D3.2 Deriving a minimum set of key ecosystem condition indicators per ecosystem type

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1. Preface

The importance of biodiversity, natural capital and healthy ecosystems and the services they supply has increasingly been acknowledged in diverse policy initiatives (e.g., the EU nature restoration and amending Regulation from 2024, EU Biodiversity Strategies 2020 and 2030, Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES), UN's Natural Capital and Ecosystem Services Accounting (SEEA-EA), Intergovernmental Panel on Climate Change (IPCC) and Convention on Biological Diversity (CBD)).

The EU Horizon Research and Innovation Action "Science for Evidence-based and sustainabLe decIsions about NAtural capital" (SELINA) aims to provide robust information and guidance that can be harnessed by different stakeholder groups to support transformative change in the EU, to halt biodiversity decline, to support ecosystem restoration and to secure the sustainable supply and use of essential Ecosystem Services (ES) in the EU by 2030.

SELINA builds upon the Mapping and Assessment of Ecosystems and their Services (MAES) initiative that has provided the conceptual, methodological, data and knowledge base for comprehensive assessments on different spatial scales, including the EU-wide assessment (Maes et al. 2020a) and assessments in EU member states. Knowledge and data for different ecosystem types are increasingly available.

The overall objective of Work Package (WP)3 "Ecosystem type, biodiversity & condition mapping and assessment" is to:

- Develop and evaluate methodologies to map and assess the condition of terrestrial and aquatic ecosystems to assist the EU in implementing the System of Environmental Economic - Ecosystem Accounting (SEEA-EA), defining legally binding restoration targets in the EU Biodiversity Strategy (BDS) and integrating the Ecosystem Condition (EC) in public and private decision-making processes.
- Advance the sustainability of the EU economy and human well-being through the definition of minimum requirements for ecosystems to reach or maintain high ecological integrity and good EC.

Deliverable D3.2 "Derive a minimum set of key ecosystem condition indicators per ecosystem type" presents details on the development of the minimum set of spatially explicit EC indicators, drawing on a comprehensive review of all available data sources and an in-depth survey of Ecosystem Type (ET) experts involved in WP3.

2. Summary

Work Package 3 of SELINA aims to develop and test a methodology for mapping and assessing the condition of terrestrial and aquatic ecosystems. Task 3.2 'Derive a minimum set of key ecosystem condition indicators per ecosystem type' focuses on reviewing the available approaches for developing spatially explicit Ecosystem Condition (EC) indicators, with the aim of providing a proposal for minimum, operationalizable EC indicators. Deliverable D3.2 presents several activities carried out in this pursuit within the task.

First, we present the results of a literature review focused on applications of spatially explicit EC indicators in recent published work, with the objective of identifying indicators that are operationalizable and repeatable across multiple contexts, serving as potential candidates for the selection of minimum indicator sets. In our review, we found biases in the types of ecosystem characteristics covered by indicators, and we identified gaps in research on underrepresented ecosystem types. While the data sources used to develop metrics vary by ecosystem, remote sensing emerged as a predominant tool for producing spatially explicit and continuous indicators. This reflects both its accessibility and its potential for standardized monitoring. Our findings underscore the essential role of spatially explicit data in assessing ecosystem condition, yet also highlight persistent challenges in capturing complex ecosystem attributes comprehensively.

Secondly, we advance the SEEA-EA Ecosystem Condition Typology (ECT) framework by developing an approach to separate ecosystem condition and pressure indicators. The MAES framework, which provides an essential foundational guidance for ecosystem assessment, distinguishes between pressure indicators as "measured in units per unit time" (flows) and condition indicators as "point in time measurements" (stocks). However, our approach advocates for a different classification criterion based on causality and origin rather than temporal characteristics. Human impact variables are often measured as static amounts but create ongoing pressure, while natural flow measurements capture rates of change but actually reflect the ecosystem's fundamental state. Under our approach, which builds on the existing SEEA-EA framework, the Ecosystem Condition Index exclusively comprises variables that characterize ecosystem attributes and internal processes, while the Ecosystem Pressure Index encompasses variables of anthropogenic origin acting as external drivers of change. This adjustment addresses the conceptual ambiguity that can arise when anthropogenic pressure variables are classified as condition indicators under the MAES framework. While maintaining full compatibility with MAES data collection methodologies and acknowledging the framework's pragmatic flexibility and stakeholder-oriented design as indispensable contributions, our refinement provides enhanced conceptual rigor for distinguishing between condition and pressure indicators.

Drawing on the results of the literature for examples of commonly-used metrics, the framework proposed was populated to produce longlists of potential indicators. The relative strengths and weaknesses of these indicators were evaluated in consultation with expert groups representing the ecosystem types targeted by WP3 (Agroecosystems, Forests, Urban, Wetlands, Heath and shrublands, Grasslands, Rivers and Lakes, and Marine and coastal). Continued refinement with the expert groups **enabled the development of a minimum set of**

indicators, for both condition and pressure per ecosystem type. We provide discussion on the suitability and limitations of these indicators for representing ecosystem condition and pressure.

Finally, we show the possibilities offered by the use of spatially explicit data at European level by creating a dedicated ecosystem pressure index, the **Human Pressure Index** (HPI) (see Chapter 6). Our proposition entails developing an index that exclusively measures anthropogenic drivers affecting ecosystems, using a minimum set of indicators. This index could advance our ability to quantify and visualize the potential impact of human activities on terrestrial ecosystems and will allow understanding of the complex interactions between human activities and ecosystem condition.

3. List of abbreviations

AC	Abiotic Characteristics
AOT40	Accumulated Ozone exposure over a Threshold of 40 ppb
BC	Biotic Characteristics
BD	Bird Directive
BDS	EU Biodiversity Strategy
DPSIR	Driver-Pressure-State-Impact-Response (framework)
CAP	Common Agricultural Policy
CBD	Convention on Biological Diversity
CIA	Cumulative Impact Assessment
CLC	CORINE Land Cover
EASIN	European Alien Species Information Network
EBBA	European Breeding Bird Atlas
EBVs	Essential Biodiversity Variables
EC	Ecosystem Condition
ECT	Ecosystem Condition Typology
EEA	European Environment Agency
EFI	European Forest Institute
EFT	Ecosystem Functional Type
EIA	Environmental Impact Assessment
EMEP	European Monitoring and Evaluation Programme
EMODnet	European Marine Observation and Data Network
EQS	Environmental Quality Standards

EO	Earth Observation
ESA	European Space Agency
ES	Ecosystem Services
ESDAC	European Soil Data Centre
ET	Ecosystem Type
EU	European Union
EVI	Enhanced Vegetation Index
FAO	Food and Agriculture Organization
GEE	Google Earth Engine
GFCM	General Fisheries Commission for the Mediterranean
HD	Habitat Directive
HANPP	Human Appropriation of Net Primary Production
HELCOM	Helsinki Commission (Baltic Marine Environment Protection Commission)
HPI	Human Pressure Index
IAS	Invasive Alien Species
ICCAT	International Commission for the Conservation of Atlantic Tunas
ICES	International Council for the Exploration of the Sea
IPBES	Intergovernmental Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature
JRC	Joint Research Centre
LC	Landscape Characteristics
LST	Land Surface Temperature
LiDAR	Light Detection and Ranging

LST	Land Surface Temperature
LULC	Land Use/Land Cover
MSFD	Marine Strategy Framework Directive
MAES	Mapping and Assessment of Ecosystems and their Services
MS	Member State
NDBSI	Normalised Difference Bare Soil Index
NDII	Normalized Difference Infrared Index
NDMI	Normalised Difference Moisture Index
NDVI	Normalised Difference Vegetation Index
NPP	Net Primary Productivity
MedQSR	Mediterranean Quality Status Report
OECD	Organisation for Economic Co-operation and Development
PM	Particulate Matter
PRISMA	Preferred Reporting Items for Systematic reviews and Meta-Analyses
PSR	Pressure-State-Response (framework)
RSEI	Remote Sensing Ecological Index
SAR	Synthetic Aperture Radar
SEEA	System of Environmental Economic Accounting
SEEA-EA	System of Environmental Economic Accounting - Ecosystem Accounting
SEA	Strategic Environmental Assessment
SDGSAT-1	Sustainable Development Goals Satellite-1
SOC	Soil Organic Carbon
SSB	Spawning stock biomass
SWO	Surface Water Occurrence

UN	United Nations
UNCLOS	United Nations Convention on the Law Of the Sea
WEI+	Water Exploitation Index plus
WFD	Water Framework Directive
WISE	Water Information System for Europe
SWI	Soil Wetness Index
WWF	World Wildlife Fund
WWPI	Water and Wetness Probability Index

4. Key definitions

Ancillary data: Measurements of ecosystem characteristics that do not meet the criteria for inclusion as ecosystem condition variables or indicators, and therefore are not recommended for use in condition accounts. However, these data can support ecosystem asset delineation and ecosystem service flow modelling. (based on Keith et al., 2020).
Anthropogenic ecosystems: Ecosystems influenced predominantly by human activities where a stable natural ecological state is unobtainable and future socioeconomic interventions are required to maintain a new stable state (SEEA-EA glossary).
Ecosystem accounting: Organizing biophysical information about ecosystems, measuring ecosystem services, tracking changes in ecosystem extent and condition, valuing ecosystem services and assets and linking this information to measures of economic and human activity (SEEA-EA 1.2).
Ecosystem assets: Contiguous spaces of a specific ecosystem type characterized by a distinct set of biotic and abiotic components and their interactions (SEEA-EA glossary).
Ecosystem characteristics: System properties of an ecosystem and its major abiotic and biotic components (water, soil, topography, vegetation, biomass, habitat and species), with examples of those characteristics including vegetation type, water quality and soil type (SEEA-EA glossary).
Ecosystem condition: Quality of an ecosystem measured in terms of its abiotic and biotic characteristics (SEEA-EA glossary).
Ecosystem degradation: Decrease in the value of an ecosystem asset over an accounting period that is associated with a decline in the condition of an ecosystem asset during that

accounting period (SEEA-EA glossary).
Ecosystem function: Flow of energy and materials through the biotic and abiotic components of an ecosystem. It includes many processes such as biomass production, trophic transfer through plants and animals, nutrient cycling, water dynamics and heat transfer (IPBES glossary). Ecosystem function underpins the capacity of an ecosystem to deliver ecosystem services (Haines-Young and Potschin, 2010).
Ecosystem health: Status and potential of an ecosystem to maintain its organizational structure, vigor of function, and resilience under stress, and to continuously provide quality ecosystem services for present and future generations (based on Lu et al, 2015).
Ecosystem integrity: Ecosystem's capacity to maintain its characteristic composition, structure, functioning and self-organization over time within a natural range of variability (Pimentel and Edwards, 2000).
Ecosystem pressure: Cumulative effect of external stressors of anthropogenic origin, including artificial features or substances, that affect, or risk altering, an ecosystem's structure, processes, or composition beyond its natural range of variability
Ecosystem quality: Condition of an ecosystem relative to a reference state. The reference state can be a past, present, or potential future situation/condition of an ecosystem (Wood et al., 2018).
Ecosystem resilience: Capacity of an ecosystem to absorb disturbances or stress without undergoing a fundamental shift in structure, function, or identity, and to recover its essential characteristics and processes after a disturbance (MEA, 2005).
Ecosystem services: Contributions of ecosystems to the benefits that are used in economic and other human activity (SEEA-EA glossary).
Indicators: Ecosystem condition indicators are rescaled versions of ecosystem condition variables (SEEA EA Glossary).
Natural characteristics: Ecological characteristics and processes, whether occurring spontaneously or supported within human-modified systems, that sustain the structure, composition, and functioning of an ecosystem within its current environmental and land-use context.
Natural ecosystems: Ecosystems influenced predominantly by natural ecological processes characterized by a stable ecological state maintaining ecosystem integrity; ecosystem condition ranges within its natural variability (SEEA-EA glossary).
Reference condition: Condition against which past, present and future ecosystem condition is compared in order to measure relative change over time (SEEA-EA glossary).
Reference level: Value of a variable at the reference condition, against which it is meaningful to compare past, present or future measured values of the variable (SEEA-EA glossary).

Semi-natural ecosystem: Ecosystem with most of its processes and biodiversity intact, though altered by human activity in strength or abundance relative to the natural state (IPBES glossary).
Variable: Ecosystem condition variables are quantitative metrics describing individual characteristics of an ecosystem asset (SEEA EA Glossary).

5. Introduction

Why a minimum set?

A minimum set of ecosystem condition indicators represents a pragmatic compromise between scientific comprehensiveness and operational feasibility, designed to capture essential ecosystem characteristics while remaining implementable across diverse contexts with existing resources and data infrastructure. In our work, we imposed an additional constraint by focusing exclusively on variables currently available in spatially explicit formats with coverage across Europe, further distinguishing our minimum set from theoretical optimum approaches. This core set prioritizes indicators that are applicable, readily measurable with current technologies, and sufficiently sensitive to detect major changes in ecosystem condition, accepting that some ecologically important but data-poor, locally measured, or methodologically complex parameters must be excluded.

In contrast, a comprehensive set of indicators would provide coverage of all relevant ecosystem characteristics, incorporating specialized metrics for specific ecosystem subtypes, high-resolution temporal and spatial data, field-based measurements, and emerging indicators that may currently lack standardized protocols, spatial coverage, or widespread monitoring capacity. While a minimum set necessarily involves trade-offs, potentially missing subtle ecosystem degradation signals or locally important ecosystem features, it ensures consistent, comparable assessments across large scales and diverse management contexts through harmonized spatial datasets. The initial implementation focuses on establishing a robust baseline of core indicators derived from existing European-wide spatial data infrastructure.

It is important to note that a minimum set of indicators may, depending on the context, not represent the 'optimal' set. Indeed, the purpose of the ecosystem condition assessment may call for a set of indicators tailored to specific ecosystem sub-types or a local policy context , which may better reflect the full complexity of ecological processes and interactions. Developing such nuanced approaches would however require further research, stakeholder input, and improved data availability over time.

5.1. Introduction to SEEA-EA and Its Conceptual Foundation

The System of Environmental Economic Accounting - Ecosystem Accounting (SEEA-EA), complementary to the SEEA Central Framework, is a comprehensive spatially explicit framework developed by the United Nations to integrate environmental and economic data (UN et al., 2024). It was adopted by the United Nations Statistical Commission in March 2021, as an international statistical standard for ecosystem accounting and is intended to align with the concepts and principles of national accounting (System of National Accounts). The SEEA-EA aims to provide a standardized approach for organizing biophysical information on ecosystems and measuring the contributions of ecosystems to the economy and human well-being (i.e., Ecosystem Services (ES)). The SEEA-EA consists of five key inter-linked accounts: (1) ecosystem extent (i.e., spatial distribution and extent), (2) ecosystem condition (EC) (i.e., quality or health assessment), (3) biophysical ecosystem services accounts (i.e., flow and use), as well as (4) monetary ecosystem services and (5) asset accounts (Fig. 1). The SEEA-EA uses a spatial dimension in its accounting method, recognizing that the benefits received from ecosystems rely on their location and their dimensions in the landscape relative to the beneficiaries. Environmental accounts are intended to be regularly updated to create consistent and comparable time series data on both the biophysical and monetary aspects of ecosystem assets.

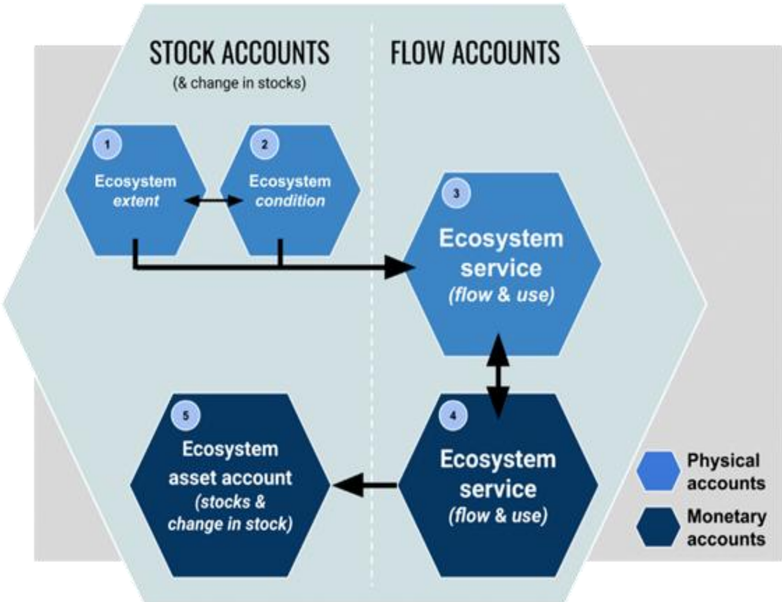


Figure 1: Ecosystem accounts of the SEEA-EA and their interconnections (UN et al., 2021).

The SEEA-EA supports a comprehensive set of strategic objectives designed to enhance evidence-based policymaking, cross-country comparability, and long-term sustainability planning. These objectives include:

- **Harmonized measurement and reporting**
  Establish standardized methodologies for compiling and disseminating environmental-economic data, ensuring consistency and comparability across countries and regions.
- **Integrated decision-making**
  Enable the incorporation of environmental information into national accounts and economic planning processes, fostering policy coherence between economic development and environmental conservation objectives.
- **Policy monitoring and evaluation**
  Provide a statistical foundation for assessing the effectiveness of environmental policies and programs, facilitating time-series analyses and long-term monitoring of ecosystem conditions.
- **Alignment with international frameworks**
  Support the implementation of global and regional environmental commitments, including the Sustainable Development Goals (UN DESA, 2020), the Kunming-Montreal Global Biodiversity Framework (CBD, 2022), and European Union initiatives such as the Biodiversity Strategy for 2030 (European Commission, 2020), the Soil Strategy for 2050

(European Commission, 2021), and the Nature Restoration and Amending Regulation (European Union, 2024).

- **Capacity building and institutional strengthening** Promote training, knowledge transfer, and resource allocation to build technical and institutional capacity for the effective adoption and maintenance of SEEA-EA practices.

5.2. The SEEA-EA Ecosystem Condition assessment

The EC account, a central component of the SEEA-EA, evaluates the health, quality, and overall status of ecosystems. EC is defined in the SEEA-EA *as "**the quality of an ecosystem measured in terms of its abiotic and biotic characteristics.** Condition is assessed with respect to an ecosystem's composition, structure and function, which, in turn, underpin the ecosystem integrity of the ecosystem, and support its capacity to supply ecosystem services on an ongoing basis. Measures of ecosystem condition may reflect multiple values and may be undertaken across a range of temporal and spatial scales*" (UN et al., 2024). This assessment provides a comprehensive understanding of the current condition-state of ecosystems, which is essential for managing and conserving them effectively. The notion of EC plays a vital role in the requirements outlined in the EU Habitats Directive, the Marine Strategy Framework Directive (MSFD), the Water Framework Directive (WFD) and the Birds Directive, which require Member States to evaluate the conservation status of habitats and species on a regular basis. Moreover, besides providing policymakers with the information needed to allow informed decisions, EC assessment may also help identifying potential threats to ecosystem health and function, allowing for early intervention and prevention.

Czúcz et al. (2021a) proposed a hierarchical ecosystem condition typology (ECT) for organizing data on condition characteristics, containing three major groups (abiotic, biotic and landscape-level characteristics) and six classes nested within these groups (Table 1). The ECT was designed to be universal and each characteristic is described by different metrics (i.e., variables and indicators). These characteristics and metrics should be selected according to specific criteria (Czúcz et al., 2021b) (see section 6.3) and the selection of metrics should generally focus on those that play a role in ecosystem processes, contributing to overall ecosystem functioning, and considering their risk of change (Mace, 2019). It is worth noting that the SEEA-EA typology is flexible enough to host pressure indicators when no suitable state variables are available (see sections 5.3 and 6.2 for pressure accounting detail) and the relationship between pressure and state variables is well understood.

Table 1: SEEA-EA Ecosystem Condition Typology for ecosystem accounting with examples of variables that can be used (sources: UN et al., 2024).

Group	Class	Description
A: Abiotic ecosystem characteristics	A1: Physical state characteristics	Physical descriptors of the abiotic components of the ecosystem(e.g. soil structure, water availability)
	A2: Chemical state characteristics	Chemical composition of abiotic ecosystem compartments (e.g. soil nutrient levels, water

Group	Class	Description
		quality, air pollutant concentrations)
B: Biotic ecosystem characteristics	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)
	B2. Structural state characteristics	Aggregate properties (e.g. mass, density) of the whole ecosystem or its main biotic components (e.g. total biomass, canopy coverage, chlorophyll content, annual maximum NDVI)
	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)
C: Landscape level characteristics	C1: Landscape and seascape characteristics	Metrics describing mosaics of ecosystem types at coarse (landscape, seascape) spatial scales (e.g. landscape diversity, connectivity, fragmentation)

In the SEEA-EA framework, defining a reference level is essential for assessing ecosystem condition. It provides a benchmark against which current ecosystem states can be compared, helping to determine whether an ecosystem is degraded, stable, or improving. The reference level may reflect a natural or historical state, a minimally disturbed condition, or a scientifically informed typical state, depending on the context and purpose of the assessment (see D3.3 "Definition of reference conditions that describe good ecosystem condition" for more information). Importantly, reference levels differ from policy targets. While reference levels serve as neutral, science-based baselines to measure change, policy targets are normative goals set by governments or institutions to define desired future conditions. These targets may align with, exceed, or fall short of reference levels, depending on what is deemed socially, economically, or politically feasible. By comparing current conditions to a reference level, analysts can objectively evaluate ecosystem trends, inform policy design, and clearly communicate the state of ecosystems to decision-makers and the public.

Additionally, EC is closely linked to the ability of ecosystems to perform essential functions, i.e., natural processes such as nutrient cycling, primary production (e.g., photosynthesis) and decomposition. These functions underpin the overall health and resilience of ecosystems and occur independently of human needs, maintaining the internal dynamics of nature. In contrast, ecosystem services are the benefits that humans derive from these functions, such as clean water, fertile soils, and crop pollination. While ecosystem functions describe how ecosystems operate internally, ESs translate these operations into contributions to human well-being. Thus, changes in ecosystem condition can have significant implications for the provision of ES. In situations where direct measurements of ecosystem services are limited or costly, indicators based on ecosystem condition and function can serve as effective proxies for estimating service supply. For instance, Hein et al. (2016) highlighted how condition indicators like standing biomass and net primary production (NPP), which reflect core ecosystem functions, can be used to estimate an ecosystem's capacity to sustainably provide services such as carbon sequestration or timber harvesting. Similarly, Andersson et al. (2021) demonstrated how the condition and spatial arrangement of green-blue infrastructure (GBI) in cities (e.g., parks, trees or wetland) can proxy for regulating and cultural services like local temperature regulation, recreational opportunities, and stormwater management. These examples demonstrate that understanding and tracking ecosystem functions through condition indicators is not only ecologically meaningful but also practically useful for informing policy and planning decisions around ecosystem service management.

5.3. The Condition-Pressure Dilemma: Toward Separate Assessment Frameworks

We propose here that separating ecosystem condition and pressure indicators represent a necessary development from the current SEEA-EA approach, which permits integration of pressure metrics within the Ecosystem Condition Typology when condition variables are unavailable. This integration, while pragmatic, creates conceptual ambiguity by classifying anthropogenic stressors as aspects of ecosystem condition, thereby confusing external drivers with intrinsic ecosystem properties. Such classification obscures the causal relationships between human activities and ecological outcomes, potentially misdirecting policy interventions.

It is worth noting that, in the SEEA-EA glossary, the term “variable” refers to a *quantitative metrics describing individual characteristics of an ecosystem asset* while “indicator” refers to a *rescaled version of ecosystem condition variable* in comparison to a reference level. In this Deliverable, we apply the term “indicator” broadly to include both rescaled and non-rescaled variables, recognising that selecting condition indicators and defining reference levels are often treated as distinct steps.

The distinction between ecosystem condition (state) and pressure indicators has been subject to ongoing scientific debate. The MAES (Mapping and Assessment of Ecosystems and their Services) framework (Maes et al., 2018) has adopted a pragmatic approach where pressure indicators are "measured in units per unit time" while environmental quality indicators use "point in time measurements" (i.e., stock). However, this temporal distinction alone proves insufficient for certain indicators. For example, accumulated pollutants or impervious surfaces still represent anthropogenic pressures despite being measured as stocks. Our framework therefore shifts from a primarily temporal classification to one based on causality and origin, where anthropogenic influences are consistently classified as pressures regardless of their measurement type. This adjustment addresses the conceptual ambiguity that arises when external stressors are integrated within ecosystem condition assessments.

By establishing a distinction between Ecosystem Condition and Ecosystem Pressure, we develop a framework that maintains conceptual integrity, in which ecosystem condition exclusively reflects the fundamental natural characteristics of ecosystems, defined as those ecological features and processes that support functioning in the prevailing environmental and land-use context, while ecosystem pressure specifically captures anthropogenic influences driving ecosystem change. This framing allows for assessing ecosystem condition even in anthropogenic landscapes, by focusing on functional integrity rather than pristine status, although the latter can still be used for the reference level. This separation enhances analytical clarity, enables more direct examination of cause-effect relationships, improves policy targeting, and facilitates clearer communication to stakeholders about the distinction between ecosystem condition and the forces affecting them. Ultimately, this approach strengthens the SEEA-EA's utility for sustainable ecosystem management by differentiating between what ecosystems are (condition) and what humans do to them (pressure). Additionally, this separation may facilitate the use of condition indicators as proxies for ES, allowing for more efficient monitoring and assessment of the capacity of ecosystems to deliver benefits to people.

While the MAES framework provides valuable guidance, our approach refines its classification system for three key reasons:

1. Conceptual clarity: MAES allows pressure indicators within condition accounts when state data is unavailable. This pragmatic compromise, while understandable, conflates drivers with outcomes and obscures causal relationships essential for policy targeting.
2. Analytical precision: By strictly separating anthropogenic influences (pressures) from ecosystem properties (conditions), we enable clearer cause-effect analysis, more accurate ecosystem trajectory modelling and facilitation of using EC indicators to proxies for overall ecosystem functioning and ES bundles.
3. Policy alignment: The SEEA-EA framework requires accounts that directly support decision-making. Separating pressure from condition allows policymakers to target specific pressures while monitoring resulting ecosystem condition changes, improving intervention effectiveness.

Our definitions maintain compatibility with MAES data collection efforts while improving the conceptual rigor necessary for ecosystem accounting applications.

A Dual-Index Framework: Separating Ecosystem Condition and Pressure

Our proposed approach creates two separate indices that reflect fundamentally different aspects of environmental assessment:

1. **Ecosystem Condition Index** - exclusively comprising indicators that:
    - Play significant roles in ecosystem processes
    - Contribute to overall ecosystem functioning
    - Reflect the natural biotic and abiotic characteristics of ecosystems
2. **Ecosystem Pressure Index** - exclusively comprising indicators that:
    - Express stock or flow of anthropogenic origin
    - Act as external drivers of change in ecosystem condition
    - Represent forces acting upon, rather than properties of, ecosystems

This separation introduces causality as a primary classification criterion:

- Metrics describing inherent ecosystem properties and processes are classified as ecosystem condition indicators, regardless of whether they represent stocks or flows

- Metrics representing human-induced stressors are classified as pressure indicators, whether measured as accumulated stocks or ongoing flows

This approach resolves a key conceptual tension in ecosystem accounting. Anthropogenic stock indicators like nitrogen accumulation or impervious surface coverage, while stationary in nature, fundamentally represent external pressures rather than intrinsic ecosystem characteristics. By creating separate indices, we avoid the semantic confusion that occurs when pressure indicators are labelled as "condition".

Operational Definitions for Separate Condition and Pressure Indices

To reflect this understanding, we propose the following definitions:

- **Ecosystem Condition**

Within the SEEA-EA framework, EC represents a crucial tool for evaluating ecosystem health and functionality. Our proposed approach focuses exclusively on natural ecosystem characteristics, aligning with the definition of ecosystem condition as "..***the quality of an ecosystem measured in terms of its abiotic and biotic characteristics.*** *Condition is assessed with respect to an ecosystem's composition, structure and function, which, in turn, underpin the ecosystem integrity of the ecosystem*…" (UN et al., 2024). Condition indicators encompass here both stock and flow variables, provided they reflect internal ecosystem attributes or dynamics of natural origin, including properties that emerge from interactions among natural processes, even within human-modified landscapes (but see Box 1).

This refined EC assessment can serve a dual purpose in environmental governance: offering essential baseline ecological information to inform policy-development and enabling early identification of emerging threats to ecosystem health and function. The approach is consistent with several EU directives, including the Habitats Directive, Birds Directive, WFD, and MSFD, all of which require regular evaluation of conservation status.

Ecosystem Condition Indicator will be then defined as any state metric, whether stock or flow, of natural origin that characterises the ecosystem's attributes (e.g. biomass, species richness, vegetation configuration) or internal ecological processes (e.g. net primary productivity, nutrient cycling), and contributes to assessing its health, integrity, and resilience with respect to pre-defined reference or target conditions.

- **Ecosystem Pressure**

Ecosystem pressure refers to the cumulative effect of external stressors of anthropogenic origin that affect, or risk altering, an ecosystem's structure, processes, or composition beyond its natural range of variability.

The term "anthropogenic" encompasses all human-induced pressures, which can be categorized into two types: (1) **artificial** elements—human-made or engineered features and substances such as synthetic pollutants and impervious surfaces—and (2) pressures involving natural-origin elements modified by human activities, such as land-use change or altered hydrological flows. This distinction is important because not all anthropogenic pressures involve artificial components. Critically, the presence of artificial elements does not preclude ecological function. Many ecosystems, particularly urban ecosystems and agroecosystems, incorporate artificial components while maintaining their ecological processes (Maes, 2020b).

Ecosystem pressure can be measured using both **stock-type indicators** (e.g., accumulated pollutants, impervious surface cover) that represent the current state of pressure accumulation, and **flow-type indicators** (e.g., emission rates, land-use conversion rates, extraction intensity) that capture ongoing pressure dynamics.

The systematic measurement of such pressures developed alongside industrial expansion, with formal indicator frameworks emerging in the 1970s and 1980s. International organizations played a leading role in structuring pressure assessments, notably through the OECD's Pressure-State-Response (PSR) framework (OECD, 1993) and the EU's more comprehensive Driver-Pressure-State-Impact-Response (DPSIR) model (EEA, 1999), both of which established causal links between human activities and environmental outcomes. Moreover, the DPSIR framework helps conceptualise the negative impacts of human activities and resource uses, including externalities (i.e., unintended negative effects on ecosystems and society), on ES and human well-being. It enhances the capacity to detect degradation early, in line with the precautionary principle and allows policymakers to trace the effectiveness of regulations and policies, supporting adaptive management (see Box 2). The EU's first report on environmental pressure indicators (European Commission, 1999) introduced a classification system that, when combined with state indicators, enables a comprehensive assessment of diverse ecosystem types (Maes et al., 2018).

Ecosystem Pressure Indicator will be then defined as any state metric (stock or flow) of anthropogenic origin that acts as an external driver of change in the condition of ecosystems. Examples include rates of emissions or land cover change (flows), and concentrations of pollutants, imperviousness, or pesticide residues (stocks).

Box 1: Anthropogenic Ecosystems.

Special Considerations for Anthropogenic Ecosystems

Urban, agricultural, forestry or other heavily modified ecosystem types present unique challenges for the condition-pressure dichotomy. In these systems:

- The baseline "natural" state is often undefined or irrelevant.
- Human modifications may constitute the system's fundamental structure.
- Certain anthropogenic elements (e.g., green infrastructure, crop diversity) can enhance specific ecosystem functions.

