

In the case of **sparsely vegetated land,** definition of 'homogeneous ecosystem areas' might not be highly required due the special land cover types that it includes. For instance, in the case of bare rocks, this distinction might not be required since the biotic components are practically absent. Only in the case of burnt- and sparsely vegetated areas, the distinction of 'homogeneous ecosystem areas' may be needed, by making distinction by biogeographical region.

Most of the variables included for the condition assessment of both, 'heathland and shrub' and 'sparsely vegetated land' do not present reference levels already defined. The method found to be suitable for the largest number of variables is the statistical analysis based on ambient distribution (Table 10). In some cases, reference levels are already defined for some variables making use of prescribed levels (based on either scientific evidence and/or aligned with legal targets/thresholds).

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[51] https://ies-ows.jrc.ec.europa.eu/gtb/GTB/psheets/GTB-Pattern-LM.pdf

[52] https://esdac.jrc.ec.europa.eu/content/distribution-peatland-europe

Table 10. Methods for setting reference levels of condition variables for ‘heathland and shrub’ and ‘sparsely vegetated land’

Reference levels		Variable	Values
Existing reference levels	Prescribed levels (scientific evidence)	Exceedance of critical loads for acidification/eutrophication	Zero exceedance (Hettelingh et al., 2017)
	Prescribed level (aligned to legal targets)	Exposure to ozone	Long term target 6 000 (µg/m^3)
		Percentage of species with good population status	All species with good conservation status of population size (aligned with the draft NRL)
		Percentage of wild birds with increasing or stable population trends (short term)	All species with increasing or stable population trends (aligned with the NRL)
	Prescribed levels (legal thresholds aligned with scientific evidence)	Heavy metals in soils	At country level: Carlon et al. 2007 (no EU standard)
Reference levels to be defined	Statistical analysis based on ambient distribution	Soil moisture deficit during the vegetation growing season, soil water index, soil organic carbon stock, P and N content in soils, species richness, Fcover, tree cover density, small woody features, burnt area/fire recurrence, landscape naturalness, fragmentation	Data driven
	Expert opinion & contemporary condition	Dry matter productivity, aboveground vegetation productivity, pressure by invasive alien species	Data and experts driven
	Contemporary condition / Historical observation or paleo-environmental condition (modelled)	Sea level anomaly	Data driven
	To be defined when indicator available	Wild pollinators indicator	To be defined

Carlon et al. (2007) Derivation methods of soil screening values in Europe. A review and evaluation of national procedures towards harmonisation - EUR 22805-EN, European Commission, Joint Research Centre, Ispra

Hettelingh et al. (2017) European critical loads: database, biodiversity and ecosystems at risk: CCE Final Report 2017. RIVM, Coordination Centre for Effects, Bilthoven, Netherlands

4.4.4 Conclusions

The selected variables to assess the condition of 'heathland and shrub' and 'sparsely vegetated land' provide information on the most important ecological characteristics for which there are data available, in term of water balance, productivity and natural disturbance. Indeed, those ecosystems are maintained over time because the vegetation has only a low to moderate productivity, limited by resource constraints (e.g. water balance, soil quality, climate) and/or recurring disturbances, like browsing and recurring low-intensity fires that prevent the transition to forests. Most of the variables suggested can be documented at EU Level, with spatially explicit data and representative time series. In addition to assessing the main ecological characteristics of the ecosystem, further datasets could be identified to document generic threatening processes, like exceedance of critical loads of eutrophication, heavy metals in soil, pressure by IAS or tree encroachment (i.e. tree cover density).

For some key variables, multiple datasets were identified and only a detailed analysis of the data will help to find the most suitable for the condition assessment. This is the case for example for monitoring the water balance ('soil moisture deficit during the vegetation growing season' or 'soil water index'), the productivity ('dry matter productivity', 'above ground vegetation productivity' or 'vegetation phenology' and productivity parameters) or the vegetation dynamics ('Fcover' or 'tree cover density'). In addition, some of the identified datasets allow to assess the physical or chemical changes (abiotic parameter), while other inform on the biological response (biotic parameter) of the same degradation process. This is the case for eutrophication ('N content' and 'exceedance of eutrophying substances', or 'dry matter productivity').

Importantly, 'sparsely vegetated land' extent from coastal areas to polar and alpine domains, and not a single indicator can assess this ecosystem as a whole. Therefore, different types of variables are needed to assess different ecosystem sub-types.

The EU ecosystem assessment published in 2020 concluded that a detailed interpretation of the current results for 'heathland and shrub' was limited due to the limited availability of data related to abandonment or decrease of traditional management practices. Although they are very relevant drivers of ecosystem condition, including information related to the type of management (or lack of management) would not be consistent with the SEEA EA. For a better alignment with the SEEA EA, only state variables are included with the exception of ozone exposure as a proxy of ozone damage. State variables shall already capture the impact of abandonment (or changes in the management) on the condition of heathland and shrub. For instance, the fraction of green vegetation cover would capture overgrazing, while all data related to productivity would capture how management is affecting the functioning of the ecosystem.

4.5 Wetlands

4.5.1 Definition and delineation of wetlands

Two complementary approaches have been set to assess the condition of wetland ecosystems, depending on the criteria used to define them (Table 11):

1) **General approach**: wetlands are assessed following a definition as done in most restrictive approaches and instruments used in Europe for monitoring and assessments. This definition includes wetlands corresponding to **Inland and coastal wetlands (from the land-side only) based on CORINE land cover classes** (i.e. peatbogs, inland marshes, salt marshes, salines, intertidal flats, coastal lagoons and estuaries). The condition assessment of wetlands in this case does not spatially overlap with other ecosystem types. However, it provides a very restrictive definition and delineation of wetland ecosystems by addressing a small share (33%) of their total extent in the EU (Maes et al., 2020a). The other 67% of wetlands are ecosystems that have other uses and/or have been classified as a different ecosystem type in the EU without taking into consideration their hydro-ecological boundaries.

2) **Thematic approach: wetlands as defined under the Ramsar convention** are ‘*areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salty, including areas of marine water the depth of which at low tide does not exceed six meters*’. Furthermore, wetlands ‘*may incorporate riparian and coastal zones adjacent to the wetlands, and islands or bodies of marine water deeper than six meters at low tide lying within the wetlands*’. This is the most comprehensive definition of wetlands provided in the convention on wetlands, an intergovernmental treaty ratified by 171 parties (but not the EU) in 1971 that provides the framework for national action and international cooperation for the conservation and wise use of wetlands and their resources. In 1995, the Commission adopted a communication to the European Parliament and the Council on the wise use and conservation of wetlands, which recognised the important functions these habitats perform for the protection of water resources. A first crosswalk between Ramsar and CLC classes was developed in the framework of the Horizon 2020 SWOS project supporting the MAES working group (Fitoka et al., 2017). It was then refined through the EU ecosystem assessment to ensure an ecologically sound delineation of wetlands in this process (Maes et al., 2020a) (Annex 4).

Table 11. Wetlands classification following the proposed approaches (extended version in Annex 4)

Wetlands coverage under the EU-wide methodology			
Thematic approach (Ramsar definition)	**General approach**: no overlap with other ecosystem types	Inland wetlands	
		Coastal wetlands	
	Partial overlap with other ecosystem types (only in the thematic assessment)	Other wetlands	Agroecosystems
			Forest
			Heathland and shrubland
			Sparsely vegetated areas
			Freshwater
			Marine

The thematic assessment of wetlands integrates the hydro-ecological boundaries of wetlands that partially overlap with other ecosystem types. Since this definition overlaps with other ecosystem types, it can be considered as a ‘thematic assessment’. The SEEA EA makes reference to ‘thematic accounts’ as a complementary type of ecosystem accounts focused on environmental themes of specific policy relevance, such as biodiversity, climate change or urban areas. Thematic accounts are also applicable to develop inclusive assessments of important habitats when alternative classifications are provided, as in this case, the definition of wetlands using their hydro-ecological boundaries as set by the Ramsar convention. Therefore, the thematic assessment for wetlands is consistent with the SEEA EA and it is essential to ensure that their holistic definition and delineation are well understood and considered when assessing wetlands condition.

4.5.2 Variables to assess the condition of wetlands at EU level

Variables identified to assess the condition of wetlands are presented in Table 12. Many of the variables included were previously used in the assessment of wetlands condition (Maes et al., 2020b). New variables consistent with the SEEA EA were also added when ensuring a consistent coverage of the different types of wetland ecosystems. Integration of variables underpinning the reporting of ecosystem status under the MSFD and WFD was not here considered. Many variables are specific to the rivers and lakes ecosystem, which is object of a specific assessment; on the other side, variables which could be relevant for the wetlands assessment, such as for instance the water table depth, are not reported by MS in most cases. However, the possibility to use WFD information could be further explored in the future, by analysing in detail which variables used for the MSFD and/or WFD reporting could inform in more detail the condition of wetland habitats covered by these directives. However, in this case, consistency would not be ensured due to the partial overlap between directives. Different variables would be used for each wetland habitat depending on the directive considered.

Table 12 also shows the type of data stream from which the different variables can be obtained (i.e. mapping or EU/MS reporting).

The description and justification of the variables selected to assess condition of wetlands is included below.

Relevance of physical state variables

Soil moisture deficit during the vegetation growing season: Wetlands are areas where a water table is near or just above the surface, and where soils are water-saturated for a sufficient length of time such that excess water and resulting low soil oxygen levels are principal determinants of vegetation and soil development (Banner & MacKenzie, 2000). A deficit in soil moisture indicates a negative change in the fluctuations of the hydrological balance of the ecosystem (Muneepeerakul et al., 2008). By definition, the deficit (hence a worse ecosystem condition) is indicated by negative values. The indicator is computed on a yearly basis (vegetative growing season), it is available for a long time series (1995–2019) for the whole EEA38 region and it has a satisfactory spatial resolution (500x500 m).

Sea water salinity anomaly: Higher levels of sea level anomaly are indicative of a worse ecosystem condition due to the major impacts on aquatic ecosystem assemblage structure and functioning. The effects of changing salinity on the ecology of different habitats is driven ultimately by the underlying physiology and tolerance of organisms and their ability to cope with salinity fluctuations on both long and short time scales (Smyth & Elliot, 2016a). For this reason, the suggested variable measures the level of sea salinity, and data are derived from remote sensing and observational data (Copernicus product), providing accurate and reliable data, covering the EU marine regions with comparable time series.

Water exploitation index: Although this is primarily a pressure indicator, it has been included in this list of condition indicators since it can also be considered as a proxy for groundwater level (which is currently missing), hence an indirect measure of how well the wetland ecosystem is working. Given the spatial resolution of data (sub-basin), the index cannot be directly linked to a single wetland feature. Nevertheless, it can be reasonably assumed that the groundwater level in the sub-basin affects to a certain extent all water-related habitats in the same sub-basin. Water level changes induced by climate change and anthropogenic disturbance (e.g. drainage) could in fact substantially influence the capacity of wetlands to provide ecosystem services (for instance, C storage in peatlands; Zhong et al. (2020)). This indicator hence complements the one listed above on soil moisture. The defined thresholds are positive values (De Roo et al., 2021) and indicate depletion of the ecosystem: the higher the value, the worse the physical state of the ecosystem. The indicator is multi-temporal (1990-2018) and has an adequate spatial resolution (sub-basin).

Relevance of chemical state variables

Exceedance of critical loads for eutrophication: This indicator complements the one above and looks at the exposure of wetland habitats to eutrophication. For each grid cell the exceedances of the critical loads for eutrophication by nitrogen is reported. Eutrophication of wetlands leads to drastic changes with major effects on their structure and functions (Alvarez-Cobelas et al., 2001; Vaithiyanathan & Richardson, 1999). Eutrophication amplifies the negative effects on climate change by increasing the net emissions of greenhouse gases to the atmosphere (Verhoeven et al., 2006). Nutrient enrichment within a wetland results in a large increase of primary productivity in what are often low nutrients/production systems.

Table 12. Variables for the condition assessment of wetland ecosystems

Ecosystem Condition Typology	Data stream[1]	Wetland approach[2]	Variable	Units	Source of the variable at EU level	Temporal series	Spatial resolution	Type[3]
A1. Physical state	Mapping	General & Thematic	Soil moisture deficit during the vegetation growing season	Dimensionless	EEA	2000-2019	500 m	Optimal
		Thematic (only marine and transitional waters)	Sea water salinity anomaly	psu	CMEMS	1993-2019	Marine region / subregion	Optimal
	EU/MS reporting / Mapping	General & Thematic	Water exploitation index (WEI+)	Dimensionless	JRC	1990-2018 (yearly)	Sub-basins	Modelled
A2. Chemical state	Mapping	General & Thematic	Exceedance of critical loads for eutrophication	mol nitrogen eq / ha / year	EMEP	2000, 2005, 2010, 2016, 2020	0.5° longitude; 0.25° latitude	Modelled
	EU/MS reporting Mapping	General & Thematic	P and N content in soils	mg/kg (P); g/kg (N)	LUCAS / JRC	2009/2012/ 2015/2018	Sampling points/ 250 m	Complementary / Modelled
		General & Thematic	Heavy metals in soil	µg/g	LUCAS / JRC	2009 (2018 coming soon)	Sampling points / JRC 500 m	Complementary / Modelled
	EU/MS reporting	Thematic (only marine and transitional waters)	Percentage of samples classified as 'good' or 'excellent' state of bathing water	Percentage (%)	EEA/ EMODnet	1990-2020 (yearly)	Point data	Complementary
	Mapping	General & Thematic	Pressure by invasive alien species on wetland ecosystems	Dimensionless	JRC-EASIN	No	10 km	Complementary (currently no time series)

Ecosystem Condition Typology	Data stream[1]	Wetland approach[2]	Variable	Units	Source of the variable at EU level	Temporal series	Spatial resolution	Type[3]
B1. Compositional state	EU/MS reporting	General	Percentage of wetland species with good population status	Percentage (%)	Habitats Directive reporting Art. 17	Reporting periods:2001 -2006; 2007-2012; 2013-2018)	MS per biogeographical region	Complementary (very coarse spatial resolution)
		General	Richness of wetland species	Number of species	Art. 12 Birds Directive, Art. 17 Habitats Directive	Reporting periods of the HD and BD	10 km	Complementary (no spatially or temporally consistent)
		General	Percentage of wetland birds with increasing or stable population trends (short term)	Percentage (%)	Art. 12 Birds Directive	Reporting periods: 2008-2012; 2013-2018; (2019-2024)	Country	Complementary (very coarse spatial resolution, not spatially or temporally consistent)
B2. Structural state	Mapping	General & Thematic	Water occurrence decrease intensity	Percentage (%)	GSWE	1984-2020; monthly	30 m	Optimal
		Thematic (only marine and transitional waters)	Seagrass coverage	Percentage (%)	EMODnet	Not available	100-500 m	Complementary
B3. Functional state	Mapping	Thematic (only riparian forest, wet grassland)	Vegetation productivity (PPI - Plant phenology index)	Dimensionless	EEA	2000-2021	2000-2016 at 500 m; 2017-2021 at 10 m	Complementary (not spatially consistent time series)
		General & Thematic	Imperviousness of the local drainage basin	Percentage (%)	EEA	2018, 2021 (not available yet)	10 m	Complementary (not spatially consistent)
	EU/MS reporting	General & Thematic	Wild pollinators indicator	Dimensionless	STING/ SPRING projects	2024	EU (finer resolution to be decided)	Coming soon

Ecosystem Condition Typology	Data stream[1]	Wetland approach[2]	Variable	Units	Source of the variable at EU level	Temporal series	Spatial resolution	Type[3]
C1. Landscape and seascape	Mapping	General & Thematic	Connectivity	km (distance from the nearest neighbour)	CLC	2000, 2006, 2012, 2018	100 m	Optimal

[1] The ‘general approach’ refers only to wetland ecosystems which do not overlap with other ecosystem assessments (CLC Inland and Coastal wetlands; see Table 11). The ‘thematic approach’ refers to the whole ecosystem (apart from Rivers and Lakes which are already considered in the EU-wide methodology as Freshwater ecosystems)

[2] EU Reporting (Reported data by MS or EU monitoring), Mapping (spatial data)

[3] Type: Optimal (EU map and temporal series), modelled (maps are a modelled outcome), complementary (when data match at least one of these criteria: no full EU coverage, no time series, not spatially or temporally consistent, require modelling-point data, very coarse spatial resolution, coming soon (data that are currently not available but there is a project or initiative currently working on it), data gap (key variables currently missing for which there are no plans to be developed).