For these ecosystems, we propose that:

- Condition indicators could focus on ecosystem services supply capacity rather than naturalness.
- Pressure indicators emphasize unsustainable practices or pollution rather than all human influences.
- Reference conditions should reflect "sustainable managed states" rather than pristine conditions that do not exist. The reference conditions could also be defined at the socio-ecological level by considering participatory consensus approaches to define reference levels.

Example: In urban ecosystems, tree canopy coverage would be a condition indicator (contributing to temperature regulation and air quality), while particulate matter concentrations remain a pressure indicator (degrading ecosystem and human health).

Application to Sustainable Use and Management

These considerations are essential for supporting the sustainable use and management of anthropogenic ecosystems. By focusing on maintaining or enhancing their capacity to deliver key ecosystem services while minimizing harmful pressures, policy and management strategies can promote long-term ecological functionality, human well-being, and resilience. Recognizing that human influence is inherent to these systems allows for more realistic and actionable sustainability goals, tailored to specific land uses and societal needs.

Assessing environmental pressures is frequently seen as an indirect approach for evaluating ecosystem condition, but its representation is not formally included within the SEEA-EA. The current framework operates on the assumption that comprehensive condition data would render pressure indicators unnecessary for accounting purposes. In practice, pressure indicators, initially considered ancillary data (Czúcz et al., 2021a), are often included in condition accounts as proxies when suitable state indicators are unavailable, despite potentially violating methodological criteria (Czúcz et al., 2021b). This integration, while pragmatic, creates conceptual challenges by combining external anthropogenic drivers with intrinsic ecosystem properties, which can obscure causal relationships between human activities and ecological outcomes.

Existing classification approaches, such as MAES, have addressed this through temporal criteria (flows vs. stocks), though this can lead to classification challenges for anthropogenic stocks such as accumulated pollutants or impervious surfaces. Including pressure indicators requires justifying pressure-state relationships (Bland et al., 2018) and acknowledges that pressure indicators are sometimes easier to measure, as human activities often generate more comprehensive databases than complex ecosystem states. However, the inclusion of pressure in the ECT may limit opportunities for assessing direct relationships between pressures and ecosystem states, potentially affecting integration into decision-making processes for sustainable ecosystem management.

Defining and classifying pressure indicators

Burkhard et al. (2018) and Czúcz et al. (2021b) have defined human pressures as "*processes or activities exerted by society that negatively affect the condition of ecosystems*". These pressures manifest through physical, chemical, or biological stressors that induce quantifiable changes in biological systems (Côté et al., 2016).

This conceptualization aligns with multiple international classification systems, including the Living Planet Index (WWF, 2018), IPBES assessments (IPBES, 2019), and the IUCN Threats Classification Scheme (IUCN, 2020). The Convention on Biological Diversity recognizes five principal pressures leading to ecosystem degradation:

1. Land-use change (including intensification)
2. Climate change
3. Exploitation of species
4. Pollution
5. Invasive alien species

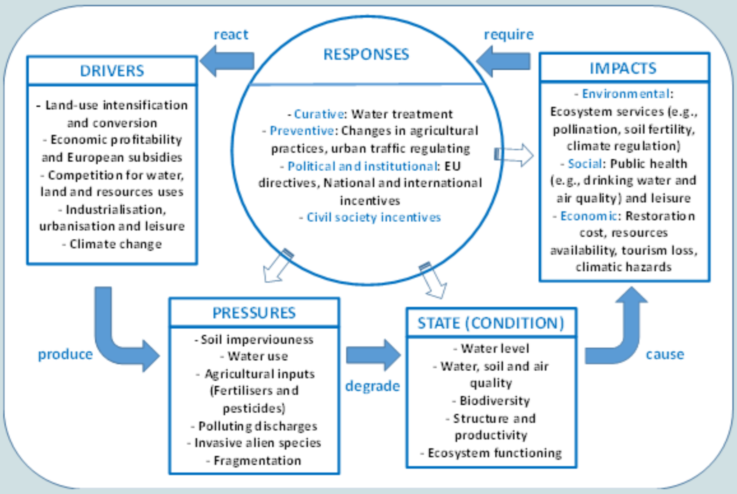
We will use an adapted version of the Czúcz et al. (2021b) ECT framework to assess the Ecosystem pressure indicators (see Section 6.2).

Box 2. The DPSIR Framework

From Cause to Action: Leveraging the DPSIR Framework for Smarter Environmental Policy

Overview

The **DPSIR framework** (Drivers–Pressures–State–Impact–Response) provides a clear, structured method for understanding and managing the interactions between society and the environment. It is widely used in environmental assessment and policy development at national and EU levels.



Why It Matters

Effective environmental policy requires a systemic view of how human activities influence ecosystems. The DPSIR framework allows for the conceptualization of the negative impacts of human activities and resource uses, including externalities (i.e., unintended negative effects on ecosystems and society), by linking drivers to human well-being. By conceptualising these causal chains, it helps identify not only the sources of degradation but also appropriate societal responses to mitigate and manage those impacts.

Key Components

- **Drivers**: Underlying social, economic, and demographic trends (e.g., urbanization, agriculture).
- **Pressures**: Direct effects on the environment (e.g., pollution, fragmentation).
- **State**: Current conditions of ecosystems (i.e., biophysical structures, processes and functions).
- **Impacts**: Consequences for ecosystems services, human well-being and economy.
- **Responses**: Policy measures and societal actions (e.g., regulations, restoration projects, awareness campaigns).

Policy implications

- DPSIR helps monitoring and managing how environmental changes impact the flow of ecosystem services to society. This requires policies that address not just ecological status, but the human benefits derived from nature (Müller and Burkhard, 2012).
- DPSIR helps identifying where interventions will be most effective, supports integrated environmental management and planning, and improves communication between scientists, stakeholders, and decision-makers.

Recommendation

Integrate the DPSIR framework into policy assessments and planning processes to enhance the effectiveness, coherence, and accountability of environmental strategies. Policy should shift focus to preventive actions, such as green infrastructure, sustainable land use, and agro-ecological practices, rather than relying on costly downstream solutions like water treatment or habitat restoration.

5.4. Deriving a minimum set of EC indicators

A concise and well-defined set of indicators would allow for a standardized and consistent monitoring of ecosystem health across different regions and ecosystem types. Besides ensuring that all critical aspects of EC are considered (i.e., biological, physical, and functional characteristics), standardized indicators may allow for a better understanding of EC worldwide. This would empower international reporting and collaboration on environmental issues and guarantee transparency and accountability. This consistency is indeed crucial for comparing data over time and space, enabling better tracking of changes and trends in EC. Defining a minimum set may also allow efficient resource allocation to monitor and manage ecosystems, by focusing on a core set of indicators to avoid redundancy and ensure that the most relevant aspects of ecosystem health are addressed.

This deliverable D3.2 “Derive a minimum set of key ecosystem condition indicators per ecosystem type” presents details on how the development of the minimum set of EC indicators (following the SEEA-EA recommendations and our proposed reform, see above) was carried out. This process draws on a comprehensive review of available data sources and an in-depth survey of the partners involved in each WP3 Ecosystem Type (ET) expert groups. It highlights the key data gaps required to fulfil a minimum set of indicators and the potential for a common set of indicators across terrestrial ecosystems. Section 6.1 of this report describes a systematic review performed to identify indicators and spatially explicit dataset types used in the scientific literature in the immediate period preceding the SELINA project. Section 6.2 presents the methodological approach for operationalizing the separation of pressure and condition indicators within the SEEA-EA framework. Building on these two chapters, Section 6.3 takes the longlists of indicators derived from the previous sections and elaborates on the development of minimum sets of indicators per ecosystem type. In line with the structure of WP3, we provide results for 8 Ecosystem Type groups (Agroecosystems, Forests, Urban ecosystems, Wetlands, Heath- and Shrublands, Grasslands, Rivers and Lakes, and Marine and Coastal ecosystems. In addition to potential minimum indicator sets, each Ecosystem Type section (Sections 6.3.2 to 6.3.9) provides detailed information on:

- Specific data gaps for that ecosystem type
- Priority variables requiring enhanced monitoring
- Existing data sources and their limitations
- Recommendations for filling critical information needs

Finally, Section 7 aims to illustrate how an ecosystem pressure index - the Human Pressure Index (HPI) - on terrestrial ecosystems could be developed, based on a minimum set of indicators, with the ultimate aim of understanding how human activities affect biodiversity, ecosystem functions and ultimately ES.

6. Review of Indicators

6.1. Review of ecosystem condition indicators

6.1.1. Aims and objectives of the review

To support Deliverable D3.2's aim to develop sets of indicators for standardized and consistent EC monitoring, a systematic literature review was carried out to identify key spatially explicit indicators and dataset types used to assess ecosystem condition. We examined the comprehensiveness of spatial data applications in describing essential ecosystem characteristics. The results help to identify those indicators that are operationalizable and repeatable across multiple contexts, serving as potential candidates for the selection of minimum indicator sets developed later in this report. Furthermore, the reviewed literature items will be included in the SELINA EASE database developed in Task 6.6.

The review responded to two main research questions:

(i) What is the state of the art of spatially explicit EC assessment in the recent scientific literature?

(ii) What are the main indicators being applied for the assessment of EC in different ecosystem types, and what types of data are used for their development?

6.1.2. Methods and data for the review

6.1.2.1. Key working concepts for the review

The review focused on scientific articles in which indicators were applied in a spatially explicit assessment of EC. For our analysis, we defined spatially explicit assessments as having continuous coverage across the studied area and being specified at the level of basic spatial units (grid/pixel values), small ecosystem assets, or accounting areas. Throughout the review, we accepted a variety of different synonyms and related concepts as being equivalent to EC, including ecosystem and ecological *state*, *health*, *integrity*, *quality*, and *function*. Considering that non-rescaled variables are frequently referred to as 'indicators' within the literature, in our review we applied the term broadly to include both rescaled and non-rescaled variables. During the review, we distinguished between individual EC indicators, describing a single characteristic, and composite EC indices (composite indicators formed from the aggregation of multiple individual EC indicators to form an 'overarching' quantification of condition).

Indicators were classified according to the ECT classes during the review. However, a significant number of the indicators applied in the literature fall outside the scope of these classes. We therefore applied an expanded set of indicator classes, as proposed by Czúcz et al. (2021a), to identify the use of auxiliary information on pressures, stable environmental characteristics and ecosystem services which, whilst often used as proxies for condition, do not reflect the key characteristics of ecosystems within the context of the ECT. The details of these additional classes, referred to as the 'ECT+' classes, are included in Annex 2. As the review focuses on assessment of the recent literature, the dichotomy of condition and pressure indicators was interpreted as per Czúcz et al., 2021a, i.e. indicators of pressure were classified as an ECT+ class, and the full 'pressure framework' proposed in Section 5.3 was not imposed on the results.

6.1.2.2. Identification of relevant literature

To ensure transparency and minimise bias in literature selection, we took into account the recommendations of the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) statement (Moher et al., 2009), which provides guidance for the stages of identification, screening and inclusion of relevant items for systematic literature reviews. Fig. 2 details these steps up to retrieval of data from the final selection of studies. To identify relevant items, we first developed a search query to filter a central literature corpus developed within SELINA. The "SELINA Super-Query database" collated entries from the Scopus and Web of Science (WoS) online citation databases on research topics covering ecosystem condition, ecosystem services and ecosystem accounting. As the SELINA project focuses on the most recent developments in these areas to reflect the revision of the SEEA, the literature identified was limited to items published from 2018 to 2022. The full details of the development of this database and the search strategies used are described in Seguin et al. (2025).

We filtered the initial 108,064 publications included in the database using a search strategy formed of four English key terms: i) synonyms of 'ecosystem' (i.e. 'ecosystem', 'ecological', 'habitat', 'environment', biological', and the specific ecosystem types according to the MAES typology (Maes et al., 2013)); ii) synonyms of 'condition' (i.e. 'condition', 'quality', 'function', 'state/status', 'health', 'naturalness'); iii), terms indicating 'quantification' (i.e. 'indicator', 'variable', 'assessment'); and iv) terms indicating spatially explicit assessment (i.e. 'spatially explicit', 'map', 'spatial distribution', 'spatial modelling', 'spatial variability', 'spatial relationship'). Full details of the search terms used to filter the database, including the synonyms of condition considered in this work, are included in Supplementary Material. From the resulting 10,224 publications, we excluded 4,369 duplicate records. We excluded an additional 64 records which either referred to retractions, book chapters, and 1,164 studies which were published in journals targeting disciplines such as health science and medicine, mechanical and electrical engineering, and sociology, because of a low probability these papers were related to ecosystem condition. We manually screened the 4,627 remaining publications to exclude those that did not include a map (1,583 publications), as a proxy for use of spatial data. We excluded 127 records for which no full text was available.

We screened the titles and abstracts of 2,917 publications to determine whether they met the inclusion criterion of being an application of EC indicators. For this stage, we implemented an automated approach using the generative AI model gpt-3.5, the details of which are provided in Nicholson Thomas et al. (2024). This resulted in 853 papers being assessed for eligibility based on the full text, which were randomly assigned to 18 reviewers. The team of reviewers was made up of WP3 members and other SELINA Consortium partners.

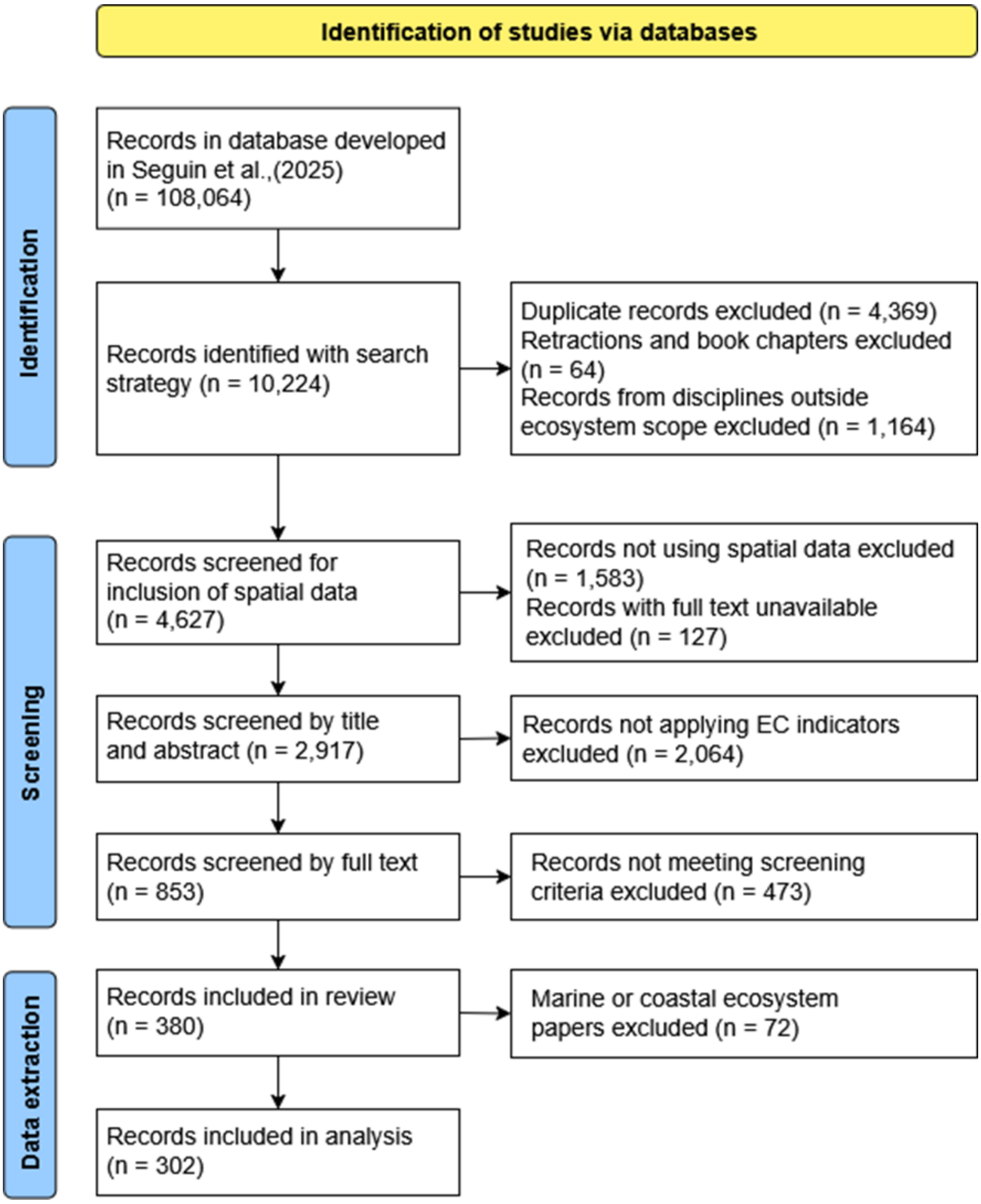


Figure 2: Identification of relevant literature for systematic review, adapted from the PRISMA statement (adapted from Page et al. (2021), CC BY 4.0).

6.1.2.3. Screening and data extraction

Screening for eligibility and subsequent data collection were carried out using an online questionnaire developed specifically for the review. Reviewers were first asked to indicate whether the study met the criteria for inclusion in the review based on an assessment of the full text. The criteria for inclusion were as follows:

- Screening criterion 1: The publication is a scientific article written in English and published from 2018-2022.
- Screening criterion 2: The publication contains at least one metric that is spatially explicit, based on quantitative data, linked to a specific ecosystem type and used by the authors to characterise the condition of the ecosystem studied.

Upon affirmative answers to both screening questions, reviewers were guided to respond to a series of questions in three sections. The questions collected details of the study and its context, the indicators used to quantify EC, and the datasets used for each indicator. Data for publications covering marine and coastal ecosystems were collected but not analysed within the scope of this review. Instead, these data were considered separately as qualitative input for the development of Section 6.3.8, reflecting the extensive coverage of these ecosystems under the MSFD and their distinct management priorities.

To ensure consistency and objectivity in the process, the questionnaire template was developed collaboratively in Google sheets with most of the reviewers, and questions were given predefined response options where possible and appropriate. Additionally, reviewers received a guidance manual to clarify potential responses and were offered weekly help sessions during the data collection period to ensure a clear understanding of the review criteria and a high consistency in data collection. Reviewers were encouraged to avoid interpretation of what constitutes an appropriate indicator of EC during the review process beyond the accepted synonyms. For quality control, an initial pilot review was carried out on a sample of publications to identify potential issues and collect feedback to adjust the questionnaire as necessary and correct differences in understanding. Additionally, 2 papers were assigned to 2 reviewers to provide a qualitative estimate of reviewer consistency, helping to identify points where guidance might need to be updated.

Data from the papers were compiled into a single database, which was then processed, cleaned and analysed in R Statistical Software (v4.2.2; R Core Team, 2021), using the Tidyverse package (Wickham et al., 2019) with additional visualisations created using the packages UpsetR (Conway et al., 2017) and ggsankey (Sjoberg 2021).

6.1.3. Results of the review

6.1.3.1. Context and applications of spatially explicit EC indicators

Information was retrieved from 302 papers covering terrestrial and freshwater ecosystems including forests, urban ecosystems, rivers and lakes, agroecosystems, heathlands and/or grasslands, and wetlands. The details of these papers are available at https://doi.org/10.5281/zenodo.15096859. Research on EC shows disparity in geographical coverage, reflecting known English language publication biases. A large number of studies assess ecosystems in China (number of papers (n_p) = 97), the United States of America (n_p = 38) and India (n_p = 28) (Fig. 3). There was a lower representation of studies in African, as well as Central and South American countries, and studies addressing the European/EU (n_p = 7) or global scale (n_p = 7).

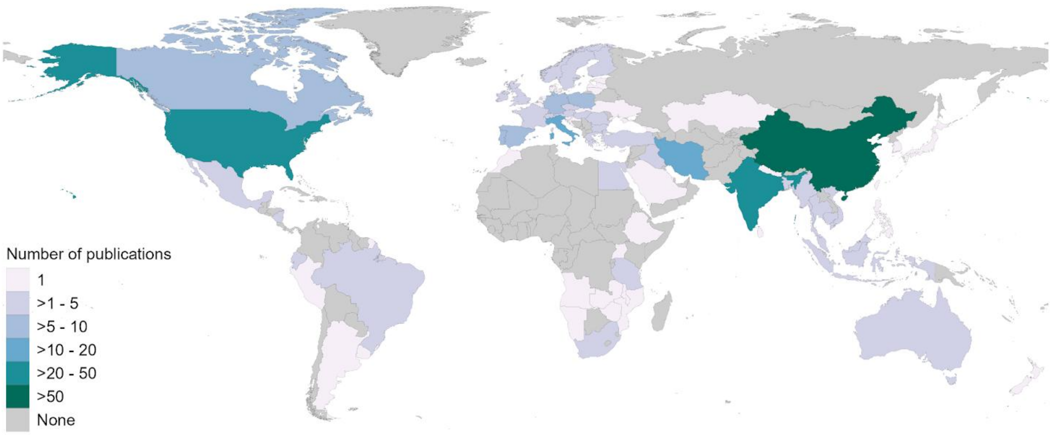


Figure 3: Number of reviewed publications per country. Note that 15 continental, EU, and global studies do not appear on the map. Countries with no studies included in the review are shown in grey.

Fig. 4 shows that there is also a clear bias in the type of ecosystems in which spatially explicit EC indicators have been applied. 63 studies (21%) focused on the condition of forests. Otherwise, 59 studies quantified the condition of more than one ecosystem type ('multiple', 20%). 56 studies addressed rivers and lakes (18%), and 48 urban ecosystems (16%). There was a much lower representation of wetlands (n_p = 16), heathlands and/or grasslands (n_p = 16), and agroecosystems (n_p = 16), which accounted for around 5% of reviewed literature each. Studies applied indicators across the full range of potential spatial scales from patch to global scale, but were less likely to apply spatially explicit indicators to a geographic extent at the national scale or larger (n_p = 28 national scale studies). The primary motivation for using EC indicators was the mapping and assessment of condition directly (n_p = 201). 87 studies used indicators for the planning or evaluation of conservation and restoration measures. Some studies also used EC indicators in the mapping or assessment of ES (n_p = 40).

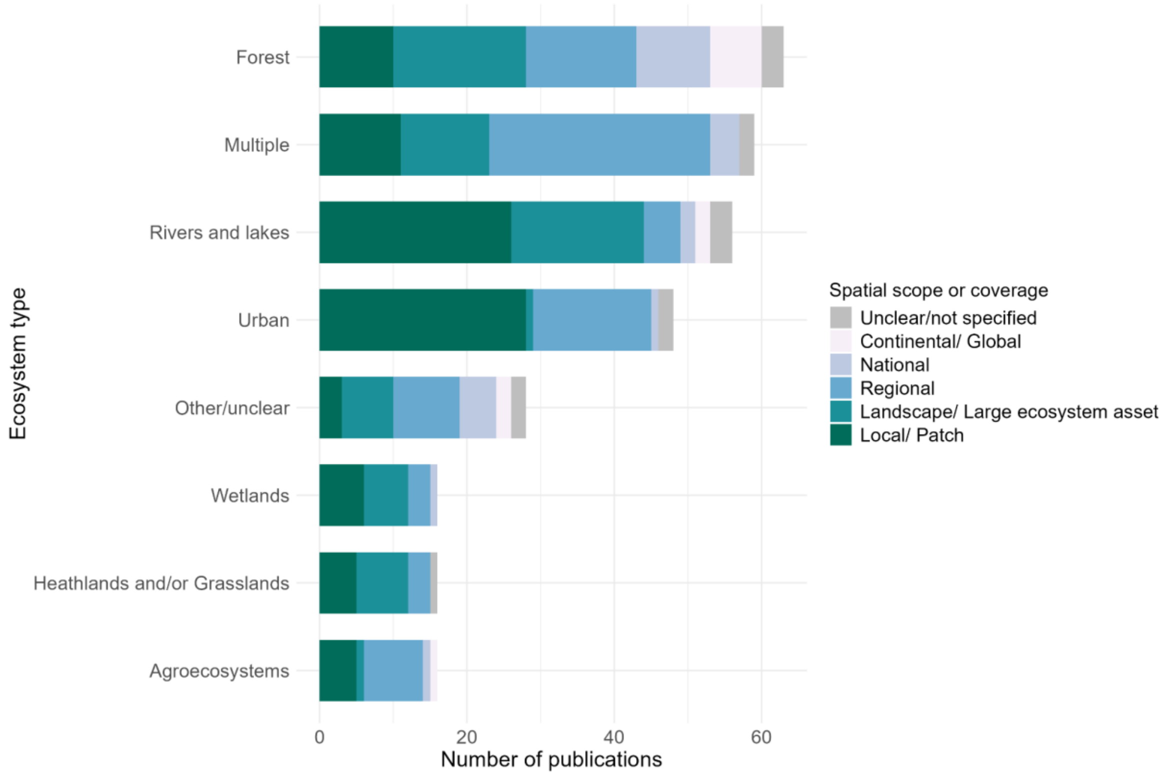


Figure 4: Ecosystem type and spatial scale covered by reviewed publications.

Information for a total of 1,694 indicators were retrieved across all studies including 121 composite EC indices. There was a low level of reporting on the reliability of indicator applications (Fig. 5) with some validation or ground-truthing of indicator values carried out for 20% of indicators. Uncertainty of indicator values was considered for only 16% of indicators, with 10% of indicators accompanied by a quantitative assessment of uncertainty. A small proportion of studies provided qualitative statements on the uncertainty of indicator values.

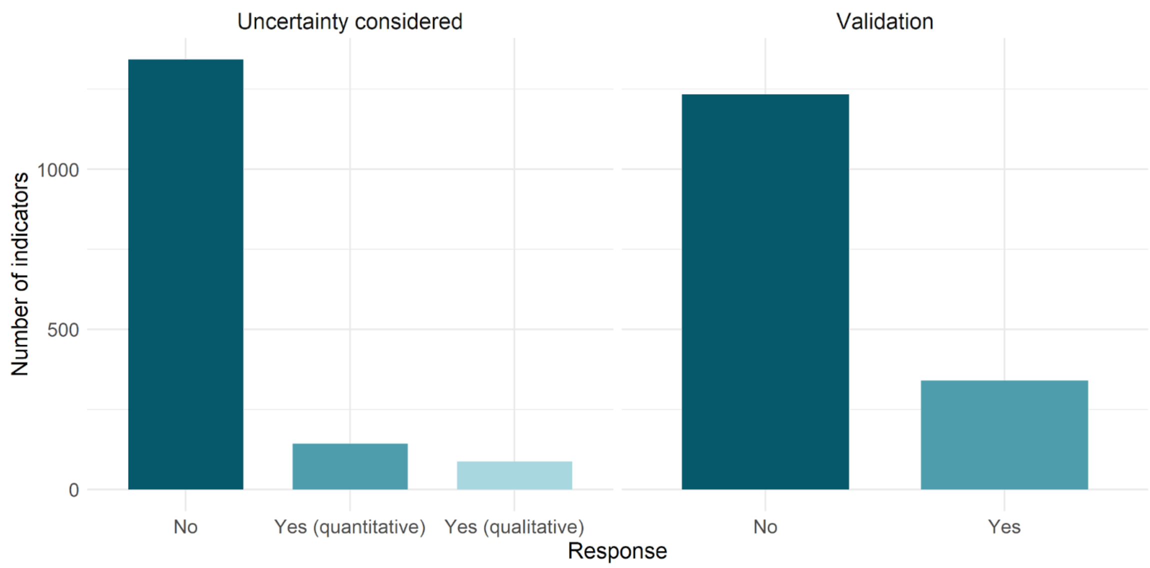


Figure 5: Responses for a) validation of indicator values and, b) consideration of uncertainty across individual indicators recorded.

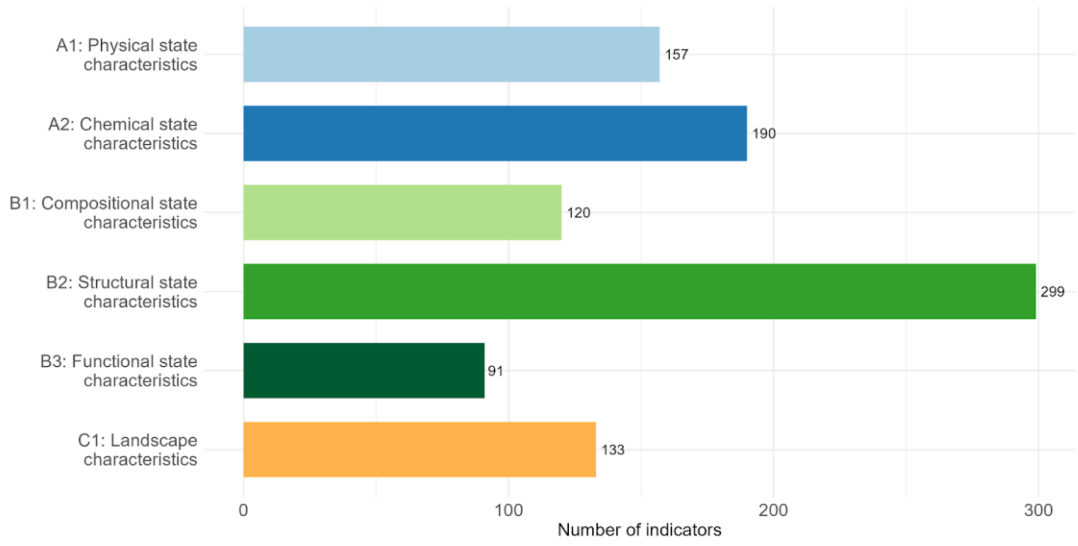
The indicators were in the majority of cases presented as values per basic spatial unit (pixel or grid cells) with a tendency towards a spatial resolution less than 500 m x 500 m (number of indicators (n_i) = 465). In general, studies quantified EC at a single point in time, with 121 publications (n_i = 502) recording values at multiple points in time. The spatial resolution and temporal recurrence of underlying data were, however, in general not specified. In the majority of the cases where spatial resolution was retrieved during the review, this was in reference to remote sensing data products with a spatial resolution of 10 m x 10 m to 30 m x 30 m.

6.1.3.2. Alignment of spatially explicit indicator applications with comprehensive assessment of EC

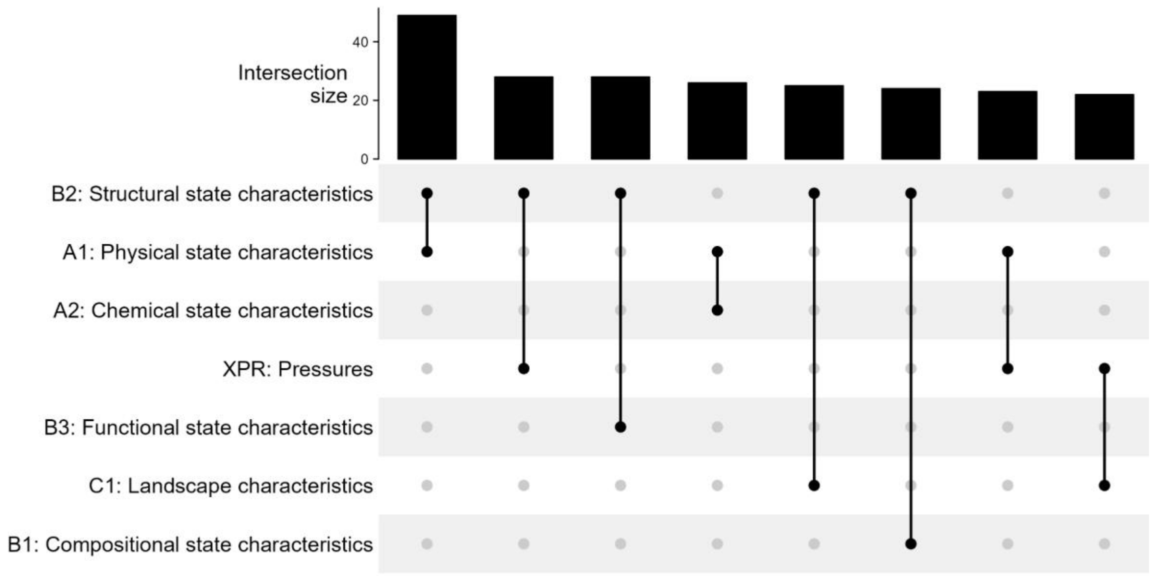
The approaches to indicator applications identified by the review are indicative of the multiple perspectives from which the quantification of ecosystem condition has been quantified within the scientific literature. Indeed, whilst only 40 studies placed their assessment within the context of a previously published EC conceptual framework, those that did align their indicator selection with a variety of different frameworks, including the MAES framework, the WFD, and Ecological Integrity metrics. Indicator selection varied significantly by spatial and theoretical context, with high diversity in indicators; based on name we identified 1,033 of the total 1,694 indicators as unique, of which 154 appeared in multiple studies. Most indicators (83%) were not compared to reference levels or reference conditions, essentially remaining unscaled variables. In the event that reference levels or conditions were used, and sufficiently described for reviewers to classify the approach, the reference was mostly set through an expert-based approach (n_i = 80), a simple data-driven approach (n_i = 50), or using a natural reference condition (n_i = 40).

Our data highlights a prevalence of indicators of structural, physical, and chemical state characteristics, with limited examples of indicators of landscape, and compositional state and functional state characteristics (Fig. 6a). Not including composite indicators, studies used an average of 5.5 EC indicators (with a range from 1 to 43) but employed a restricted scope in terms of the ecosystem characteristics that these indicators represented. Indeed, none of the reviewed literature items addressed all the 6 indicator classes of the ECT (physical, chemical, compositional, structural, and functional state, and landscape characteristics). Instead, where multiple classes of indicators were used to quantify ecosystem condition, the most common combinations were the use of indicators of structural state with indicators of physical state or stable environmental characteristics such as temperature and precipitation (Fig. 6b). Notable differences in the ecosystem characteristics covered can be observed across the main ecosystem types recorded (Fig. 6c), with a bias towards indicators of structural state applied in forest ecosystems and chemical state in rivers and lakes. Urban ecosystems showed a variety of approaches, with some studies relying on physical or structural state indicators, and others largely based on landscape characteristics.

a)


A1: Physical state characteristics
A2: Chemical state characteristics
B1: Compositional state characteristics
B2: Structural state characteristics
B3: Functional state characteristics
C1: Landscape characteristics
157
190
120
299
91
133
0
100
200
300
Number of indicators

b)


Intersection size
0
20
40
B2: Structural state characteristics
A1: Physical state characteristics
A2: Chemical state characteristics
XPR: Pressures
B3: Functional state characteristics
C1: Landscape characteristics
B1: Compositional state characteristics

c)

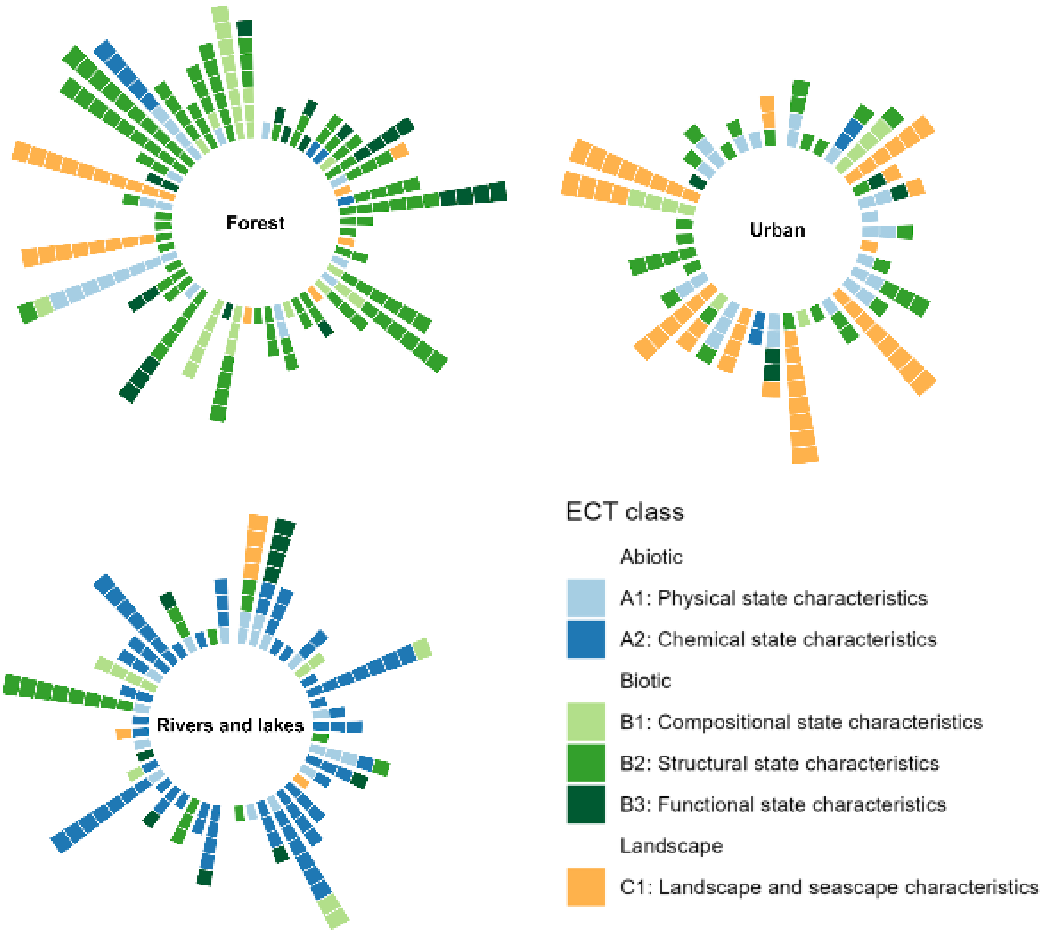


Figure 6: a) Coverage of ECT classes across all indicators, b) Most frequent intersections of ECT classes in the form of co-occurrence in studies, across all publications (more than 20 studies), c) Indicators per publication for Forest, Urban, and Rivers and lakes, coloured by ECT class. Each radial line represents a publication.

The use of approaches outside the current framework was widespread in the literature reviewed, with 583 indicators (37%) recorded that do not align with the descriptions of the ECT classes (Fig. 7). These metrics primarily quantified stable environmental characteristics (n_i = 176) or represented the range of diverse pressures acting on ecosystems (n_i = 147) such as land use intensity or the application of pesticides and fertilisers. Studies also used pre-aggregated indicators including soil or water quality indices, or indicators of ecosystem extent and ecosystem services to quantify EC. Indicators falling outside the ECT classes were rarely employed exclusively to describe EC and were generally combined with ECT indicators. For example, Fernandez et al. (2019) used indicators of pressures of road density and landscape development intensity to support metrics of imperviousness and fragmentation of wetlands.

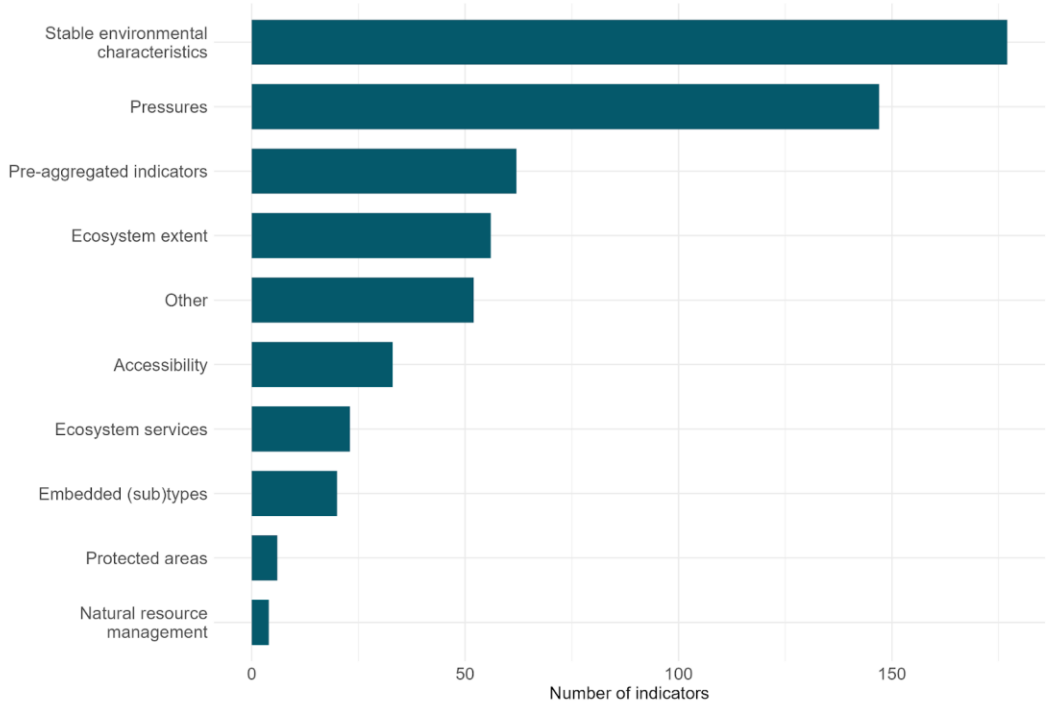


Figure 7: Distribution of indicators across auxiliary ECT+ classes.

6.1.3.3. Main types of data used to operationalize spatially explicit EC indicators

The use of remote sensing data products was prevalent in the studies reviewed, appearing in 172 publications. Satellite imagery, including the use of long-term multispectral imagery from Landsat, Sentinel as well as minor usage of hyperspectral data, was the most frequently applied dataset subtype (n_i = 357). In particular, the use of vegetation indices derived from satellite imagery was widespread across ecosystem types (e.g. Abdollahnejad and Panagiotidis, 2020; Firozjaei et al., 2020; Kayet et al., 2019; Li et al., 2021; Roshani et al., 2023). The use of variables derived from this type of data may include some redundancy, with 66% of studies using long-term multispectral imagery calculating multiple indicators from the same data source (e.g. set of Landsat or Sentinel images). For example, in the study of Chen et al. (2019), in which structural and functional variables of canopy closure, stand density, forest age, stand volume and soil fertility were derived from Landsat imagery to describe EC, it was noted that the spatial variation was primarily driven by a subset of the indicators used to describe functional state characteristics. We found few examples of studies using key continental and global processed datasets, such as various MODIS processed data products and CORINE Land Cover (n_i = 24 and 19 respectively) despite their accessibility, high temporal availability and spatio-temporal resolution.

Remote sensing data was used in all ecosystem types to derive indicators of all characteristics but was less frequently used to calculate indicators of compositional state characteristics, with the few instances recorded restricted to indicators of tree species composition (e.g. Riedler and Lang (2018)). More frequently, indicators of compositional state relied on the use of direct measurement data interpolated from point locations to produce spatially explicit values as defined by the inclusion criteria (e.g. Pompeu (2020)). In other cases, the calculation of functional metrics required support from complementary data types to provide a comprehensive assessment. For example, Zelený et al. (2021) focused primarily on applying functional indicators, such as net primary productivity and metabolic respiration, derived from satellite imagery to assess EC in the context of agroecosystems and forests. However, their approach required the use of secondary spatial datasets including agricultural census data of harvest values to show functional indicators of biomass production.

The widespread adoption of remote sensing data has significantly advanced the ability to produce high-resolution estimates of EC in forest ecosystems by leveraging multiple structural variables for assessment (e.g. Riedler and Lang (2018), Virkkala et al. (2021), López Serrano et al. (2021)), see Fig. 8. To a lesser extent, we also observed the use of active remote sensing techniques including radar and Light Detection and Ranging (LiDAR) to derive metrics of forest structural state.

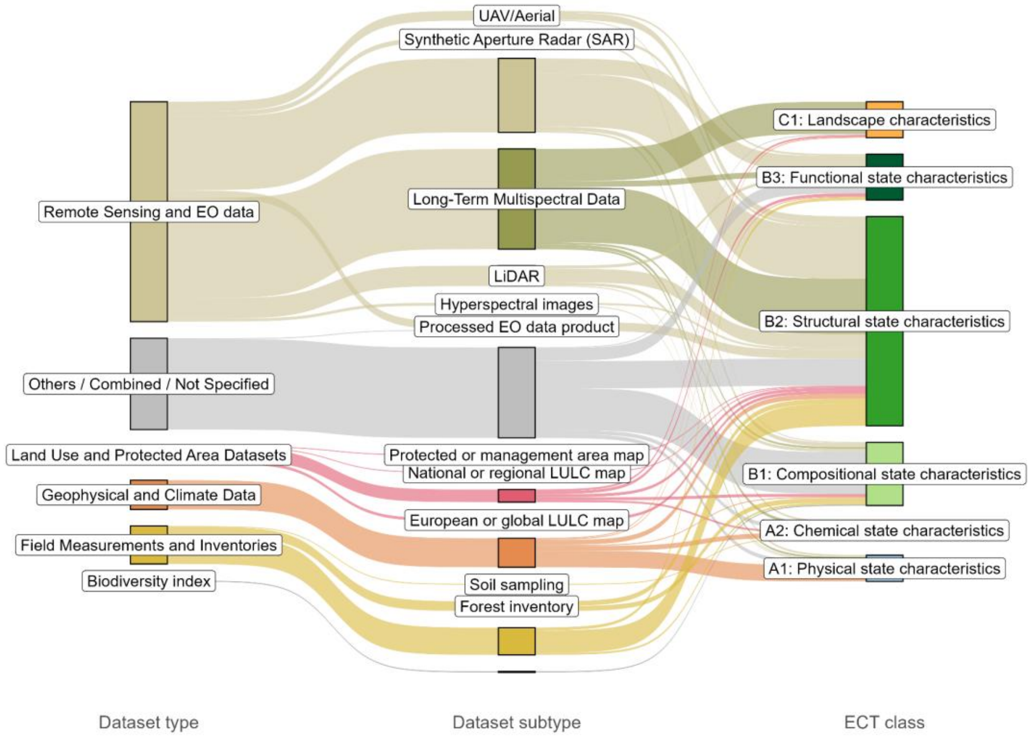


Figure 8: Sankey diagram showing the data types and subtypes used in developing the different classes of indicators used in EC studies in forests. Full size in Annex 3.

River and lake ecosystems were assessed primarily using chemical state metrics, as these studies tended to equate EC with water quality. These indicators relied heavily on measurement and field data to produce EC estimates at the local and large ecosystem asset scale (Fig. 9). With a focus on water quality, consideration of the landscape characteristics of freshwater ecosystems was more common in publications which also assessed other ecosystem types alongside rivers and lakes (reclassified as 'various'). Whilst remote sensing data was also applied to estimate many of these water quality indicators, such as chlorophyll-a concentration, total nitrogen/phosphorus and Secchi depth (reflecting water clarity), the use of long-term multispectral images was commonly combined with in-situ measurements to strengthen the validity of indicator values (e.g. Markogianni et al., 2022).

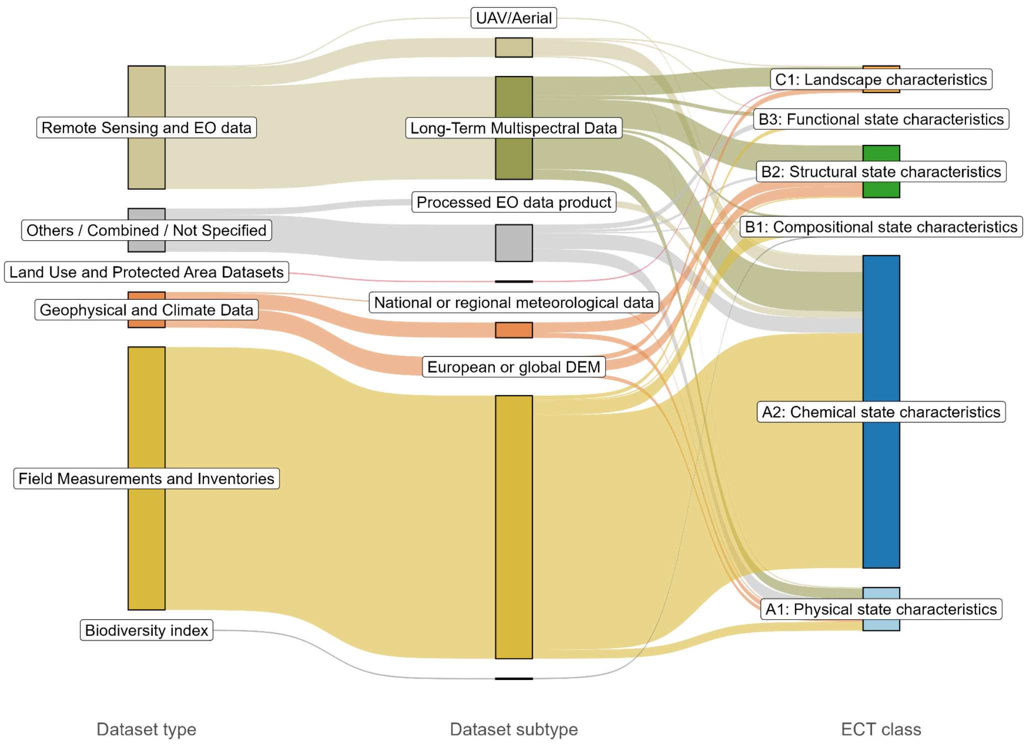


Figure 9: Sankey diagram showing the data types and subtypes used in developing the different classes of indicators used in EC studies in rivers and lakes. Full size in Annex 3.

Studies of urban ecosystems, however, were more likely to use indicators of landscape characteristics respectively, with publications assuming the urban ecosystem to be a mosaic of green space and other uses (Fig. 10). The use of remote sensing data products was again observed for all types of indicators. However, compared with other ecosystem types, a higher proportion of indicators were based on land use or land cover datasets. For example, Soltanifard and Jafari (2019) assessed the ecological quality of urban green space in Iran using indicators of landscape composition and configuration. For urban ecosystems, we also observed use of socio-economic datasets and indicator values derived from expert opinion.

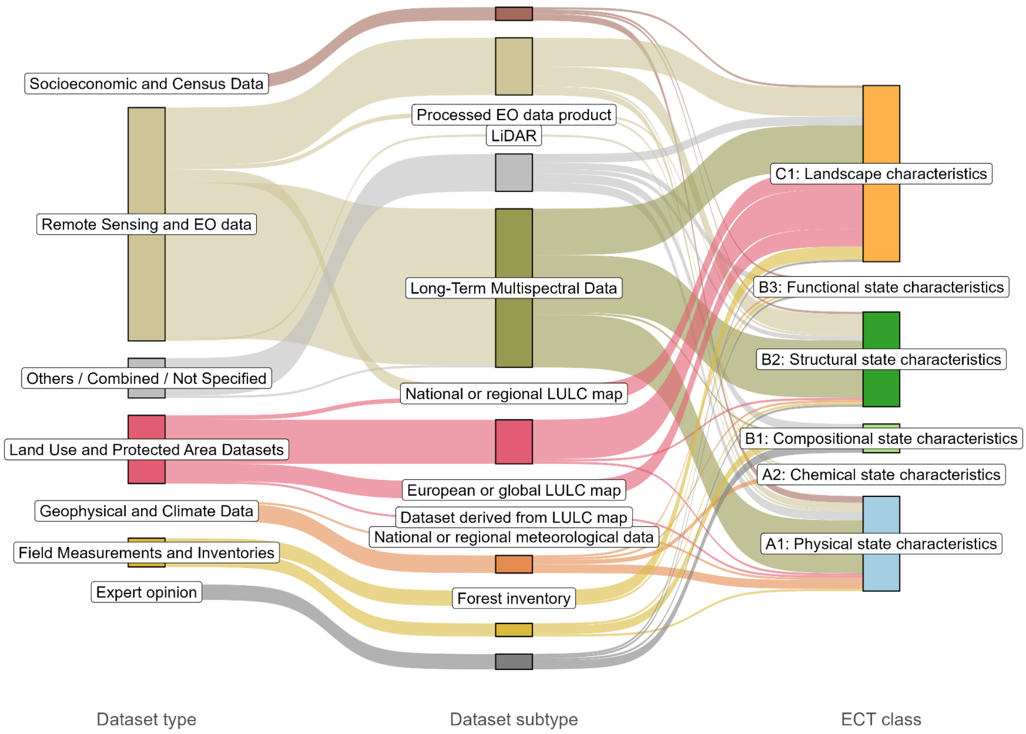


Figure 10: Sankey diagram showing the data types and subtypes used in developing the different classes of indicators used in EC studies in urban ecosystems. Full size in Annex 3.

In studies of agroecosystems, a variety of data types were used to develop indicators primarily of physical state, such as metrics referring to soil structure and erodibility. Studies of wetlands also focused on physical state characteristics, relying mostly on remote sensing data or Land Use/Land Cover (LULC) datasets to develop indicators such as imperviousness. Studies on heathlands and/or grasslands followed the general trends observed in the whole dataset, with remote sensing data frequently used to develop indicators of the most commonly applied ECT classes.

6.1.3.4. Most common EC indicators operationalized in the literature and datasets used for their development

There was a high variety in the unique indicators used across ecosystem types, with only 1 indicator (*Normalised Difference Vegetation Index* (*NDVI*)) appearing across all ecosystem types surveyed. Fig. 11 summarises the main indicators identified in the literature by ecosystem type, focusing on those used in more than two studies. Amongst agroecosystems, wetlands, and heathlands and/or grasslands, the previously stated low coverage in the reviewed literature and high variety of individual indicators applied lead to only one indicator from agroecosystems being included in Fig. 11. Within studies on forests, urban ecosystems and rivers and lakes, long-term multispectral imagery is the dataset subtype most frequently used for repeated indicators, and is employed to derive indicators such as *NDVI*, *biomass*, and *Chlorophyll-a*. This dataset type is often combined with other remote sensing data products, field measurements, and processed Earth Observation (EO) data. In forest ecosystems, structural state indicators like *NDVI*, *above-ground biomass*, and *forest height* are prevalent.

These indicators are typically derived from long-term multispectral images, LiDAR, and field data. In rivers and lakes, chemical state indicators, such as *Chlorophyll-a* and *Secchi depth* dominate and are mainly derived from multispectral imagery but with many cases also incorporating field data. The use of fine spatial resolution (< 500 m x 500 m) is consistent across all ecosystems, and most records include multitemporal assessments to track changes over time. However, those indicators that also use active remote sensing methods, such as Synthetic Aperture Radar (SAR) and LiDAR, are less likely to have indicator values assessed at multiple points in time within the same study.

Urban ecosystems presented a greater diversity of indicators and dataset types. NDVI, Land Surface Temperature (LST), Wetness (referring to moisture content in both vegetation and soil as derived from spectral reflectance patterns), and Normalised Difference Bare Soil Index (NDBSI) were commonly used, reflecting the inclusion of studies primarily assessing ecosystems in China, in which these spectral indices were applied in the context of ecosystem health assessment using the Remote Sensing Ecological Index (RSEI) (e.g. Shi & Li (2021), Sun et al. (2022), Xiong et al.(2022)). In terms of datasets, in addition to multispectral imagery, there was significant use of socio-economic datasets, LULC maps, and national census data. These datasets were applied to measure pressures, such as population and household density, which are specific to urban environments. In some contexts, LULC data was directly used in the form of the coverage or extent of specific classes (see Land Use/ Land Cover (LULC) in Fig. 10). Despite the prevalence of landscape indicators used in urban settings, the most frequently observed landscape indicator, contagion (reflecting the degree of aggregation of landscape elements), was only applied in 3 different studies of urban ecosystems. This reflects the high variety of individual landscape metrics applied.

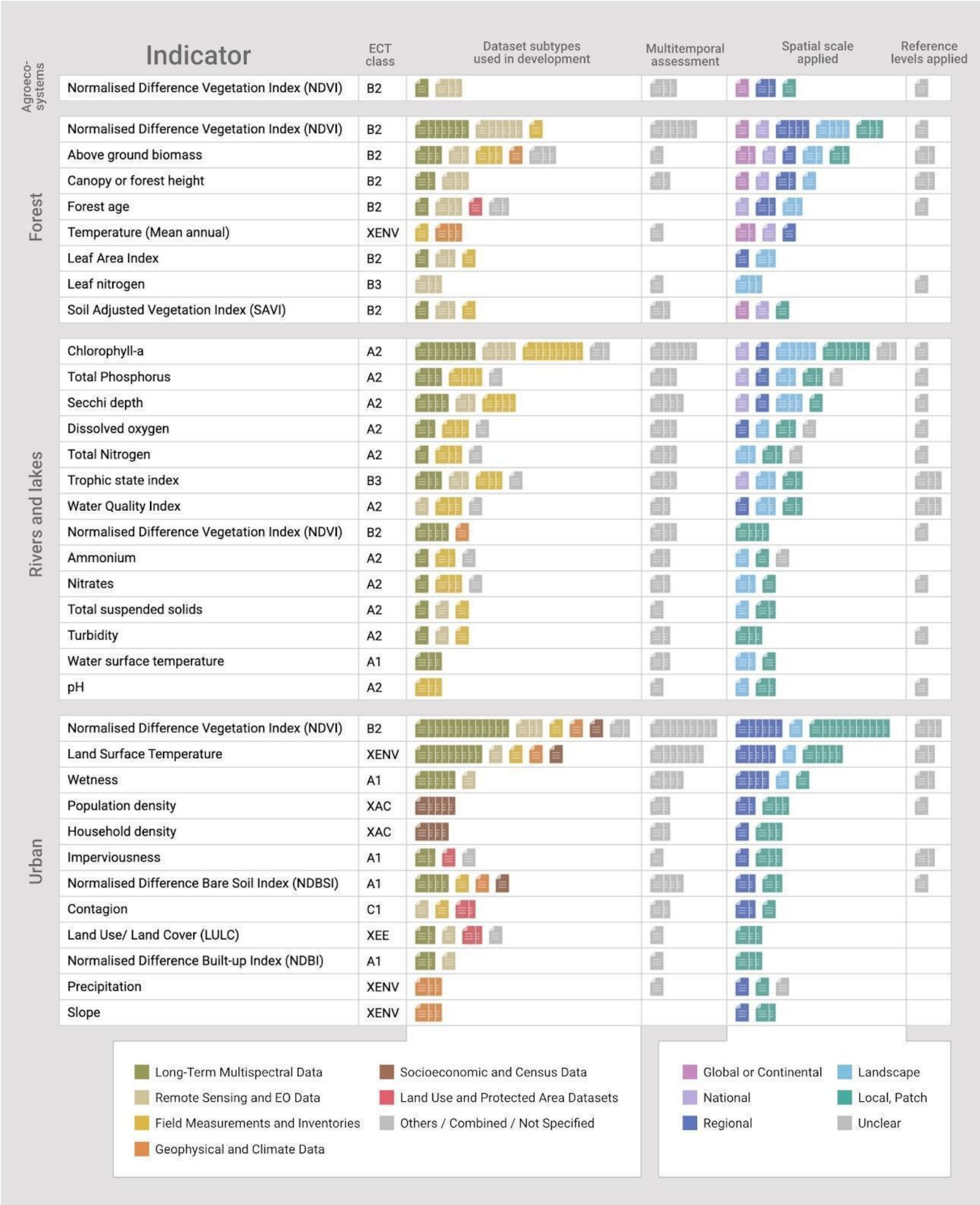


Figure 11: Summary of main indicators (>2 instances) identified in the literature by ecosystem type.

6.1.4. Synthesis

The systematic literature review carried out in Task 3.2 provides key insights for the process of developing minimum sets of ecosystem condition indicators.

RQ1: What is the state of the art of spatially explicit EC assessment in the scientific literature?

We identified an imbalance in terms of the characteristics of EC being assessed in the scientific literature. Notably, there was a low frequency of applications of spatially explicit indicators of compositional and functional state characteristics. In contrast, Maes et al. (2020b) did not identify such deficits in their review, which focused on national-level assessments and placed less-demanding requirements on the use of spatially explicit data. The absence of similar gaps in their findings suggests that the biases observed in coverage of the ECT classes are likely driven by limitations in data availability and usability rather than a lack of recognition of their instrumental relevance. This also points to the relative complexity in defining and measuring meaningful compositional and functional indicators compared to other elements of the ECT. Efforts have been made to collate globally available datasets on biodiversity, but inconsistent update frequencies and gaps in taxonomic and geographical coverage remain a barrier to widespread usage (Stephenson and Stengel, 2020). The imbalance in operationalized EC indicator classes limits the capacity to characterise the full range of dimensions relevant for exploring relationships with ES provision. These limitations constrain the evidence base available to decision-makers, particularly where spatially nuanced information is needed to prioritise actions or assess trade-offs. Addressing these gaps is a pressing priority for improving our understanding of ecosystem capacity to provide services and for advancing more accurate and policy-relevant ecosystem service accounts.

There is significant potential for such gaps to be filled, including for example developments in process-explicit models which are facilitating increasingly realistic estimation of spatiotemporal species diversity (Pilowsky et al., 2022). In addition to developing reliable datasets that are spatially explicit and encompass diverse ecosystem characteristics, understanding the uptake and validity of these datasets when used should be improved. The development of a minimum set of EC indicators therefore needs to place emphasis on the data and methodological gaps and potential solutions to ensure indicator proposals are operationalizable. Furthermore, the limited use of reference levels observed in this review highlights a key gap in the applicability of indicators as indices and for accounting purposes and strengthens the need for the methods being developed under SELINA Deliverable D3.3.

RQ2: What are the main indicators being applied for the assessment of EC in different ecosystem types, and what types of data are used for their development?

In forest ecosystems, key indicators include structural state metrics such as *NDVI*, *above-ground biomass*, and *forest height*. Rivers and lakes rely on chemical state indicators like *chlorophyll-a* and *Secchi depth*. Urban ecosystems use a broader mix including *NDVI*, *Land Surface Temperature* (*LST*), and *NDBSI*. A series of indicators were identified in multiple publications and provide inspiration for the longlists of EC indicators on the basis of inferred transferability across contexts.

However, across the literature reviewed, a high variability in datasets and indicators was observed across ecosystem assessments, adding complexity to the definition of universal minimum indicators. We observe that ecosystem types have been assessed differently, with distinct focuses reflecting the environmental attributes deemed more or less essential for a well-functioning ecosystem. This underscores the need for ecosystem-specific sets of indicators while maintaining comparability across studies. While standardisation would aid compatibility, an overly rigid approach risks overlooking critical local ecosystem-specific nuances and reducing legitimacy of indicators towards stakeholders. Additionally, the limited coverage of agroecosystems, wetlands, heathlands and grasslands limits the insight that can be carried forward from the review for these ecosystem types.