Phosphorus (P) and Nitrogen (N) content in soils: Nutrients such as P and N, when exceeding certain levels in wetlands, become pollutants that can impact wetland condition negatively in terms of their capacity to provide ecosystem services. For instance, long-term elevated P and N deposition and accumulation strongly correlates with increased organic matter decomposition and lower carbon accumulation in peatlands and salt marshes (Schillereff et al., 2021). N pollution poses also a threat to biodiversity of low-nutrients ecosystems (i.e. peatlands), causing a decline of typical plant and moss species (Robroek et al., 2017). Peatlands store up to 15% of global soil N but often have low plant nutrient availability owing to slow organic matter decomposition under acidic and waterlogged conditions. In rainwater-fed ombrotrophic peatlands, elevated atmospheric N deposition has increased N availability with potential consequences to ecosystem nutrient cycling. Nutrients data are derived from the LUCAS dataset and available for 2009, 2012, 2015 and 2018.

Heavy metals in soils (As, Cd, Cr, Cu, Hg, Pb, Mn, Sb, Co, Ni, Zn): While low levels of heavy metals are required in the form of micro-nutrients for good ecosystem functioning, high levels are of concern. Heavy metals cannot be easily degraded and are sometimes difficult to be stabilised or to be modified to reduce the associated risks. Moreover, heavy metals tend to bio-accumulate in many trophic chains, presenting a long-term risk for the local biota as well as humans (Briffa et al., 2020). In the case of forest ecosystems, heavy metals are also of special concern because they are a common type of soil pollutant consequence of past and present commercial and industrial activities. LUCAS data on metal content in wetlands are available for 2009 (limited trend data from 2018 soon). Discussions are ongoing regarding further analysis on samples collected during 2022 and on the development of risk indicators (i.e. going beyond concentrations). The JRC makes available the first modelled results (500 m resolution) of copper distribution in European Union topsoils. More detailed maps on heavy metals and soil contaminants will become available soon (https://esdac.jrc.ec.europa.eu/themes/soil-contamination).

Percentage of samples classified as 'good' or 'excellent' state of bathing water: This indicator assesses the chemical state of the marine part of the wetland ecosystem (shallow marine water up to 6 m depth at low tide); it is based on the presence of bacteria indicating pollution from sewage or livestock. This parameter is an essential factor in public health. It indicates microbial and chemical contamination and eutrophication which affects the capacity of this part of the ecosystem to provide services (*in primis*, support to biodiversity and provision of recreation). In addition to good water quality for bathing, clean unpolluted water is in fact required for healthy ecosystems sustaining biodiversity and functioning, and to support economic activities such as tourism and sustainable aquaculture (Borja et al., 2020). Although this indicator assesses only one kind of pollution, it has been selected since it provides, for a long time-series, yearly assessments based on legal targets ('excellent', 'good', 'sufficient' or 'poor' levels). Nevertheless, it can only be considered as a complementary dataset, since it provides point data.

Relevance of compositional state variables

Pressure by invasive alien species on wetland ecosystems: The pressure by IAS on ecosystems has a potential negative effect on their condition due to the increased threat (Pyšek et al., 2020). Pressure by IAS can be measured as the cumulative pressure exerted by IAS based on the sum of their occurrence in an area, weighted by the extent of the ecosystem(s) potentially affected. This cumulative pressure indicator was developed for the EU ecosystem assessment (Maes et al., 2020a) using species records from the baseline distribution of IAS of Union concern available on the European Invasive Species Information Network (https://easin.jrc.ec.europa.eu/easin/Documentation/Baseline). It will be possible to infer trends in relation to the baseline of IAS when the EU MS second reporting under the IAS Regulation becomes available in 2025.

Percentage of wetland species with good population status (see Box 1 on indicator species): Population size of different (non-bird) species is assessed against a 'favourable reference population' (FRP) under the Article 17 of the HD to report status of population size. A favourable reference population is the population in a given biogeographical region considered the minimum necessary to ensure the long-term viability of the species (DG Environment, 2017). Thus, larger percentage of wetland species with good population status (i.e. population size less than 5% below the FRP) ensures the species maintenance in the long term, hence contributing to the ecosystems' integrity (De Leo & Levin, 1997). Population data reported under the HD currently presents limitations in terms of spatial resolution. Each population assessment per species is done per country and biogeographical region. It can potentially be mapped at 10 km resolution making use of occurrence polygons also reported for each species. An important caveat is that the reporting for different time periods are not fully comparable to assess changes over time.

Richness of wetland species: see Box 3 on the use of species richness as indicator of ecosystem integrity for further information. Available data at EU level are derived from Article 12 reporting of the BD and Article 17 of the HD. Existing reported data of Art. 12 of the BD present important spatial gaps (not all countries are currently reporting bird distributions) and time series reported are not fully comparable. In this sense, statistical modelling could potentially be applied to overcome data limitations, as described for forest ecosystems. Available data at EU level for species of conservation concern (except birds) are derived from Article 17 reporting of the HD. This variable, although not directly reported under the HD, can be easily calculated with the polygons used for reporting species occurrence. Data are based on a reference grid of 10 km spatial resolution, but the reporting is done by biogeographical region and country, which usually is a spatial resolution too coarse for an ecosystem condition mapping. These data currently present important spatial gaps and no straightforward comparable time series.

Percentage of wetland birds with increasing or stable population trends (short term) (Box 1 on indicator species): Larger percentage of bird species with increasing or stable population trends is related to a better ecosystem condition (Turner et al., 2007). Ultimately some species might be more indicative than others depending on their level of specialization (Morelli, 2020). Although the use of trend indicators is not encouraged under the SEEA EA, in the case of the Birds Directive data, short-term population trends (last 12 years) was the most suitable indicator for the integration in the SEEA. Bird population data reported under Article 12 of the BD do not provide comparison of the population size against a 'favourable reference population' (as done under the HD; see the variable 'Percentage of heathland and shrubland species with good population status), which would be a more SEEA EA compliant indicator. The main limitation of this data is the coarse spatial resolution (only available at country level).

Relevance of structural state variables

Water occurrence decrease intensity: Given the nature of this ecosystem, surface water occurrence can be considered an aggregate property of the whole ecosystem (and therefore be considered as structural variable). This indicator assesses the main aggregate property of the terrestrial part of the wetland ecosystem, identifying the sites where surface water occurrence increased, decreased or remained stable across 32 years. Changes in surface water occurrence can be the response to anthropogenic and/or climatic drivers in wetlands; understanding changes in hydrological connectivity and patchiness resulting from the spatial and temporal distribution of surface water occurrence is relevant for the conservation of river delta ecosystems (Aminjafari et al., 2021) and wetlands in general. Any decrease of surface water occurrence is hence indicating a depletion of ecosystem conditions. The dataset covers a wide temporal series (1984-2020) with a high spatial resolution (30x30 m).

Seagrass coverage: This indicator complements the previous one covering the marine part of the ecosystem. As cited by Weatherdon et al. (2018), seagrass condition is dependent on belowground biomass, which plays an important role in carbon storage, carbohydrate storage, and stabilization of sediments (Christianen et al., 2013; Vonk et al., 2015); its decrease in extent will entail a depletion of the ecosystem and its capability to provide these services. Due to the features of available data (no time series available), this indicator can only be considered as complementary.

Relevance of functional state variables

Vegetation productivity (PPI - Plant phenology index): This indicator aims to assess the functional state of the wetland habitats fully covered by natural vegetation (riparian and swamp forest, wet grassland). The positive or negative change in vegetation phenology is a sensitive indicator of a depletion of ecosystem condition due to changing climatic condition (Meier et al., 2021; Montgomery et al., 2020). Due to the features of available data (a time series is available but the spatial resolution is not consistent), for now this variable can only be considered as complementary.

Imperviousness of the local drainage basin: Soil sealing, expressed as 'the substitution of the original (semi-) natural land cover or water surface with an artificial, often impervious cover'[53], can be considered a quantifiable indicator of wetlands functional state closely correlating with impacts on water resources (Arnold & Gibbons, 1996). Wetland condition degradation occurs at relatively low levels of imperviousness: Hicks (1995) could define a direct relationship between wetlands habitat quality and impervious surface area, with wetlands being impacted once the imperviousness of the local drainage basin exceeded 10%. Due to the features of available data (a time series of comparable data is not currently available) this variable can only be considered as complementary.

Wild pollinators indicator: Pollinators ensure healthy ecosystem functioning and maintain biodiversity of terrestrial ecosystems, providing very valuable information on the functional state of ecosystems and thus, on their condition. See section 5.2.1 for further details on how insect pollinator monitoring can inform the assessment of ecosystem condition.

Relevance of landscape characteristics

Connectivity: Wetland connectivity can be broadly used as a wetland landscape/seascape indicator of the ecosystem condition. A well-connected network of wetland habitats is crucial for the ecological functioning of this ecosystem since its deterioration can have a significant impact, for instance, on waterbird populations (Merken et al., 2015). The spatial distribution of wetlands is a key aspect in determining their connectivity (Amezaga et al., 2002) as well as addressing management and planning efforts to restore and maintain connectivity patterns (UN Environment, 2017).

Wetland connectivity can then be assessed through the simplest measure of structural connectivity which is calculated as the distance from one wetland to its nearest neighbouring wetland (Calabrese & Fagan, 2004). This index, although simple, reflects different scales and/or probabilities of movement for animal species, as well as the dispersal range of plants and invertebrate propagules. The indicator can be defined as 'optimal', since it has adequate temporal and spatial resolution.

4.5.3 Definition of reference levels for wetlands

About half of the variables suggested for wetlands present existing reference levels (Table 13). The methods used to define reference levels are mainly prescribed levels or the use of contemporary data. Due to the absence of reference levels for the other half of the variables, further analysis would be needed to define them. Methods suggested for the identification of reference levels largely vary across the suggested variables but, very often, a combination of methods is suggested. For the indicators which require data analysis, it remains to be assessed the feasibility of the methods suggested and specially to identify pristine sites in 'minimally-disturbed' condition or the availability of historical observations.

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[53] https://land.copernicus.eu/pan-european/high-resolution-layers/imperviousness/status -maps/2006?tab=metadata

Table 13. Methods for setting reference levels of condition variables for wetlands

Reference levels		Variable	Values
Existing reference levels	Prescribed levels (scientific evidence)	Water exploitation index*	WEIc > 0.2 indicates excessive use; >0.4 indicates significant depletion (de Roo et al. 2021)
		Exceedance of critical loads for eutrophication*	Zero exceedance (Hettelingh et al., 2017)
		Imperviousness of the local drainage basin*	10% of sealed area of the local drainage basin (Hicks 1995)
	Prescribed level (aligned to legal targets)	State of bathing water*, percentage of wetland species with good population status*, percentage of wetland wild birds with increasing or stable population trends*	Bathing water in favourable state, all species in good population status, all with increasing stable trends
	Prescribed levels (legal thresholds aligned with scientific evidence)	Heavy metals in soils	At country level: Carlon et al. 2007 (no EU standard)
	Contemporary data	Soil moisture deficit during the vegetation growing season	Deficit based on the 1995–2019 period
		Water occurrence decrease intensity	Reference period 1984-1999
Reference levels to be defined	Contemporary condition / Historical observation or paleo-environmental condition (modelled)	Sea water salinity anomaly	Data driven
	Statistical methods based on ambient distribution	P and N content in soils, richness of wetland wild birds	Data driven
	Expert opinion / contemporary condition	Pressure by invasive alien species on wetland ecosystems*	Data driven
	Combination of methods (expert rules and statistical methods based on ambient distribution)	Connectivity	Data driven
	Minimally-disturbed condition ('pristine' ecosystems with no or minimal disturbance)	Seagrass coverage, vegetation productivity (only thematic assessment)	Data driven
	To be defined when indicator available	Wild pollinators indicator	To be defined

*Variables for which there is no need to define ‘homogeneous ecosystem areas’

Carlon et al. (2007) Derivation methods of soil screening values in Europe. A review and evaluation of national procedures towards harmonisation - EUR 22805-EN, European Commission, Joint Research Centre, Ispra

De Roo et al (2021) The Water-Energy-Food-Ecosystem Nexus in the Mediterranean: Current Issues and Future Challenges. Frontiers in Climate, 3. 10.3389/fclim.2021.782553

Hettelingh et al. (2017) European critical loads: database, biodiversity and ecosystems at risk: CCE Final Report 2017. RIVM, Coordination Centre for Effects, Bilthoven, Netherlands

Hicks, A. (1995) Impervious surface area and benthic macroinvertebrate response as index of impact from urbanization on freshwater wetlands, U.S. Environmental Protection Agency, Washington, D.C., EPA/600/R-95/074

As mentioned in section 3.3, the **definition of 'homogeneous ecosystem areas'** is required as a preliminary step before setting reference levels, which allows thus rescaling the ecosystem variable into a meaningful indicator on ecosystem condition. In the case of wetlands, not all variables require the definition of 'homogeneous ecosystem areas' because the meaning of some variable suggested in relation to the ecosystem condition is equivalent across the EU territory. This is the case for variables that make use of prescribed level, but also for the pressure by invasive alien species on wetlands (Table 13).

For other variables for which reference levels do not exist, criteria to define 'homogeneous ecosystem areas' may vary, making the definition of reference levels in the case of wetlands especially complex due to their large heterogeneity. The assessment of the mapped wetland habitats (Annex 4) in the context of the biogeographical regions they belong to may be a suitable approach for variables such as 'soil moisture deficit during the vegetation growing season', 'richness of wetland wild birds', 'water occurrence decrease intensity' and 'vegetation productivity'. However, in the case of variables related to marine and transitional waters, such as 'seawater salinity anomaly' and 'seagrass coverage', the delineation of marine regions would be more suitable, also for consistency with the MSFD. Further investigation would be needed to consistently identify 'homogeneous ecosystem areas' for P and N content in soils. In the case of soil indicators, soil typology or structure might be a more important driver of natural variation in P and N content in soils than biogeographical regions. However, this would require further testing of the methodology proposed.

4.5.4 Conclusions

The selected variables aim at providing information on the different condition typologies of the wetland ecosystem as set in the assessment framework. Due to the diversity of wetland habitat types in terms of their ecological and environmental conditions, in some cases, there was a need to propose variables specific for a certain wetland typology (coastal, marine, inland wetlands). WFD and MSFD provide information that could inform the condition of some of the wetland habitat types, but only for those habitats covered by these directives. This possibility could be further explored in the future by analysing in detail which variables monitored under the WDF and/or MSFD are consistent with the SEEA EA. However, in this case, consistency would not be ensured due to the partial overlap between directives. Different variables would be used for each wetland habitat depending on the directive considered. Moreover, data coming from WFD reporting obligations for wetlands cover only part of the whole ecosystem, with no consistent time series and are very fragmented (Maes et al., 2020a).

The condition class which can be better assessed based on the proposed variables and available data is the one on physical state; all the proposed variables are defined as 'optimal', based on their temporal and spatial features. Alternatively, all the other classes should be assessed based on datasets, which have different types of limitations. In particular, no compositional state variable is deemed as optimal. All of the three variables in this class are based on EU reporting mechanisms (Art.17 of the HD and Art.12 of the BD) reported at very coarse spatial resolution (10x10 km), with no spatial or temporal consistency hence limiting the usefulness of such data. It is necessary to improve these reporting mechanisms to make available crucial information on a regular basis, for this as for other ecosystems.