We find remote sensing, particularly multispectral imagery from Landsat and Sentinel satellite missions, central to EC indicator development due to its accessibility, and scalability and wide applicability of indicators derived from this data across ecosystem types. Drawing inspiration from the concepts used to identify candidate variables for *Essential Biodiversity Variables* (EBVs) (Pereira et al., 2013; Reddy et al., 2021), remote sensing has the potential to provide a consistently updated data source for monitoring of EC. However, some ecosystem types, rely more heavily on other data sources, reflecting their unique assessment needs and the diverse ecosystem subtypes they encompass. Our findings highlight the broad usability of remote sensing indicators while underlining the importance of integrating additional datasets for context-specific assessments. While remote sensing offers significant advantages, its limitations, such as potential gaps in fine-scale validation, necessitate complementary field-based measurements. Field data provide critical contextual insights and validation, enhancing the accuracy and reliability of an ecosystem condition assessment based on remote sensing-derived indicators. Approaches that take into account the benefits of multiple types of data can result in robust, accessible sets of indicators that balance global applicability with local relevance.

6.1.4.1. Limitations of the review

Despite the contributions of the review to understanding of the use of EC indicators, there are several limitations to the approach taken. Firstly, the study aimed to cover a broad understanding of ecosystem condition. However, the variety of contexts in which potentially relevant indicators are used may mean that relevant spatially explicit indicators for ecosystem condition may have been overlooked. As with most systematic literature reviews, the ability to identify relevant trends is inherently shaped by the disciplinary focus and the specific terminology employed, which may limit the scope of insights captured. In particular, the search strategy was not designed to capture studies focusing on partial ecosystem characteristics without the goal of comprehensive ecosystem assessment. Additionally, the review was limited to English language published literature, excluding grey literature, and covered a short timeframe. This restricted scope provides only a snapshot of the potential for EC assessment and may not fully reflect the diversity of available approaches adapted to local jurisdictions. Newly published research rarely focuses on already established monitoring methods, which may lead to the over-representation of certain newer data types (e.g. remote sensing) and the under-representation of some otherwise relevant and widely used data and databases. This is an important consideration for the later stages of the work described in this report (Section 6.3), as it highlights the need to give expert groups the opportunity to suggest additional indicators that may not have been identified.

Challenges related to indicator evaluation also emerged during our analysis. The study focused on commonly used indicators, assuming these to be representative of usability and transferability across contexts. However, this does not amount to a full assessment of their relevance for evaluating ecosystem conditions or of factors influencing their application beyond data availability. We note also that, whilst the extension of indicator classification to include the ECT+ classes allows for some indication of relevance to ecosystem characteristics, the relevance of some of these indicators, deemed important by individual authors, could still be questioned. Distinguishing 'individual' indicators adds further complexity, with different approaches observed in the literature, such as treating maximum and minimum values of a metric as multiple or one single indicator. Similarly, distinguishing and classifying individual datasets posed challenges in some reviewed studies, as reflected in the high proportion of datasets categorized as "other". Additionally, many studies utilized subsets of larger datasets, which may have different spatial or temporal coverage, potentially limiting a comprehensive understanding of dataset characteristics.

6.2. Ecosystem Pressure

6.2.1. Pressure consideration and the SEEA-EA framework

Building on the conceptual framework outlined previously in Chapter 4, this section details the methodological approach for operationalizing the separation of pressure and condition indicators within the SEEA-EA framework. While the theoretical justification for this separation has been established, implementing it requires a systematic approach to indicator classification and validation. The development of a consistent framework for operationalizing pressure concepts enables identification of appropriate indicators and establishment of quantitative relationships between pressure and ecosystem condition. This separation provides opportunities for identifying data gaps and addressing the urgency to revert trends leading to species loss and disruption of fundamental ecological processes (IPBES 2019).

6.2.2. Operationalizing the separation of pressure and condition indicators within the SEEA-EA framework

We developed a comprehensive typology of pressure indicators consistent with the SEEA-EA ecosystem condition indicators framework through a literature review (e.g., Vallecillo et al. (2022); Maes et al. (2020a)). Our methodology structured qualitative data on pressure, derived from biophysical accounts, to create a spatially-based framework categorizing pressures into three primary groups: abiotic, biotic, and landscape. For each group, we defined indicator classes, categories and sub-categories enabling proper identification of potential metrics. We then assessed sub-categories for which metrics were readily available at European level to identify data gaps. To validate both ecosystem pressure and condition indicator typologies, we conducted a survey within the SELINA WP3 group, asking participants to validate these typologies through specific questions about indicator classification. This validation process was informed by discussions during Session 8 (Break-out #1: Selection of data, indicators and methods to conduct EC assessment & Definition of reference levels in different ecosystem types) at the SELINA workshop #4 in Trondheim, Norway (17-20 June 2024). Through this consultation process, the development of the pressure typology was endorsed, though participants noted that exact relationships between pressure and ecosystem condition require further investigation. Natural pressures such as climate variability and natural events (e.g., wildfire, flooding) were excluded from the typology, as they are not direct anthropogenic drivers and can be captured through condition indicators (e.g., vegetation productivity). Tables 2 and 3 present the final general typology for pressure and condition indicators applicable to respective ecosystem assessments. These typologies serve general purposes and may require modification for marine ecosystems where certain categories lack relevance (e.g., imperviousness, erosion in pressure; water availability in state). The primary modification to the original SEEA-EA ecosystem condition typology involves decomposing the landscape group into structural and compositional components. Our gap analysis and literature review identified significant data limitations for biotic components in both pressure and condition indicators, highlighting priority areas for future research (see Section 6.3).

Table 2: General condition indicator typology. 'Indicators availability' shows for which sub-category potential spatially explicit indicators are currently available at European level. Air, water and soil qualities should be expressed based on a ranking derived from the chemical abiotic pressures.

Group	Class	Category	Sub-category	Indicators availability
Abiotic characteristics	AC1 – Physical condition	Water	Availability	Available
		Soil / sediment	Nature / State	Available
	AC2 – Chemical condition	Air	Quality	Available
		Water	Quality	Available
		Soil / sediment	Quality	Available
Biotic characteristics	BC1 – Compositional condition	Species diversity	Taxonomic diversity	Data gap/ Available (depending on ecosystem)
			Functional diversity	Data gap
	BC2 – Structural condition	Vegetation cover	Cover	Available
	BC3 – Functional condition	Productivity	Productivity	Available
Landscape characteristics	LC1 – Structural condition	Connectivity	Patches connectivity	Computation
	LC2 – Compositional condition	Species diversity	Beta diversity	Data gap

Table 3: General pressure indicator typology. 'Indicators availability' shows for which sub-category potential spatially explicit indicators are currently available at European level.

Group	**Class**	**Category**	**Sub-category**	**Indicators availability**
Abiotic pressures	AP1 – Physical pressure	Water	Water use	Available
		Soil	Imperviousness	Available
			Erosion	Available
	AP2 – Chemical pressure	Air pollution	Pollutants	Available
		Water pollution	Pollutants	Available
		Soil / Sediments pollution	Pollutants	Available
Biotic pressures	BP1 – Compositional pressure	Species	Pathogens and diseases	Data gap
			Invasive Alien Species (IAS)	Available
Landscape pressures	LP1 – Physical pressure	Land/Sea-use	Disturbance intensity	Computation
	LP2 – Structural pressure	Fragmentation	Mesh density	Available

Based on these typologies, we proposed an overall picture of an ecosystem quality assessment with all potential relationships between pressure and condition indicators (Fig. 12). This can be assessed through overall sub-indicators of environmental, biological and landscape qualities against a reference level, leading to an index of ecosystem condition, ranging from very poor to excellent quality score. Climate change and human drivers (e.g., population growth, urbanisation and industrialisation) are considered as ancillary data (i.e., indirect drivers of change) that may affect pressure and the overall ecosystem quality, and so are not included in the condition or pressure assessment.

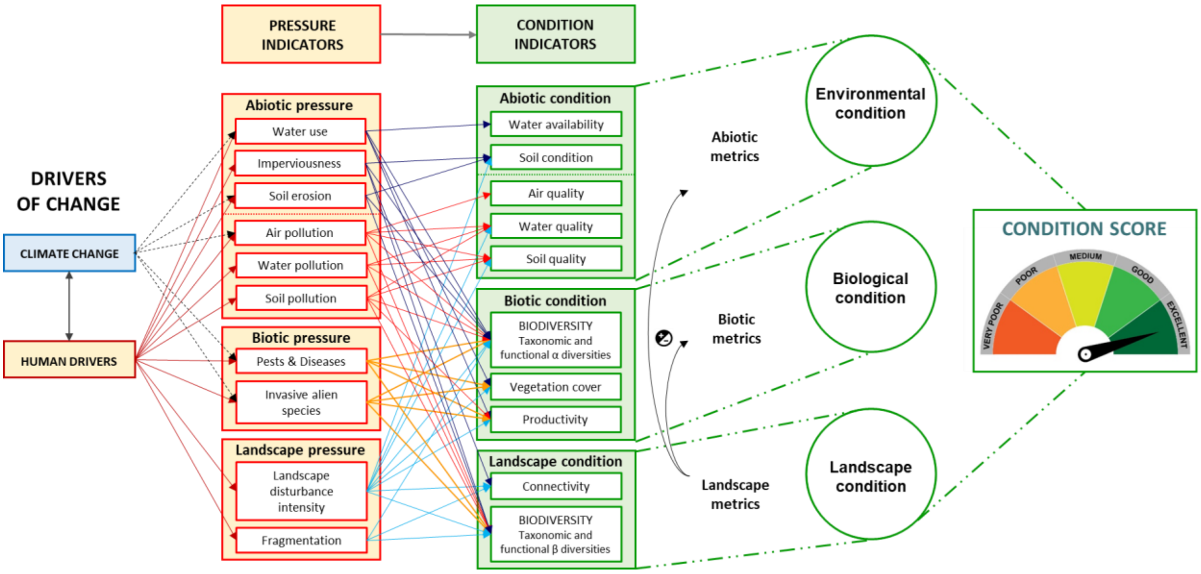


Figure 12: Overall picture of an ecosystem condition assessment. Due to data gaps on biodiversity indicators, the biological condition of an ecosystem appears the most limited assessment despite its crucial relevance.

6.3. Evaluation of Ecosystem Condition Indicators by Ecosystem Types

6.3.1. Methods

To provide evidence supporting the selection of a minimum set of indicators, by assessing the relevance and relative strength of the previously proposed indicator frameworks for evaluating EC, a survey was completed by expert groups formed within SELINA WP3 for each ecosystem type. The objective was to ensure that the indicators align with different ecosystem types, verifying that they are both meaningful and applicable across varied ecosystem contexts. The survey also provided an opportunity to identify missing indicators that may be both relevant and operationalizable, but were not initially included in the framework. The results contribute to the knowledge generation processes aiming to derive minimum sets of indicators, by highlighting which spatially-explicit indicators are deemed to most effectively capture ecosystem condition and ecosystem pressure across the EU.

Three long-lists of indicators were developed based on the framework with minor specific adjustments for terrestrial, urban, and marine ecosystem types. These were supplemented with key indicators that appeared multiple times in the reviewed literature, resulting in seven ecosystem-specific indicator lists for the ecosystem types addressed by WP3 (Urban, Forest, Agroecosystems, Heath- and Shrublands, Grasslands, Wetlands, Rivers and Lakes, Marine, and Coastal). Questions were developed using the selection criteria for EC indicators established in Czúcz et al. (2021b) (Table 4). The survey began by asking whether the proposed indicator was a good measure of EC for the respective ecosystem type, followed by a series of questions rated on a five-point scale which were then aggregated by criteria. Respondents were then asked whether they were aware of available spatially-explicit data sources at the European scale, requiring a yes/no response with the option to specify sources. Participants also ranked each indicator's relative importance within its class on a scale of 1–10. For all questions, respondents could provide qualitative comments. While expert groups had flexibility in structuring their discussions, each group was required to submit a single, consolidated response.

Table 4: Criteria for indicator selection and questions developed to assess these criteria.

Criteria	Question
Intrinsic relevance	I think that this is a good indicator of ecosystem condition
Framework conformity	The proposed class is appropriate
Framework conformity	The proposed category is appropriate
Framework conformity	This indicator could also be recorded under other classes/categories in the framework
Validity	This indicator meaningfully represents a characteristic of the ecosystem in question
Parsimony	There are other indicators in the provided list which represent the same characteristic
Validity/(Parsimony)	There are other indicators which could more accurately represent the same characteristic
Instrumental relevance	There are documented quantitative links between this indicator and some ecosystem services
Directional meaning	It is clear if an increase in this indicator is favourable or unfavourable
Directional meaning	The directional meaning of this indicator would change for different ecosystem sub-types
Directional meaning	The directional meaning of this indicator would change for applications at different spatial scales
Intrinsic relevance	The relevance of this indicator would change for different ecosystem sub-types
Intrinsic relevance	The relevance of this indicator would change for applications at different spatial scales
Sensitivity to human influence	The values of this indicator are responsive to changes in pressure or management
Simplicity	This indicator is easy to calculate
Simplicity	This indicator is easy to understand
Reliability	The values of this indicator are subject to errors
Availability	I am aware of potential datasets that could be used to calculate this indicator at the European scale
General assessment	Please rank this indicator for its importance within its ECT class (1-10)

The indicator shortlists produced from this evaluation were then refined through an iterative process in consultation with the expert groups. Feedback from these consultations informed the selection, adjustment, and consolidation of indicators to derive minimum indicator sets tailored to each ecosystem type.

The following sections present the minimum sets of ecosystem condition and pressure indicators per ecosystem type. Because beta diversity was identified as a missing indicator for all ecosystem types, this category (LC2: landscape characteristics - Compositional condition) has been removed from the following tables. Specific comments on additional data gaps have been made in the sections below.

6.3.2. Agroecosystems

Definition of the ecosystem type

Agroecosystems, as defined by the MAES (Maes et al., 2018, 2020a) framework, are classified into cropland and grassland ecosystems, which together make up nearly 48% of the EU's terrestrial ecosystems (i.e., 36.4% cropland and 11.4% grassland). Croplands encompass cultivated and land temporarily left fallow, as well as horticultural and domestic areas, while grasslands include natural and managed grass-dominated landscapes such as meadows and pastures. Semi-natural features, like field margins, hedges, grass strips, lines of trees, ponds, terraces, patches of uncultivated land, are essential components, providing important ecological functions and ecosystem services such as habitat connectivity, pollination, and pest regulation. Agroecosystems host some of the most species-rich habitats in the EU, with around 50% of European species depending on agricultural habitats. Agrobiodiversity, including genetic resources for food and agriculture, is vital for resilience against climatic and economic crises, ensuring food security. As heavily human-modified systems, agroecosystems lack a natural reference level; instead, their health is gauged by their ability to support biodiversity, maintain abiotic resources, and deliver ecosystem services. Sustainable management is crucial for preserving their long-term functionality and resilience. EU policies, especially the Common Agricultural Policy (CAP), along with the Habitats and Birds Directives, Natura 2000, and water and climate regulations, play a pivotal role in shaping agroecosystem sustainability by integrating environmental priorities into agricultural practices.

Agroecosystems face major pressures such as habitat conversion from soil sealing to shifts in farming intensity, alongside climate change, which affects crop yields, growth patterns, and distribution. Pollution from nitrogen, phosphorus, and pesticide use leads to nutrient enrichment, while overexploitation involves unsustainable water use and disruptions in ecosystem energy flows, as indicated by the HANPP metric (i.e., Human Appropriation of Net Primary Production; Krausmann et al., 2012). Additional pressures include invasive alien species (IAS), soil erosion, and the loss of soil organic matter.

Evaluation of the ecosystem condition indicator long-list

For agroecosystems, the evaluation was carried out for a total of 18 condition indicators and 17 pressure indicators, for which the results are included in Annex 4.

Agroecosystem condition

The expert group identified several additional indicators specific for agroecosystems not included in the shortlist, and incorporated them into the assessment, including *Soil moisture deficit*, *Species richness (specifically regarding key species groups such as farmland birds)* and *Share of cover crops*. *Soil erodibility* was proposed as a replacement for *Soil erosion*. Outside of the initially proposed categories, *Density of semi-natural areas*, and *Fragmentation* were additionally suggested as indicators of landscape structure. No relevant indicators of water quality were identified for agroecosystems. *Livestock density* was suggested to be more reflective of ecosystem services and therefore removed from the selection.

Among the 17 remaining condition indicators, 14 had data reported as available. Indicators such as *Soil Organic Carbon* (*SOC), C:N ratio, Density of semi-natural areas,* and *Taxonomic diversity* were rated highly for importance, validity, and instrumental relevance. Scores for simplicity were generally high, with many indicators considered both easy to understand and calculate. Sensitivity to human influence varied: indicators like *Soil moisture deficit* and *Species richness* scored high, while *Taxonomic diversity* and *Soil packing density* received lower scores. *NDVI* was rated lower across importance, parsimony, and simplicity. Parsimony and reliability were more mixed. Indicators such as *SOC* and *C:N ratio* were viewed as both distinctive and reliable, while others, including *Soil erodibility* and *Net Primary Production*, showed greater overlap with other indicators or lower reliability.

Agroecosystem pressure

It was recommended by the expert group that water pollution pressures should be removed from the framework for agroecosystems and only be applied exceptionally in cases where reliable on-field data is available, and that air pollution should also not be considered as it represented an external pressure acting on the ecosystem. Of the 11 pressure remaining indicators evaluated, 9 had data reported as available. *Soil imperviousness*, *Fertilizer surplus*, *Pesticide residues*, and *Disturbance intensity* received higher scores for importance and validity.

Scores for directional meaning and sensitivity varied. Indicators such as *Fertilizer surplus* and *Pesticide residues* were rated as interpretable and responsive to pressures, while *Human population* and *Fragmentation pressure* received lower scores for clarity and reliability. Several pressure indicators showed moderate scores across most criteria but did not rank highly for overall importance due to perceived redundancy or weaker connections to ecosystem services.

<u>Potential minimum indicators</u>

Tables 5 and 6 show the potential minimum indicators for describing agroecosystem condition and pressure, respectively.

Table 5: Potential minimum condition indicators for agroecosystems (see Annex 5 for details). * = Indicators in the EU-wide methodology to map and assess ecosystem condition.

Class	Category	Variable	Resolu-tion	Unit	Year	Source
AC1	Water availability	Soil water index	1 km	%	2015 - present	EU Copernicus Land Monitoring Service
	Soil condition	Bulk density	100 m	Mg/m^3	2018	EU JRC ESDAC
AC2	Air	na				
	Water	na				
	Soil	Soil Organic Carbon (SOC)*	500 m	g/kg	2014	JRC ESDAC
BC1	Species diversity	Farmland bird diversity*	10 km	n°/10 km	2013 - 2018	EEA
		Bumblebee diversity	10 km	n°/10 km	1991 - 2012	Polce et al., 2018
		Crop diversity*	10 m	n	2022	EU JRC
BC2	Vegetation	Share of cover crops	100 m	%	2016	EU JRC ESDAC
		Small Woody Features*	5 m to 100 m	m/m^2	2017 - 2019	EU Copernicus Land Monitoring Service
BC3	Productivity	Soil biomass productivity	1 km	Unitless	2016	EU JRC ESDAC
		Net Primary Production	300 m	$g.C/m^2/d$	2023 - present	Copernicus
LC	Connectivity	Density of semi-natural areas	10 m	%	2018-2021	EU Copernicus Land Monitoring Service

Table 6: Potential minimum set of pressure indicators for Agroecosystems (see annex 5 for details). * = Indicators in the EU-wide methodology to map and assess ecosystem condition.

Class	Category	Variable	Resolu-tion	Unit	Year	Source
AP1	Water use	Water Exploitation Index plus (WEI+)	River sub-basins	%	2019	EEA
	Soil	Imperviousness	10 m	%	2018	EU Copernicus Land Monitoring Service
AP2	Air pollution	Accumulated Ozone over Threshold of 40 ppb (AOT40)*	2 km	µg/m^3/h	2018	EEA
	Water pollution	na				
	Soil pollution	N & P surplus	1 km	kg/ha/y	2009	EEA
		Heavy metals*	1 km	g/ha/y	2009	EU JRC ESDAC
BP1	Species	Pressure by IAS*	10 km	Unitless	2022	Polce et al., 2023
CP1	Land-use	na				
CP2	Fragmentation	Mesh density	100 m	n°/1000 km^2	2009 - 2019	EEA

<u>Discussion</u>

Agroecosystems cover a significant share of European land and are central to discussions on ecosystem condition. As highly managed ecosystems, their assessment involves distinct challenges when identifying a minimum, yet meaningful, set of EC indicators. The expert group stressed that this selection was only an initial attempt at an EU-wide applicable set of agroecosystem condition indicators. Many indicators had to be set aside due to lack of consistent data. The group also acknowledged that one size may not fit all regions. Agroecosystems in Europe are diverse and the importance of certain condition aspects can vary. A minimal set inherently risks overlooking some region-specific condition issues. The agreed strategy was to focus the minimum set on broadly relevant indicators (e.g. soil organic carbon is universally relevant; semi-natural habitat cover is broadly applicable) and allow for additional indicators at regional level to complement the core set. As data availability improves, the optimal indicator set may shift. Thus, a forward-looking perspective is maintained: the minimum set should be revisited periodically.

One foundational challenge was the strict classification of indicators as either ecosystem “condition” or “pressure”. As mentioned above, condition indicators describe the state or quality of the ecosystem, whereas pressure indicators describe external or anthropogenic influences. In practice, however, this boundary can blur. Certain phenomena are considered pressure only if they reach a certain level, which muddles definitions. The group noted that the measurement units of a metric often hint at its role: indicators measured as rates or fluxes (per unit time or area per year) frequently signify pressures or flows, whereas metrics measured as quantities or concentrations (stock at a given time) tend to indicate condition. The expert group agreed that, wherever possible, actual condition variables should be prioritized instead of direct pressure metrics, aligning with SEEA-EA guidance (UN et al., 2024). In SELINA, ecosystem condition is understood more strictly as the ecological state of the system, whereas the JRC approach incorporates a broader set of variables, including aspects related to management practices. For example, within SELINA, soil nutrient concentrations (e.g., total nitrogen) are considered indicators of ecosystem condition, while nutrient flows, such as annual nutrient balances or surpluses, are classified as pressures. Notably, the indicator "soil total nitrogen" was ultimately dropped from the minimum set during the selection process, despite its alignment with this conceptual framework.

A specific debate emerged around pressures emanating from agroecosystems (e.g., nutrient runoff leading to water eutrophication, pesticide drift affecting adjacent habitats) versus pressures impacting agroecosystems. Another point of discussion related to air and water pollution (Table 6, AP2 - Chemical pressure). Here, the boundary issues were highlighted. Air and groundwater extend beyond agroecosystem limits.

An interesting dimension of the discussion was how indicators are framed in terms of naming and calculation, and the implicit normative judgements that come with that. Some ecosystem condition indicators can be calculated and expressed in multiple ways. The expert group gave examples: For instance, "water balance" is a neutral term compared to "water deficit", even when based on the same input data. Similarly, "N balance" vs. "N surplus" may influence interpretation. The group leaned toward value-neutral calculation and naming to maintain objectivity, recommending thresholds or reference levels for determining condition quality. However, some agroecosystem experts argued that using indicators such as "water deficit" would reduce effort needed with regard to further calculations and/or interpretation.

Soil erosion proved to be a nuanced case. On the one hand, actual soil erosion rate (e.g. tonnes of soil lost per hectare per year) is a process of degradation often driven by external forces (rainfall, wind) and land management (tillage, vegetation cover). On the other hand, severe ongoing erosion clearly signals a worsening condition of the soil. The expert group distinguished between soil erodibility and erosion as a process. Soil erodibility (often represented by the K-factor in the Universal Soil Loss Equation) is an inherent property of the soil – essentially a condition indicator reflecting how prone the soil is to erosion based on its texture, organic matter, structure, etc. It does not measure erosion happening, but the vulnerability or resilience of the soil. In contrast, soil erosion (e.g. in the form of modelled annual soil loss) involves the interaction of soil condition, landscape, climate (rainfall erosivity), and management (a pressure component). Including "erosion" as a core indicator raised concerns because it conflates these factors. The group therefore suggested replacing soil erosion in the core set with soil erodibility. Indeed, prior agroecosystem assessments have adopted this approach: for example, Steinhoff-Knopp and Burkhard (2018) use soil erodibility (K-factor) as a condition metric.

When considering heavy metals as a pressure indicator, it is important to recognize that some heavy metals occur naturally in soils due to underlying geological conditions. Therefore, distinguishing between natural background levels and anthropogenic inputs is essential to accurately interpret their presence as a pressure on ecosystem condition. Moreover, the forthcoming EU Soil Monitoring Law identifies exceedances of critical heavy-metal concentrations or inputs as core soil-health metrics because of their implications for soil biodiversity, ecosystem services, and food security(Panagos et al., 2025). Embedding a heavy-metal exceedance indicator in our agroecosystem indicator set therefore ensures coherence with the monitoring obligations that EU Member States are expected to begin implementing when this law comes into force.

Landscape structure indicators, such as habitat fragmentation or connectivity, are common in ecosystem condition assessments. However, the expert group noted that fragmentation has a different flavour in agroecosystems compared to forests or other natural habitats. In many ecosystems, fragmentation (the breaking up of habitat into smaller, isolated patches) has inherently negative effects for ecosystem condition, as it usually signifies habitat loss and isolation affecting wildlife. Classic fragmentation metrics (e.g. patch size, edge density) often interpret a more fragmented landscape as one of poorer condition for biodiversity. In agroecosystems, by contrast, the land is primarily under production and not habitat in the traditional sense – yet within farmland landscapes, having many semi-natural patches interwoven can actually be beneficial. In other words, a “fragmented” agricultural landscape (with fields broken up by hedgerows, woodlots, grass margins, etc.) might even increase landscape connectivity for wildlife and boost ecosystem service provision (like pollination and biological pest control), relative to a vast homogeneous expanse of cultivation. The group therefore stressed that traditional fragmentation metrics must be interpreted carefully for agroecosystems. The agroecosystem group highlighted that indicators should rather emphasize connectivity and heterogeneity. For instance, the density of semi-natural areas is well-supported in landscape ecological literature as a key agroecosystem condition metric (Tscharntke et al., 2005; 2012).

The use of biomass-related indicators such as *NDVI* or *Net Primary Productivity* (*NPP*) in agroecosystems requires caution. While these metrics are often used to assess ecosystem functioning or productivity, their interpretation as condition indicators in managed systems is problematic. High *NDVI* or *NPP* values may reflect intensive cultivation, high fertilizer input, or short-term biomass gains, but not necessarily ecological sustainability, good functionality, or a good condition.

The treatment of invasive species provoked debate on whether it signifies a condition or a pressure. Invasive alien species can drastically alter ecosystem condition by outcompeting native flora and fauna, so their presence and abundance can be viewed as a proxy for ecosystem degradation (i.e. a condition indicator, where high abundance of IAS implies poorer condition). However, invasions are dynamic processes, so one might classify rates of new invasions or spread as a pressure on the ecosystem. The decision was taken to include this indicator in the pressures table in line with the framework developed in Section 6.2.

Atmospheric nitrogen deposition was not included under the chemical pressure class AP2 – air pollution, as it is already integrated into the calculation of the nitrogen balance indicator (surplus/deficit), which is prioritized in this framework. According to EUROSTAT and EEA methodologies, nitrogen balance accounts for all relevant inputs, including atmospheric deposition, biological fixation, and direct applications via fertilizers and manure (see EUROSTAT, EEA: (EEA, 2018). Since the nitrogen balance provides a more comprehensive view of nutrient pressures, including both indicators would result in double counting. Therefore, the nitrogen balance is prioritized as the primary indicator of nutrient-related pressure, and the *Eutrophication risk* (*N deposition exceedance*) should only be used as a substitute when no nitrogen balance data are available.

Limitations and constraints of the minimum indicator set

Agroforestry represents a distinct and complex land-use system that combines elements of both forestry and agriculture. As such, it was not the primary focus of the current assessment, but clearly warrants dedicated attention in future work to ensure its unique structural, functional, and compositional characteristics are adequately reflected in ecosystem condition indicators.

It was highlighted that several agroecosystem indicators are season sensitive. For example, soil water content or vegetation cover might need to be interpreted in relation to the growing season. Annual averages may obscure critical seasonal lows (e.g. summer droughts). Thus, indicators should be defined with appropriate temporal resolution, focusing on ecologically significant periods.

Comparison with the EU-wide methodology to map and assess ecosystem condition

The group discussed the example of the JRC's earlier (such as the MAES framework) and more recent work (Paracchini et al. 2025), which take a more comprehensive "many variables" approach. The comprehensive approach offers maximum information and flexibility (one can derive various indices or focus on particular issues as needed), whereas a minimum set forces prioritization but may enhance consistency.

Data gaps and recommendations

Several relevant data gaps, especially related to the biodiversity assessment, have been identified in the current framework due to the lack of large-scale monitoring and spatially explicit data, although these data are essential to fully assess agroecosystem condition. Addressing these data gaps will enhance our understanding of ecosystem health and dynamics, enabling more effective environmental management and conservation strategies. These include:

- BC3: Soil biodiversity indicators such as earthworms and dung beetles are essential for assessing soil health and functionality
- BC1: The retained condition indicators for this category include bumble bee species as pollinators, but this may be limited by regional differences in diversity. Additionally, the available data source is outdated and may not reflect current bumble bee populations. Other pollinator groups, especially wild bees and hoverflies, play an important role in pollination ecosystem service supply. However, monitoring data at EU scale is lacking. The European Pollinator species monitoring scheme (EuPoMS), Potts et al., 2024 could provide valuable data to fill this gap in the future. Additionally, the abundance and diversity of butterflies is an important indicator of grassland health and biodiversity. However, data is not available for the EU.

- BP1: Monitoring pests and diseases is essential for understanding their impact on ecosystem condition and resilience.
- CP1: Whilst a general indicator of land-use intensity was rejected due to overlap with other pressure variables, tillage and machinery use were identified as being interesting variables with no current suitable datasets.
- AC2: Information on pesticides is highly relevant for agroecosystems. However, spatially explicit data on pesticides is only made available by the JRC at NUTS2 level, which limits its use to define spatially explicit pressures acting on agroecosystems.

While data on farmland birds is available, significant challenges remain in how this data is interpreted in the context of ecosystem condition assessments. Future research should aim to refine the methodological approaches used - such as the example from Hungary, where expected species composition in agroecosystems was first defined and then compared to actual observations. When interpreting data on pollinators, it is important to recognize that factors such as weather conditions in the preceding year can strongly influence population dynamics and distribution patterns. Therefore, changes in pollinator distributions should be interpreted with caution, as they may reflect short-term climatic variability rather than underlying shifts in ecosystem condition.

6.3.3. Forests

Definition of the ecosystem type

There is no universally accepted definition of a forest, as highlighted by Lund (2018), who documented over 800 distinct definitions used globally. These definitions vary significantly depending on institutional, legal, ecological or cultural contexts, with differences in criteria such as minimum area, canopy cover, tree height, and land use. This diversity reflects the complexity of forest classification and underscores the importance of clearly stating the definition used in any given assessment.

For the selection of forest ecosystem condition indicators, we adopt the definition provided by the United Nations Food and Agriculture Organization (FAO) (2000): “Land spanning more than 0.5 hectares with trees higher than 5 metres and a canopy cover of more than 10 percent, or trees able to reach these thresholds in situ. It does not include land that is predominantly under agricultural or urban land use”. Plantation forests (including Christmas tree plantations) are included in this assessment, acknowledging their ecological and economic relevance. However, forest ecosystem conditions are varying in relation to the naturalness of forest types. Agroforestry systems, in contrast, are generally excluded unless they meet the minimum canopy cover and land use criteria defined before or by national or EU-level forest typologies. Urban forests are also not considered in this section.

Forest ecosystems face multiple human pressures, including deforestation, land-use change, and fragmentation from agriculture and infrastructure development. Pollution (e.g., acid rain from industrial emissions), overexploitation of resources, and climate change further degrade forest health, while invasive species, recreational overuse, and fire mismanagement disrupt ecological balance. These pressures often act together, intensifying their impact and threatening forest biodiversity and resilience.

Evaluation of the ecosystem condition indicator long-list

For forests, the evaluation was carried out for a total of 39 condition indicators and 32 pressure indicators, for which the results are included in table Annex 4.

Forest ecosystem condition

The expert group identified several additional indicators and incorporated them into the assessment, primarily focused on indicators of structural state reflecting forest structural complexity, such as *Variance in forest canopy height* and *Variability of size (e.g. number of diameter classes)*. More contextually specific indicators for BS1 (*Proportion of native tree species*) and CS1 (*Variance in forest patch size*) were also proposed for evaluation.

Among the 36 state indicators, 29 had data reported as available. A number of indicators, including *Functional diversity, Net Primary Production, Tree cover, Mean patch size,* and *Variance in forest patch size,* were rated highly for both importance and validity. These were also supported by strong scores for instrumental and intrinsic relevance. Scores for simplicity were generally high, with many indicators considered easy to interpret and calculate. Indicators such as *Forest age*, *SOC*, and *Tree height (average)* demonstrated strong consistency across simplicity, reliability, and sensitivity to human influence. Several indicators capturing vegetation structure (e.g. *Canopy height*, *Variance in canopy height*, *Enhanced Vegetation Index*) also performed well across multiple criteria. Some indicators, including *Leaf Area Index*, *NDVI*, and *PSRI*, received lower importance and parsimony scores, suggesting limited distinctiveness or perceived relevance. While these indicators were supported by data, their conceptual fit appeared weaker compared to others. Sensitivity to human influence was variable. Indicators like *Forest cover density* and *Connectivity index* were rated as moderately responsive, while indicators representing static attributes, such as *Basal area*, scored lower in this dimension.

Forest ecosystem pressure

The expert group proposed to exclude indicators of water pollution, *Nitrogen deposition* and fertilizers (*NP surplus*) for forest ecosystems. Of the 22 remaining pressure indicators, 12 were associated with available data. Indicators such as *Soil imperviousness*, *Sulphur dioxide*, *Heavy metals*, and *Land consumption* received high importance scores and were also rated favourably in terms of validity and sensitivity. Indicators covering air pollution (*Ozone*, *Particulate matter*, and *Nitrogen dioxide*) received moderately consistent scores across validity, instrumental relevance, and reliability. In contrast, *Burn severity* and *Increase in air temperature* had more mixed profiles, with lower reliability and simplicity scores despite their importance. Simplicity and parsimony varied widely. *Land consumption* and *Pressure by invasive alien species* performed well in these areas, whereas others like *Soil acidity* and *CO levels* showed lower reliability and clarity in interpretation. Among those scored, pressures associated with chemical inputs and structural change in the landscape were generally better supported than biological or hydrological pressures.

Potential minimum indicators

Tables 7 and 8 show the potential minimum indicators for describing forest condition and pressure, respectively.

Table 7 : Potential minimum condition indicators for forests (see Annex 5 for details). * = Indicators in the EU-wide methodology to map and assess ecosystem condition.

Class	Category	Variable	Resolu-tion	Unit	Year	Source
AC1	Water availability	Soil water index	1 km	%	2015 - present	EU Copernicus Land Monitoring Service
	Soil condition	Soil erodibility	500 m	t.ha.h / ha.MJ.mm	2014	JRC ESDAC
		Bulk density	100 m	Mg/m^3	2018	JRC ESDAC
AC2	Air	na				
	Water	na				
	Soil	SOC*	500 m	g/kg	2014	JRC ESDAC
		C:N ratio	500 m	Unitless	2019	JRC ESDAC
BC1	Species diversity	Forest bird diversity	10 km	n°/10 km	2013 - 2018	EEA
		Proportion of native tree species	1 km	%	1993 - 2013	De Rigo et al., 2016
BC2	Vegetation cover	NDVI*	1 km	Unitless	1999 - 2020	EU Copernicus Land Monitoring Service
		Above-ground biomass*	100 m	Mg/ha	2022	Santoro et al., 2025
		Tree cover density*	10-100 m	%	2021	EU Copernicus Land Monitoring Service
		Canopy height	30 m	m	2019	Popatov et al., 2020

Class	Category	Variable	Resolu-tion	Unit	Year	Source
BC3	Productivity	Net primary production	300 m	$g.C/m^2/d$	2023 - present	EU Copernicus Land Monitoring Service
		Soil Biomass Productivity	1 km	score	2016	JRC ESDAC
LC	Connectivity	Connectivity index of semi-natural areas	100 m	%	2018-2021	EU Copernicus Land Monitoring Service

Table 8 : Potential minimum pressure indicators for Forests (see Annex 5 for details). * = Indicators in the EU-wide methodology to map and assess ecosystem condition.

Class	Category	Variable	Resolu-tion	Unit	Year	Source
AP1	Water use	na				
	Soil	Imperviousness	10 m	%	2018	EU Copernicus Land Monitoring Service
		Soil loss due to harvesting and fire	100 m	Mg/ha/y	2010	JRC ESDAC
AP2	Air pollution	Exceedance of critical loads for acidification	point grid	eq/ha/y	2000 - 2020	EMEP/EEA
		Exceedance of critical loads for eutrophication *	point grid	mol Neq/ha/y	2022	EMEP/EEA
		AOT40*	2 km	$\mu g/m^3/h$	2018	EEA
	Water pollution	na				
	Soil pollution	Soil acidity	10 m	pH	2012 - 2018	EU Copernicus Land

Class	Category	Variable	Resolu-tion	Unit	Year	Source
						Monitoring Service
BP1	Species	Insect and disease disturbances	1 km	area affected (ha)	1963 - 2021	Forzieri et al., 2023
		Pressure by IAS*	10 km	unitless	2022	Polce et al., 2023
CP1	Land-use	na				
	Disturbance	Number of disturbance events	30 m	n° events	1985-2023	Viana-Soto and Senf, 2024
CP2	Fragmentation	Mesh density	100 m	n°/1000 km²	2009 - 2019	EEA

Discussion

The distribution of forest condition indicators across EC categories is notably uneven. Structural indicators, such as *canopy height* and *above-ground biomass*, are overrepresented. The popularity of studies focusing on indicators of forest structure is largely due to their usefulness as proxies for biodiversity (McElhinny et al. 2005). Monitoring the various populations of organisms typically requires substantial expertise, financial resources, and time investment. Forest stand structure can serve as an easily measurable surrogate variable, as well as a factor that helps explain the causes and patterns of biodiversity within a forest ecosystem (Spies 1998, Melin et al. 2019). The availability of remote sensing data, their ease of measurement and their quantifiable relationship with forest structure measurements has significantly increased their popularity as proxy condition variables (Surovy and Kuželka 2019, Fassnacht et al. 2023).

In contrast, functional and compositional indicators, although ecologically vital, are underrepresented, primarily because of data limitations and the complexity of their assessment. Compositional data are available from national inventories, which are often not harmonised or accessible (Vidal et al. 2016). Whereas remote sensing data are suitable to identify tree species (Schadauer et al., 2024), mixed deciduous forests represent a serious challenge (Rueva et al. 2025). The most effective methods, usually combining LiDAR and optical, especially hyperspectral data, require special expertise and resources, which still prevent them from being used over large areas in many countries. However, so far they were tested mainly on the local scale (Riedler et al.,2015; Likó et al., 2022).

Recent advances in remote sensing have opened new avenues for assessing ecosystem functioning. Satellite-based approaches offer promising tools for monitoring ecosystem functional attributes, such as productivity, seasonality, and energy balance (Pettorelli et al., 2018). In particular, the concept of Ecosystem Functional Types (EFTs) has gained traction as a means to classify ecosystems based on their functional dynamics rather than solely on structural or compositional traits (Alcaraz-Segura et al., 2006; Alcaraz-Segura et al., 2009; Cazorla et al., 2021). These approaches, often based on time-series analysis of vegetation indices, provide a valuable framework for integrating functional diversity into conservation and monitoring strategies.

Discussions among experts highlighted the need to ensure that each indicator class is represented to avoid overlooking critical aspects of forest condition. It was also suggested that weighting indicators based on ecological relevance and data reliability could help address this imbalance and improve the robustness of condition assessments.

Limitations and constraints of the minimum indicator set

The concept of a minimum common set of indicators, while intended to standardise assessments across the EU, presents several challenges. One key limitation is the risk of over-simplification, as for some purposes, such as assessing the local effectiveness of forest management measures, the minimum set may obscure important ecological nuances, particularly in diverse forest types.

Another challenge is the presence of overlapping indicators that measure similar aspects of forest condition. For instance, both *NDVI* and *LAI* provide information on vegetation cover, but they usually correlate and thus using them together may exaggerate certain characteristics without offering additional insight. Specific purposes such as integration with ES assessment may call for prioritising one indicator over the other (Cimburova and Barton, 2020). Having a fixed set of indicators can be too rigid, making it difficult to adapt assessments to the specific ecological conditions and data availability of different regions.

While relevant for specific policy assessments, indicators such as *deadwood* or *endemic species* were omitted due to data or methodology limitations. This further reduces the completeness and ecological relevance of the assessment. The selection of indicators for forests also lacks a variable of intensity of use. The ratio between available wood biovolume and wood extracted was raised as a potential indicator, however it was decided to not include this indicator due to potential for confusion and double counting of ES.

Comparison with the EU-wide methodology to map and assess ecosystem condition

The EU-wide methodology to map and assess ecosystem condition (Vallecillo et al., 2022) adopts a narrower scope in its selection of indicators, particularly within the chemical pressure category. It places a strong emphasis on compositional indicators, which, while important, are often difficult to implement due to data gaps and limited spatial coverage. In contrast, the approach used in this review advocates for a broader and more flexible framework that integrates expert judgement and accommodates regional specificity. Notable differences involve the inclusion of plantation forests, whereas Vallecillo et al,. (2022) tend to focus on more natural forest types. This review also places greater emphasis on functional indicators and landscape metrics, recognising their importance in capturing ecosystem processes and spatial dynamics.

Data gaps and recommendations

Several limitations affect the robustness and comparability of forest condition indicators. Firstly, spatial resolution remains a significant challenge. Many indicators are derived from EU-wide datasets, which, while comprehensive, may not capture local variability. In contrast, national- and municipal-level data often offer higher resolution, but suffer from a lack of harmonisation across countries, despite ongoing efforts in Europe (ENFIN, 2024). Functional diversity, which is essential for ecosystem resilience and ES supply, is difficult to quantify and often lacks consistent reference levels. Meanwhile, indicators such as *NDVI* are widely used due to their comparably high accessibility, despite their limited ecological specificity. The inclusion of game species and browsing pressure, such as deer and wild boar, as indicators of forest ecological balance and sustainability, is also inconsistent, despite their recognised impact on forest regeneration and structure (Zoltán et al. 2023), and on forest biodiversity (e.g., Afonso et al 2024, Lecomte et al. 2024). This is often due to data availability issues, or the quality of the available data (Hardalau et al. 2024), and to the modelling approaches that may not allow reliability at small forest patch level (see ENETWILD consortium et al. 2022).

Temporal gaps also pose a problem. Creating field data time series is resource-intensive and thus large-scale datasets inevitably have a relatively low frequency of revisits. Although remote sensing data-derived indicators such as the *NDVI* and the *Normalized Difference Infrared Index* (NDII) provide valuable time-series data with high temporal resolution, their interpretation is difficult or even impossible without contextualising with auxiliary data (e.g., on age, species, site, earlier management activities) or local knowledge. Furthermore, many of the more easily accessible indicators (derived from optical satellites) are only suitable for the study of the highest canopy levels, failing to catch vertical diversity and the characteristics of the lower canopy layers. Another limitation is the lack of spatially explicit data for certain indicators. For example, variables such as soil organic carbon are frequently modelled or inferred, which can reduce their precision and reliability. National inventories, which may be suitable to detect such changes, are usually point-like and as such do not provide complete coverage. Thus, for different reasons, the indicators may fail to detect subtle ecological changes or the impacts of forest management practices. Moreover, discrepancies can arise between indicators derived from statistical models and those based on direct observation. Some indicators rely on proxies, such as nitrogen deposition exceedance, which may not align with observed forest conditions on the ground. Lastly, agroforestry systems are notably underrepresented in current datasets, despite their ecological importance in transitional zones. Despite these limitations, there are significant opportunities to enhance forest condition assessments through synergies with ongoing EU programmes. Notably, Sentinel data offers a powerful platform for improving spatial and temporal resolution across the EU. With 10-meter spatial resolution and 5-day revisit cycles, Sentinel-2 enables consistent and scalable monitoring of forest ecosystems (Copernicus, 2023). Sentinel-1, with its radar capabilities, further supports biomass estimation and structural analysis of forests (ESA, 2022). While models and fieldwork remain essential, integrating Copernicus data can strengthen the accuracy, coverage, and timeliness of forest condition indicators.

These limitations and opportunities together highlight the need for improved data integration, methodological transparency, and the development of more context-sensitive indicators. As an applicability example, Box 3 shows how the use of a reduced number of indicators can be used for assessing EU forest condition.

Box 3: Key Messages for Forests

Tracking the Pulse of Europe's Forests: A Condition-Based Approach to Restoration

Why Forest Condition Accounts Matter

Forests cover 35% of Europe's land area and are crucial for biodiversity conservation and climate change mitigation. Despite overall forest expansion, degradation continues to threaten the ecosystem services they provide. The lack of a consistent EU-wide standard for assessing forest health hinders effective monitoring, restoration, and policy enforcement. Forest condition accounts address this gap by providing a robust, repeatable, and internationally recognized framework for measuring and tracking the ecological condition of forests.

How Forest Condition Indicators Works

Using the SEEA-EA and high-resolution spatial data, Maes et al. (2023) assessed 44 forest types (2000–2018) across 1.96 million km², scoring forests from 0 (degraded) to 1 (natural reference). The method includes:

- Selecting 7 variables spanning abiotic, biotic, and landscape characteristics: *Vegetation water content*, *Soil organic carbon*, *Species richness of threatened forest birds*, *Tree cover density*, *Forest productivity*, *Forest connectivity* and *Landscape naturalness*
- Benchmarking conditions against primary/protected forests to derive reference level
- Rescaling indicators and aggregating them into a condition index (0–1 scale)
- Visualizing and reporting results in maps and accounting tables

Benefits and Limitations

- Enable cost-efficient, broad scale and consistent EU forest monitoring
- Support forest spatial planning and policy decisions
- Reference condition estimation is limited by human-altered baselines
- Data gap constrains the effectiveness of the result (i.e., risk of over-simplification)
- Policies must support long-term monitoring because condition changes are slow

Policy Applications

- Aligns with the EU Green Deal, Biodiversity Strategy, and LULUCF* targets
- Identifies priority areas for restoration and funding (e.g., EU Forest Strategy and LIFE investments)
- Supports integration of natural capital into national accounting
- Aids territorial planning through spatially detailed insights

Recommendations

- Strengthen in situ validation with forest inventories for enhancing forest data system
- Integrate forest management-sensitive indicators (e.g., *deadwood*, *Tree species richness, Age structure*)
- Improve spatial data resolution, temporal update and harmonization across regions

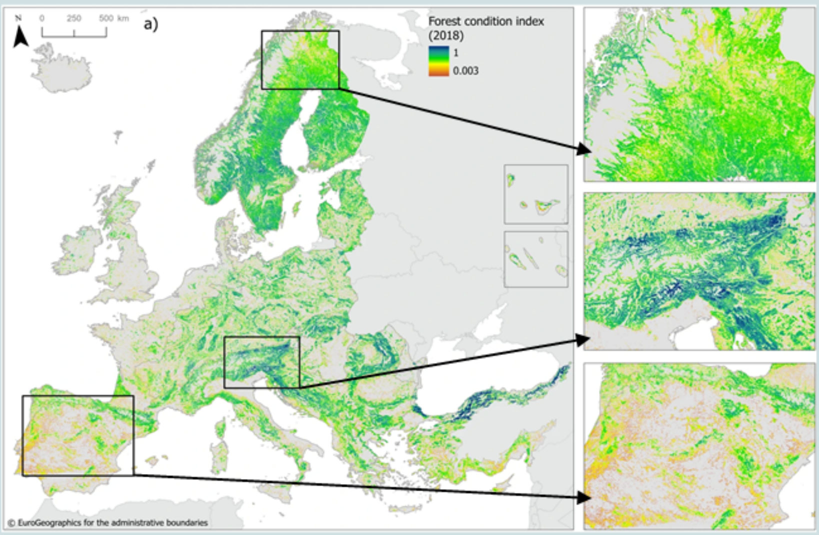


Figure: Forest condition in Europe for the year 2018. Forest condition varies widely across Europe, with particularly healthy forests found in the eastern Alps, the Carpathians, Scandinavia, and along the Black Sea coast. In contrast, regions such as the Atlantic plain, the British Isles, and the Iberian Peninsula exhibit a more scattered forest distribution with generally lower forest conditions. Between 2000 and 2018, 63% of the forest area improved, but 37% declined, especially in Southern and Eastern Europe. (Maes et al. 2023).

*LULUCF (Land-Use, Land Use Change and Forestry) covers carbon emissions and sequestration by forest ecosystems

6.3.4. Urban ecosystems

Definition of the ecosystem type

Urban ecosystems can be defined as built-up land and the surrounding socio-ecological-technological systems where the majority of people live (Andersson et al.2021). Urban ecosystems are therefore a mosaic of anthropogenic, natural and semi-natural land covers (Vallecillo et al., 2022).

Urban ecosystems are primarily impacted by human pressures such as land-use change, habitat loss, and pollution. Urbanization replaces natural areas with buildings and infrastructure, leading to fragmentation and a decline in biodiversity. Air, water, noise, and light pollution are prevalent, affecting both human and ecological health. High resource consumption and waste generation strain local environments, while the urban heat island effect alters local climate conditions. Urban systems are primarily designed to meet human habitat needs, with green infrastructure often focused on delivering cultural and regulating services rather than supporting biodiversity. Invasive alien species, frequently introduced through gardens for their aesthetic and cultural value, exemplify this prioritization. However, the spread of these species, displacing native vegetation and reducing biodiversity, combined with the limited availability of green spaces, places additional stress on urban ecosystems and diminishes their capacity to provide essential ecosystem services (e.g., air quality and climate regulation, pest and disease control).

Evaluation of the ecosystem condition indicator long-list

For urban ecosystems, the evaluation was carried out for a total of 31 condition indicators and 24 pressure indicators, for which the results are included in Annex 4.

Urban ecosystem condition

The expert group identified several additional indicators for Urban ecosystems that were not already included in the shortlist, and incorporated them into the assessment, including *BOD (Biochemical Oxygen Demand)*, *Tree canopy cover*, and *Share of green (and blue) space*. Additionally, it was proposed to include multiple potential air quality indicators under class AS2, including *PM2.5, PM10,* NO_2, and SO_2. A total of 9 indicators received negative feedback, with 7 marked as "Disagree" and 2 as "Strongly disagree" regarding their position as a good indicator of urban EC.

Among the 20 remaining condition indicators, 15 had data reported as available. Indicators such as *Tree canopy cover*, *Soil imperviousness*, *PM2.5*, and NO_2 were scored as most important, and also received consistently high ratings across validity, directional meaning, and instrumental relevance.

Simplicity scores were generally high, particularly for indicators related to vegetation cover and air quality. Indicators such as *Tree canopy cover* and *Share of green and blue space* were rated as both easy to understand and operationally feasible. *SOC* and *NDVI* also performed well across multiple dimensions. Sensitivity to human influence was more variable. Indicators such as *SOC*, *NDMI*, and *Connectivity index* were viewed as responsive, while composite metrics like *Patch Cohesion Index* and *Landscape Fragmentation Index* received more moderate ratings across sensitivity and reliability. Indicators addressing air quality (*PM10*, *PM2.5*, *SO_2*, and *NO_2*) were consistently rated highly for validity and instrumental relevance, reflecting both their interpretability and their documented links to urban environmental conditions.

Urban ecosystem pressure

Among the 21 remaining pressure indicators, 10 had data reported as available. *Annual rate of net soil sealing, Noise pollution levels*, and *Light pollution levels* were identified as highly important and performed well across simplicity, directional meaning, and relevance criteria. The group ranked 'Soil imperviousness' highly but proposed it would be more appropriate as an indicator of state.

Air pollutant indicators (*CO*, *NO_2*, *PMx*, *Ozone*, and *SO_2*) received moderately high ratings across most criteria, though their importance scores varied. Ratings for validity, instrumental relevance, and simplicity were generally consistent across this group. Indicators related to waste, water extraction, and some chemical inputs were deemed not suitable for assessing urban ecosystem condition. Water-related indicators were not discussed by the expert group and are treated in the section dedicated to "Rivers and Lakes". Overall, pressure indicators for urban ecosystems were particularly focused on atmospheric and physical pressures.

<u>Potential minimum indicators</u>

Tables 9 and 11 show the potential minimum indicators for describing urban ecosystem condition and pressure, respectively.

Table 9 : Potential minimum condition indicators for Urban ecosystems (see annex 5 for details). * = Indicators in the EU-wide methodology to map and assess ecosystem condition

Class	Category	Variable	Resolu-tion	Unit	Year	Source
AC1	Water availability	Data gap				
	Soil condition	Data gap				
AC2	Air	na				
	Water	na				
	Soil	Data gap				
BC1	Species diversity	Data gap				
BC2	Vegetation cover	Tree cover density*	10-100 m	%	2021	EU Copernicus Land Monitoring Service
	Natural elements	Share of green (and blue) space*	10 m	%	2021	EU Copernicus Land Monitoring Service

Class	Category	Variable	Resolu-tion	Unit	Year	Source
BC3	Productivity	Net primary production	300 m	g.C/m²/d	2023 - present	EU Copernicus Land Monitoring Service
LC	Connectivity	Connectivity index of semi-natural areas	100 m	%	2018-2021	EU Copernicus Land Monitoring Service

Table 10 : Potential minimum pressure indicators for Urban ecosystems (see Annex 5 for details). * = Indicators in the EU-wide methodology to map and assess ecosystem condition

Class	Category	Variable	Resolu-tion	Unit	Year	Source
AP1	Water use	na				
	Soil	Imperviousness	10 m	%	2018	EU Copernicus Land Monitoring Service
AP2	Air pollution	Annual average concentration of PM2.5	1 km	$\mu g.m^{-3}$	2022	EEA
	Water pollution	na				
	Soil pollution	Data gap				
BP1	Species	Pressure by IAS*	10 km	unitless	2022	Polce et al., 2023
CP1	Land-use	Light pollution levels	10-40m	nW/cm²/sr	2021 - present	SDGSAT-1
CP2	Fragmentation	Mesh density	100 m	n°/1000 km²	2009 - 2019	EEA

Discussion

- Air quality indicators and imperviousness, whilst deemed important by the expert group, are not included in the minimum set of condition indicators, as they were deemed to be pressures under the definitions proposed in Section 5.3.
- A clear definition of the boundary of the assessment is a precondition for any application, since many indicators are meaningful only when applied at a specific spatial scale (single semi-natural patch within the urban matrix vs. neighbourhood vs. entire city). While the resolution specified in the tables above always refer to a

hypothetical raster map, the variables can also be calculated on different spatial units, which can be more meaningful than a grid, depending on the purpose of the assessment.
- Because of data gaps (expanded upon below) the minimum set of condition indicators is rather limited to indicators related to vegetation.

Limitations and constraints of the minimum indicator set

- The use of a single metric to describe landscape characteristics such as connectivity in urban ecosystems is limited, since landscape metrics only capture a very specific aspect of the green network. Combining several metrics is always a good practice.
- *PM2.5* was selected by the urban ET group as the most important air quality parameter in urban areas due to its direct link to human health. Other indicators linked to more direct impacts on vegetation could have also been considered, such as *AOT40*, but they are not commonly monitored in urban areas.
- *NPP* is a relevant variable linked to several functions and to the supply of ecosystem services by urban ecosystems. However, it requires careful interpretation to duly consider the limitations of the most common methods used to calculate it as well as the human inputs involved and their potential negative impacts.

Comparison with the EU-wide methodology to map and assess ecosystem condition

Only some of the variables listed in the EU-wide methodology are present in the minimum set described in Tables 9 and 10 above. This is partly due to data gaps, already acknowledged in the JRC report, especially related to soil (*soil carbon stock* and *heavy metals in soil*), to species composition (*autochthonous woody vegetation species richness, urban bird species richness,* and *wild pollinators indicator*), and to *noise pollution exposure*. All these variables have been discussed by the urban ET group and the lack of data to measure them in a consistent way across the EU was highlighted as a major constraint to urban condition assessments (see subsection below).

The EU-wide methodology also includes two variables related to riparian vegetation: *(semi)natural riparian land cover* and *riparian fragmentation*. Although deemed highly informative, these were not included in the proposed set as they apply only to a subset of European cities.

The main commonalities between the proposed set and the EU-wide methodology are in two key structural state variables focusing on vegetation, i.e. *tree canopy cover* (estimated here as *tree cover density*) and *green space %* (which we renamed into "share of green (and blue) space, to also highlight the contribution of water areas). Besides being simple to measure and to understand, and having a clear directionality, these two variables are of great policy relevance as they are at the basis of the targets set in Article 8 of the Nature Restoration Regulation. The urban ET group also discussed the use of *greenness (max annual NDVI)* as a suitable variable for urban areas. Despite acknowledging its usefulness, especially in data scarce contexts, the two proposed variables based on a detailed mapping of green/blue elements and vegetation now available in the Copernicus datasets were considered more precise and of easier interpretation.

Analogous considerations were done on two other variables based on remote sensing data included in the EU-wide methodology: *NDMI* and *plant evapotranspiration*. Both variables can be used to describe vegetation physiological status and functionality, but their interpretation is not easy, especially if taken alone without additional information on the state of vegetation and soil (e.g., canopy cover and vegetation type). Setting a single reference level for such variables considering the climatic variability across European urban areas was also considered impractical.

Similar issues with interpretation were raised regarding variables that combine physical conditions of urban areas with population, for example *imperviousness per inhabitant* or *green space per inhabitant*. A correct interpretation of changes in such variables, especially in urban areas characterized by a shrinking population, was considered potentially challenging by the members of the urban ET group. Besides these limitations, the variable included in the EU-wide methodology *waste generated per inhabitant* was criticised because the impacts generated by urban metabolism affect areas larger than human settlements, often involving telecoupling effects that would be too simplistic to attribute only to urban areas. *Air pollutants' concentration* and *pressure by invasive alien species*, instead, were regarded by the group as highly important variables to measure urban conditions and were both included in the proposed set.

Finally, landscape characteristics captured by variables such as *integrity and fragmentation of the green network* were considered key to understanding the condition of urban ecosystems. Several alternative landscape metrics were discussed, with the limitations already highlighted above. However, the variable proposed in the EU-wide methodology *patch richness or Shannon Diversity Index of land cover types* was criticized as its values depend too much on the land cover classification adopted and changes in the value of such variable are hardly interpretable. According to the urban ET group, other landscape metrics, focused on the connectivity and fragmentation of green and blue patches, are more suitable to describe relevant characteristics of urban areas. These indicators assess spatial patterns across the urban landscape, reflecting the ability of cities to support biodiversity and human well-being. Improved connectivity enhances habitat quality for species and access to nature for people, linking EC to the delivery of ES (e.g., climate and flood regulation, recreation and mental well-being) in a meaningful way, especially in densely built environments where multifunctional green infrastructure is essential.

<u>Data gaps and recommendations</u>

Generally, discussions with the expert group highlighted that many indicators used for other ecosystem types are highly relevant for urban ecosystems, but that the data tends to be less available for urban areas or to have a resolution unsuitable to capture relevant properties of urban areas. For example, while urban areas have a key role in the global carbon cycle, the distribution and magnitude of soil organic carbon stocks in urban areas is insufficiently described (Guo et al., 2024). Similarly, available maps at European level based on the interpolation of the LUCAS database (see e.g. Panagos et al. 2024 on soil bulk density) do not cover urban areas due to the limited number of soil samples. Ongoing efforts to improve monitoring activities, e.g. in the context of the Soil Monitoring and Resilience Directive, aim at strengthening existing initiatives and enhancing standardized data collection across the EU and will provide valuable datasets to monitor urban EC in the future.

- BC1: As is common across all ecosystem types, taxonomic diversity is highly relevant, but limited by data gaps. Pollinators, native bird species, native vascular plants, and specific arthropod groups (e.g. butterflies, beetles, bees) are among the key species groups that are often monitored in urban areas, for example in the cities that apply the Singapore Index to monitor biodiversity. No data source of urban areas at EU level can currently be identified, but ongoing initiatives will produce relevant data in the future. Among them is the EU Pollinators Monitoring Scheme that will also focus on urban habitats, for which guidelines have been developed by the Safeguard project (Tremblay and Underwood 2023). Citizen science initiatives are also more widespread in cities than in other ecosystem types, and can be leveraged as a source of data to feed and complement modelling approaches.

- BP1: Density of street dogs and feral cats was raised as an important indicator of species-related pressures on urban ecosystems in certain settlement areas and their surroundings, but the relevance of such indicator depends on the context and no consistent monitoring of this is currently in place at the EU level.
- CP2: Alongside light pollution levels, noise pollution is a priority area for future research. However this currently lacks sufficient and spatially explicit data. As part of the reporting under the Environmental Noise Directive 2002/49/EC, some Member States provide, besides the mandatory indicators, also maps of noise pollution levels in urban areas (see EEA, 2024b). However, not all cities in the EU are targeted by the Directive.

An alternative approach to help fill data gaps and inconsistencies for assessing urban areas could be the use of performance indicators used in green point systems. These indicators are valuable policy tools for assessing urban sustainability, liveability, and resilience, by integrating environmental, social, economic criteria, and ecosystem services (Cortinovis and Geneletti 2020), however the expert group chose not to include them as condition indicators. These indicators are typically composite indices that combine various green area types, weighted according to their contributions to biodiversity and ecosystem services. Collectively known as Green Area Indicators (GAIs), these systems assign scores to urban features at the city, neighborhood, or building level. They support sustainability assessments, guide planning decisions, benchmark progress, and inform both policy and investment. Developed to meet specific local policy priorities in different European cities (e.g., Ring et al. 2021; Stange et al. 2022), GAIs cover a broad range of performance dimensions: environmental (e.g., air quality), social (e.g., access to green spaces), technological (e.g., smart infrastructure), resilience (e.g., flood mitigation), and spatial planning (e.g., mixed-use zoning). While not suited for condition accounting due to their composite nature, these systems play a critical role in supporting urban climate goals, green infrastructure strategies, and evidence-based policy-making. Their potential could be further enhanced by establishing a harmonized framework across Europe, including a core set of common indicators, to enable consistent mapping and comparison of urban areas.