Given the heterogeneous and complex nature of this ecosystem, 'homogenous ecosystem areas' had to be proposed to enable deriving more meaningful reference levels. The proposal to define these areas resulted to be a challenging and complex process, which is anyway open to further revisions. In general, most of the variables rely on already defined reference levels.

4.6 Condition assessment beyond ecosystem ‘status’

As previously justified in section 3.4, freshwater and marine ecosystems are fully covered by the WFD and MSFD, respectively. Therefore, condition for these ecosystem types is considered as equivalent to the concept of ecosystems status reported by the directives.

Although in general terms, the methodologies in place under the WFD and MSFD seem compatible with the ecosystem condition accounts (SEEA EA), the potential integration of the data used to report on status under these Directives with the SEEA standard should be further tested. In this sense, the EU-wide methodology illustrates, **as case study, to what extent the assessment of environmental status under the MSFD is consistent with the ecosystem condition assessment under SEEA EA**. This exercise on marine ecosystems represents just a first attempt to integrate the underpinning data of the MSFD into the SEEA EA. However, a more in-depth analysis and testing would be required, since the lack of access to data or harmonised information can hamper its re-use for other purposes. In this exercise, integration of additional spatially explicit data such as remote sensing data (e.g. Copernicus products for marine ecosystems) that ensures regular updates and spatial-temporal consistency is also considered. These spatial data can also be considered to provide a more comprehensive assessment of ecosystem condition (further refinement beyond the status assessment required by law).

Case study for marine ecosystems: beyond environmental status

4.6.1 Definition and delineation of marine ecosystems

Marine ecosystems are covered by Water Framework Directive (WFD), legally up to 1 nautical miles (12 nautical miles for chemical status) from the coastline, and Marine Strategy Framework Directive (MSFD), where ‘marine waters’ are defined as:

1. Waters, the seabed and subsoil on the seaward side of the baseline from which the extent of territorial waters is measured extending to the outmost reach of the area where Member State has and/or exercises jurisdictional right […];
2. Coastal waters as defined by the WFD, their seabed and subsoil, in so far as particular aspects of the environmental status of the marine environment are not already addressed through that Directive or other community legislation.

Therefore the overlap between WFD and MSFD is represented by coastal waters.

The ecosystem classification to be adopted for the condition assessment should follow the MSFD broad habitat classification, which equate to one or more habitat types of the European nature information system (EUNIS) classification. The Commission Decision 2017/848 on criteria and methodological standards on good environmental status of marine waters refers to EUNIS v2016 habitat classification. However, it is important to consider the update of the classification of marine ecosystems based on EUNIS v2019, which is very well developed for benthic habitats and covers the pelagic habitats as well. Despite there are some pelagic classes in the latest EUNIS v2019, these are not fully representative of the pelagic realm. Member states experts from the MSFD Technical Group on seabed habitats and sea-floor integrity have 'accepted' the EUNIS v2019 habitat classification as reference to define the level of assessment.

MSFD applies the benthic/pelagic broad habitat types (BHT) that include their associated biological communities, which equate to one or more habitat types of the EUNIS habitat classification. Effort are ongoing to evaluate the possibility to assess the status of pelagic habitat using a regular gridded approach with spatiotemporal data (e.g., satellite remote sensing data) to account for its high variability. Classification used in the MSFD can be compatible with the SEEA EA Ecosystem Condition Typology based on the IUCN Global Ecosystem Typology through the crosswalk in Annex 5.

Importantly, under the EU-wide methodology, coastal wetlands (salt marshes, salines, intertidal flats) and marine waters defined as coastal lagoons and estuaries are considered as wetland ecosystems for better alignment of the definition of wetlands with the Ramsar definition. Likewise, ‘Coastal lagoons’ require special attention, since they are differently classified by each MS as ‘transitional and coastal waters’ (WFD) or ‘Marine waters’ (MSFD). Thus, data is reported accordingly to MS classification. In addition, other marine benthic and pelagic habitats (not mentioned in the HD) are included (e.g. kelp forest; marine animal forests; chemosynthetic ecosystems).

The comparison of different classification systems for habitats and ecosystems highlights the need for a better EU legislation alignment (e.g. MSFD-WFD-HD) and MAES classification and for an update of the MSFD and HD in terms of list of detailed marine (benthic and pelagic) habitats and species.

Finally, it is important to take into account that the MSFD is currently under review and potential changes in the upcoming directive revision might have implications on the EU-wide methodology. Therefore, any relevant changes in the up-coming MSFD must also be reflected when implementing the EU-wide methodology.

4.6.2 Variables to assess the condition of marine ecosystems at EU level

The variables identified to assess the condition of marine ecosystems are presented in Table 14. This list includes as variables some of the underpinning data following the MSFD primary criteria and WFD indicators, as well as the target of the EU Biodiversity Strategy 2030 and the selection indicators used in the EU ecosystem assessment (Maes et al., 2020a) that are consistent with the SEEA framework. In this sense, Table 14 also shows the data source, whether it is derived from reported data (e.g. MSFD, WFD) or from other mapping initiatives.

This case study is testing the potential integration of variables reported under the MSFD criteria within the SEEA EA condition accounts. Below only the description and justification of those variables of Table 14 that are not already reported under the MSFD, but were included to further assess ecosystem condition beyond environmental status, are presented.

Relevance of physical state variables

Climate change is a pressure with an impact on different marine ecosystem components. Therefore, variables that are reflecting the physico-chemical condition of marine ecosystems affected by climate change are taken into consideration:

Ocean acidification: Reported ocean acidification effects span from changes in cellular metabolism, organism physiology, and sensory perception to population and community, biogeochemical, and ecosystem-level dynamics (Doney et al., 2020). Rising levels of carbon dioxide (CO_2) in the ocean are indicative of a worse ecosystem condition due to the reduction of the amount of carbonate that is a key building block in seawater. For this reason, the variable suggested measures the level of acidification and data are derived from remote sensing and observational data (Copernicus Marine Environment Monitoring Service (CMEMS) product), providing accurate and reliable data, covering the EU marine regions with comparable time series.

Sea temperature anomaly: Ocean warming effects have driven widespread changes in the performance and distribution of species in many regions, with consequent shifts in assemblage structure and ecosystem functioning, and such community reconfiguration may alter core ecosystem processes, such as productivity or nutrient cycling (Gilson et al., 2021). Altered levels of sea temperature are indicative of a worse ecosystem condition due to the shift of the geographic distributions and the accentuated negative fitness of marine organisms (Godwin et al., 2020). Therefore, the suggested variable provides a measure of sea temperature and data are derived from remote sensing and observational data (CMEMS product), providing accurate and reliable data, covering the EU marine regions with comparable time series.

Table 14. Variables for the condition assessment of marine ecosystems

Ecosystem Condition Typology	Data stream[1]	Variable	Units	Source of the variable at EU level	Temporal series available	Spatial resolution	Type[2]
A1. Physical state	Mapping	Ocean acidification	pH	CMEMS	1985-2020	Marine region/subregion	Optimal
		Sea temperature anomaly	Celsius or %	CMEMS	1981-2020	25°	Optimal
		Sea level anomaly	meters or %	CMEMS	1993-2019	25°	Optimal
		Sea water salinity anomaly	psu or %	CMEMS	1993-2019	Marine region/subregion	Optimal
		Sea-ice extent anomaly (Arctic and Baltic)	km^2 or %	CMEMS	1981-2020	25°	Optimal
		Riverine litter	item/hr	RIMMEL (Riverine Litter Observation Network)	2016-2017 (ongoing)	Marine region/subregion	Complementary (not spatially or temporally consistent)
	EU/MS reporting	Marine macro-litter	(no. item / 100 m) or (no. item / km^2)	WISE MARINE (MSFD)	2012/2018 (6 years reporting)	1 km	Complementary (not spatially or temporally consistent)
		Marine micro-litter	(g/m^2) or (g/km^2)	WISE MARINE (MSFD)	2012/2018 (6 years reporting)	1 km	Complementary (not spatially or temporally consistent)
		Underwater noise (anthropogenic impulsive and continuous low-frequency sound sources)	(pulse/day/month) (%) (km^2)	WISE MARINE (MSFD)	2012/2018 (6 years reporting)	1 km	Complementary (not spatially or temporally consistent)
A2. Chemical state	EU/MS reporting	Contaminants concentration	μmol/l	WISE WATER (WFD)	2015/2021 (6 years reporting)	Marine region/subregion	Complementary (require modelling-point data)

Ecosystem Condition Typology	Data stream[1]	Variable	Units	Source of the variable at EU level	Temporal series available	Spatial resolution	Type[2]
		Nutrient concentration (Dissolved inorganic nitrogen DIN)	µmol/l	WISE WATER (WFD, MSFD)	2015/2021 or 2012/2018 (6 years reporting)	Marine region/subregion	Complementary / Modelled
		Nutrient concentration (Total nitrogen TN)	µmol/l	WISE WATER (WFD, MSFD)	2015/2021 or 2012/2018 (6 years reporting)	Marine region/subregion	Complementary / Modelled
		Nutrient concentration (Dissolved inorganic phosphorous DIP)	µmol/l	WISE WATER (WFD, MSFD)	2015/2021 or 2012/2018 (6 years reporting)	Marine region/subregion	Complementary / Modelled
		Nutrient concentration (Total phosphorous TP)	µmol/l	WISE WATER (WFD, MSFD)	2015/2021 or 2012/2018 (6 years reporting)	Marine region/subregion	Complementary / Modelled
		Dissolved oxygen at the bottom of the water column	mg/l	WISE MARINE (WFD, MSFD)	2015/2021 or 2012/2018 (6 years reporting)	Marine region/subregion	Complementary / Modelled
		Chlorophyll-a concentration	µg/l	WISE MARINE (WFD, MSFD)	2015/2021 or 2012/2018 (6 years reporting)	Marine region/subregion	Complementary / Modelled
B1. Compositional state	EU/MS reporting	Fishing mortality of commercially exploited fish and shellfish exceeding F_{MSY} (fishing mortality at maximum sustainable yield)	MSY	WISE MARINE (CFP, MSFD)	2003-2019 or 2012/2018 (6 years reporting)	Marine region/subregion	Optimal
		Percentage of marine species with good population status	Percentage (%)	Article 17 Habitats Directive (HD)	Reporting periods:2001-2006; 2007-2012; 2013-2018	MS per biogeographical region	Complementary (very coarse spatial resolution)
		Marine species richness of conservation concern	Number of species	Art. 17 HD	Reporting periods of the HD and BD	10 km	Complementary (no spatially or temporally consistent)

Ecosystem Condition Typology	Data stream[1]	Variable	Units	Source of the variable at EU level	Temporal series available	Spatial resolution	Type[2]
		Number of (newly-introduced) non-indigenous species	Number of species	JRC-EASIN (IAS, MSFD)	1970 – 2017	10 km	Optimal
B2. Structural state	EU reporting	Spawning stock biomass B_{MSY} (biomass producing maximum sustainable yield) of commercial fish and shellfish	tonne per spp	WISE MARINE (CFP, MSFD)	2003-2019 or 2012/2018 (6 years reporting)	Marine region/subregion	Optimal
B3. Functional state	EU reporting	Adversely affected benthic habitats	km^2 or %	WISE MARINE (MSFD)	2012/2018 (6 years reporting)	1 km	Complementary (no time series)
C1. Seascape characteristics	Mapping	Marine functional connectivity - ecological corridors, marine habitat fragmentation	NA	NA	NA	NA	Data gap

[1] EU Reporting (Reported data by MS or EU monitoring), Mapping (spatial data)

[2] Type: Optimal (EU map and temporal series), modelled (maps are a modelled outcome), complementary (when data match at least one of these criteria: no full EU coverage, no time series, not spatially or temporally consistent, require modelling-point data, very coarse spatial resolution, coming soon (data that are currently not available but there is a project or initiative currently working on it), data gap (key variables currently missing for which there are no plans to be developed).

Sea level anomaly: Sea level rise could diminish coastal ecosystems available to nesting species by removing habitat and inundating nests during incubation (Von Holle et al., 2019). Higher oscillation in the sea level is indicative of a worse ecosystem condition due to the major physical impacts such as erosion of beaches, inundation of deltas as well as flooding and loss of habitats (Smyth & Elliot, 2016b). Hence, the variable provides a measure of the sea level rise and data are derived from remote sensing and observed data (CMEMS product), providing accurate and reliable data, covering the EU marine regions with comparable time series.

Sea water salinity anomaly: The effects of changing salinity on the ecology of different habitats is driven ultimately by the underlying physiology and tolerances of organisms and their ability to cope with salinity fluctuations on both long- and short- time scales (Smyth & Elliot, 2016b). Altered levels of sea water salinity anomaly are indicative of a worse ecosystem condition due to the major impacts on aquatic ecosystem assemblage structure and functioning (Maes et al., 2020a). Accordingly, the variable suggested measures the level of sea salinity, and data are derived from remote sensing and observational data (CMEMS product), providing accurate and reliable data, covering the EU marine regions with comparable time series.

Sea-ice extent anomaly (Arctic and Baltic): Higher extents of sea ice anomaly are indicative of a worse ecosystem condition due to the major impacts on organisms associated with sea ice, including shifts in species composition, abundance and distribution, as well as altered trophic interactions with subsequent impacts on ecosystem structure and function, from the poles to the lower latitudes (Steiner et al., 2021). The effects of changing cryosphere ecosystems will have overall negative consequences for human health and well-being, especially for Arctic Indigenous Peoples and local communities that depend on these ecosystem services for subsistence (Steiner et al., 2021). Thus, the variable suggested measures the level of sea-ice extent anomaly in Arctic and Baltic Sea, and data are derived from remote sensing and observational data (CMEMS product), providing accurate and reliable data, covering the EU marine regions with comparable time series. It is worth noting that the melting ice will add to the steric sea level rise, increasing the impact of sea level anomaly.

Riverine litter: similarly to previous variables, high levels of land-source litter are indicative of a worse ecosystem condition due to the major impacts of pollution in the marine ecosystem (González-Fernández et al., 2018; Maes et al., 2020a). Therefore, the suggested variable measures the level of riverine litter, which aims at providing accurate and reliable data, covering the EU marine regions with comparable time series. In addition, riverine litter, as well as marine litter, are fundamentally linked to climate change as climate change influences the sources and pathways of litter (Lincoln et al., 2022), e.g. riverine litter could be partially impacted by changes in freshwater flow (i.e. quantity of water), which is dependent on climate change and could alter the river runoff that is one of the land-based source of anthropogenic litter. A first ever database of riverine floating macrolitter across Europe has been developed but further work still need to be done (González-Fernández et al., 2021).

Relevance of compositional state variables

Percentage of marine species with good population status (see Box 1 on indicator species): Population size of different (non-bird) species is assessed against a 'favourable reference population' (FRP) under the Article 17 of the HD to report status of population size. A favourable reference population is the population in a given biogeographical region considered the minimum necessary to ensure the long-term viability of the species (DG Environment, 2017). Thus, larger percentage of marine species with good population status (i.e. population size less than 5% below the FRP) ensures the species maintenance in the long term, hence contributing to the ecosystems' integrity (De Leo & Levin, 1997). Population data reported under the HD currently presents limitations in terms of spatial resolution. Each population assessment per species is done per country and biogeographical region. It can potentially be mapped at 10 km resolution making use of occurrence polygons also reported for each species. An important caveat is that the reporting for different time periods are not fully comparable to assess changes over time.

Marine species richness of conservation concern (Art. 17 HD, no birds): see Box 3 on the use of species richness as indicator of ecosystem integrity for further information. Available data at EU level for species of conservation concern (except birds) are derived from Article 17 reporting of the HD. This variable, although not directly reported under the HD, can be easily calculated with the polygons used for reporting species occurrence. Data are based on a reference grid of 10 km spatial resolution, but the reporting is done by biogeographical region and country, which usually is a spatial resolution too coarse for an ecosystem condition mapping. These data currently present important spatial gaps and no straightforward comparable time series.