6.3.5. Wetlands

Definition of the ecosystem type

The EU does not have a single, formal definition of "wetland" enshrined in any law. Wetlands are complex ecosystems that interact strongly with adjacent terrestrial and aquatic ecosystems. Although usually they are defined based on the presence of water, and the geological/ geomorphic, hydrological, hydro-chemical and biotic characteristics (Fitoka et al 2017). They often encompass transitional zones and spatially and temporally dynamic areas, so the exact placement of the wetland boundary is difficult. Further, they have been defined with different criteria (e.g. vegetation composition, hydromorphological properties, etc), which has posed challenges to agree on harmonized typologies (Vehmaa et al. 2024). Also, international definitions of wetlands (Ramsar[1]) encompass various ecosystem types, including fresh water bodies and marine systems, that are classified as separate types in European ecosystem typologies (Maes et al. 2013). Therefore, in Europe, wetland ecosystem management is partially addressed by different legislative instruments (EU Biodiversity Strategy and Nature Directives, Climate Strategy, WFD, Flood Directive, MSFD). Though actions under the different EU legislations have some synergetic effects on wetland management and conservation, they nevertheless lack objectives explicitly targeting the whole wetland ecosystem integrity (Biodiversity Information System for Europe (BISE) (n.d.)).

The MAES typology (Maes et al. 2013), defines two broad types of wetlands, based primarily on water salinity: 1. Inland wetlands: The class includes natural or modified mires, bogs and fens, as well as peat extraction sites. 2. Marine inlets and transitional waters: ecosystems on the land-water interface under the influence of tides with salinity higher than 0.5%. They include coastal wetlands, lagoons, estuaries and other transitional waters, fjords and sea lochs as well as embayments (Snethlage 2015, Fitoka et al. 2017). In this section, we include the ecosystem types “Inland wetlands” and “Coastal marshes” (also referred to as salt marshes, coastal wetlands, coastal grasslands, and seashore meadows (Vehmaa et al. 2024)), which are types within the broader class of coastal ecosystem type, i.e. “11. Coastal beaches, dunes and wetlands” within the EU ecosystem typology (Eurostat 2024). Surface water bodies are covered in Section 6.3.8. on “Rivers and Lakes”, and other ecosystems belonging to marine inlets, transitional waters, and coastal ecosystems are referred to in Section 6.3.9 on “Marine and Coastal Ecosystems”.

European inland wetland types are very diverse, including riparian and swamp forests, wet grasslands and heathlands and open mires (Carré et al. 2021). Coastal marshes are highly heterogeneous as well (Vehmaa et al. 2024). However, they share three common features: 1. Presence of water, at the soil surface or within the root zone. 2. Soil conditions that differ from adjacent habitats. 3. Biota adapted to wet conditions and the absence of flooding-intolerant species (Mitsch and Gosselink 2015 in Fitoka et al. 2017). The wetland habitats listed in Annex I of the Habitats Directive (92/43/EC) includes some 40 wetland habitat types (EC 2007).

[1] Home page | The Convention on Wetlands, The Convention on Wetlands

Wetlands have historically faced intense human pressures including drainage and land conversion for agriculture and development, eutrophication and pollution from agricultural and industrial runoff, and altered water flow due to dams, embankments and water extraction. Janssen et al. (2016) report that the highest proportion of threatened habitats in the EU28 has been found among Mires and bogs (85%) and Coastal habitats (45%). They are the habitat types most affected in recent times in Europe with long-term and recent decline in extent of more than 30%. Peat extraction and conversion to agriculture and forestry have been the main and continuing threats. Beyond land-use changes, shifts in hydrological functionality by drainage and abstraction in mire watersheds and eutrophication are also important pressures. Climate change is becoming an increasingly important factor through higher incidence of droughts, but also critically important for permafrost-dependent mire types (Janssen et al. 2016).

Evaluation of the ecosystem condition indicator long-list

The evaluation was carried out for a total of 13 condition indicators and 24 pressure indicators, for which the results are included in table Annex 4.

Wetlands ecosystem condition

Wetlands are a highly diverse group of ecosystems with particular associated biodiversity depending on their ecological and hydrological properties. The main factors determining wetland species composition, their physical structure and their function are flooding regime (length and frequency), nutrient content in water, and water salinity, the latter distinguishing between freshwater systems and brackish/saline water systems. Given this background, the group considered that ecosystem condition indicators should reflect these specific properties, and how they are affected by human activities.

Hence, the expert group stated that some indicators that may be meaningful to other ecosystems were less relevant for wetlands and proposed additional indicators specific for Wetland ecosystems and incorporated them into the assessment, including *Flooding frequency* and *Hydroperiod*. *Water salinity* was deemed to be an indicator that is only relevant for coastal marshes where drainage and embankment, accelerated sea level rise are pressing challenges (Vehmaa et al. 2024).

The expert group also proposed to use *Bulk density* instead of *Soil packing density.* Dry bulk density and total porosity are the most frequently used indicators to characterize the state of compactness of a topsoil (Panagos et al., 2024), but the variable needs to be standardized with respect to soils of the same physical properties, since soil porosity will depend on both particle size and the soil structure provided by organic matter content. For peat-forming wetlands, soil bulk density is not a relevant indicator of ecosystem condition.

In the case of *NPP*, although considered a fundamental ecosystem function, there was uncertainty about the level of validation for wetlands of current models based on remote-sensing-derived variables. The global MODIS Gross Primary Production (GPP) and Net Primary Production (NPP) products (MOD17) are widely used for monitoring GPP and NPP at coarse resolutions and broad spatial extents. However, there are well-known limitations to the applicability of the MOD17 product at finer scales (Robinson et al 2018). Global and regional NPP models have primarily used meteorological factors of temperature, precipitation and solar radiation as inputs rather than vegetation properties (Cramer et al. 1999) and current models used to project changes in biodiversity and ecosystem services, e.g. in IPBES assessments, do not include specifically wetlands as land-cover inputs (Kim et al. 2018). Current development of High-Resolution Vegetation Phenology and Productivity parameters at pan-European level provide productivity parameters based on vegetation indices, that combined with remote-sensing-based delineation of land cover types, which include wetlands (CEOS, 2024) present promising opportunities.

Among the 9 remaining condition indicators, all had data reported as available, however it was highlighted that the quality of data on wetland extent could pose a problem for deriving *Connectivity index (contagion)*.

Regarding scoring indicators according to their importance, *C:N ratio, SOC, Taxonomic diversity*, and *Connectivity index (contagion)* were rated highly across multiple criteria including importance, validity, and instrumental relevance, although it was highlighted that *SOC* more effectively represented long-term than short-term conditions, and that the indicator is not relevant for the large group of peat-forming wetlands. *Functional diversity* also received strong support across most dimensions, since the biological characteristics of wetland types are important for their distinctiveness and ecological functions.

Regarding the *simplicity* criterion, for these indicators, scores were generally high. *SOC* and *C:N ratio* were considered clear and practical to use when relevant. *Connectivity index* received high scores across nearly all criteria, reflecting strong conceptual and operational support. Sensitivity to human influence varied across indicators. *Taxonomic diversity* and *C:N ratio* were viewed as moderately responsive, while *NDVI* was rated lower for both sensitivity and reliability (see comment above on primary productivity). Despite moderate importance and its widespread usage, *NDVI* also received lower scores for conceptual clarity.

Wetland ecosystem pressure

A series of considerations were made, including making conceptual distinction between ecosystem condition and pressures, and how these concepts are operationalized in accounting and monitoring. For instance, 'invasive species' is a broad term that can be operationalized both as ecosystem condition and pressures by using different variables. The expert group proposed that pressure from invasive species be re-defined as *Risk of invasion of alien species.* The risk of invasion can be assessed as e.g. the distance of a wetland to invasive species sources (e.g. invasive species foci in the vicinity of the wetland would imply a high level of invasion risk). In contrast, the *Presence or Percentage cover of invasive species* was considered an indicator of ecosystem condition.

The group disagreed with the inclusion of the indicators *Carbon Monoxide* and *Pests and diseases*. In the case of *Carbon Monoxide*, we found the indicator of limited relevance to assess and monitor pressure on wetlands properties. In the case of *Pests and diseases*, the group considered that the presence of these organisms is not a suitable indicator of pressures on wetlands. However, it was suggested that the *Likelihood of pest and disease outbreaks* (beyond the natural cycles of these organisms) could be a possible indicator of condition, although not of pressures.

Among the 22 remaining pressure indicators, 17 had data reported as available. Chemical pressures were especially well represented, with *Nitrate*, *Nitrite*, *Phosphate*, and *Pesticides* all scoring highly for importance, validity, directional meaning, and instrumental relevance. These indicators were also generally rated as simple to understand and calculate. *Heavy metals*, and *Fertilizer surplus* also received strong support. Scores for directional meaning were high across this group, reflecting consistency in interpretation across spatial scales and ecosystem sub-types.

Among physical pressures, *Water extraction* and *Soil imperviousness* were rated moderately across most criteria, while *Fragmentation* and *Road density* were evaluated as suitable on account of their conceptual fit and operational clarity. Water extraction is a critical pressure on inland wetlands (Janssen et al. 2016), but a direct linkage between extraction points and volume levels to a particular wetland may be difficult to establish.

Simplicity and reliability scores for structural pressures were more variable. Air pollutant indicators showed less consistent support. While *NO_2*, *SO_2*, and *Particulate matter* received acceptable scores for simplicity and relevance, their sensitivity and validity ratings were generally lower. Overall, pressure indicators for wetlands reflect a strong emphasis on chemical and hydrological influences, in agreement with other assessments of pressure on these ecosystems.

Potential minimum indicators

Tables 11 and 12 show the potential minimum indicators for describing wetland condition and pressure, respectively.

Table 11 : Potential minimum condition indicators for wetlands (see Annex 5 for details). * = Indicators in the EU-wide methodology to map and assess ecosystem condition.

Class	Category	Variable	Resolu-tion	Unit	Year	Source
AC1	Water availability	Water-Wetness-Probability-Index (WWPI)	10 m / 100 m	occurrence of water	2018	EU Copernicus Land Monitoring Service
	Soil condition	Bulk density	100 m	Mg/m^3	2018	JRC ESDAC
AC2	Air	na				
	Water	Data gap				
	Soil	C/N ratio	500 m	unitless		JRC ESDAC
BC1	Species diversity	Percentage of wetland species with good population status	biogeographical region	%	Every 6 years	EEA
BC2	Vegetation	NDVI*	1 km	Unitless	1999 - 2020	EU Copernicus Land

						Monitoring Service
BC3	Productivity	Net primary production	300 m	g.C/m²/d	2023 - present	EU Copernicus Land Monitoring Service
LC	Connectivity	Connectivity index of semi-natural areas	100 m	%	2018-2021	EU Copernicus Land Monitoring Service

Table 12 : Potential minimum pressure indicators for wetlands (see Annex 5 for details). * = Indicators in the EU-wide methodology to map and assess ecosystem condition.

Class	**Category**	**Variable**	**Resolu-tion**	**Unit**	**Year**	**Source**
AP1	Water use	Water Exploitation Index plus (WEI+)	river sub-basins	%	2019	EEA
	Soil	Imperviousness	10 m	%	2018	EU Copernicus Land Monitoring Service
AP2	Air pollution	Exceedance of critical loads for acidification	point grid	eq/ha/y	2000 - 2020	EMEP/EEA
	Water pollution	Data gap				
	Soil pollution	na				
BP1	Species	Pressure by IAS*	10 km	unitless	2022	Polce et al., 2023
CP1	Land-use	na				
CP2	Fragmentation	Mesh density	100 m	n°/1000 km²	2009 - 2019	EEA

Discussion

For inland wetlands, the hydrological regime is a fundamental ecological property that is subjected to change by human activities through drainage and infrastructure development, so indicators that reflect changes in water regime and water table depth are relevant. The work considered the Water-Wetness-Probability index, a Copernicus HRL derived-index. In principle, the index shows the proportion of days (during the 3-year timeframe of the product) where there is surface water / wetness observable with remote sensing, which could be a suitable proxy of "water availability" metric from inland wetlands.

Regarding biological indicators (BP1), these indicators need to be generated from sampling data and do not consist of continuous data coverage across Europe. The status of selected wetland bird species are monitored and reported regularly under the Birds Directive and the Habitats Directive. These data are of relevance for European level assessments, but they are sample data from specific locations, they do not provide wall-to-wall European level data coverage. Species distribution models are often used to extrapolate these data, but the integration of land cover and land uses into species distribution models is still in early stages.

Limitations and constraints of the minimum indicator set

The suitability of indicators for wetlands is difficult to determine in some cases because indicators may not have been calibrated for specific wetlands. Wetlands are highly diverse systems, with very high granularity (and therefore with a need for high resolution data), and reliable maps are lacking in many areas. As they are not managed systems, unless drained for wood or food production, there tends to be less data available compared to forests or agroecosystems. In these cases, they are considered as forest or cropland.

Maps with European coverage of broad wetland categories (i.e. peatlands, floodplains and coastal wetlands) are being produced (Tegetmeyer et al. 2024) but wetland types with very distinctive properties can be small, so in these cases, large errors should be expected when data layers are aggregated at coarse resolutions (e.g. Soil water index for which the available data is at a resolution of 1km^2). In addition, there has been a lack of harmonized typologies. Vehmaa et al. (2024) highlight the limitations of overlapping and inconsistent habitat classification systems, and several unique and uncoordinated typologies used on regional and national scales for different purposes. Data calibration, establishment of suitable reference levels that correspond to comparable ecological conditions between wetland sites as well as improved delineation of wetland occurrences, is needed.

SOC is relevant and well-defined for many ETs, but it is not suitable for wetland types that form peat, often referred to as organic soils. Peatlands contain very large carbon stocks that can be depleted through peat extraction. Drainage and drought (lowering of the water table) also cause degradation of peat stocks, which cannot be assessed through the SOC indicator.

We recognized that some indicators which may be meaningful to other ecosystem types were less relevant for wetlands, due to limitations in the current delineation and mapping of wetlands. Most of the detailed developed land cover / land use maps have concentrated on agricultural and forest systems, while wetlands have been generally neglected. Hence, there is a general lack of calibration with field data, which have been more common in managed ecosystems. There is large variability in wetlands, so effort needs to be put to delineate these types, including those that can be classified under other ecosystems such as swamp forest and wet grasslands. In the case of spatially continuous, remote sensing-derived indicators such *NPP*, which in turn is modelled, it would need to be calibrated for the various wetland types.

Given that delineation of wetland systems is still unresolved, there are further challenges for developing this kind of indicator of wetland condition.

The main drivers of change of wetlands together with the critical ecological conditions that distinguish wetlands from other ecosystem types need to be considered when defining condition. The main driver of change has been the conversion of wetlands to agricultural land or for forestry production purposes. In an ecosystem accounting context, these changes would be recorded as changes in the wetland ecosystem extent (the area). In some instances, managed wetland croplands (like rice fields) are still considered as wetlands. In other instances, the hydrological regime has been changed through drainage, without transforming into cropland, for instance through water extraction. These aspects need to be considered when using wetland condition indicators to identify restoration areas and set restoration targets. The biological properties of wetlands are very distinct, given the particular transitional characteristics between water and land systems that require particular adaptations by species. Amphibians, and water logging- and salinity-tolerant plants have developed adaptations to these particular habitats. Also, some wetland habitats included in the Habitats Directive host regional or national endemic species. Improved and harmonized sets of indicators suitable to capture changes in biological properties of wetlands are important to develop. These should be sensitive to climate change and to shifts in hydrological regimes. The occurrence or cover of invasive species would also be a simple indicator to set restoration targets and to monitor progress in restoration actions directed to species invasions. The expert group discussed further the distinction between condition and pressure indicators, and considered that in some instances, what may be understood as pressure variables, can represent proxy variables of condition that are feasible to measure while providing meaningful information about the state of the wetland ecosystem. For example, in the case of soil imperviousness, regarded by other ecosystem type groups as a pressure indicator, soil imperviousness was considered a suitable indicator of the reduced hydrological integrity of a wetland, which may be difficult to otherwise assess.

Comparison with the EU-wide methodology to map and assess ecosystem condition

Delineation of wetlands. We agree that in the case of wetlands, a major limitation remains to translate current typologies into maps of wetland ecosystems, on which ecosystem condition assessments can be meaningfully related to.

Water availability: We propose the use of the *Water-Wetness-Probability-Index* (WWPI) an indicator that appears to be more related to wetlands hydrological regimes than the *Soil moisture deficit* which can inform about the condition of land systems. In fact, likely because there are no reliable wetland maps, the EEA does not report this index for wetlands (EEA, 2024a). Nevertheless, the WWPI requires validation.

Salinity anomalies: This may be a suitable indicator to monitor sea water and wetland habitats in coastal areas. However, threshold and reference values require validation. The variable could be used as a warning of change indicator, rather than a condition indicator. The variable will not capture changes in hydrological dynamics of coastal wetlands, if for instance, the connection with sea water is partly or completely broken by infrastructure development, which is likely to be a more meaningful indicator.

Exceedance of critical loads for eutrophication. Eutrophication is the second most important driver of change of wetland condition after changes in hydrological regimes. Extrapolation of Exceedance of critical loads from LUCAS data may be difficult to link to wetlands, given that application of fertilizers occur in agricultural land and that maps of wetlands are incomplete. Meaningful reference levels would be difficult to establish. Indicators based on data collected to report to the WFD and the MSFD could be developed for use in inland wetlands.

Heavy metals in soils. We agree about the importance of monitoring these elements in nature. It is uncertain whether the available data are robust enough to establish a reliable condition indicator for wetlands, including defining reference levels. The data would need to be validated, and correlated with pollutant sources.

Pressure by invasive alien species on wetland ecosystems: Wetlands are not included in the baseline reporting, likely due to incomplete wetland maps. The spatial resolution of European Alien Species Information Network (EASIN) maps is low. Thereby, this indicator could be used as a pressure indicator, close to our suggestion of the likelihood of invasiveness, rather than using it to establish the condition of the wetlands. However, the data would be helpful to guide prioritisation of restoration actions to be implemented locally.

Percentage of wetland species with good population status: We agree that these data can be potentially relevant ('Favourable Reference Population' (FRP) under the Article 17 of the HD to report status of population size) but as acknowledged, the resolution is too coarse, if the intention is to produce wall-to-wall maps, as well as uneven reporting timing. Primary data could be considered as representative statistics and reported as such.

Richness of wetland species: We also agree that these data are incomplete, but as other wetland species, primary data could be reported, aggregated by bioregion, without an attempt to wall-to-wall coverage. Richness data would need to be related to levels in ecologically comparable states.

Water occurrence decrease intensity: It may be problematic as a metric of ecosystem condition change and to establish reference conditions for this index since water decrease can be a matter of seasonal changes or natural hydrological dynamics (see Google Developers, 2024). We propose the Water-Wetness-Probability-Index (WWPI) which could be a more suitable indicator of wetland water regime. The indicator needs to be validated.

Imperviousness of the local drainage basin: We agree that this indicator is highly relevant for assessing the condition of wetlands, since it is a factor directly affecting the wetland's hydrologic regime.

Wild pollinators indicator: We have not included this indicator because we consider there is limited data of pollinators in wetlands. Reference levels would be at present difficult to establish.

Connectivity: We stress the importance of being able to monitor hydrological integrity and habitat connectivity, but this may be difficult to assess when wetland maps are incomplete. Also, a more systemic perspective of the wetland ecosystem could provide more meaningful information of condition. Often used measures of habitat connectivity developed for purely terrestrial ecosystems are likely to be difficult to assess. But, an indicator developed from e.g.

area covered by infrastructure /impervious surfaces that restrict water movement, would be meaningful. (see Box 4)

Data gaps and recommendations

- Delineation: A major limitation remains to translate current typologies into wetland maps with enough quality regarding the levels of error/uncertainty of the delineation of wetland units and level of spatial coverage to be able to infer their status. For instance, peatland habitats (mires, bogs and fens) differ considerably in their compositional and ecological properties. Coastal marshes are highly heterogeneous as well, based on level of coastal exposure, tidal system as well as shape, size and level of connectivity (Yando et al. 2023). Efforts should be made to achieve this goal.
- For the time being, given that maps of wetlands are incomplete, the assessment of wetlands condition could be based on statistics reported from sites where primary data are collected. These could include both reporting obligations under the BD and HD, but also other primary data sources with good European coverage (e.g. EBBA and EBBA2). This would provide sufficient information for SEEA-EA reporting and accounting, in which ecosystem condition indicators would not need to have wall-to-wall coverage. Primary data could be used for further analyses including, for instance, those based on modelling (e.g. species distribution models (SDM), see e.g. Soultan et al. 2022).
- Nutrient contents: Indicators based on data collected to report to the WFD and the MSFD could be developed, and considered as pressures for wetland ecosystems (the nutrient load in water getting into the wetland system). The correspondence of the nutrient load inputs and wetland condition would need validation.
- BC1: Wetlands form part of the Nature 2000 network, and there are reporting obligations of indicators under both the Birds Directive and the Habitats Directive. Better harmonization of typologies (Vehmaa et al. 2024) and field data collection on these wetland sites would improve the data-base for wetland condition reporting and monitoring with primary data-based statistics.
- BC2: New vegetation-based indicators based on representative field survey data and scoring the different plant species according to their response traits (e.g. "Ellenberg-index"- like scores) would in many cases be relevant to track changes in water regime, salinity, and nutrient content of wetlands, as well as encroachment by shrubs and trees. Vegetation moisture indicator, Vegetation light indicator, Vegetation pH indicator, Vegetation nitrogen indicator. These kinds of indicators are being developed for Norway.
- BC3: Primary productivity variables are modelled based on remote sensing data-derived indicators such as *NDVI*, and given that maps of wetlands are still incomplete, and that the area of some wetland types is very small, we expect considerable uncertainty in these data. Also, the diversity of wetland types and their ecological conditions hinders the use of this kind of data to monitor changes or to set restoration targets. Indicator development and calibration is needed.
- CP1: Different indicators of fragmentation could be used - see De Montis et al. (2017).

Box 4: Key messages for European wetlands

Wetlands and flood risk in Europe: Time for a Smarter Land Strategy

Why Wetlands Matter

Wetlands are vital ecosystems that provide a wide range of **regulating services**, including **water purification**, **carbon storage**, and provide **habitat for species** adapted to the particular ecological conditions of water logged terrestrial ecosystems. Wetlands also provide **natural flood regulation service, by acting as natural sponges,** retaining excess rainfall, slowing runoff, and reducing peak flood levels downstream.

From Sponge to Risk: How Wetland Loss Increases Flooding

The loss and degradation of wetlands, primarily due to agricultural expansion, urbanisation and infrastructure development pressures, has significantly reduced their capacity to deliver flood control:

- Impervious surfaces in floodplains disrupt infiltration and increase surface runoff.
- Soil sealing and compaction degrade the hydrological function of wetlands, reducing water storage and accelerating drainage.
- Disconnected floodplains (via levees, dikes) prevent water storage and slow release

"The water-retention capacity to reduce overland flow is reduced owing to soil sealing... affecting both peak and low flows" (EEA, 2016)
"Imperviousness reduces ecosystem potential to control floods, even in naturally high-performing areas like wetlands" (Vallecillo et al., 2020)

Policy Evidence and Context

- The **EU Floods Directive** and the **Water Framework Directive** both recognise the need to integrate ecosystem-based approaches in water and flood management.
- The **EU Biodiversity Strategy** set a target to restore 15% of degraded ecosystems by 2020, highlighting wetlands and floodplains as priorities.
- **Floodplain restoration projects** across Europe show strong returns for flood mitigation, biodiversity, and water quality (EEA, 2016).

Policy Recommendations

- Recognize wetlands and riparian zones as natural infrastructure in **Flood Risk Management Plans** (FRMPs).
- Restrict further sealing and urban expansion in floodplains: Introduce spatial planning regulations to limit development in ecologically sensitive or hydrologically critical areas.
- Use **Nature-Based Solutions**, such as **Natural Water Retention Measures** (NWRMs) and **Green Infrastructure funding**, to recover floodplain functions (wetland restoration and reconnection to river).
- Incorporate **imperviousness** as a pressure indicator in ecosystem accounts: Track changes in wetland hydrology and flood regulation service following restoration actions that remove impervious surfaces.
- Leverage **EU funding tools** (e.g., CAP, LIFE, and Cohesion Fund): Align agricultural and climate funds with floodplain and wetland restoration objectives to deliver multiple policy goals.

Picture: Severe flooding on the Elbe River floodplain near Roßlau (Germany, June 6, 2013), where extreme rainfall overwhelmed wetlands and flood defences in a landscape heavily altered by levees, agricultural expansion, and infrastructures. This led to reduced floodplain connectivity and buffering capacity, causing mass evacuations, and billions € in damages (Photo credit: ©André Künzelmann/UFZ)

6.3.6. Heath- and Shrubland

Definition of the ecosystem type

Heath- and shrubland ecosystems are characterized by low-growing woody vegetation dominated by shrubs, dwarf shrubs, and herbaceous plants. According to European classification systems, heathlands are defined as areas dominated by dwarf shrubs typically below 2 meters in height, with sparse tree cover (generally less than 10 percent canopy cover). These ecosystems include dry heaths, wet heaths, and scrublands, encompassing both natural and semi-natural vegetation communities that often result from extensive grazing or traditional management practices. For this assessment, both natural heathlands and managed shrubland systems are included, acknowledging their ecological importance and cultural landscape value.

Heathlands and shrublands face significant human pressures including land-use change, abandonment of traditional management, and nutrient enrichment from agriculture. Pollution, invasive species, and climate change further threaten their low-nutrient ecosystems, while recreational activities cause habitat degradation. These combined pressures risk biodiversity loss and the transformation of these unique landscapes.

Evaluation of the ecosystem condition indicator long-list

Health- and Shrubland ecosystem condition

The Ecosystem Type group identified that *crude protein concentration*, an indicator applied in multiple papers in the review, was deemed irrelevant for heath and shrubland ecosystems and was therefore excluded from further evaluation. Among the 11 remaining state indicators, 9 had data reported as available.

A number of indicators, including *C:N ratio*, *SOC* (topsoil), *NDVI* or *Enhanced Vegetation Index (EVI)*, and *NPP*, were rated highly for both importance and validity. These indicators also demonstrated strong performance across instrumental relevance and sensitivity to human influence. Scores for simplicity were generally high, with most indicators considered comparably easy to interpret and calculate. *NDVI* or *EVI* was particularly well-rated across all evaluation criteria, demonstrating consistently high scores for reliability, operational feasibility, and conceptual clarity. Indicators such as *Soil bulk density* and *Tree cover density* also showed strong overall support across multiple assessment dimensions.

Sensitivity to human influence was variable among the evaluated indicators. Indicators like *SOC* and *C:N ratio* were rated as moderately responsive to anthropogenic pressures, while *Surface Soil Moisture* received lower scores for this criterion, despite receiving acceptable ratings for simplicity and data availability.

Health- and Shrubland ecosystem pressure

The categories of water pollution and soil pollution were deemed inappropriate for heath- and shrubland ecosystems. Among the remaining 10 pressure indicators, 8 had data reported as available. *Soil imperviousness*, *Nitrogen deposition*, *Ozone*, and *Pressure by invasive alien species* were rated highly for importance and validity, with consistently good scores across directional meaning, reliability, and simplicity.

Indicators addressing structural pressures such as *Encroachment by human population*, *Disturbance intensity*, and *Fragmentation pressure* received more varied scores. While rated as important, their scores for reliability and sensitivity were lower on average, suggesting greater uncertainty in their application or interpretation. Air pollutant indicators, particularly *Ozone* and *NO_2*, were well supported across most criteria, including conceptual clarity and operational relevance. *Sulphur dioxide* was evaluated similarly, though with slightly lower scores for validity and reliability. The evaluated pressure indicators overall reflect a strong emphasis on physical and chemical pressures, with good support for their use in heathland monitoring and assessment.

Potential minimum indicators

Tables 13 and 14 show the potential minimum indicators for describing heath- and shrubland condition and pressure, respectively.

Table 13 : Potential minimum condition indicators for heathlands and shrublands (see Annex 5 for details). * = Indicators in the EU-wide methodology to map and assess ecosystem condition.

Class	**Category**	**Variable**	**Resolu-tion**	**Unit**	**Year**	**Source**
AC1	Water availability	Minimum annual Soil Wetness Index (SWI)	1 km	%	2015 - present	EU Copernicus Land Monitoring Service
	Soil condition	Bulk density	100 m	Mg/m^3	2018	JRC ESDAC
AC2	Air	na				
	Water	na				
	Soil	SOC*	500 m	g/kg	2014	JRC ESDAC
BC1	Species diversity	Bumblebee diversity	10 km	n° species	1991 - 2010	Polce et al., 2018
BC2	Vegetation	Enhanced Vegetation Index	1km	Unitles s	2016 - 2021	Open Data Science Europe (2021)
		Canopy height*	30 m	m	2019	Popatov et al., 2021
BC3	Productivity	Net Primary Production*	300 m	$g.C/m^2/d$	2023 - present	EU Copernicus Land Monitoring Service
LC	Connectivity	Connectivity index of semi-natural areas	100 m	%	2018 - 2021	EU Copernicus Land Monitoring Service

Table 14 : Potential minimum pressure indicators for heathlands and shrublands (see Annex 5 for details). * = Indicators in the EU-wide methodology to map and assess ecosystem condition.

Class	Category	Variable	Resolu-tion	Unit	Year	Source
AP1	Water use	na				
	Soil	Imperviousness	10 m	%	2018	EU Copernicus Land Monitoring Service
AP2	Air pollution	AOT40*	2 km	$\mu g/m^3/h$	2018	EEA
		Exceedance of critical loads for eutrophication*	point grid	mol N eq/ha/y	2022	EEA
	Water pollution	na				
	Soil pollution	na				
BP1	Species	Pressure by IAS*	10 km	Unitless	2022	Polce et al., 2023
CP1	Land-use	na				
CP2	Fragmentation	Mesh density*	100 m	n°/1000 km^2	2009 - 2019	EEA

Discussion

The proposed minimum indicator set for heathland and shrubland ecosystems comprises 8 condition indicators and 5 pressure indicators, reflecting the considerable ecological diversity encompassed within this broad and heterogeneous ecosystem type across Europe. These ecosystems manifest across a wide range of bioclimatic conditions and soil types, from Atlantic wet heaths on waterlogged podzols to Mediterranean dry shrublands on calcareous substrates. This inherent variability presents particular challenges for developing a unified assessment framework, as indicators relevant for hygrophilous heath communities may have limited applicability in xerophytic shrubland contexts.

The distribution of condition indicators across typological categories reveals an emphasis on structural and functional measurements. Structural indicators, including *Enhanced Vegetation Index* and *Canopy height*, represent 25% of the condition indicators, while functional indicators account for 12.5% through *NPP*. Compositional indicators are represented solely by *Bumblebee diversity* (12.5%), and abiotic characteristics comprise 50% of the indicators through physical condition (*Minimum annual Soil Wetness Index SWI, Bulk density*) and chemical condition *(SOC)* measurements. This distribution reflects both data availability constraints and the fundamental role of abiotic limitations in defining these ecosystems.

The ecological diversity of these systems reflects their occurrence under various limiting conditions that naturally restrict forest development, whether through soil poverty, exposure, hydrological extremes, or recurrent disturbance. In many European contexts, these ecosystems exist within a complex interplay of natural constraints and anthropogenic influences, particularly fire regimes that may be naturally occurring but are often human-mediated or -modified. This dual nature, functioning as climax vegetation under limiting conditions (e.g., Nordic tundra) or as disturbance-dependent systems (e.g., Mediterranean maquis or Atlantic heathlands), complicates the selection and interpretation of both condition and pressure indicators.

The predominance of remotely sensed vegetation metrics in the condition indicators represents a pragmatic compromise, offering broad applicability across diverse heathland and shrubland types while potentially missing ecosystem-specific nuances. *NDVI/EVI* provide robust vegetation-related variables across the moisture gradient from wet to dry systems, though their interpretation must account for the naturally sparse vegetation structure characteristic of many shrubland types.

The soil indicators included, chemical (*SOC*) and physical (*Bulk density*) properties, which appear particularly relevant given that edaphic limitations often determine the presence and character of these ecosystems. However, the absence of soil moisture indicators may inadequately represent the fundamental divide between wet and dry heath/shrubland types, each with distinct species assemblages and ecological processes.

The pressure indicator selection, with its emphasis on atmospheric deposition (*AOT40, Critical loads exceedance*), acknowledges a universal threat across heathland types. The deliberate exclusion of water pollution and soil pollution categories may be more appropriate for dry shrublands than for wet heath systems potentially affected by catchment-level nutrient inputs. The absence of explicit fire regime indicators, whether as pressure or condition variables, represents a notable gap given the fundamental role of fire in maintaining many Mediterranean shrublands and some Atlantic heathlands.

<u>Limitations and constraints of the minimum indicator set</u>

Several limitations affect the robustness and comparability of heathland and shrubland condition indicators. Spatial resolution varies considerably across the indicator set, ranging from 1 m resolution for canopy height to 10 km resolution for biodiversity data. This spatial heterogeneity introduces scale-dependent limitations where fine-scale ecological processes that are characteristic for heathland mosaics may be inadequately captured at coarser resolutions, while high-resolution data may prove computationally demanding for extensive assessments.

Temporal resolution presents additional constraints, with some datasets offering near-real-time updates while others provide only periodic snapshots. The temporal coverage spans from historical data (1972-present for *EVI*) to recent assessments (2018-2020 for *canopy height*), creating temporal heterogeneity that may complicate integrated assessments and trend detection.

The reliance on modelled or remotely sensed data for several indicators introduces uncertainty in case of insufficient ground-truthing. For instance, soil bulk density and SOC are derived from continental-scale models that may not capture local pedological variations critical for heathland ecosystem functioning. Similarly, the connectivity index depends on land cover classifications that may not adequately distinguish between different shrubland types or capture management-induced variations in habitat quality.

The limited representation of biodiversity indicators through Bumblebee diversity alone appears insufficient to capture the distinct biological communities associated with different heathland and shrubland types. Wet heaths support specialized bryophyte and invertebrate assemblages, while Mediterranean shrublands harbor unique reptile and endemic plant communities. This diversity means their ecological significance cannot be fully measured by just one pollinator metric. This constraint reflects data availability limitations across the European gradient, but risks overlooking biodiversity values that often justify conservation efforts in these ecosystems.

Comparison with the EU-wide methodology to map and assess ecosystem condition

The proposed framework demonstrates substantial alignment with established EU assessment approaches, particularly through the adoption of widely used remote sensing products and atmospheric deposition models. The incorporation of Copernicus data products ensures compatibility with broader European monitoring initiatives, facilitating cross-border comparisons and contributing to continental-scale assessments. Five of the thirteen indicators (marked with asterisks in Tables 15 and 16) correspond directly to JRC indicator lists, ensuring methodological consistency with EU-wide approaches.

However, certain departures from standard EU methodologies merit consideration. The limited explicit linkage to Habitats Directive Article 17 reporting parameters may create challenges for Member States seeking to harmonize monitoring efforts. While functional indicators like *NPP* represent advances in ecosystem assessment, their relationship to established conservation status criteria remains to be fully elaborated.

The pressure indicators show closer correspondence with existing EU frameworks, particularly through the adoption of critical loads methodology and standard fragmentation metrics. This alignment facilitates policy integration, though the absence of certain pressure categories addressed in other ecosystem assessments, particularly water quality parameters relevant to wet heath systems, may require justification in specific contexts.

Data gaps and recommendations

Critical data gaps identified include the absence of fire regime indicators, limited representation of soil moisture gradients, and insufficient biodiversity metrics beyond pollinator communities. The lack of harmonized data on grazing pressure and management intensity represents a significant constraint given the anthropogenic origin of many European heathlands.

To address these limitations, development of multi-scale indicator frameworks supporting assessments at EU-wide, national, and local levels is recommended. Enhanced integration of remote sensing data with ground-based monitoring, particularly from national habitat monitoring programs, would improve spatial resolution and ecological accuracy. Establishing reference condition levels for different heathland and shrubland types, including both wet and dry variants, would provide more robust comparative baselines.

Where data limitations persist, expert-based assessments should be encouraged, supported by transparent criteria and comprehensive documentation. Flexibility in indicator selection should be promoted to accommodate the diverse ecological and management contexts of European heathland and shrubland ecosystems.

- AC2: Current coverage of abiotic factors appears limited relative to the known environmental drivers of heathland dynamics. Development of standardized approaches to monitor soil pH and base saturation could provide early warning of acidification impacts.
- BC1: The taxonomic scope of biodiversity indicators would benefit from expansion. While bumblebee diversity provides one window into pollinator communities, the rich assemblages of characteristic species, from reptiles to specialized plant communities, remain largely unrepresented. Development of indicators based on plant functional types or community composition could provide more comprehensive coverage while remaining feasible for routine monitoring. The potential for citizen science contributions to biodiversity monitoring in these often publicly accessible landscapes deserves exploration.
- LC1: The single connectivity metric may insufficiently capture the complex spatial dynamics of heathland systems. Consideration of additional landscape metrics, particularly those addressing edge effects and habitat quality gradients, could enhance understanding of landscape-level pressures.
- AP: Several potentially significant pressure types lack representation in the current framework. Climate-related pressures if managed to express the anthropogenic climate effect could be interesting to consider.
- BP: The framework would benefit from more comprehensive treatment of biological pressures. Herbivore impacts from domestic livestock represent a primary management consideration in many heathland systems, but yet lack explicit indicators. Similarly, metrics for woody encroachment rates could support targeted intervention strategies. The single invasive species indicator may require supplementation with habitat-specific metrics.
- LP: Contemporary landscape pressures extend beyond traditional fragmentation concerns. The proliferation of renewable energy infrastructure in heathland landscapes suggests a need for specific impact indicators. Similarly, the intensification of surrounding agricultural systems may create edge effects not captured by current metrics. Development of integrated pressure indices that account for cumulative impacts could provide more realistic assessments of landscape-level threats. Additionally, beta diversity involves assessing the variety of species at landscape level. This understanding is vital for thorough biodiversity evaluations and for exploring potential interactions among different ecosystem types.

6.3.7. Grasslands

Definition of the ecosystem type

Grassland ecosystems are characterized by herbaceous vegetation communities dominated by grasses and forbs, with minimal woody vegetation cover. According to European classification systems, grasslands are defined as areas where graminoid species constitute the dominant vegetation layer, typically with tree and shrub cover below 10 percent. These ecosystems encompass both natural grasslands occurring under climatic or edaphic limitations and semi-natural grasslands maintained through agricultural practices such as mowing, grazing, or burning. For this assessment, both permanent grasslands and extensively managed agricultural grasslands are included, acknowledging their ecological significance and role in European landscapes. Intensively managed agricultural grasslands and temporary leys are generally excluded from the Grassland ecosystem type and included in the agroecosystems type.

Grasslands are under pressure from agricultural expansion, overgrazing, and land abandonment, which alter their structure and biodiversity. Pollution from fertilizers and pesticides, urban development, invasive species, and climate change further degrade these ecosystems, threatening their ecological balance and ability to provide essential services like soil stability and carbon storage.

Evaluation of the ecosystem condition indicator long-list

For grassland ecosystems, the evaluation was carried out for a total of 14 condition indicators and 18 pressure indicators, for which the results are included in Annex 4.

Grassland ecosystem condition

Crude protein concentration was deemed irrelevant for grasslands by the ecosystem type group. Among the 13 remaining condition indicators, 9 had data reported as available. Indicators such as *Surface Soil Moisture*, *C:N ratio*, and *SOC* (*topsoil*) were rated highly for both importance and validity, and also received consistently strong scores for simplicity, instrumental relevance, and sensitivity to human influence.

Scores for simplicity were generally high, with most indicators considered easy to interpret and calculate. *Surface Soil Moisture* stood out for its consistently high scores across all criteria. Indicators like *NDVI* and *NPP* were also well supported, though *NDVI* was rated slightly lower for sensitivity and reliability.

Sensitivity to human influence varied across the set. *Surface Soil Moisture* and *C:N ratio* were seen as responsive to changes in pressure or management, while others, such as *Soil Biomass Productivity*, were rated lower in this regard. Overall, the evaluated indicators reflected a good balance of conceptual clarity and operational feasibility.

Grassland ecosystem pressure

Among the 11 pressure indicators, 9 had data reported as available. *Nitrogen deposition*, *Ozone*, and *Fragmentation pressure* were rated highly for importance and validity and were also supported by strong scores across directional meaning, instrumental relevance, and sensitivity to human influence.

Soil imperviousness, *Livestock density*, and *Pressure by invasive alien species* received consistently high scores across multiple criteria, indicating strong relevance and usability for grassland contexts. Simplicity scores were generally high for this group, reflecting ease of interpretation and implementation. *Water extraction* was rated lower for directional meaning and reliability, despite moderate importance. Air pollutant indicators such as *Sulphur dioxide* and *Nitrogen dioxide* showed moderate to high scores for simplicity and relevance, though there was some variation in their perceived sensitivity and distinctiveness.

Potential minimum indicators

Tables 15 and 16 show the potential minimum indicators for describing grassland condition and pressure, respectively.

Table 15 : Potential minimum condition indicators for Grasslands (see Annex 5 for details). * = Indicators in the EU-wide methodology to map and assess ecosystem condition.

Class	Category	Variable	Resolu-tion	Unit	Year	Source
AC1	Water availability	Minimum annual SWI*	1 km	%	2015 - present	EU Copernicus Land Monitoring Service
	Soil condition	Bulk density	100 m	Mg/m^3	2018	JRC ESDAC
AC2	Air	na				
	Water	na				
	Soil	SOC*	500 m	g/kg	2014	JRC ESDAC
BC1	Species diversity	Bumblebee diversity	10 km	n°/10 km	1991 - 2011	Polce et al., 2018
BC2	Vegetation	Enhanced Vegetation Index	1km	Unitless	2016 - 2021	Open Data Science Europe (2021)
		Small Woody Features*	5 m to 100 m	m/m^2	2017 - 2019	EU Copernicus Land Monitoring Service
BC3	Productivity	Net Primary Production*	300 m	$g.C/m^2/d$	2023 - present	EU Copernicus Land Monitoring Service
		Soil biomass productivity	1 km	score	2016	JRC ESDAC
LC	Connectivity	Connectivity index of semi-natural areas	100 m	%	2018-2021	EU Copernicus Land Monitoring Service

Table 16: Potential minimum set of pressure indicators for Grasslands (see Annex 5 for details). * = Indicators in the EU-wide methodology to map and assess ecosystem condition.

Class	Category	Variable	Resolu-tion	Unit	Year	Source
AP1	Water use	na				
	Soil	Imperviousness	10 m	%	2018	EU Copernicus Land Monitoring Service
AP2	Air pollution	AOT40*	2 km	µg/m^3/h	2018	EEA
	Water pollution	na				
	Soil pollution	N & P surplus*	1 km	kg/ha/y	2010	EEA
BP1	Species	Pressure by IAS*	10 km	Unitless	2022	Polce et al., 2023
CP1	Land-use	Livestock density	10 km	n° / km^2	2010 - 2020	FAO
CP2	Fragmentation	Mesh density*	100 m	n°/1000 km^2	2009 - 2019	EEA

Discussion

The proposed minimum indicator set for grassland ecosystems addresses a remarkably heterogeneous ecosystem type that encompasses permanent agricultural grasslands, semi-natural hay meadows, montane pastures, and steppe-like formations across Europe's diverse bioclimatic zones. This ecological amplitude, from the species-rich Nardus grasslands of mountain areas to the productive ryegrass leys of Atlantic regions, presents inherent challenges for developing universally applicable indicators. The selected indicators must therefore balance broad applicability with sensitivity to detect changes across this ecological gradient.

The distribution of condition indicators demonstrates reasonable coverage of ecosystem components, with notable emphasis on productivity-related metrics comprising 22% of the total through *NPP, Soil biomass productivity,* and *Enhanced Vegetation Index*. This focus appears appropriate given that grassland management fundamentally revolves around biomass production and utilization, whether for conservation, agricultural, or ecosystem service objectives. The inclusion of soil moisture indicators (*Minimum annual SWI*) acknowledges the critical role of water availability in determining grassland productivity and species composition, particularly relevant given the increasing frequency of drought events across European grasslands.

The soil indicators (*SOC*, *bulk density*) represent 22% of the condition set and reflect recognition that many grassland ecosystem services (carbon sequestration, water regulation, nutrient cycling) operate primarily through soil processes. However, the framework's treatment of biodiversity remains notably limited, with *Bumblebee diversity* serving as the sole compositional indicator (11% of the total). This constraint appears particularly problematic for grasslands, where plant species richness often serves as a primary conservation target and management objective.

Among pressure indicators, the inclusion of *Livestock density* addresses a fundamental driver of grassland condition, representing direct management pressure that shapes ecosystem structure and function. The framework appropriately recognizes both agricultural intensification pressures (fertilizer surplus) and abandonment-related pressures (implied through fragmentation metrics), reflecting the dual threats facing European grasslands. The emphasis on atmospheric deposition through *AOT40* aligns with documented impacts on species-rich grasslands, though the single soil pollution indicator may inadequately capture the diversity of agricultural inputs.

Limitations and constraints of the minimum indicator set

Several methodological and practical constraints affect the proposed indicator framework. Spatial resolution varies considerably across indicators, ranging from 5m for *Small Woody Features* to 10km for biodiversity and livestock density data. This spatial resolution mismatch complicates integrated assessments at meaningful management scales, as semi-natural grasslands often occur as small patches within agricultural landscapes, potentially falling below the detection threshold of coarser resolution indicators.

The temporal dimensions of grassland dynamics receive limited attention within the framework. Grasslands exhibit pronounced seasonal variation and respond rapidly to management changes, yet most indicators provide annual aggregates or periodic snapshots. This temporal averaging may obscure ecologically significant patterns, particularly for ecosystems where timing of management interventions critically affects biodiversity outcomes.

The framework's limited engagement with management regime indicators represents a significant constraint. Mowing frequency, grazing intensity, and timing of interventions fundamentally determine the grassland’s ecological character, yet these drivers remain largely unrepresented in the available datasets. Similarly, the absence of indicators for grassland structural heterogeneity (tussock distribution, sward height variation, bare ground patches) overlooks habitat features critical for many specialist species.

Comparison with the EU-wide methodology to map and assess ecosystem condition

The proposed framework demonstrates substantial alignment with established EU assessment approaches, particularly through the adoption of standardized Copernicus products and EEA datasets. The incorporation of fertilizer surplus indicators aligns with existing agri-environmental monitoring frameworks, facilitating integration with Common Agricultural Policy reporting mechanisms.

However, certain divergences from standard EU approaches merit consideration. The limited explicit connection to Habitats Directive Annex I grassland types may complicate reporting obligations for Member States. While the framework includes relevant parameters for some priority habitats (e.g., *Soil moisture* for *Molinia* meadows), others lack specific indicators (e.g., calcareous substrate indicators for orchid-rich grasslands). The framework's productivity focus, while pragmatic, may inadequately address the inverse relationship between productivity and biodiversity characteristic of many high-nature-value grasslands.

The pressure indicators show closer correspondence with existing EU frameworks, particularly through the critical load methodology and landscape fragmentation metrics. However, the absence of explicit links to Common Agricultural Policy indicators represents a missed opportunity for policy integration, given that CAP measures fundamentally shape grassland management across much of Europe. The framework could benefit from stronger integration with agri-environmental scheme monitoring data, which often provides detailed management information at farm level.

Data gaps and recommendations

- AC: The current abiotic indicator set would benefit from expansion to address known ecological drivers. Soil pH monitoring appears essential given its role in determining species composition, particularly for calcareous versus acidic grassland types. Nutrient status indicators beyond carbon, particularly plant-available phosphorus, could help identify systems at risk from eutrophication. Hydrological regime indicators that capture flooding frequency and duration would support assessment of floodplain meadows and other wetland-associated grasslands.
- BC1: The biodiversity indicator gap requires urgent attention. Development of plant species richness indicators, potentially utilizing systematic vegetation survey data, should be prioritized. Functional group representation (grasses, forbs, legumes) could provide management-relevant information while remaining feasible for routine monitoring. Invertebrate indicators beyond pollinators, particularly those targeting grassland specialists like Orthoptera, would better represent the full biodiversity value of these ecosystems. The potential for acoustic monitoring to provide standardized assessments of characteristic species merits investigation. See also the discussion about pollinators in the agroecosystem type Section above.
- LC: Beyond simple connectivity, indicators addressing grassland patch quality and landscape context would enhance assessment capabilities. Historical continuity indicators could identify ancient grasslands of particular conservation value. Beta diversity evaluation at landscape level is also highly relevant for exploring potential interactions among different ecosystem types.
- AP1: Drainage impacts on wet grasslands require specific indicators. Climate-related pressures beyond simple drought indices, such as human induced changing precipitation seasonality, may better capture emerging threats to grassland persistence.
- BP: The framework requires substantial enhancement of biological pressure indicators. Quantified grazing pressure metrics, differentiated by livestock type, appear essential. Under-grazing indicators, potentially based on shrub encroachment or litter accumulation, would address abandonment threats. Specific indicators for problematic species in grasslands, such as *Rumex obtusifolius* in productive systems or competitive grasses in species-rich meadows, could support targeted management. The role of seed addition and species introduction in grassland restoration suggests potential indicators for genetic pressures.
- LP: The conversion pressure from arable agriculture or afforestation schemes requires explicit monitoring. Recreational pressure indicators would address impacts in accessible areas. The cumulative effects of multiple pressures, particularly relevant in multifunctional grassland landscapes, suggest the need for integrated pressure assessment approaches.

6.3.8. Rivers and Lakes

Definition of the ecosystem type

Rivers and lakes are freshwater ecosystems that play crucial roles in the global water cycle and support diverse biological communities. As defined by Directive 2000/60/EC WFD, a river is "a body of inland water flowing for the most part on the surface of the land but which may flow underground for part of its course". Rivers are significant in the context of the WFD because they are often the primary focus of river basin management plans, which aim to achieve good ecological and chemical status for these water bodies. River ecosystems are dynamic and typically characterized by flowing water, which creates habitats such as riffles, pools, and floodplains. These habitats support organisms adapted to changing water flow, oxygen levels, and sediment transport. In contrast, a lake is defined as "a body of standing inland surface water" (Directive 2000/60/EC WFD) and are generally divided into distinct zones: the littoral (nearshore), limnetic (open water), and benthic (bottom) zones. These zones support different types of aquatic life, from rooted plants and algae to fish and invertebrates. Lakes are important ecosystems and are also subject to the environmental objectives of the WFD, which include achieving good ecological status and good surface water chemical status. The ecological status of rivers and lakes is determined based on several biological (e.g., composition and abundance of aquatic flora, benthic invertebrate and fish fauna), hydromorphological (e.g., hydrological regime, river continuity, morphological conditions), physical quality (e.g., temperature, oxygenation) and chemical quality (as defined by the Environmental Quality Standards (EQS)) elements (Directive 2008/105/EC).

Rivers and lakes located within or near urban, industrial and agricultural areas are significantly affected by human activities. Urban and industrial environments introduce pollutants such as heavy metals, excess nutrients, and microplastics through stormwater runoff and wastewater discharge, degrading water quality and ecosystem health. In agricultural settings, runoff containing fertilizers and pesticides can trigger eutrophication, algal blooms, and a decline in aquatic biodiversity. Despite these pressures, freshwater ecosystems continue to play a vital ecological role by delivering services such as water purification, flood mitigation, and habitat provision. Effectively understanding and managing the interactions between these water bodies and surrounding human-altered landscapes is crucial for preserving ecological integrity and ensuring long-term benefits for society.

Evaluation of the ecosystem condition indicator long-list

The evaluation was carried out for a total of 29 condition indicators and 25 pressure indicators, for which the results are included in Annex 4.

River and lake ecosystem condition

Of the 29 condition indicators, 21 had data reported as available. Indicators such as *Dissolved oxygen*, *SOC*, *Phosphates*, and *Turbidity* were rated highly across importance, validity, and simplicity, and were consistently supported by moderate to high scores for reliability and sensitivity to human influence.

Simplicity scores were generally favourable, particularly for indicators relating to vegetation cover, nutrient concentrations, and temperature. Indicators such as *Tree cover*, *Enhanced Vegetation Index*, and *Water surface temperature* were considered clear, accessible, and operationally feasible. Water chemistry indicators like *Nitrates*, *pH*, and *Total phosphorus* also performed well across multiple criteria. Most indicators were rated moderately for sensitivity to human influence. Indicators covering productivity and nutrient status, such as *Net Primary Production* and *Total nitrogen,* reflected a good balance of conceptual clarity and responsiveness to pressure.

River and lake ecosystem pressure

Of the 25 pressure indicators, 21 were positively assessed, with 20 having data reported as available. Chemical pressures were particularly well supported: *Nitrate*, *Phosphate*, *PFAS*, and *Pesticides* all received high ratings across importance, directional meaning, instrumental relevance, and simplicity.

Air pollutants such as *NO_2*, *PMx*, and *SO_2* were also rated favourably, though generally lower in sensitivity and reliability. *Heavy metals* and *Soil imperviousness* showed strong conceptual support and operational applicability. Indicators representing physical pressures, such as *Water extraction*, *Soil imperviousness* in the riparian zone, and *Barrier density*, received high ratings across most criteria, particularly directional clarity and instrumental relevance. Structural pressures linked to fragmentation were rated lower for directional meaning but were otherwise well supported. Across the group, pressure indicators demonstrated good consistency in scoring and reflected well-established linkages between environmental drivers and aquatic ecosystem condition.

Potential minimum indicators

Tables 17 and 18 show the potential minimum indicators for describing rivers and lakes condition and pressure, respectively.

Table 17 : Potential minimum condition indicators for rivers and lakes (see Annex 5 for details). * = Indicators in the EU-wide methodology to map and assess ecosystem condition.

Class	Category	Variable	Resolu-tion	Unit	Year	Source
AC1	Water availability	Surface Water Occurrence (SWO)	30 m	mm-month	2018	JRC
	Riparian soil	Bulk density	100 m	Mg/m^3	2018	JRC ESDAC
AC2	Air	na				
	Water	Dissolved oxygen	point data	mg/l	1968 - 2017	Heinle et al., 2024
		pH	point data	point data	2018	Heinle et al., 2024
	Soil/Sediments	SOC	500 m	g/kg	2014	JRC ESDAC
BC1	Species diversity	Fish diversity in rivers	river basin	n	1995 - 2024	Mameri et al., 2025

Class	Category	Variable	Resolu-tion	Unit	Year	Source
BC2	Riparian Vegetation cover	NDVI	1 km	Unitless	1999 - 2020	EU Copernicus Land Monitoring Service
BC3	Riparian Productivity	Net primary production	300 m	g.C/m²/day	2023 - present	EU Copernicus Land Monitoring Service
LC	Connectivity	Connectivity index of semi-natural areas	100 m	%	2018-2021	EU Copernicus Land Monitoring Service

Table 18 : Potential minimum pressure indicators for rivers and lakes (see Annex 5 for details). * = Indicators in the EU-wide methodology to map and assess ecosystem condition.

Class	Category	Variable	Resolu-tion	Unit	Year	Source
AP1	Water use	Water Exploitation Index plus (WEI+)	river sub-basins	%	2019	EEA
	Soil	Imperviousness	10 m	%	2018	EU Copernicus Land Monitoring Service
AP2	Air pollution	na				
	Water pollution	Nutrients concentrations (N and P)	Point stations	µg/m³	2023	EEA (WISE SoE)
		Pesticides concentrations	Point stations	µg/m³	2023	EEA (WISE SoE)
	Soil pollution	na				
BP1	Species	Pressure by IAS	10 km	Unitless	2022	Polce et al., 2023
CP1	Land-use	Agricultural land cover in catchment area	10 m	%	2018-2021	EU Copernicus Land Monitoring Service
CP2	Fragmentation	Mesh density	100 m	n°/1000 km²	2009 - 2019	EEA

Discussion

The suitability of indicators for rivers and lakes is difficult to determine in some cases because indicators may not have been calibrated for rivers and lakes. Rivers and lakes are highly diverse ecosystems, with very high detail and linearity, which necessitates high-resolution data. In river ecosystems, spatial data is typically represented as linear features, which poses challenges when aggregating or integrating it with lake ecosystem data, which is generally polygon-based. The selection of indicators also reflects the inclusion of riparian zones, including vegetation metrics such as *NDVI* and *NPP*.

Among the condition indicators, water quality holds particular importance due to its direct and immediate impact on aquatic life. This significance is underscored by the fact that it is the only category represented by two indicators, *Dissolved Oxygen* and *pH*.. *Dissolved oxygen* levels determine the habitability of water for most aerobic organisms, while *pH* affects nutrient availability and toxicity of certain contaminants. The expert group also stressed the importance of indicators of water availability and sediment as representative of ecosystem function. Water availability, represented by *Surface Water Occurrence*, shows that the presence and persistence of water is a fundamental prerequisite for any freshwater ecosystem. The soil sediment category, with Soil Organic Carbon (SOC) in the riparian zone as the selected indicator, plays a vital role in nutrient cycling, carbon sequestration, and maintaining habitat quality.

Functional attributes, captured through *NPP*, are highly valued as integrative indicators of ecosystem metabolism and energy flow. *NPP* reflects the balance between carbon assimilation and ecosystem respiration, making it a valuable proxy for ecological productivity and overall ecosystem vitality..

Limitations and constraints of the minimum indicator set

The development of a minimum indicator set for rivers and lakes faces several significant limitations and constraints, primarily resulting from data availability, spatial resolution, and ecosystem-specific characteristics.

A key limitation in assessing the condition and pressures of rivers is the reliance on point data, which restricts the ability to capture spatial variability across entire ecosystems. While point-based measurements, such as those for water quality parameters and pollution, provide valuable localized insights, they often lack the spatial coverage needed to represent broader ecosystem patterns. This limitation is particularly critical for heterogeneous and dynamic freshwater systems, where conditions can vary significantly over short distances. As a result, point data alone are insufficient for comprehensive, ecosystem-wide assessments and may lead to gaps in understanding the full extent of anthropogenic pressures and ecological responses. Moreover, indicators like fish diversity are reported at aggregated scales (i.e., river basin level), which also constrains fine-scale analysis and hampers meaningful comparisons across different river systems with varying levels of human influence. Expanding spatial datasets and integrating remote sensing or modelled data could help address this constraint and improve the effectiveness of ecosystem monitoring.

Rivers and lakes are structurally different systems (i.e., linear and dynamic, vs. polygonal and stable), which poses a challenge in harmonizing indicator datasets. For rivers, high-resolution linear datasets are essential but often lacking, making integration with polygon-based lake data difficult. This can result in the underrepresentation of microhabitats and local variations that are crucial for ecological assessments.

Finally, although the minimum indicator set captures many key stressors, it currently omits emerging contaminants whose ecological impact may be profound. Among these, perfluorooctane sulfonate (PFOS), a persistent “forever chemical” from the PFAS family, is of particular concern, posing serious ecological risks by accumulating in aquatic organisms, disrupting endocrine systems, impairing growth and reproduction, and biomagnifying through food webs. PFOS is now included as a Priority Hazardous Substance under the EU’s Water Framework Directive (WFD) and may be considered to be incorporated into the indicator framework to ensure comprehensive monitoring of ecosystem condition and to address emerging threats to water quality.

Data gaps and recommendations

- AC2: Chlorophyll-a concentration: important indicator to evaluate the health and productivity of aquatic ecosystems like rivers and lakes, serving as a key indicator of phytoplankton biomass, which forms the foundation of the aquatic food web. Elevated levels can also signal eutrophication and potential harmful algal blooms that threaten both wildlife and humans by depleting oxygen and producing toxins. Although the EU Copernicus Land Monitoring Service provides chlorophyll-a concentration maps for lakes, equivalent data for rivers is currently unavailable. This data gap has led to the exclusion of chlorophyll-a as an indicator in the minimum set for rivers and lakes.
- BC1: While the new RivFISH database (Mameri et al., 2025) provides essential data on fish diversity and a map of native fish presence across Europe at river basin resolution, fish diversity in lakes is missing and will require future research. A large range of species will require special attention and monitoring: Macroinvertebrates (e.g., Ephemeroptera, Trichoptera, Odonata), amphibians (e.g., Ranidae, Salamendridae), aquatic plants and algae as indicators of water quality and environmental changes; Benthic organisms (e.g., Chironomidae) as indicators of sediment health.
- AP1: Plastic pollution: This pollution in rivers and lakes is a significant environmental concern, primarily caused by improper waste management, littering, and the inadequate disposal of plastic products. Plastics can enter these water bodies through urban runoff, industrial discharges, and agricultural practices, leading to widespread contamination. Once in aquatic environments, plastics can harm wildlife through ingestion and entanglement, disrupt ecosystems, and pose risks to human health as microplastics enter the food chain. Additionally, plastic pollution can degrade water quality and affect recreational activities. Addressing plastic pollution requires improved waste management practices, public awareness campaigns, and policies aimed at reducing plastic use and promoting recycling.
- AP2: Soil pollution in the riparian zone: Assessing soil pollution in riparian zones is crucial for maintaining ecosystem health and ensuring clean water supplies, as these areas act as natural buffers against pollutants from agricultural, industrial, and urban sources. The main causes of riparian soil pollution include agricultural runoff, industrial discharge, urban runoff, sewage, mining activities, deforestation, and atmospheric deposition. These pollutants can degrade soil quality, disrupt local biodiversity, and pose risks to both aquatic ecosystems and human health. Effective management and conservation practices are essential to mitigate these impacts and protect these vital

habitats. Addressing soil pollution in riparian zones may also help to properly manage landscape habitats surrounding rivers and lakes.

6.3.9. Marine and coastal ecosystems

Definition of the ecosystem type

Marine ecosystems cover approximately 70% of Earth's surface area. They are mostly vast offshore areas outside continental shelves, but the shallower shelf area, coastal waters, estuaries and littoral zone host more diverse underwater life. In the EU, the Marine Strategy Framework Directive (MSFD) gives the definition "marine waters means 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 a Member State has and/or exercises jurisdictional rights, in accordance with the United Nations Convention on the Law Of the Sea (UNCLOS), and coastal waters as defined by Directive 2000/60/EC WFD". The littoral zone between the sea and land is included in the definition and includes the zone which regularly is covered by tides or wind-driven splashes.

In SELINA WP3, coastal terrestrial ecosystems are associated with the marine expert group, because their plant species and communities are characterized by salt content in soil. This habitat includes coastal dunes, beaches and sandy and muddy shores, rocky shores,and salines. All other coastal ecosystem types are covered by the main ecosystem types presented earlier in this document.

Marine ecosystems are under intense pressure from overfishing, pollution, and habitat destruction due to coastal development and unsustainable practices. Climate change adds further stress through warming, acidification, and sea-level rise. Shipping, invasive species, and unregulated tourism also contribute to the degradation of marine environments, threatening biodiversity and the services oceans provide.