Relevance of seascape characteristics

Marine functional connectivity - ecological corridors, marine habitat fragmentation: Connectivity corridors are key to link habitats, thereby maintaining necessary demographic transitions in marine species under threat, and the future resilience of food webs as climate and ocean change continues (Peterson et al., 2020). Hence, the variable suggested should measure the level of ecological corridors in the marine ecosystem. The variable should be developed providing accurate and reliable data, and covering the EU marine regions with comparable time series.

4.6.3 Definition of reference levels for marine ecosystems

In the case of marine ecosystems, definition of reference levels is based on the different ecosystem types within each marine region defined under the MSFD. Marine regions are defined under the MSFD as sea regions including: Baltic Sea, Black Sea, Mediterranean Sea and North-east Atlantic Ocean (Article 4 of the MSFD). Marine regions and their sub-regions are designated for facilitating implementation of the MSFD and are determined taking into account hydrological, oceanographic and biogeographic features. Under the EU-wide methodology framework, marine regions are considered in terms of homogeneous ecosystem areas to define robust reference levels.

Integration of variables derived from the MSFD makes also necessary to make use of the thresholds set to define good environmental status. Although the use of ('sustainable') thresholds is not among the recommended methods under the SEEA EA, this example is a particular case in which the use of thresholds is justified to strengthen the linkage to current legislation. Currently, huge efforts are devoted to set consistent thresholds across the EU marine territory (Vasilakopoulos et al., 2021).

In this sense, many variables to assess condition of marine ecosystems present already defined thresholds (used as reference levels) according to the legal EU frame (MSFD) (Table 15). Further work would be required to know in more detail the methods used to define these thresholds.

Variables not derived from the MSFD currently do not have defined reference levels. The most common methods suggested to define reference levels is contemporary condition / Historical observation or paleo-environmental condition (modelled).

4.6.4 Conclusions

This exercise on marine ecosystems is a first attempt to illustrate the potential integration of the MSFD variables into the SEEA EA that allows assessing the possible consistency between the two approaches. The case study highlights how the SEEA EA and the MSFD, although following in general terms the same logic, are not fully comparable. The 'environmental status' reported under the MSFD integrates other criteria reflecting pressures and impacts, which are not part of the SEEA EA. On the other hand, the SEEA EA could benefit of several CMEMS and other remote sensed data that offer high spatial and temporal coverage. There is therefore scope for further analysis on how to integrate the two approaches. Ultimately, more in-depth analysis and testing would be required, since the lack of access to underlying MSFD data or harmonised information can hamper its re-use for other purposes.

Table 15. Methods for setting reference levels of condition variables for marine ecosystems

Reference levels		Variable	Values
Existing reference levels	Prescribed levels - legal thresholds (MSFD and/or WFD)	Number of (newly-introduced) non-indigenous species, spawning stock biomass BMSY (biomass producing maximum sustainable yield) of commercial fish and shellfish, marine macro-litter	Partly agreed at regional and component level - ongoing work by experts
		Contaminants, nutrient concentration (DIN, TN, DIP, TP), dissolved oxygen at the bottom of the water column, chlorophyll-a concentration	Partly agreed at country level - ongoing work by experts
		Adversely affected benthic habitats, marine micro-litter, underwater noise	Ongoing work by experts
	Prescribed levels - legal thresholds (CFP/MSFD)	Fishing mortality of commercially exploited fish and shellfish exceeding F_{MSY}	Sustainable threshold: maximum sustainable yield (F_{MSY})
	Legal reference level (HD-NRL)	Percentage of marine species with good population status	All species with good population status (in consistency with the NRL law)
Reference levels to be defined	Contemporary condition / Historical observation or paleo-environmental condition (modelled)	Acidification, sea temperature anomaly, sea level anomaly, sea water salinity anomaly	Data driven
	Modelled reference condition/expert opinion	Marine connectivity	Data driven / experts
	Prescribed level/expert opinion	Riverine litter	Data driven / experts

The proposed variables under the EU-wide methodology provide a comprehensive assessment of ecosystem condition in agreement with the SEEA EA. The main strength of the proposed list is that the majority of variables are derived from several existing EU legislations, such as MSFD, WFD, IAS Regulation and Common Fisheries Policy (CFP), and this guarantees the EU reporting of data at MS level, at least every 6 years. Moreover, EU legislation drives the ongoing discussion on the methods and definition of reference levels for the majority of the variables listed (Vasilakopoulos et al., 2021). Nevertheless, the use of EU reported data presents also important limitations in terms of spatial and temporal consistency, but also possible important data gaps. In this context, modelling should be considered to harmonise available data, and mapping variables over-time in a more harmonised and consistent way. Many variables (e.g. riverine litter) and models (e.g. floating marine litter) are still under ongoing work by JRC and technical groups of experts (for further details see (González-Fernández et al., 2021; González-Fernández et al., 2018) that will provide better data for the condition assessment.

Importantly, the EU-wide methodology integrates additional spatially explicit variables such as remote sensing data (e.g. European Marine Observation and Data Network (EMODnet) and CMEMS products for marine ecosystems) to assess physical condition of ecosystems, which is currently missing under the MSFD. EMODnet and CMEMS data were used in the EU ecosystem assessment (Maes et al., 2020a) since they provide regular updates and spatial-temporal consistent information very valuable in the context of climate change, which is a key driver of ecosystem integrity. MSFD, WFD, CFP, IAS Regulation are ‘managements tools’ i.e. legislations with overall aim of promoting sustainable use of marine resources and conserving marine ecosystems. They are not focused on assessing directly the condition of marine ecosystems. For this reason, most of physical state variables were not derived from the aforementioned EU legislations. Moreover, variables on compositional state derived from other reporting obligations such as the HD were integrated since they can provide valuable information for the condition assessment of marine ecosystems.

5 Discussion

5.1 Limitations to the integration of data reported under EU environmental directives

The development of the EU-wide methodology highlights the **challenges to integrate in-situ monitoring data used for the reporting under the EU Nature Directives into the SEEA EA framework**. The most limiting data integration was found under the Habitats Directive (HD), especially concerning the data reporting on habitats. This is mainly due to the **knowledge gap at the EU level with respect to the physical attributes monitored for the condition assessment of Annex I habitats** (Ellwanger et al., 2018). Complementarily to this knowledge gap, there is also a lack of access to the monitored data used for the reporting on habitat condition, which hampers their integration into the SEEA EA at the EU level.

Although the use of data monitored for the condition assessment of Annex I habitats is not feasible at the EU level due to the lack of harmonisation, their integration into the SEEA is realistic at Member State (MS) level, since MS own these data (i.e. underpinning data of the 'structure and functions' parameter). Moreover, data integration at MS level does not require consistency across MS, whereas such harmonisation is needed for data included at the EU level. As illustrated in the 'Case study of Greece' (see section 5.1.1), these data have the potential to be consistently framed within the SEEA EA. In this regard, **MS could further investigate the potential integration and alignment of data collected for the HD reporting into the SEEA EA condition accounts**. Integration of these data requires a better and more detailed mapping of Annex I habitats to avoid double counting, which would impact the quality of condition accounts. The current work of the EEA to map Annex I habitats/EUNIS habitats will be relevant to better address this limitation (Box 4).

Complementarily to the habitats reporting, the HD also comprises the species reporting. In this case, **the integration of species reporting under the HD seems more feasible**, providing valuable information on the compositional state of ecosystems. Two SEEA EA compliant variables have been included in the EU-wide methodology derived from the species reporting of the HD: 'percentage of species with favourable population status' and 'species richness'. The 'percentage of species with favourable population status' was included for all ecosystems but urban. Although some species of the HD are also associated with urban areas, none of them had urban ecosystems as single preferred ecosystem, and therefore would not be a good indicator of urban ecosystem condition (see Box 1). Population status is based on the comparison of the current population size with a 'favourable reference population' (FRP), making the variable fully consistent with the SEEA EA recommendations. Population size, as such, does not represent a meaningful condition indicator (e.g. larger populations do not necessarily imply better condition) and the comparison with the FRP is needed to ensure linearity (correlation) with ecosystem condition (i.e. higher values show better condition). Population status is considered favourable when the FRP is smaller than or equal to the current population size.

Another variable derived from the species reporting under the HD is 'species richness'. This variable is not directly reported under the HD, but it can be easily calculated with the polygons reporting species occurrence. However, **the use of species richness as an ecosystem condition indicator should be done with caution (Box 3)**.

Box 3. Biodiversity metrics as indicators of ecosystem integrity

Species richness is the simplest and the most common indicator of biodiversity used in the assessment of ecosystems condition (Rendon et al., 2019). However, this indicator is frequently reported in the literature as a potential misleading (and/or risky) indicator of ecological integrity (Alexandrino et al., 2017; Fleishman et al., 2006; Hillebrand et al., 2018). Although species richness is an important ecological state variable, it only retains a small portion of the available information that describes the concept of biodiversity (Magurran, 2004). Degradation of a given location might result in no net changes, or even in an increase, of species richness if specialist species are replaced by generalists that are more frequently found in degraded areas (Devictor et al., 2007). Consequently, the relationship between species richness and ecosystem condition could be compromised depending on the species group targeted to build the indicator.

When using species richness as indicator, narrowing the scope of the target group to species with more specialised ecological niches can help in the development of a more robust indicator of ecosystem condition or integrity (Alexandrino et al., 2017) (Box 1 on indicator species).

Alternatively, there are currently other biodiversity metrics, such as the Community Specialization Index (CSI), among others, that have been shown to be powerful and robust in reflecting community response to spatial and temporal disturbance (Devictor & Robert, 2009). The CSI usually requires species abundance data, which are scarce at the EU level; however, there are also alternatives that could be further explored to develop a CSI at the European level based on more simple occurrence data (Vimal & Devictor, 2015).

Data reported under the Birds Directive (BD) can also be integrated in the condition assessment, similarly to the species reporting under the HD. For the BD, however, population size is not compared to FRP as done under the HD. The most suitable available indicator is bird population trends (i.e. short-term trends reported). In general, the use of trend indicators is discouraged by the SEEA EA. Preference goes to measuring the state of condition variables at two or more points in time to derive a trend. However, in the case of the BD data, the population trends indicator was deemed an appropriate indicator for condition. This indicator is to some extent aligned with other well-known indicators related to population trends such as the Grassland Butterfly Indicator and the Farmland and Forest Bird Indicator (see further discussion on section 5.4 on 'contemporary condition').

Beyond the Nature Directives described above, the integration of reported variables under the WFD and MSFD could not be fully analysed within the context of the EU-wide methodology, since further detailed analyses would be required (see section 3.4 and 4.6). However, the **case study of marine ecosystems demonstrates that a certain level of alignment between the MSFD and the SEEA EA is possible**. The application of the SEEA EA framework also allows the integration of physical condition variables which provide very valuable information regarding the climate change impact on marine ecosystems (e.g. acidification, increase in sea temperature), which are currently absent in the MSFD. Still, the alignment and availability of MSFD parameters (the equivalent to ecosystem variables under the SEEA EA) reported by each MS should be further explored. At the very least, in case of lack of harmonisation, similarly to the HD case, the methodology could be implemented at the MS level. A similar exercise could also be applied in the future for freshwater ecosystems by integrating the underpinning data used for the reporting of status of water bodies under the WFD. Complementarily to data reported under the WFD, indicators used under the EU ecosystem assessment (Maes et al., 2020a), but also those proposed under the NRL, on natural connectivity of rivers and natural functions of the related floodplains, would be very relevant to provide a more inclusive assessment of the overall condition of freshwater ecosystems, including also landscape characteristics.

A more in-depth analysis and testing is required for both marine and freshwater ecosystems, since the lack of harmonised information, and sometimes access to some underlying data, can hamper its re-use for the condition assessment at EU level.

Still, the existing EU legislation shows some overlap in the monitoring and assessment of condition/status for some ecosystems types, making use of different methodologies. This overlap may generate different conclusions depending of the Directive of reference (e.g. HD, WFD and MSFD). This is a critical issue, especially for wetlands, due to the large overlap in their coverage by Environmental Directives, which highlights the **need to apply a coherent and common method for the assessment of their condition**, as the one proposed here following the international standard of the SEEA EA.

Beyond the EU environmental legislation, more directly linked to the ecosystem condition concept, there are **other legal EU initiatives which also provide relevant data flows to improve the knowledge on ecosystem condition in the EU**. This has been clearly illustrated by integrating indicators already being used under the CAP and the Forest Strategy. Moreover, data reported under the IAS Regulation could also be used to develop time series of the 'Pressure by invasive alien species', but this would require further research and analyses of reported data.

5.1.1 Case study of Greece: Integration of data monitored for the HD reporting

Data derived from the in-situ field surveys under the HD monitoring are not available at EU level, hampering their integration into the SEEA EA condition accounts framework. This case study of Greece illustrates to what extent the field data collected for the 'structure and functions' parameter and typical species, to report on forest habitat condition under the HD, can be used under the SEEA EA, at the Member State level. Below, a short overview of this case study for forest habitats is presented, highlighting the main outcomes:

- All parameters (25 in total) that were common for all forest habitats were extracted from the Greek HD monitoring database and integrated as variables into the SEEA EA (Table 16). This list also includes species coverage estimates on a semi-quantitative/ordinal scale (Braun-Blanquet), which are not fully consistent with the SEEA EA, however they can be easily adjusted to allow their integration into this framework.

- In-situ monitoring data collected to report on the condition of forest habitats (i.e. 'structure and functions' parameter) under the HD in Greece are frequently based on presence/absence observations, which requires the aggregation of information at coarser spatial scale to derive quantitative variables compliant with the SEEA EA framework (e.g. proportion (%) of plots recorded as presence within a predefined spatial unit, which in this case was a 5 km grid, based on the EEA Reference Grid for Greece specifications).

- Data monitored for the HD reporting of forest habitats in Greece cover practically all types of ecosystem characteristics, but chemical (Table 16).

- Different methods are used to set reference levels for each variable and rescale them into condition indicators (Table 16). When statistical methods are applied (e.g. 90th percentile), estimates of reference levels are done separately by forest type (i.e. floodplain forests, Mediterranean coniferous, Mediterranean deciduous, Mediterranean sclerophyllous, mixed, temperate deciduous, temperate mountainous coniferous).

- The method applied to define good or not-good habitat condition under the HD is not SEEA EA compliant. It is based on rules that take into account the proportion of indicators marked as present for the 'structure and functions' parameter and the values of the index of conservation degree of typical species (more information can be found in Tsiripidis et al. (2018)). Therefore, the decision of good or not-good habitat condition depends on the aggregation of indicators and not on specific reference levels defined for each indicator as required under the SEEA EA.

- Although under the HD monitoring there is no full coverage of all condition classes of the SEEA EA (i.e. chemical condition is missing), this information can be integrated for the mapping and assessment of ecosystem condition together with other variables available beyond Annex I habitats.

- The map below depicts the woodland and forest condition index (aggregated), at 5 km grid, for the Natura 2000 sites of conservation importance and their buffer zones, from in-situ monitoring data collected for the HD reporting and by applying the SEEA EA framework (Figure 7).

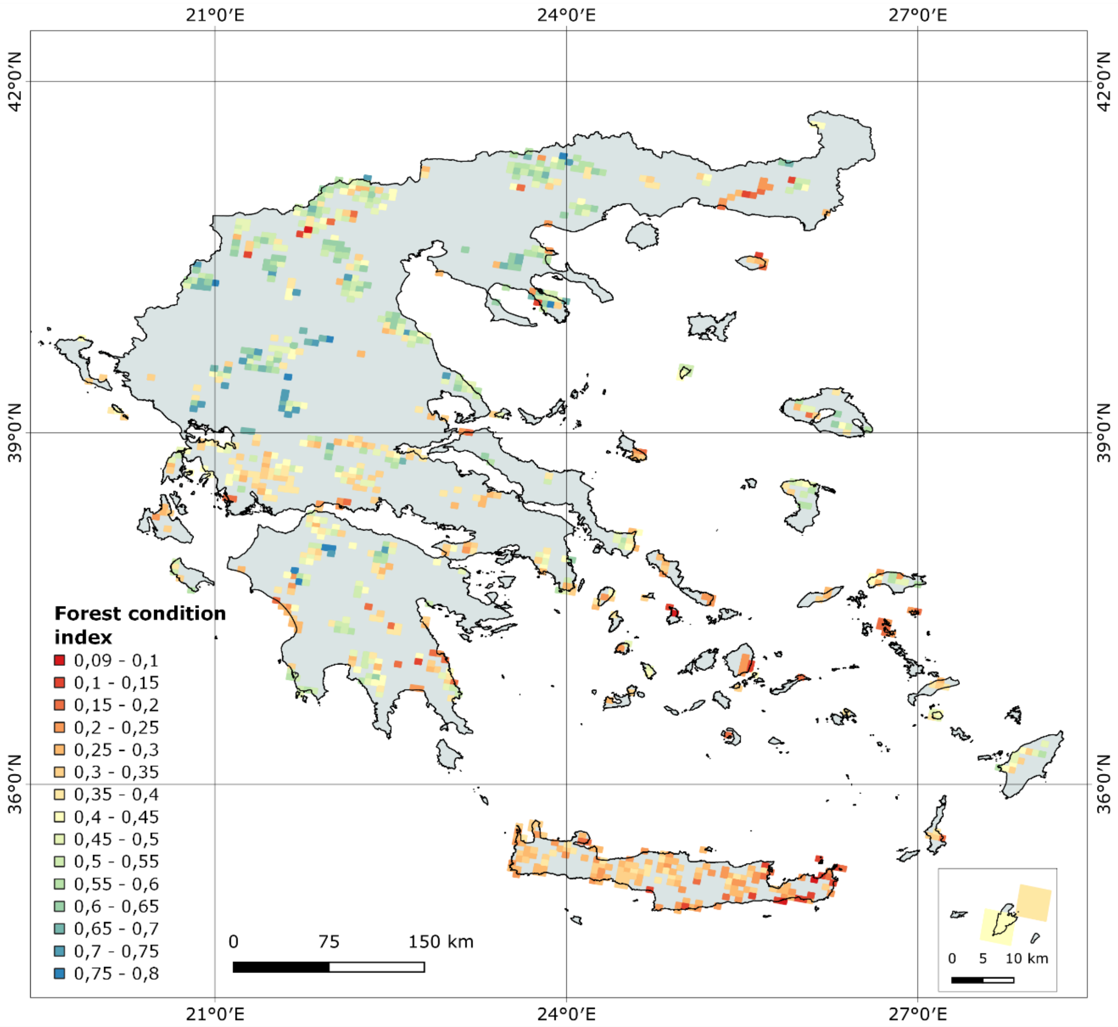
- This case study suggests that integration of the underlying data used for the reporting under the HD into the SEEA EA framework is feasible.

Table 16. SEEA EA compliant variables that are extracted from the Greek HD monitoring database

SEEA Ecosystem Condition Typology Class		Variables	Units (HD monitoring plot level)	Thresholds used for the in-situ assessment	Units (SEEA EEA)	Methods to set reference levels
Abiotic (Weight: 0.2)	**Physical state**	Existence of 'Ah' horizon above a threshold	Presence/ absence	50–75 % cover and depth 4-10 cm (depending on habitat type)	Percentage of presences at 5x5 km	Prescribed levels (0-100%)
		No signs of erosion	Presence/ absence	Furrows depth <30 cm, in less than 20% of the area	Percentage of presences at 5x5 km	Prescribed levels (0-100%)
	Chemical state	Not available	-	-	-	-
Biotic (Weight: 0.6)	**Compositional state** (Weight: 0.2)	Typical species richness	Species occurrence	-	Number of species	Statistical method (90th percentile)
		Alien species cover	Braun-Blanquet scale	-	Braun-Blanquet scale	Prescribed levels (0-9)
		Xeric species cover	Braun-Blanquet scale	-	Braun-Blanquet scale	Prescribed levels (0-9)
		Grassland species cover	Braun-Blanquet scale	-	Braun-Blanquet scale	Prescribed levels (0-9)
		Ruderal species cover	Braun-Blanquet scale	-	Braun-Blanquet scale	Prescribed levels (0-9)
		Existence of cryptogam layer	Presence/ absence	> 5–10% (depending on habitat type)	Percentage of presences at 5x5 km	Prescribed levels (0-100%)
		Species richness relatively high	Presence/ absence	Expert judgement	Percentage of presences at 5x5 km	Prescribed levels (0-100%)
		Dominance of typical species	Presence/ absence	Expert judgement	Percentage of presences at 5x5 km	Prescribed levels (0-100%)
		Adequate coverage of typical woody dominant species	Presence/ absence	> 30%	Percentage of presences at 5x5 km	Prescribed levels (0-100%)
	Structural state (Weight: 0.2)	Tree layer cover	Area cover (%)	-	Area cover (%)	Prescribed levels (0-87.5%)
		Forest herb layer cover	Presence/ absence	> 5-25% (depending on habitat type)	Percentage of presences at 5x5 km	Prescribed levels (0-100%)
		Occurrence of at least two tree layers	Presence/ absence	-	Percentage of presences at 5x5 km	Prescribed levels (0-100%)
		Stand stratified (tree, shrub, herb layers present)	Presence/ absence	-	Percentage of presences at 5x5 km	Prescribed levels (0-100%)

SEEA Ecosystem Condition Typology Class	Variables	Units (HD monitoring plot level)	Thresholds used for the in-situ assessment	Units (SEEA EEA)	Methods to set reference levels
	Occurrence of old trees above a threshold	Presence/ absence	Diameter >30-50 cm, cover >10-30% (depending on habitat types)	Percentage of presences at 5x5 km	Prescribed levels (0-100%)
Functional state (Weight: 0.2)	Litter cover	Area cover (%)	-	Area cover (%)	Prescribed levels (0-87.5%)
	No signs of regressive or progressive succession	Presence/ absence	-	Percentage of presences at 5x5 km	Prescribed levels (0-100%)
	Adequate regeneration of dominant species	Presence/ absence	Expert judgement	Percentage of presences at 5 km	Prescribed levels (0-100%)
	Absence of species indicating desertification	Presence/ absence	-	Percentage of presences at 5 km	Prescribed levels (0-100%)
	Absence of coppiced stems	Presence/ absence	< 20-40% (depending on habitat type)	Percentage of presences at 5 km	Prescribed levels (0-100%)
	Absence of signs of significant disturbance (e.g. from logging, grazing)	Presence/ absence	-	Percentage of presences at 5 km	Prescribed levels (0-100%)
Landscape and seascape (Weight: 0.2)	Absence of planted species	Presence/ absence	-	Percentage of presences at 5 km	Prescribed levels (0-100%)
	Dominant typical species not highly fragmented and coverage above a threshold	Presence/ absence	25 to 50 % (depending on habitat type)	Percentage of presences at 5 km	Prescribed levels (0-100%)
	Diversity of age classes of dominant species	Presence/ absence	Expert judgement	Percentage of presences at 5 km	Prescribed levels (0-100%)

Figure 7. Map of the condition index for forest habitats in areas of conservation importance (based on in-situ monitoring data collected for the HD reporting applying the SEEA EA framework)



Source: Own elaboration

5.2 EU legislation and initiatives relevant for the condition assessment

Beyond the specific policies and strategies that play a key role in driving changes in the condition of certain ecosystem types, and in their assessment (e.g. the CAP for agroecosystems and the EU Forest Strategy for forest), there are other legal initiatives that have a large potential in the near future to be relevant for the condition assessment of a group of ecosystems: EU Pollinator Monitoring Scheme framed under the EU Pollinators Initiative (5.2.1), the National Emission reduction Commitments Directive (5.2.2) and the Soil Health Law (5.2.3).

5.2.1 How can insect pollinator monitoring inform the assessment of ecosystem condition?

Europe supports a rich diversity of wild pollinator insects that collectively provide a wide range of benefits to society. Pollinators, among other important roles, enhance the reproduction and genetic diversity of an average

80% of crop and wild plant species (Convention on Biological Diversity, 2018; Klein et al., 2007; Ollerton et al., 2011), which are critical for the continued functioning of ecosystems. Therefore, **pollinators ensure healthy ecosystem functioning and maintain biodiversity** of terrestrial ecosystems, providing very valuable information on the functional state of ecosystems and thus, on their condition.

Many pollinating species are declining within and outside Europe, and numerous are extinct or threatened with extinction. However, **major gaps remain in our knowledge regarding the status and trends of pollinating insects**. A standardised EU pollinator monitoring scheme is currently being developed under the **EU Pollinators Initiative** (European Commission, 2018), to provide high quality data on the abundance, diversity and occupancy of pollinator species, and potentially pollination services. A proposal for an **EU Pollinator Monitoring Scheme (EU-PoMS)** was designed (Potts et al., 2021) to monitor representative pollinator taxa across the EU: wild bees, butterflies, hoverflies and moths, including rare and threatened pollinator species.

In support to the EU-PoMS, in June 2021 the Commission launched the **SPRING project (Strengthening pollinator recovery through indicators and monitoring)** to pilot the methodological approach, further develop specific modules (e.g. moths, wider insect biomass), test and validate new indicators, explore pathways to integrate emerging technologies and increase the taxonomic and recorder capacity. The full deployment of such an EU-wide pollinator monitoring scheme could be expected at the earliest in 2025, if the adequate financial, technical and administrative capacity will be ensured.

Data gathered and developed through the **EU-PoMS would provide valuable information to assess ecosystem condition over time and across the geographic space**. *In-situ* monitoring would provide relevant data to derive a wild pollinators indicator based on trends in abundance (similarly to the grassland butterflies and common bird indicators), as well as on species richness and changes over time. Data collected through the EU-PoMS would be used to develop a general pollinator indicator at Member State level, and by ecosystem type at the EU level. Further level of detail (e.g. by ecosystem type for each country, and beyond) would enhance the utility of EU-PoMS to inform the condition assessment by ecosystem type. Ultimately, the spatial resolution at which the indicator will become significant will depend on the statistical power of the monitoring scheme finally implemented. Primary data collected during the EU-PoMS are expected to be made accessible, which is essential to further explore possibilities to develop spatially explicit pollinator indicators (e.g. species richness distribution) to better inform the ecosystem condition assessment.

The EU-PoMS is expected to use a **baseline year (still to be defined) to make robust comparisons over time**. This baseline year would be used as reference level for the assessment of ecosystem condition (e.g. method of 'contemporary data' under the SEEA EA).

In the context of the EU-wide methodology to map and assess ecosystem condition, the **'wild pollinators indicator' has been in principle proposed for all terrestrial ecosystems.** It remains to be seen if the scheme would deliver valuable information for terrestrial ecosystems at finer spatial resolution than the EU level. Moreover, a better understanding of the relationship between pollinators and condition of each ecosystem type is also required (Barendregt et al., 2022). For instance, in forests, the focus on relevant species or taxa (e.g. hoverflies) may be needed to derive a meaningful indicator of forest condition (Larrieu et al., 2015).

5.2.2 Ecosystem impact monitoring of air pollution under Article 9 of the NEC Directive

The National Emission reduction Commitments Directive (NECD; (EU) 2016/2284)[54] aims to limit emissions of air pollutants in order to protect the human health and the environment against adverse effects of air pollution. As it

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[54] NEC Directive: Directive (EU) 2016/2284

relates to impacts on the environment, these materialise through acidification, eutrophication and ground-level ozone. Article 9 of the NEC Directive sets the obligation for the EU MS to ensure the **monitoring and reporting of negative impacts of air pollution on ecosystems** based on a network of monitoring sites that is representative of their freshwater, natural and semi-natural habitats. Annex V of the Directive also refers to the monitoring of ozone damages to vegetation growth, which also relates to croplands. The reporting obligation foresees reporting every 4 years on the location of the sites and the list of parameters monitored, with first deadline set on July 2018. Air pollution impacts monitored at those sites must be reported every 4 years, but starting from July 2019. MS report data to the European Commission, which are hosted by the European Environment Agency. The European Commission has to report to the European Parliament and the Council every 4 years, starting on April 2020, on the Union's biodiversity and ecosystem objectives (Article 11.1(a) (iii))[55].

The monitoring scheme is designed to be fit for purpose to monitor direct and indirect impacts of eutrophication, acidification and ozone on ecosystems and their habitats at the national level. The list of proposed parameters to be measured is available in the guidance document and indicative reporting template[56]. It includes, amongst others, information about pollution concentrations and load, vegetation composition, element concentrations in vegetation and soil and soil water.

In the first reporting round (2018-2019), the **limited number of monitoring sites, especially in some MS, made the network insufficiently representative to provide robust information on ecosystem condition** in relation to the air pollutants impact at EU level. Therefore, reported data under Art. 9 of the NEC Directive has not been included so far as variable for the condition assessments. To become fully useful for the ecosystem condition assessment, the NEC Directive monitoring network should ensure a more systematic coverage of the full area of the EU capturing the spatial heterogeneity of the impacts by air pollutants and guaranteeing in this way the compliance with the SEEA EA. The representativeness of NEC Directive Article 9 data will be re-assessed based on the second reporting round (2022-2023). It is expected to improve based on the recommendations passed to Member States following the first reporting round.

In the coming years, the NEC Directive monitoring of ecosystem impacts of air pollution can potentially contribute in two main ways to the assessment of ecosystem condition and to EU biodiversity objectives:

- To provide data that can feed into the development of a set of indicators on air pollution impacts on ecosystems, to be used for the ecosystem assessment for different ecosystems types;
- To provide valuable information for validating model-based ecosystem variables related to air pollutant concentrations and deposition[57] or for the initialization and validation of the critical load[58] approach, which already takes into account the sensitivity of ecosystems due to their natural site conditions. Especially important would be the information on semi-natural ecosystems and habitats such as grasslands or wetlands, since these ecosystems are not covered by the monitoring under the Working Group of Effects.

5.2.3 Alignment of the ecosystem condition assessment with the Soil Health Law

The concept of soil condition is embedded in the notion of ecosystem condition, since soil is a key component of ecosystems. For this reason, a number of soil variables are currently proposed for the assessment of different ecosystem types. The Soil Health Law is currently being developed by the Commission to define, regulate and monitor soil health based on a selection of key indicators for all ecosystems. When this law comes into force

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[55] First report: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1593765728744&uri=CELEX:52020DC0266

[56] Reduction of National Emissions - Guidance on ecosystem monitoring - Environment - European Commission (europa.eu): https://ec.europa.eu/environment/air/reduction/ecosysmonitoring.htm

[57] Such as under the co-operative programme for monitoring and evaluation of the long-range transmission of air pollutants in Europe: https://www.emep.int/mscw/pollutants.html

[58] Such as under the Coordination Centre for Effects (CCE): https://www.umweltbundesamt.de/en/cce-data-models

(tentatively in 2024), the EU-wide methodology will be updated by integrating those indicators selected under the Soil Health Law. Current work under the Soil Health Law is focused on the selection of indicators and definition of critical thresholds (i.e. prescribed levels) to set the limit between a healthy and non-healthy soil in a consistent way across the EU. Discussions are ongoing on the criteria to define these critical thresholds, which should take into account intrinsic soil characteristics, bio-climatic regions and land use (i.e. aligned with the criteria to be used for the delineation of 'homogeneous ecosystem areas' in the EU-wide methodology). Integration of variables and thresholds to be used as reference levels under the Soil Health Law will ensure the integration of soil health into the overall ecosystem condition assessment.

5.3 Modelling in support to the assessment of ecosystem condition

Modelling is a fundamental tool to provide harmonised data layers suitable for the mapping and assessment of condition at the EU level. The current data gap due to the lack of harmonised underlying data of the EU reporting could be partially covered with modelling tools that would provide proxies of ecosystem condition more consistently covering the whole EU territory over time.

Working at the EU scale, modelling examples can be summarised in two main approaches:

1. Disaggregation of regional or national statistics to a finer resolution (e.g. 1 km, 10 km raster);

Reliable environmental impact assessment of agricultural activities on the environment (e.g. nitrogen balance, GHG emissions, losses of reactive nitrogen from agricultural sources, soil erosion or soil carbon stock changes) requires the availability of the data and its dynamics at a high spatial resolution. This would contribute to a better integration of related condition variables into the SEEA EA. If the analysis of the environmental impact is based on data at a relatively coarse-scale (e.g. large administrative regions), conclusions can be misleading (Gocht & Röder, 2014) and it is not possible to map exceedance of thresholds or identifying hotspots.

Statistical data related to human activities are often published in an aggregated form, linked to administrative units. This is particularly common for agroecosystems, for which variables such as gross nutrient balance, mineral fertilizer consumption and, pesticide use are published by Eurostat ranging from NUTS3 to NUTS0 level. In the **CAPRI modelling system** (Britz W. et al., 1999) a procedure has been set to disaggregate some of the data available at regional level to smaller spatial units of agricultural land, the so-called Farm Structure Units (FSU). FSU are relatively homogeneous in their environmental and socio-economic conditions.

2. Geospatial interpolation of survey data:

This approach makes use of sparse survey data (in-situ monitoring in sampling points) to develop probabilistic models. These models are frequently applied to map species distribution or richness, but also LUCAS data to generate wall-to-wall geospatial data of soil variables and other marine variables.

For instance, the **spatial layer of farmland species richness** was obtained based on a standardised bird surveys collected for the European Breeding Bird Atlas 2 (EBBA2), which were transformed into geospatial layers developing species distribution models and producing probability of occurrence for species across the whole of Europe (Herrando et al., 2017). Model results have been used to generate the most accurate species distribution maps in Europe. EBBA2 data are not going to be updated on the short term, updates of the resulting layers can be obtained by modelling similarly data surveyed in the frame of the Pan-European Common Birds Monitoring Scheme.

Modelling of EU reported data might be crucial for filling spatial-temporal data gaps (e.g. missing information in the data reporting) **and possible inconsistencies** (e.g. no harmonised information) to reinforcing the suitability of reported data to assess ecosystem condition at EU level. For instance, **richness of threatened forest birds** is derived from a modelling approach adapted to make use of data reported under the BD. JRC has developed a linear regression for species richness as part of a pilot study on the mapping of forest condition (Maes et al., 2022). Although the model output depends on the input data and model assumptions, it provides geospatial data with certain spatial and temporal consistency for the assessment of ecosystem condition across the EU.

LUCAS (Land Use/Cover Area frame statistical Survey)[59] data is other key dataset that is frequently used as input in models to generate geospatial layers. LUCAS provides geo-referenced sample point data that can be extrapolated to continuous layers, making use of different geospatial models, to provide proxies for relevant variables for the assessment of ecosystem condition such as organic carbon content, soil biodiversity, N and P content in soil, and others. The ESDAC portal[60] makes available all the modelled outcomes.

5.4 Definition of reference levels in the EU context

Defining reference levels appears as a very challenging task that requires scientific rigour, but also consensus among stakeholders. Reference levels are essential to make ecosystem condition variables comparable and amenable for policy applications. A consistent and stable set of reference levels is necessary for measuring genuine decline (degradation) or improvement (restoration success) of ecosystem condition in a transparent and consistent way. The development of the EU-wide methodology has brought a lot of discussion on the methods available that may be used to set reference levels. Based on the methods suggested by the SEEA EA, **three broad approaches to define reference levels** can be distinguished among the variables proposed**,** which have different implications when it comes to define restoration policy targets: 1) Based on an 'optimal condition'; 2) Based on a 'sustainable condition' and 3) Based on a 'contemporary condition'.

1) Reference levels based on 'optimal condition' should be applied when using the four methods strongly recommended by the SEEA EA (i.e. reference sites, modelled reference conditions, statistical approaches based on ambient distributions, historical observations and paleo-environmental data). With this approach, the full range (scaled between 0 and 1) of condition would be captured (Figure 8a). Ultimately, the indicator range will be used to define restoration targets based on what is considered good or not good condition using ordinal condition classes (Figure 8b). **Thresholds to define good condition (frequently considered in terms of sustainability thresholds) will always be lower than the optimal condition** and they are defined as an acceptable deviation from the optimal condition for which restoration targets are set. This threshold is defined at 0.6 for the Ecological Quality Ratio (BQR) under the WFD and for the condition variables in Jakobsson et al. (2020). Especially for anthropogenic ecosystems, thresholds definition might also be based on policy decisions taking into account socio-economic factors which are beyond the ecosystem condition assessment, however, they should still guarantee social-ecological resilience of the system.

This is the most recommended approach for setting reference levels, especially recommended for those variables with a positive relationship with condition (i.e. higher values are related to a better condition).

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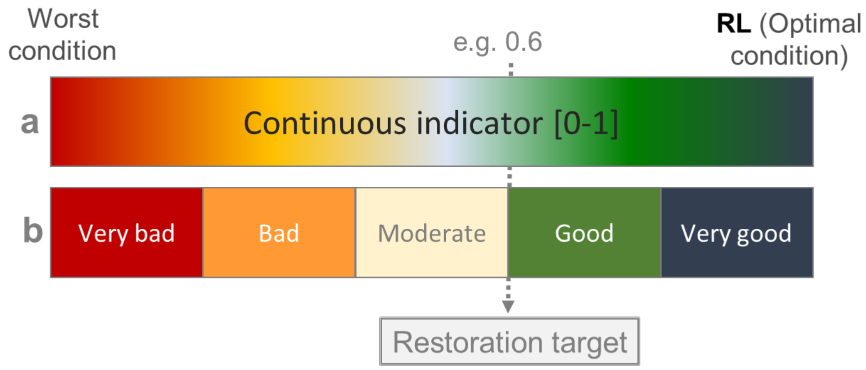
[59] https://esdac.jrc.ec.europa.eu/projects/lucas

[60] https://esdac.jrc.ec.europa.eu/

Figure 8. Definition of reference levels based on 'optimal condition' (recommended for positive variables). Rescaled continuous indicator (a) can be classified into ordinal condition classes (b). The threshold between good and not good will have a key role in setting restoration targets and will always be lower than the optimal condition. Frequently, this threshold is defined as 0.6 of the continuous indicator (see the WFD and Jakobsson et al., 2020).



RL: Reference level

Source: Own elaboration

2) Reference levels based on 'sustainable condition': when prescribed levels are already defined based on scientific evidence (e.g. critical levels of pollutants) or on policy targets or thresholds. Prescribed levels are always lower than the optimal condition defined above, since their definition is related to the sustainability thresholds defined with policy purposes used to discriminate between good or not condition as described above (for the approach of optimal condition). The use of prescribed levels to define reference values is presented in the SEEA EA as a method to be applied in the case of need for consistency with policy drivers as required under the EU-wide methodology. For this reason, the use of prescribed levels based on policy targets/threshold is very frequent in the EU-wide methodology.

The use of prescribed levels based on scientific evidence also guarantee scientific robustness of the approach by making use of 'tolerable', 'sustainability' or 'risk-based'[61] thresholds, which directly point to the amount that is considered as 'tolerable' by the ecosystem without leading to its degradation based on scientific estimates. For instance, critical loads of eutrophication are deposition thresholds used to describe the sensitivity of ecosystems to atmospheric deposition of nutrients such as nitrogen. Above this critical threshold, ecosystems start degrading and the variable recorded would be the 'exceedance of critical loads' in which higher exceedance implies a worsening of ecosystem condition (Figure 9). However, in the lack of exceedance (pollutants below the critical thresholds), the ecosystem is considered equally as in 'good condition', independently of the amount of pollutants that the ecosystem may present between the critical level and the absolute zero corresponding to the 'optimal condition' (e.g. zero pollutants) (blue part in Figure 9).

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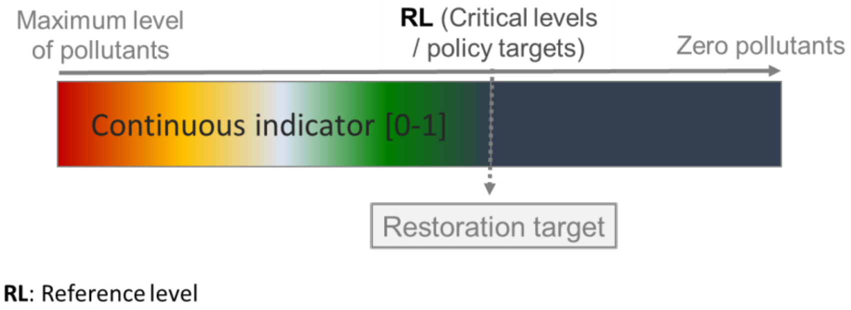
[61] 'Risk-based' in this context means that thresholds (critical limits) are designed to identify deterioration/loss of ecosystem services after degradation (e.g. to protect harm to ecosystem species, avoid productivity losses) (Baritz et al., 2021).

Figure 9. Definition of reference levels based on 'sustainable condition' (mainly recommended for negative variables such as pollutants). Critical levels are directly used as restoration targets. Above this target, the condition is always defined as good.



Source: Own elaboration

Prescribed levels are frequently available for variables with a negative relationship with condition (i.e. higher values are related to a worse condition), since these variables made previously necessary the identification of sustainability thresholds to take measures targeting the reduction of environmental impacts. The 'sustainable condition' approach is very frequent for agroecosystems, since many of the variables proposed have a negative relationship with condition and therefore already present prescribed levels defined, as in the case of many pollutants. These critical levels for pollutants are eventually aligned to policy targets such as the 'Zero pollution action plan', in which air, water and soil pollution will be reduced by 2050 to levels no longer considered harmful to human health and natural ecosystems, and that respect the boundaries with which our planet can cope.

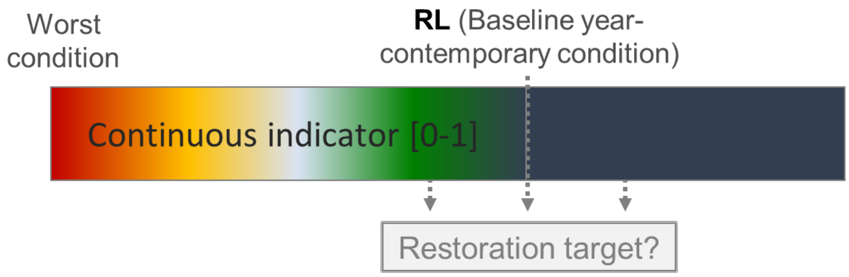
Importantly, the 'sustainable condition' approach presents very different implications in terms of defining restoration targets when compared to the 'optimal condition'. In the former, the restoration target would be exactly the same as the reference level (ignoring the range of the variable that is below the critical level), while in the latter, the restoration target would be always lower than the reference level. Using these two alternative approaches (optimal vs. sustainable condition) may bring major conceptual and methodological inconsistency in the ecosystem condition assessment.

In the EU-wide methodology, we present a feasible alternative to ensure consistency between approaches when setting reference levels, if prescribed levels are already defined, while better following the SEEA EA recommendations. Prescribed levels may potentially be used as the basis to estimate the 'optimal condition' based on a mathematical calculation for the rescaling that would ensure the correspondence of the prescribed levels with a threshold of 0.6, as in the WFD and Jakobsson et al. (2020). For instance, in the case of critical loads for eutrophication, the 'optimal condition' would be defined as zero concentration of pollutants, while the upper reference level would correspond to 2.5 times the critical load. In this way, sustainability or critical thresholds already defined (by either policy targets/thresholds or by scientific evidence) would be used as restoration targets, but not as reference levels. Then, prescribed levels already available would be the basis to calculate reference levels, following a similar scheme to the 'optimal condition' approach. Then, the method should be better called 'prescribed levels-based' to better make a distinction between 'sustainability thresholds' and optimal reference levels, and ensure further consistency.

3) Reference levels based on the 'contemporary condition' is the approach adopted for variables related to species abundance (i.e. population size). As mentioned before, species abundance as such is not a suitable condition variable (e.g. larger populations do not directly imply better condition), and it becomes only meaningful when compared to a reference value (e.g. population size of a baseline year – method of 'contemporary condition'). However, the method of 'contemporary condition' is used for really well-known variables reporting on species abundance such as the farmland bird indicator and the grassland butterfly indicator, due to the lack of better alternatives to determine the ‘optimal condition’. On the contrary, for the species protected under the HD, population sizes are compared with ‘favourable reference population', which provides more robust (less arbitrary) reference levels.

Importantly, the ‘contemporary condition’ approach presents an unclear linkage to restoration targets, since it can be below, equal to or above the reference level depending how the reference level is considered in terms of adequacy for condition (Figure 10). The baseline year might potentially be used as restoration target, if the goal is to restore the ecosystem to the situation of the baseline year (Figure 10). However, the restoration target might also defined as an improvement with regard to the baseline year as for the common farmland bird indicator under the NRL. This indicator will make use of a baseline year based on a date following 12 months after the entry into force of the Regulation, in which the indicator will take value of 100, to be used for the rescaling into a SEEA EA condition indicator. However, restoration targets under the NRL for the farmland bird indicator are proposed above the value reached in the baseline year (ranging between 105 and 130). Therefore, in this case, the rescaled indicator would not be appropriate to monitor the distance to the restoration target.

Figure 10. Definition of reference levels based on ‘contemporary condition’ (mainly for species abundance variables, if no optimal condition can be determined). The baseline value is not necessarily used as restoration target.



RL: Reference level

Source: Own elaboration

The use of the ‘contemporary condition’ is only recommended if there is a lack of better methods to define reference levels (firstly optimal condition or alternatively prescribed level). However, **the use of variables based on the contemporary condition to define reference levels may result very problematic when defining restoration targets and monitoring them**, which may compromise the suitability of such variables for the assessment of ecosystem condition according to the SEEA EA framework. In consequence, further research efforts should be dedicated to better identify alternative ways to set more robust reference levels and ensure that the restoration target can only be defined within the range of the indicator (variable rescaled).

5.5 Definition of ‘homogeneous ecosystem areas’

On top of the complexity of defining reference levels, another key challenge arises from the need to **better define ‘homogeneous ecosystem areas’** in a meaningful way to set reference levels. Definition of ‘homogeneous ecosystem areas’ may be required for some variables that show large variability across the territory, for which a finer ecosystem classification towards habitats of specific groups of species may be required (see section 3.3). The EU-wide methodology provides general recommendations on how to define ecosystem types from land cover classes from CLC (i.e. the reference land cover layer at EU level over time) making use of complementary geospatial information such as biogeographical regions and/or soil type. However, current initiatives to provide more detailed mapping of ecosystems (Box 4), may help to define 'homogeneous ecosystem areas' with a stronger ecological basis. Similarly, on the marine environment, this methodology proposes to follow the regions and sub-regions establishes by the MSFD, although other scientific initiatives propose more detailed and ecologically-based approaches (e.g. the cells of ecosystem functioning, Boero et al. (2019)).

Box 4. Towards a better mapping of EUNIS habitats

The European Nature Information System EUNIS[1] provides a comprehensive and harmonised pan-European habitat classification in a hierarchical system including information about their species. Compared to the more aggregated MAES ecosystem classification, EUNIS allows a better biological characterization of ecosystems and their habitats but does not include European wide spatially explicit maps.

EU wide probability maps for the individual terrestrial EUNIS habitats are available. Additionally a combined map was produced for terrestrial, freshwater and marine ecosystems, based on the Copernicus land service portfolio, marine bathymetry, seabed and sea ice information and auxiliary data[2]. With new land monitoring services available, mainly the CLC+ backbone component and the pan-European High-Resolution Vegetation Phenology and Productivity product suite (HR-VPP)[3], refinement of the geometric and thematic reliability of each EUNIS habitat are currently being tested using maximum-entropy-method and machine learning. National EUNIS mapping (e.g. Austria[4]) will be used for validation and further improvement.

[1] EUNIS habitat classification: https://www.eea.europa.eu/data-and-maps/data/eunis-habitat-classification-1

[2] Ecosystem types of Europe v3.1: https://www.eea.europa.eu/data-and-maps/data/ecosystem-types-of-europe-1

[3] Copernicus pan-European land monitoring services: https://land.copernicus.eu/pan-european/

[4] EUNIS habitat map-Austria: https://www.data.gv.at/katalog/dataset/1d1a8d2d-cfe8-46ef-aeda-136c88726b5d

The use of biogeographical regions may be sufficient for some ecosystem types, however, the type of soil is also especially relevant for a better distinction of 'heathland and shrub' (i.e. presence of peatland). Moreover, soil typology is also a key factor when setting reference levels for soil variables such as soil organic carbon stocks, and heavy metals content. This is currently being discussed under the context of the Soil Health Law (section 5.2.3).

Definition of 'homogeneous ecosystem areas' is especially challenging for anthropogenic ecosystems (urban and agroecosystems), since their heterogeneity does not only depend on natural factors, but also on human-driven factors, such as population and level of compactness in urban areas, or cropping systems and management in agroecosystems. Note that in the case of agroecosystems, definition of 'homogeneous ecosystem areas' is practically not required since most of the reference levels are defined according to prescribed levels, for which this is not needed. Therefore, the definition of 'homogenous ecosystem areas' in urban areas remains the most challenging.

6 General conclusions

The EU-wide methodology provides **useful insights to operationalise the international statistical standard on ecosystem condition accounts, the SEEA EA, at the EU level.** It provides a guidance for the application of a consistent method to assess ecosystem condition across all ecosystem types, and most importantly, beyond areas currently protected under EU Environmental Directives.

The adoption of the SEEA EA, as a robust framework to systematically integrate and organise information on ecosystem condition, allows **leveraging the use of data/indicators derived from EU legislation, EU monitoring programs such as LUCAS and Copernicus, but also geospatial data derived from scientific outcome**. A broad selection of ecosystem condition variables has been provided for terrestrial ecosystem types, but also for marine ecosystems as a case study. All variables included provide relevant information for the assessment of ecosystem condition at the EU level. Ultimately, the suitability of each variable for the ecosystem condition assessment will depend on the specific purpose of the study. If the focus is on tracking changes on ecosystem condition aggregated at the EU level, then all variables with time series can be chosen. If the goal is mapping degraded areas, then, only geospatial data of adequate spatial resolution will be selected. Importantly, the use of spatial data when assessing ecosystem condition presents an important added value, enabling an objective estimation and monitoring of areas at the EU level that can be considered as in good condition, or degraded. Therefore, spatial data allows for the targeting of areas where ecosystem restoration measures should be prioritised to achieve good ecosystem condition.

The lists of variables proposed in the EU-wide methodology are fully aligned with the proposal of the NRL and with the proposed legal module on ecosystem accounts (section 1.1) (Table 17). Some indicators in Table 17 refer exactly to the same ecosystem characteristics across all three initiatives (e.g. common farmland bird indicator), while others are only partially related (e.g. indicators for wetlands). Detailed definitions and/or methods to measure condition indicators proposed in the ecosystem accounts module are not yet available, which hinder a proper comparison at this stage. For instance, green areas have not been defined yet, which might be different from the concept of green space defined under the NRL.

Indicators shown for these current proposals regarding ecosystem condition are based on the most up-to-date available information. However, **they might be subject to changes before their adoption**. The incorporation of the indicators of the NRL in the EU-wide methodology will guarantee that their expected improvements to achieve the nature restoration targets will be captured when applying the EU-wide methodology for the assessment of the overall ecosystem condition.

Limitations in the use of different datasets are described in detail in section 4. As main conclusion, data **reported by MS under EU legislation related to ecosystem condition often do not ensure adequate spatial and/or temporal consistency across the EU**, which poses a major limitation to the effective application of robust methods to assess ecosystem condition at EU level. Unless efforts are put in place to ensure data consistency across the EU, integration of reported data may be only feasible at the country level. Specifically for the HD, detailed analysis of the parameters currently monitored to assess habitat condition across countries would be needed to better identify coherent variables/indicators and to measure them consistently across the EU territory. The current data limitations due to the lack of harmonised and consistent underlying data from the EU reporting obligations could be partially overcome with modelling tools that would provide proxy variables for assessing ecosystem condition, covering the whole EU territory with representative time series in a more consistent way.

Table 17. Comparison of indicators proposed in the EU-wide methodology, the proposal of the Nature Restoration Law and the proposed legal module on ecosystem accounts

Ecosystem types	ECT class	Variable in the EU-wide methodology[1]	Equivalence in the Nature Restoration Law proposal	Equivalence in the proposed legal module on ecosystem accounts
Urban	Chemical	Air pollutants concentration	-	Concentration of particulate matter (< 2.5 μm)
	Structural	Green space	Urban green space	Green areas
		Tree canopy cover	Urban tree canopy cover	-
	Functional	Wild pollinators indicator	Pollinator populations[2]	-
Agroecosystems	Chemical	Organic carbon stock in cropland mineral soils	Stock of organic carbon in cropland mineral soils	Soil organic carbon stock
	Compositional	Grassland butterfly indicator	Grassland butterfly index	-
		Common farmland bird indicator	Common farmland bird index	Common farmland bird index
	Structural	Share of landscape features	Share of agricultural land with high-diversity landscape features	-
	Functional	Wild pollinators indicator	Pollinator populations	-
Forest	Chemical	Soil organic carbon stock	Stock of organic carbon	-
	Compositional	Common forest bird indicator	Common forest bird index	-
	Structural	Deadwood	Standing/lying deadwood	Deadwood
		Tree cover density	-	Tree cover density
	Functional	Wild pollinators indicator	Pollinator populations	-
	Landscape	Percentage of uneven aged forest (age structure)	Share of forests with uneven-aged structure	-
		Forest connectivity	Forest connectivity	-
Heathland and shrubland	Functional	Wild pollinators indicator	Pollinator populations	-
Wetlands	Functional	Imperviousness of the local drainage basin	-	Share of artificial impervious area cover present in coastal area[3]
		Wild pollinators indicator	Pollinator populations	-

[1] The list includes only variables that are common with the proposal of the NRL and/or the proposed legal module on ecosystem accounts

[2] Pollinator populations under the NRL is considered a transversal indicators and all ecosystem types will be monitored

[3] Coastal area includes as ecosystem types coastal beaches, dunes and wetlands

The EU-wide methodology also presents different alternatives to set reference levels for each ecosystem condition variable. The definition of reference levels is considered a challenging task, which requires further testing and discussions. The **setting of reference levels is especially difficult for anthropogenic ecosystems** in which the criteria adopted should guarantee high social-ecological resilience, ensuring a positive feedback between the ecosystem and the socio-economic systems (section 3.3). In this context, the EU-wide methodology also contributes to better define condition of anthropogenic ecosystems, which has a much shorter history in the application of the ecosystem condition concept (section 1.3).

Reference levels for ecosystem condition should be clearly distinguished from thresholds to define good condition, which are ultimately linked to policy targets. Both terms are sometimes used in an interchangeable way. However, to ensure consistency in the assessment, it is strongly recommended to make a clear separation between them (see section 5.4. for further discussion).

Methods applied until now to define reference levels for certain variables are mainly based on prescribed levels and contemporary condition. **Prescribed levels are in general closer to the concept of 'sustainability' thresholds, which are sometimes used as policy targets** (section 5.4). Prescribed levels based on scientific evidence are historically defined for negative variables such as pollutants (i.e. higher values imply a worse condition) as a consequence of the need to take measures targeting the reduction of their environmental impacts. The use of prescribed levels presents important limitations when their definition is based on policy targets. Sometimes, policy targets may be defined to certain extent arbitrarily, without necessarily including robust scientific criteria. For instance, a 50% reduction of current pesticides use has been presented in the proposal on a new Regulation on the Sustainable Use of Plant Protection Products[62]. This target might need to be reviewed in the future, if once this target is achieved, the ecosystem is still degrading as a consequence of the use of plant protection products.

Contemporary condition is also frequently applied. It is very simple to communicate, since it refers to a fix point in time in the last few years. This method is mainly used when there is a lack of knowledge on alternative ways to define more robust reference levels. The frequent use of this method is also due to its relatively straightforward definition, as it does not require the delineation of 'homogeneous ecosystem areas' to define reference levels. However**, it shows important limitations, such as the arbitrary selection of the baseline year**, which may correspond already to a degraded condition far from the optimal situation. As discussed in section 5.4, the use of reference levels based on contemporary condition presents also difficulties for setting and monitoring restoration targets in a consistent way with the SEEA EA.

The **SEEA EA especially recommends the definition of reference levels based on the 'optimal condition'** (section 5.4). This approach has been applied in the EU under the WFD, in which reference levels are defined for the different 'water body types' (i.e. based on the ecoregion, altitude, catchment size and geology). This approach is consistent with the EU-wide methodology, in which different reference levels should be defined by 'homogeneous ecosystem area'.

The EU-wide methodology is meant to be applied at the continental scale; however, **the general framework presented is readily applicable at the MS level**. Actually, variables of the EU-wide methodology will be used as prime input for discussion with national statistical offices of MS, for a voluntary reporting on ecosystem condition beyond the legal reporting requirements of the proposed legal module on ecosystem accounts (amendment of Regulation (EU) No 691/2011 on European environmental economic accounts). Application of the EU-wide methodology at the MS level also allows the integration of more detailed variables/data that are only available at national level. For instance, the 'share of indigenous forest trees' was considered to be included as a relevant variable of forest condition; however, it is only monitored (under the National Forest Inventories) and reported by

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[62] https://ec.europa.eu/food/plants/pesticides/sustainable-use-pesticides_en

few countries, hampering its use at EU level. Other example on the integration of variables at the MS level is the use of monitored data for the reporting on habitat condition of the HD (underpinning data) as discussed above.

The EU-wide methodology provides general recommendations, but **further testing and implementation would be required, at both the EU and country level, to better assess the strengths and limitations of the approach** in practice, based on assessments using real data. The testing would be especially required to delineate robust 'homogeneous ecosystem areas', which will be the base unit to set meaningful reference levels. Importantly, once reference levels are set, they should be reviewed at least every 30 years (period to calculate long-term weather patterns, as defined by the World Meteorological Organization) for a better adaptation to new climatic conditions, but also for the application of new knowledge and data. Currently, at the EU level, there is only an example of application of the SEEA EA framework on forest ecosystems (Maes et al., 2022), but the JRC is currently applying it to urban ecosystems and agroecosystems.

The EU-wide methodology has been presented in this report by ecosystem type and **it currently does not include emergent properties of the interaction among ecosystems**. For instance, overall species richness of a given taxon would be a suitable indicator to assess the condition of the coexistence and interactions of different ecosystem types (aggregation of all ecosystem types). Another example would be landscape diversity or connectivity of the overall landscape (all natural and semi-natural ecosystem types), hampered by the fragmentation generated by artificial areas and other intensive land uses such as agriculture.

The implementation of the EU-wide methodology making use of real data may provide valuable information to identify key condition indicators capturing most of the spatial and temporal variability in ecosystem condition. Importantly, **its implementation will provide the scientific knowledge base to support the definition of new restoration targets, when required by the NRL**. The identification of reference levels and thresholds to define good condition of ecosystems at EU level constitutes a scientific base to support more in-depth discussion. A consensus should be achieved between the scientific outcome of the EU-wide methodology and broader knowledge of MS and relevant stakeholders (i.e. scientific community, NGO's) to better support policy decisions in setting further restoration targets.

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Glossary

Anthropogenic ecosystems: ecosystems predominantly influenced by human activities where a natural ecological state is unobtainable and future socio-economic interventions are required to maintain their state.

Conservation status: means the sum of the influences acting on a natural habitat and its typical species that may affect its long-term natural distribution, structure and functions as well as the long-term survival of its typical species within the territory.

Ecosystem: is 'a dynamic complex of plant, animal and micro-organism communities and their non-living environment interacting as a functional unit' (Convention on Biological Diversity, article 2, entitled 'Use of terms').

Ecosystem accounting area: is the geographical territory for which an ecosystem account is compiled.

Ecosystem assets: are contiguous spaces of a specific ecosystem type characterised by a distinct set of biotic and abiotic components and their interactions.

Ecosystem condition: is the quality of an ecosystem measured in terms of its abiotic and biotic characteristics.

Ecosystem condition indicator: are rescaled versions of ecosystem condition variables using the upper and lower reference levels.

Ecosystem condition variable: are quantitative metrics describing individual characteristics of an ecosystem asset.

Ecosystem condition index (and sub-indices): composite indicator aggregated from the combination of individual ecosystem condition indicators.

Ecosystem integrity: implies an unimpaired condition of being complete or undivided (Karr, 1993). Ecosystem integrity is defined as the ecosystem's capacity to maintain its characteristic composition, structure, functioning and self-organisation over time within a natural range of variability (Pimentel et al., 2000; United Nations, 2021). Ecosystems with high integrity or condition are typically more resilient – able to recover from disturbances or to adapt to environmental changes (Holling, 1973).

Favourable conservation status (of a habitat): when its natural range and areas it covers within that range are stable or increasing, and the specific structure and functions which are necessary for its long-term maintenance exist and are likely to continue to exist for the foreseeable future, and the conservation status of its typical species is favourable.

Good chemical status: is defined in terms of compliance with all the quality standards established for chemical substances at European level.

Good ecological status: it is measured in terms of the quality of the biological community, the hydrological characteristics and the chemical characteristics, according to standards as set under different procedures defined under the water framework directive. No absolute standards apply across the EU, due to the ecological variability.

Good ecosystem condition: ecosystem is in good physical, chemical and biological condition or of a good physical, chemical and biological quality with self-reproduction or self-restoration capability, in which species composition, ecosystem structure and ecological functions are not impaired.

Good environmental status: The environmental status of marine waters where these provide ecologically diverse and dynamic oceans and seas, which are clean, healthy and productive.

Natural ecosystems: ecosystems predominantly influenced by natural ecological processes characterised by an ecological state maintaining ecosystem integrity; ecosystem condition ranges within its natural variability.

Reference condition: is the condition against which past, present and future ecosystem condition is compared to in order to measure relative change over time.

Reference level: is the value of a variable at the reference condition, against which it is meaningful to compare past, present or future measured values of the variable.

Semi-natural ecosystems: an ecosystem with most of its processes and biodiversity intact, though altered by human activity in strength or abundance relative to the natural state.

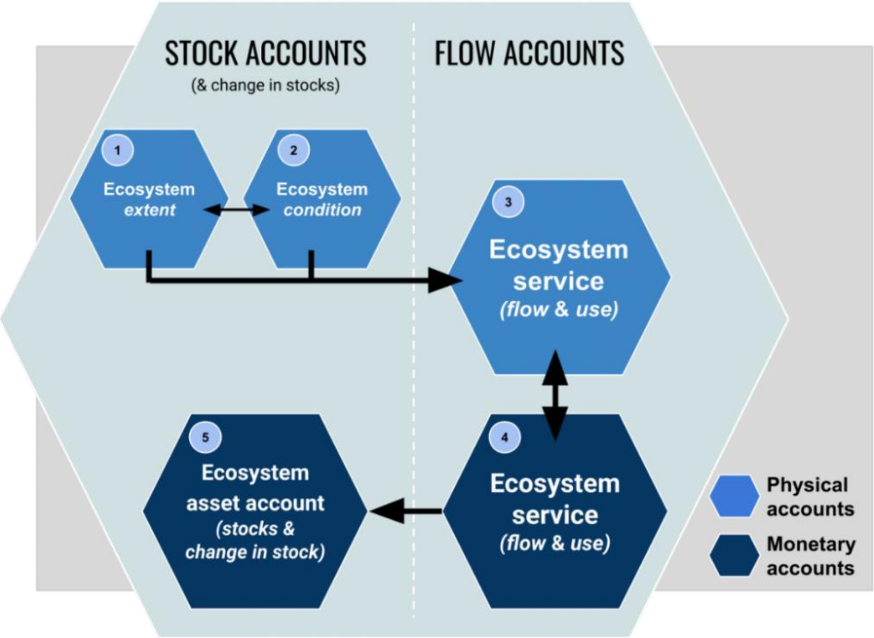
Threshold values: are used to discriminate between unsustainable and sustainable condition, or to identify limits for harming ecosystems, or as target values. Conceptually they are not the same as reference levels, although under certain circumstances they are used indistinctly.

Annexes

Annex 1. Information on the UN System of Environmental-Economic Accounting Ecosystem Accounting (SEEA EA)

The United Nations Statistical Commission adopted the SEEA Ecosystem Accounting at its 52nd session in March 2021. The SEEA EA revision process started in 2018. From the beginning, the EU has been actively involved in the revision. The European Commission has contributed financially and provided scientific and technical support to the UN SEEA. Eurostat chaired the SEEA EA Technical committee, which served as the editorial board for the revision. Experts of the Joint Research Centre and the European Environment Agency have supported the revision of ecosystem condition and ecosystem services accounting. Statisticians and scientific experts from EU countries have contributed to the different working groups and forums, provided case studies, and have reviewed twice the SEEA EA guidance report. As a result, the SEEA EA guidance is built partially on the scientific expertise that has been accumulated under MAES, INCA and the EU's implementation of the nature directives and the water framework directive. The EU also supported the Natural Capital Accounting and Valuation of Ecosystem Services (NCAVES)[63] project Brazil, China, India, Mexico and South Africa.

Figure A.1. The five ecosystem accounts of the SEEA EA.



Source: https://seea.un.org/sites/seea.un.org/files/documents/EA/seea_ea_white_cover_final.pdf

Chapters 1-7 of the SEEA EA guidance are considered as international statistical standard, including chapter 3 (Spatial units for ecosystem accounting), chapter 4 (Accounting for ecosystem extent) and **chapter 5 (Accounting for ecosystem condition)**. This means that UN member states have agreed to use the same set of procedures to account for ecosystem extent and condition. Chapters 8-11 describe internationally recognised statistical principles and recommendations.

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[63] https://seea.un.org/home/Natural-Capital-Accounting-Project

Annex 2. Crosswalk table of the ecosystem classes of the EU-wide methodology, CORINE Land Cover, MAES typology and the ecosystem types of the proposed legal module on ecosystem accounts

EU-wide methodology		CORINE Land Cover (level 3)	Maes typology	Types of the module on ecosystem accounts
Settlements and other artificial areas		Continuous urban fabric	Settlements and other artificial areas	Settlements and other artificial areas
		Discontinuous urban fabric		
		Industrial or commercial units		
		Road and rail networks and associated land		
		Port areas		
		Airports		
		Mineral extraction sites		
		Dump sites		
		Construction sites		
		Green urban areas		
		Sport and leisure facilities		
Agroecosystems		Non-irrigated arable land	Cropland	Cropland
		Permanently irrigated land		
		Rice fields		
		Vineyards		
		Fruit trees and berry plantations		
		Olive groves		
		Annual crops associated with permanent crops		
		Complex cultivation patterns		
		Land principally occupied by agriculture, with significant areas of natural vegetation		
		Agro-forestry areas		
		Pastures	Pasture	Grassland
		Natural grasslands		
Forest ecosystems		Broad-leaved forest	Forest and woodlands	Forest and woodland
		Coniferous forest		
		Mixed forest		
		Transitional woodland-shrub		
Heathland and shrubland, and sparsely vegetated land		Moors and heathland	Heathland and shrub	Heathland and shrub
		Sclerophyllous vegetation		
		Beaches, dunes, sands	Sparsely vegetated land	Sparsely vegetated ecosystems*
		Bare rocks		
		Sparsely vegetated areas		
		Burnt areas		
		Glaciers and perpetual snow		
Wetlands	Inland wetlands	Inland marshes	Inland wetlands	Inland wetlands
		Peat bogs		
	Coastal wetlands	Salt marshes	Marine inlets and transitional waters	Marine inlets and transitional waters*
		Salines		
		Intertidal flats		
		Coastal lagoons		
		Estuaries		
Rivers and lakes		Water courses	Rivers and lakes	Rivers and canals
		Water bodies		Lakes and reservoirs
Marine		Sea and ocean	Marine	Marine ecosystems

*Coastal beaches, dunes and wetlands are considered as a separate ecosystem type under the proposed legal module on ecosystem accounts

Annex 3. Methods for estimating the reference condition and reference levels

Methods for estimating the reference condition and reference levels for ecosystem condition variables under the SEEA EA (further details in United Nations (2021) page 116):

1. Reference sites: If pristine or minimally-disturbed sites are available, they can be used to determine a reliable measure of the mean and statistical distribution of condition variables. Reference sites can be identified using expert or traditional knowledge but also by using statistics and artificial intelligence if long-term time series with data describing ecosystem disturbance are available.

2. Modelled reference conditions can be based on predictive empirical models or potential vegetation models. Models can be used to infer conditions in absence of human disturbance where representative reference sites are not available. Potential vegetation can be modelled globally and can incorporate scenarios of environmental change.

3. Statistical approaches based on ambient distributions. Least-disturbed conditions or best-attainable conditions can be estimated by observing the range of values from current ecosystem monitoring and by selecting a reference condition, for instance based on the 5th percentile values as criterion or by assuming that the reference condition is equal to a state with the highest species richness.

4. Historical observations and paleo-environmental data. This method uses historical observations or paleontological data to describe a historical reference condition (typically before 1970 when routine environmental monitoring programmes started).

5. Contemporary data (condition). This method uses contemporary data to describe a contemporary reference condition (typically after 1970 when routine environmental monitoring programmes started).

6. Prescribed levels of a set of ecosystem condition variables can be used to construct a bottom-up reference condition. Examples of these reference levels include zero values for emissions or pollutants, a specific number of species, established sustainability or threshold levels such as critical loads for eutrophication and acidification, and target levels in terms of legislated quality measures (air and water quality). Scientific evidence would be therefore considered as specific case of prescribed level.

7. Expert opinion usually consists of a narrative statement of expected reference condition. Although an expert's opinion may be expressed semi-quantitatively, qualitative articulation is probably most common.

8. Combination of any of the above methods. Many of the above approaches may be used either singly or in concert for establishing and/or cross-validating reference condition.

According to the SEEA EA, Methods 1-4 represent approaches that should be considered first to describe and quantify the reference condition, and in particular for establishing the values for upper and lower reference levels of ecosystem condition variables. Methods 5-7 can be considered as alternatives if methods 1-4 cannot be applied, or when policy or legislative drivers dictate methods 5 or 6 may be used. Method 7 may be particularly relevant in capturing indigenous knowledge and perspectives. Method 8 involves a combination of methods.

Annex 4. Wetlands classification under the EU-wide methodology and mapping of different wetland habitats

Wetland coverage under the EU-wide methodology				CORINE Land Cover (Level 3)	Ecological definition	Mapping approximation (mapped wetland habitats)
Thematic approach (Ramsar definition)	**General approach**: no overlap with other ecosystem types	Inland wetlands		Peatbogs	Wetlands with accumulation of considerable amount of decomposed moss (mostly Sphagnum) and vegetation matter. Both natural and exploited peat bogs	CLC 4.1.2
				Inland marshes	Low-lying land usually flooded in winter, and with ground more or less saturated by fresh water all year round	CLC 4.1.1
		Coastal wetlands		Salt marshes	Intertidal marshes; includes salt marshes, salt meadows, saltings, raised salt marshes; includes tidal brackish and freshwater marshes.	CLC 4.2.1
				Salines	Salt exploitation sites; salt pans, salines, etc	CLC 4.2.2
				Intertidal flats	Coastal zone under tidal influence between open sea and land, which is flooded by sea water regularly twice a day in a ca. 12 hours cycle.	CLC 4.2.3
				Coastal lagoons	Stretches of salt or brackish water in coastal areas which are separated from the sea by a tongue of land or other similar topography	CLC 5.2.1
				Estuaries	Estuarine waters; permanent water of estuaries and estuarine systems of deltas.	CLC 5.2.2
	Overlapping ecosystems (only in the thematic assessment)	Other wetlands	Agroecosystems	Wet grassland/pasture	Seasonally or permanently wet grassland (including intensively managed/grazed wet meadow/pasture and natural grassland)	Combination of CLC classes 2.3.1 and 3.2.1 with information on wet/moist areas from JRC GSWE and Copernicus WaW
				Rice fields	Irrigated land; includes irrigation channels and rice fields.	CLC 2.1.3 'Rice fields'; it doesn´t cover irrigation channels
			Forest	Riparian, fluvial and swamp forest	Freshwater, tree-dominated wetlands; forested peatlands; peatwamp forests	Combination of CLC 3.1 'Forest' with information on wet/moist/riparian areas from JRC GSWE and Copernicus WaW and RZL products
			Heathland and shrubland	Wet heaths	Wet or humid ericoid-shrub dominated heaths of the Atlantic and sub-Atlantic zones, developed on peaty or semipeaty soils, waterlogged for at least	Combination of CLC classes 3.2.2 'Moors and heathland' with information on

Wetland coverage under the EU-wide methodology		CORINE Land Cover (Level 3)	Ecological definition	Mapping approximation (mapped wetland habitats)
			part of the year, sometimes temporarily inundated, and usually moist even in summer	wet/moist areas from JRC GSWE and Copernicus WaW
		Riverine and fen scrubs	Riversides, lakesides, fens and marshy floodplains dominated by woody vegetation less than 5 m high	Ecosystem Type Map v3.1, class F9
	Sparsely vegetated areas	Beaches, dunes and sand	Sand, shingle or pebble shores; includes sand bars, spits and sandy islets; includes dune systems and humid dune slacks	CLC 3.3.1 ‘Beaches, dunes, and sand plains’. It includes inland habitats
	Freshwater	Rivers and lakes	Lakes, ponds and pools of natural and artificial origin and running waters made of all rivers and streams	CLC 5.1.1 ‘Water courses’ and 5.1.2 ‘Water bodies’
	Marine	Marine waters < 6m deep	Permanent shallow marine waters in most cases less than six meters deep at low tide; includes sea bays and strait	Bathymetry layer < 6m

Annex 5. Crosswalk table between the MSFD habitat classification, EUNIS (v2016) and the SEEA EA Ecosystem Condition Typology

SEEA EA	MSFD	EUNISv2016
M1 Marine shelfs	Littoral rock and biogenic reef	MA1-2
	Littoral sediment	MA3-6
	Infralitoral rock and biogenic reef	MB1-2
	Infralitoral coarse sediment	MB3
	Infralitoral mixed sediment	MB4
	Infralitoral sand	MB5
	Infralitoral mud	MB6
	Circalitoral rock and biogenic reef	MC1-2
	Circalitoral coarse sediment	MC3
	Circalittoral mixed sediment	MC4
	Circalittoral sand	MC5
	Circalittoral mud	MC6
M2 Pelagic ocean waters	Offshore circalitoral rock and biogenic reef	MD1-2
	Offshore circalittoral coarse sediment	MD3
	Offshore circalittoral mixed sediment	MD4
	Offshore circalitoral sand	MD5
	Offshore circalitoral mud	MD6
M3 Deep sea floors	Upper bathyal rock and biogenic reef	ME1-2
	Upper bathyal sediment	ME3-6
	Lower bathyal rock and biogenic reef	MF1-2
	Lower bathyal sediment	MF3-6
	Abyssal	MG1-6
M4 Anthropogenic marine systems	Not available	

Frequently asked questions (FAQ)

1. What is the purpose of the EU-wide methodology?

The EU-wide methodology provides a general, but robust and transparent, framework to map and assess ecosystem condition consistently across all ecosystem types. In a next step, the implementation of the EU-wide methodology (i.e. common method) will provide the scientific knowledge base to support the definition of new restoration targets, when required by the NRL.

2. What is the basis of the EU-wide methodology?

The EU-wide methodology follows the System of Environmental Economic Accounting - Ecosystem Accounting (SEEA EA) as reference framework. The SEEA EA is an international statistical standard developed by the UN for organizing biophysical information about the condition of any ecosystem type and providing also methods to determine reference levels to consistently assess ecosystem condition, based on a selection of biotic and abiotic indicators.

3. What is the added value of the EU-wide methodology?

- the EU-wide methodology ensures consistency in the assessment of ecosystem condition across all ecosystem types, all scales and all policy domains
- offers a transparent framework to make use of available data/information, and is also flexible to include new indicators when available or required
- when selected condition indicators can be mapped, it is possible to quantify the ecosystem area that is in good condition (or degraded)
- allows for consistency and integration of reported data relevant for ecosystem condition derived from other policy initiatives (e.g. Nature Restoration Law, EU Forest Strategy 2021, EU Soil Strategy, Common Agricultural Policy 2021, proposal of a legal module on ecosystem accounts)

4. What is the coverage of the EU-wide methodology?

The whole EU land and seascape, covering the entire land and seascape with no overlap or gap. The methodology is also applicable to the outermost regions if data are available. The ecosystems included are:

1. Urban areas
2. Agroecosystems (cropland and grassland)
3. Forest
4. Heathland and shrubland, and sparsely vegetated land
5. Wetlands (inland and coastal)
6. [Freshwater ecosystems (rivers and lakes)]
7. [Marine ecosystems]

Since freshwater and marine ecosystems are fully covered by the WFD and MSFD, respectively, it is considered that the status reported under these Directives is equivalent to the concept on ecosystem condition. A case study is presented for marine ecosystems illustrating to what extent the underpinning data of the assessment of environmental status can be integrated into the SEEA EA. This case study shows how the EU-wide methodology includes relevant variables, complementary to those used under the MSFD. This provides a condition assessment of marine ecosystems in alignment with the SEEA EA beyond the status assessment required by law.

5. What is the spatial scale used in the EU-wide methodology?

Mapping and assessment of ecosystem condition is making use of the best available EU data streams that are available at multiple spatial scales (from site level measurements, to remote sensing and modelled data at landscape level). A need for different types of measurements of ecosystem condition was recognised in the SEEA EEA Technical Recommendations (United Nations, 2017), where both top-down and bottom-up approaches are suggested for measurements across different scales.

6. Is the EU-wide methodology aligned with environmental legislation?

a) The **WFD and MSFD** apply a methodological framework that is broadly consistent with the condition assessment under SEEA EA: 1) Define homogeneous ecosystem areas, 2) Monitor biotic and abiotic parameters of ecosystems, 3) Define reference levels, 4) Aggregate indicators and determine ecosystem status. Therefore, it is assumed that the status reported under these Directives is equivalent to the concept of condition. Still, condition assessment can optionally also include other indicators not defined by law, which contribute to provide a more comprehensive assessment of ecosystem condition (further refinement). See also question 4.

b) The **HD** follows another logic, since condition is related to the ‘structure and functions’ parameters, which is only one of the parameters to assess habitat conservation status. These parameters rely on data collected at the level of MS, which is then reported to the EU in an aggregated form. At the EU level, there is a lack of knowledge on which parameters are monitored and used to assess the 'structure and functions' parameters in the MS, which makes it very difficult to compare and integrate both approaches. The EU-wide methodology presents a case study for Greece, illustrating how the integration of monitored data under the HD into the SEEA EA can take place.

In the short-term, and to avoid and possible conflict between approaches, the EU-wide methodology can potentially be applied to only those ecosystems not covered under Annex I habitats. However, this would result in non-comparable assessments of ecosystem condition between Annex I and non-Annex I habitats, leading to possible inconsistencies.

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