Evaluation of the ecosystem condition indicator long-list

The long-list of potential indicators for marine and coastal ecosystems included a total of 9 condition indicators and 22 pressure indicators, for which the results are included in Annex 4.

Marine and coastal ecosystem condition

Among the 9 condition indicators, all had data reported as available except for *Beta diversity,* which is an index of species richness within an area, and hence its calculation is highly dependent on accurate species data. Indicators such as *Dissolved oxygen*, *Spawning stock biomass*, and *Marine species richness of conservation concern* were rated highly for importance, validity, and instrumental relevance. *Maximum depth of habitat-forming vegetation* and *Chlorophyll-a concentration* also received consistently favourable scores across most criteria. It was highlighted that compositional indicators should focus on specific groups of highly mobile species.

Simplicity and sensitivity to human influence were generally rated positively. *Dissolved oxygen* stood out for high scores across all dimensions, reflecting a clear conceptual role and strong operational feasibility. The availability of oxygen is a limiting factor to all aerobic life and it has decreased in many coastal areas where land-based organic pollution has accumulated. *Spawning stock biomass* and *Seabird status* were rated lower for parsimony and reliability, suggesting some uncertainty in their interpretation or overlap with other indicators. Indicators addressing compositional state, such as *Percentage of species with good population status*, also scored well for clarity and relevance, though some limitations were noted in their parsimony and reliability.

Marine and coastal ecosystem pressure

Among the 9 pressure indicators with available data, *Fish mortality*, *Adversely affected benthic habitats*, and *Underwater noise* received the highest ratings for importance and directional meaning, with moderate to high scores for validity and instrumental relevance. *Temperature increase* and *Contaminants in sediment* also showed strong support across multiple criteria.

Climate-related indicators (e.g. *Sea level anomaly*, *Sea water salinity*) were rated moderately across importance and sensitivity. While considered relevant, their scores for simplicity and reliability were more variable. However, these indicators were not taken forward for the minimum set, as it was decided to remove climate variables from the selections. *Harmful algal blooms* and *Non-indigenous species* received moderate ratings for importance and clarity but showed lower validity and sensitivity scores in comparison to other pressures. Indicators such as *Barrier density*, *Riverine litter*, and several water pollution indicators were not scored and are not included in this analysis.

Marine ecosystems

For the purposes of defining minimum indicator sets in this Deliverable, we distinguished coastal ecosystems from marine ecosystems following evaluation of the ecosystem condition indicator long-list, because of the large difference in relevance indicators and therefore provide specific potential minimum indicator sets for both ecosystem types.

<u>Potential minimum indicators</u>

Tables 19 and 20 show the potential minimum indicators for describing marine ecosystem condition and pressure, respectively.

Table 19 : Potential minimum condition indicators for marine ecosystems (see Annex 5 for details). * = Indicators in the EU-wide methodology to map and assess ecosystem condition.

Class	Category	Variable	Resolution	Unit	Year	Source
AC1	Water availability	na				
	Sediment condition	na				
AC2	Air	na				
	Water	Dissolved Oxygen	point data / interpolated	mg/l	2012-2024	EMODnet
		Nutrient concentrations	point data / interpolated	mg/l	2013-2024	EMODnet

Class	Category	Variable	Resolution	Unit	Year	Source
		Concentration of total suspended matter	point data / interpolated	mg/l	2014-2024	EMODnet
	Sediment	na				
BC1	Species diversity	Bird, mammal, cephalopod and turtle abundances	Varying from sources	n° / unit used	? - present	EMODnet / OSPAR / ICES / MedQSR (UNEP) / HELCOM
		Seagrass cover	Varying from sources	km^2	2019-present	EMODnet
BC2	Structural	Spawning stock biomass (SSB) of commercially important fish species (tonne per spp)	marine reporting units (MRU)	tonnes	2014 - present	WISE / ICES / GFCM/ ICCAT
BC3	Productivity	Chlorophyll-a concentration	10 km	µg/l	1998 - present	Copernicus
		Frequency and intensity of harmful algal blooms	10-100 km^2	km^2	2015 - present	Copernicus
		Coverage of habitat forming vegetation (e.g. Maximum depth of habitat-forming vegetation) (%)	10-100km^2	%	2014 - present	WISE
LC1	Structural	data gap				
LC2	Compositional	Benthic community indices (AMBI, BQI)	Coastal water body	unitless		WISE

Table 20 : Potential minimum pressure indicators for marine ecosystems (see Annex 5 for details). * = Indicators in the EU-wide methodology to map and assess ecosystem condition.

Class	Category	Variable	Resolution	Unit	Year	Source

AP1	Water	Continuous underwater noise	grid 1/3° by 1/6°	Ships /day	2018-present	EMODnet / EC
		Marine micro-litter	point data	items / m^3	2018-present	EMODnet
		Marine macro-litter	point data	items / $1000m^2$	2018-present	EMODnet
	Sediment	na				
AP2	Air pollution	na				
	Water pollution	Antifoulants	point data / interpolated	µg/l	2012 - 2024	EMODnet
		Heavy metals	point data / interpolated	µg/l	2013 - 2024	EMODnet
		Hydrocarbons	point data / interpolated	µg/l	2014 - 2024	EMODnet
		Pesticides and biocides	point data / interpolated	µg/l	2015 - 2024	EMODnet
		Nitrogen and Phosphorus loads	river basin	t/year	1990 - 2018	JRC
	Sediment pollution	Antifoulants	point data / interpolated	µg/kg	2012 - 2024	EMODnet
		Heavy metals	point data / interpolated	µg/kg	2013 - 2024	EMODnet
		Hydrocarbons	point data / interpolated	µg/kg	2014 - 2024	EMODnet
		Pesticides and biocides	point data / interpolated	µg/kg	2015 - 2024	EMODnet
	Biota pollution	Contaminants in fish and shellfish (CHASE)	point data / interpolated	µg kg^{-1}	2015-2024	EMODnet
BP1	Species	Introduced Invasive alien species	10 km	number of species	2012 - 2024	EEA
CP1	Sea-use	Fish mortality (f) of commercially exploited fish and shellfish exceeding fishing mortality at maximum	1000-100000 km^2	unitless	2016 - 2021	WISE Marine

		sustainable yield (fmsy)				
		Adversely affected benthic habitats	1-10 km^2 grid cell	km²	2016 - 2021 / 2010- 2015	WISE Marine - OSPAR
CP2	Fragmentation	Data gap				

Discussion

An essential consideration in the development of a minimum set of indicators for marine ecosystems is alignment with the requirements of the MSFD, as the central policy instrument in this domain. This is reflected in many of the indicators included in the tables above. The MSFD is a “data-hungry policy” and, in principle, covers all biotic and abiotic factors of this ET. However, the MSFD approach is not to define a minimum set of indicators. For instance, all specific hazardous substances, nutrients, species and habitats are assessed separately against their threshold values. The regional sea conventions have simplified the marine ecosystem assessments by using integrated assessments which combine multiple indicators of the same theme (e.g., eutrophication, hazardous substances or biodiversity). For the same reason (simplicity and communication purposes), the *contaminant index in sediment* (CHASE) was also rated high in this survey, as it can include any number of substances and provide an assessment result of the condition from contamination perspective.

Functioning of the food web is a component of the marine ecosystem which requires suitable indicators. In the minimum set, abundance of top predator species of cetaceans, seals, big fish and seabirds fulfil this role, whereas mesopredators are assessed by the abundance of small fish, some bird and cephalopod species. The lower levels of the marine food web are represented by benthic invertebrates and primary producers (chlorophyll indicator, seagrass meadows and width of macroalgal zones). In Table 21, the oxygen, *harmful algal blooms* and *concentrations of nutrients* and *suspended solids* are considered as condition indicators even if they could also be pressures on the condition. Nonetheless, they represent important boundary conditions for many biota and therefore deserve their place in the minimum set of indicators. The pressure indicators in Table 22 include also substance indicators, but there the concentrations of hazardous substances are seen as an anthropogenic threat to the ecosystem condition.

Human activities exert severe pressures on marine ecosystems and the extent of many of these activities have clearly degraded the ecosystem condition (see Box 5). For example, studies in the North Sea and the Western Mediterranean have shown that 30-87% of benthic shelf habitats are trawled at least once per year. Therefore, the minimum set includes an indicator of habitat disturbance (calculating share of habitats disturbed or polluted) and *fishing mortality (F-MSY) of commercially exploited stocks*.

Underwater noise by maritime traffic is probably a significant cause for the avoidance behaviour of many cetacean species and there is some evidence of its disturbance to lower organisms, too. Micro and macro litter are identified as important indicators of physical pressures, but there are many different litter types (floating, beach, seabed; synthetic, non-synthetic, etc). For operationalizing this minimum set of indicators, it would be necessary to select the specific type. It is also unclear how much marine litter impacts the marine ecosystems. Entanglement of bigger species definitely increases population mortality and microplastics are shown to convey contamination to biota, but these are not likely the key condition indicators.

Limitations and constraints of the minimum indicator set

- The marine underwater ecosystems are not well mapped and therefore spatial indicator data is scarcely available. Indirect methods by the pressure indicators are considered a good proxy for areas where biological data is not representative.
- Mobile and migrating species such as cetaceans, many fish and most seabirds have wide distribution areas and their abundance indicators do not provide spatially detailed ecosystem assessments. Habitat condition indicators may be better choices if spatial resolution is necessary.
- While many of the indicators are already operational for assessments under the MSFD, WFD, HD, BD or regional sea conventions, they may still lack reference levels indicating good ecosystem state. This may be especially true for many pressure indicators.

Comparison with the EU-wide methodology to map and assess ecosystem condition

There are many overlaps with the indicators in the EU-wide methodology, with available indicators from these lists largely retained. However, we propose a difference in classification of Spawning stock biomass (B2 structural state in JRC, here BC1 Compositional condition). Compared to the list of indicators in the EU-wide methodology, the lists above focus less on variables of physical state, in part due to the exclusion of climate variables.

Data gaps and recommendations

- Variability in data availability geographically - some indicators such as *Spawning stock biomass* are available for all of Europe, but have fewer fish species covered in the Mediterranean and Black Sea.
- BS1: Compositional condition indicators again face the problem of coarse spatial resolution, being available only at the level of marine reporting units or based on national statistics.
- CP2: Adversely affected benthic habitats is a difficult indicator to calculate, but the EU MSFD technical group Seabed is developing it for member states. In simpler cases the indicator can also be calculated as a sum of normalized spatial pressure layers in a grid, which gives relative differences in pressure intensity over the grid area.
- LC1: There is a lack of established indicators for assessing marine connectivity, such as ecological corridors that facilitate species movement and gene flow between habitats; these pathways remain undefined in both spatial and functional terms, limiting the ability to evaluate connectivity-related ecosystem processes and resilience.

Box 5. Key Messages for Europe's marine ecosystems

Mapping the Invisible: Using Pressure Indicators to Safeguard Europe's Marine Ecosystems

Why Pressure Indicators Matter

As high-resolution spatial data become increasingly available, pressure indicators offer a promising way to assess marine ecosystem condition efficiently. Traditional assessments rely heavily on field-based condition indicators, which are resource-intensive. Pressure-based models provide a cost-effective, scalable alternative by estimating potential ecosystem impacts from human activities.

How Pressure Indicators Work

Cumulative Impact Assessments (CIAs) integrate spatial data on human pressures—such as fishing, shipping, and coastal construction—with ecosystem components (e.g., species, habitats). These models apply sensitivity scores to quantify the relative vulnerability of components to each pressure (Halpern et al. 2015; Korpinen et al. 2021; Kallio et al. 2025).

Benefits and Limitations

- Enable broad-scale, consistent monitoring
- Support marine spatial planning and policy decisions
- Current models assume additive, linear impacts; non-linear interactions are still under development
- Validation with condition-based indicators is essential for credibility

Policy Applications

The European Environment Agency (EEA) implemented a pan-European CIA, combining 16 pressures and 31 ecosystem components. The results correlated with assessments under the Water Framework Directive and EU biodiversity status (EEA 2019; Vaughan et al. 2019).

- Efficiently highlight high-impact areas
- Enhance marine protection strategies
- Inform adaptive management approaches

Recommendations

- Invest in enhancing model complexity (e.g., synergistic effects)
- Standardize pressure and ecosystem datasets
- Validate with ground-based condition indicators
- Incorporate CIA results in EU and national marine policy

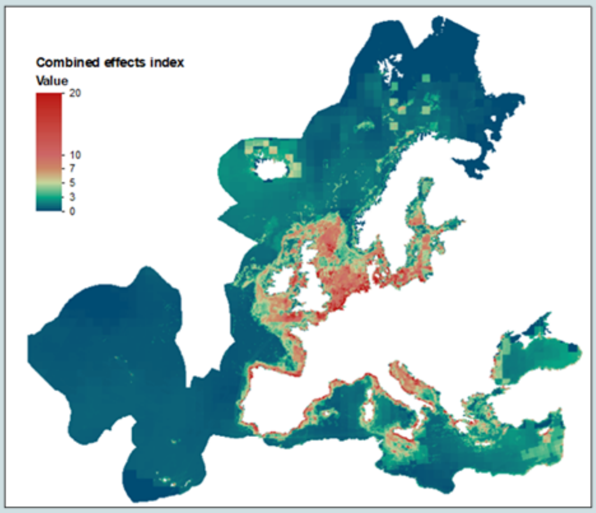


Figure. The marine cumulative impact assessment in Europe, where the higher index values indicate potentially worse ecosystem condition. The cumulative impact of human pressures extends across 96% of the European marine area. Specifically, physical disturbances affect 86% of the coastal regions and 46% of the shelf areas (Korpinen et al. 2021).

Coastal ecosystems

Here, coastal ecosystems encompass the following terrestrial and semi-terrestrial ecosystems: Coastal dunes, beaches, sandy and muddy shores, rocky shores, and salines. For three ecosystems, a separate set of minimum indicators was developed after evaluating the potential indicators for marine ecosystems, aligning more closely with the indicators for terrestrial ecosystem types.

Coastal ecosystems are heavily pressured by land use development, pollution (e.g., Runoff from agriculture and industry, sewage, plastic waste), and overexploitation of natural resources. Climate change intensifies risks through sea-level rise and extreme weather, while habitat degradation and invasive species further compromise ecosystem health. Tourism and recreational activities also contribute to environmental stress, endangering the biodiversity and protective functions of these vital coastal areas.

<u>Potential minimum indicators</u>

Tables 21 and 22 show the potential minimum indicators for describing coastal ecosystem condition and pressure, respectively.

Table 21: Potential minimum condition indicators for coastal ecosystems (see Annex 5 for details). * = Indicators in the EU-wide methodology to map and assess ecosystem condition.

Class	Category	Variable	Resolu-tion	Unit	Year	Source
AC1	Water availability	na				
	Soil condition	na				
AC2	Air	na				
	Water	na				
	Soil	na				
BC1	Species diversity	Vascular plants abundance	10 km	n° / 10 km	2013 - 2018	EEA
		Wader bird abundance	10 km	n° / 10 km	2013 - 2018	EEA
BC2	Vegetation	Small Woody Features	5 m to 100 m	m/m²	2017 - 2019	EU Copernicus Land Monitoring Service
BC3	Productivity	na				
LC	Connectivity	Connectivity index of semi-natural-areas	100 m	%	2018 - 2021	EU Copernicus Land

Class	Category	Variable	Resolu-tion	Unit	Year	Source
						Monitoring Service

Table 22 : Potential minimum pressure indicators for coastal ecosystems (see annex 5 for details). * = Indicators in the EU-wide methodology to map and assess ecosystem condition.

Class	Category	Variable	Resolu-tion	Unit	Year	Source
AP1	Water use	na				
	Soil	Coastal erosion rate	10 m	m/y	2007 - 2019	EMODnet
		Beach litter	100 m	n° items	2016 - 2021	EMODnet
AP2	Air pollution	Exceedance of critical loads for eutrophication	point grid	mol Neq/ha /y	2022	EMEP/EEA
	Water pollution	na				
	Soil pollution	na				
BP1	Species	Pressure by IAS	10 km	Unitless	2022	Polce et al., 2023
CP1	Land-use	Share of built-up areas	100 m	%	2018-2021	EU Copernicus Land Monitoring Service
CP2	Fragmentation	Mesh density	100 m	n°/1000 km²	2009 - 2019	EEA

Discussion

Terrestrial coastal ecosystems present several challenges that may hinder the selection of a minimum representative set of condition indicators. From a structural and functional perspective, these ecosystems are highly heterogeneous. Shaped by a range of coastal processes and underlying geological structures, this category includes systems that span from shingle and rocky shores to fully vegetated marshes. Such heterogeneity significantly limits the number of indicators that can adequately represent condition across all ecosystem subtypes.

Related to the above, in some areas in Europe, terrestrial coastal ecosystems are often small and patchy, which hampers their representation in a spatially explicit manner, particularly when relying on satellite data-based remote sensing products. In relation to pressures and their indicators, the same problem applies. Different pressure may impact terrestrial ecosystem subtypes differently, with more or less severe consequences for the overall condition. Therefore, defining broad pressure indicators without considering the specificities of all ecosystem subtypes is not optimal, and in many cases does not make sense.

These challenges are clearly reflected in the choice of indicators. For instance, physical condition indicators related to soil characteristics (e.g. bulk density) are often not applicable in terrestrial coastal ecosystems, as these areas are typically dominated by rocky, shingle, or sandy ground rather than true soils. The selection of indicators in this list was therefore guided by the representativeness of pressures and condition across ecosystem subtypes, as well as the potential for data availability at the EU level, which resulted in a somewhat reduced number of indicators.

Limitations and constraints of minimum set

The main limitations of the minimum set arise from the intrinsic heterogeneity and spatial configuration of terrestrial coastal ecosystems. These ecosystems encompass a diverse range of landforms - from rocky shores and shingle beaches to sandy dunes and vegetated marshes - making it difficult to identify indicators that are both ecologically meaningful and broadly representative. Indicators commonly used in other ecosystems, such as satellite data-derived vegetation indices (e.g. *EVI*) or *NPP*, are of limited value here. Many coastal ecosystems lack consistent vegetative cover, and the coarse spatial resolution of some products (e.g. 300 m for NPP) far exceeds the narrow, fragmented extent of most coastal systems. As a result, these indicators entail a high degree of spatial uncertainty and limited interpretability.

Comparison with the EU-wide methodology to map and assess ecosystem condition

The JRC's EU-wide methodology for mapping and assessing ecosystem condition does not treat coastal ecosystems as a distinct category, instead grouping them within broader marine or terrestrial classifications. This may limit the ability to capture the unique pressures and functions of coastal zones, which serve as critical transition areas with high biodiversity and vulnerability.

Data gaps and recommendations

Data availability in coastal ecosystems is often limited, which ultimately constrains the applicability of condition indicators. In many cases, the availability of data depends on the structure and design of national monitoring programmes, with only a few sites consistently monitored. Spatially explicit and continuous datasets are frequently lacking or are too coarse in spatial resolution to accurately capture the structure of these ecosystems. Furthermore, monitoring programmes are often biased towards specific ecosystem types that are integrated into ongoing or past European directives and policies. This means that data availability is not uniformly distributed across all coastal terrestrial subtypes.

- BC3: Breeding success of waders would be a relevant indicator of functional condition, which is specific to coastal inland areas (has been linked to condition of marshes. However, data is generally limited to local studies and is not spatially explicit. Breeding success of waders is also not just linked to the condition of coastal ecosystems, but also to the status of predator populations in nearby forests.

- AP1: Coastal siltation rates, referring to the rate at which silt and sediment accumulate in coastal areas, is a key indicator in coastal ecosystems. This process can be influenced by river discharge, coastal currents and tides, and human activities (e.g., dredging, construction, agriculture) and can have significant impacts on navigation, ecosystems, and coastal infrastructure. An increased rate of siltation can also counteract coastal erosion and support coastal defence. Thus, understanding the siltation rate is crucial for managing coastal zones, however, no spatially explicit data is available

To improve the effectiveness and ecological relevance of coastal monitoring and assessment, we recommend the following actions, which address key gaps in data quality, methodological consistency, and indicator suitability across diverse coastal ecosystems. The use of satellite-derived indices should be avoided unless these are complemented with in-situ data to improve interpretation and relevance for diverse coastal ecosystems. For instance, in vegetated coastal ecosystems, changes in vegetation index values (e.g. NDVI) should be validated against in-situ measurements of plant species composition, vegetation cover, and biomass (BC1), to distinguish between actual ecological changes and artefacts driven by factors such as soil moisture or tidal dynamics. In unvegetated coastal areas, satellite-derived spectral data should be calibrated with ground-based observations to derive reliable estimates of erosion rates (AP1). Regarding coastal erosion specifically, multitemporal LiDAR datasets provide more accurate elevation change estimates than optical satellite data, although their broader adoption would require harmonization across EU member states to address inconsistencies in data resolution, format, and availability. Secondly, strengthening field-based monitoring is essential to capture the structural and functional variability of coastal terrestrial habitats. The growing availability of small, low-cost environmental sensors offers opportunities to improve not only spatial but also temporal monitoring of key abiotic parameters such as soil moisture, temperature, and salinity. These parameters are critical for understanding ecosystem responses to pressures like sea-level rise or altered freshwater input. We recommend integrating sensor networks with EU-wide citizen science initiatives, which can provide valuable observations of pressure indicators such as the presence and spread of invasive species (BP1).

Finally, it is also necessary to develop ecosystem-specific condition indicators that reflect the diversity of coastal landforms and vegetation types. For instance, vegetation cover or biomass might be relevant in dune grasslands, but such metrics are less informative in shingle beaches or mudflats, where bare substrate is natural and essential for ecosystem functioning. Similarly, indicators such as sediment compaction or surface stability, which are highly relevant for beaches and mudflats, are less commonly integrated into monitoring schemes. Using generalized indicators risks misinterpreting natural dynamics as degradation or missing early warning signs of ecosystem stress. Thereby, we recommend that coastal ecosystem condition assessments adopt habitat-typology-specific indicators, grounded in ecological function and disturbance regimes.

6.3.10. Common features of discussion across ecosystem types

The discussions across ecosystem type groups reveal strong convergence on several foundational issues: the importance of ecological specificity, clarity in indicator definitions and purpose, and flexibility in implementation. Despite differences in ecosystem structure and management intensity, there is a shared commitment to developing robust, policy-relevant, and scientifically credible condition assessment indicators that reflect the realities of each ecosystem while enabling coherent EU-wide reporting. Distinguishing between pressure and condition indicators is essential for effective ecosystem assessment. Pressure indicators, such as nutrient loading and soil imperviousness, describe external influences on ecosystems, while condition indicators, like species diversity and soil health, reflect the internal state of ecosystems. The interplay between these indicators is complex, and their clear delineation is crucial for identifying causal relationships and developing and evaluating targeted management strategies. Moreover, there may be ambiguity in classifying indicators. For example, indicators like *Chlorophyll-a concentration* and *Harmful algal bloom frequency* reflect eutrophication pressure, but are also used to infer biological productivity or condition. A precise definition of the optimal condition (i.e. the reference level) is therefore clearly necessary.

Several common points of discussion can be identified across the ecosystem type groups:

- Difficulty in balancing feasibility and ecological relevance within the 'minimum' set: ET groups emphasise the tension between developing a minimum set of indicators, and the ecological complexity of ecosystems. The simplification necessary to develop a minimum set, whilst contributing to the standardised and comparable monitoring, may risk omitting context-specific elements (e.g. peat integrity in wetlands, trophic indicators in marine ecosystems). Depending on the ultimate application of the information on Ecosystem Condition, more or less context relevance may be required. The challenge is especially evident in marine and coastal zones, where pressures and biodiversity are highly dynamic and spatially diffuse. Furthermore, given the diversity within ecosystem types across Europe, there may be additional, regionally relevant, variables that are key for effectively representing condition. There is therefore an important trade-off to consider between indicators with EU-wide comparability and relevance for local policy, and other indicators may be more appropriate in achieving this balance in local applications.
- Indicator selection and interpretation: The selection of indicators involves trade-offs between simplicity, relevance, and sensitivity. Indicators like the NDVI and EVI are favoured for their accessibility and ease of interpretation but may not capture the full ecological complexity of ecosystems. Conversely, more specialized indicators, such as those related to specific species groups or functional traits, provide deeper ecological insights, but are often constrained by data availability and methodological challenges.
- Integration of remote sensing data: Remote sensing data, particularly from Copernicus Sentinel missions, play a crucial role in ecosystem monitoring. These data provide consistent, high-resolution information on vegetation cover, water occurrence, and other key parameters. However, the integration of remote sensing data with ground-based observations remains a challenge, particularly in ensuring that remote sensing metrics accurately reflect on-the-ground conditions.

Across all ecosystems, common data gaps were identified:

- Biodiversity indicators, particularly those related to species richness and abundance, often lack comprehensive, spatially explicit datasets. This limitation hampers the ability to conduct thorough assessments and set meaningful conservation targets. For bird diversity, it is worth noting that sources such as the European Breeding Bird Atlas (EBBA and EBBA2, 2025; Keller et al., 2020) could be really useful to mapping European occurrence. EBBA2 is a comprehensive project mapping the distribution and abundance of breeding birds across Europe between 2013 and 2017. It provides vital data for conservation, showing changes in bird populations and guiding biodiversity policy at the continental scale. This kind of monitoring initiative is a very important source of primary data; effort should be put into their maintenance and integration with other data sources from MS (Soultan et al. 2022).
- Functional diversity and beta diversity at the landscape level - two indicator categories which represent two parts of biodiversity and are essential for understanding ecosystem processes and resilience, and potential interactions between ecosystem patches.
- Plastic and Emerging Pollutants (e.g., PFAS) are largely unmonitored across ecosystem types, particularly in aquatic ecosystems, including wetlands, despite a growing ecological risk. Monitoring them would be essential to capture chronic and persistent contamination.
- Point-based data or aggregated tables (e.g., NUTS2 level) for nutrients and pesticides does not provide sufficient resolution for assessing impact on ecosystem condition, especially for aquatic ecosystems where nutrient runoff and agrochemical loading are key pressures.

Tables 23 and 24 provide an overview of the variables included in the minimum indicator sets for the 7 different terrestrial ecosystem types considered in D3.2. Whilst initially, this deliverable also aimed to develop a common minimum set of indicators for terrestrial ecosystems, no indicators were deemed universally relevant by all ecosystem types. The minimum sets across terrestrial ecosystems reflect the need to assess the same core ecosystem characteristics, however these characteristics manifest differently by ecosystem type. This includes the use of general indices, such as the soil water index, which require further specification for particular applications, and varied forms of vegetation cover (e.g. cover crops in agroecosystems and tree cover in forests).

It was also noted that development of a common list would face multiple considerations:

- The directionality of a variable is often specific to the ecosystem type in question; for example, higher soil moisture might indicate better condition for wetlands but not for dry grasslands.
- The exact definition of indicator, such as the method by which data points are aggregated to a coarser temporal resolution (e.g the calculation of annual or seasonal values from a data set of daily values), may need to be different for different ecosystem types.

- The accuracy of potential datasets will depend on the granularity of the ecosystem type. However it is important to note that the required accuracy depends on the application purpose (Zulian et al., 2018)

Table 23: Summary of all condition indicators included in minimum sets (A: Agro, F: Forest, U: Urban, W: Wetland, H&S: Heathland and Shrubland, G: Grassland, C: Coastal)

Class	Category	Variable	A	F	U	W	H&S	G	C
AC1	Water availability	Soil water index	X	X			X	X	X
		Water-Wetness-Probability-Index (WWPI)				X			
	Soil condition	Soil erodibility		X					
		Bulk density	X	X			X	X	X
AC2	Air	na							
	Water	na							
	Soil	SOC	X	X			X	X	
		C:N ratio		X					
BC1	Species diversity	Bumblebee diversity	X				X	X	
		Crop diversity	X						
		Farmland bird diversity	X						
		Forest bird diversity		X					
		Proportion of native tree species		X					
		Wetland bird diversity				X			
		Vascular plants abundance							X
BC2	Vegetation	Share of cover crops	X						
		Small Woody Features	X					X	X
		NDVI		X					
		Above-ground biomass		X					
		Tree cover density		X	X				X
		Canopy height		X			X		

Class	Category	Variable	A	F	U	W	H&S	G	C
		Share of green (and blue) space				X			
		Enhanced Vegetation Index					X	X	
BC3	Productivity	Net Primary Production	X	X	X	X	X	X	
		Soil biomass productivity	X	X				X	
LC	Connectivity	Density of SN-areas	X						
		Connectivity index of SN areas		X	X	X	X	X	X

Table 24: Summary of all pressure indicators included in minimum sets (A: Agro, F: Forest, U: Urban, W: Wetland, H&S: Heathland and Shrubland, G: Grassland, C: Coastal)

Class	Category	Variable	A	F	U	W	H&S	G	C
AP1	Water use	Water Exploitation Index (WEI+)	X						
	Soil	Imperviousness	X	X	X		X	X	
		Soil loss due to harvesting and fire		X					
AP2	Air pollution	AOT40	X	X				X	
		Exceedance of critical loads for acidification		X					
		Exceedance of critical loads for eutrophication		X			X		
		Annual average concentration of PM2.5			X				
	Soil pollution	Fertilizers (NP surplus)	X					X	
		Heavy metals	X						
		Soil acidity		X					
BP1	Species	Pressure by IAS	X	X			X	X	
		Insect and disease disturbances		X					
CP1	Land use	Light pollution levels			X				
		Livestock density						X	
	Disturbance	Number of disturbance events		X					
CP2	Fragmentation	Mesh density	X	X			X	X	

7. Evaluation of Ecosystem Pressure Indicators: The Human Pressure Index for terrestrial ecosystems

The aim of this work is to show the possibilities offered by the use of spatially explicit data at European level and to develop a concrete application of all the work carried out by the SELINA Task 3.2. All the maps presented are intermediary versions that will require further work, as for example including Norway, Switzerland and the UK, for which some data is missing or needs to be adapted to be comparable with that published by European institutes. The next step of this work will evolve applying and testing this approach through a case study linking our human pressure index to ecosystem condition metrics for pressure-condition relationship assessment.

7.1. Context

Recent global evaluations by the Intergovernmental Panel on Biodiversity and Ecosystem Services (IPBES 2019) have emphasized the urgency to reverse trends causing species loss and ecological process disruption. Despite decades of acknowledging the importance of environmental conservation and sustainable ecosystem management (MEA, 2005), how to effectively maintain ecosystems in good condition, ensuring species thrive and nature supports human well-being over the long term remains a major challenge (European Commission 2021a, IPBES 2019). We now have a fairly good understanding of the main causes affecting ecosystems, as reported at European level (EEA 2020). However, how these pressures, acting together, affect ecosystem condition remain ambiguous. Quantifying human pressure is therefore of major interest for better understanding the impact of human activities on ecosystem condition, ensuring adequate environmental management, and promoting the sustainable development of human society.

7.2. Developing the Human Pressure Index (HPI)

We developed a spatially explicit aggregated pressure index, the Human Pressure Index (HPI), to assess the overall anthropogenic impact on terrestrial ecosystems. By integrating multiple stressors, the HPI aims to establish more consistent correlations with ecosystem condition metrics compared to individual stressors alone. This index utilizes the standardized yet flexible reporting frameworks of the SEEA-EA to monitor pressures, as described in section 6.2.2, and will contribute to ongoing ecosystem assessment and management initiatives. It will serve as a tool to inform policy decisions, direct conservation strategies, and ultimately promote the sustainable coexistence of human activities and thriving ecosystems.

The HPI covered all 27 European Union member states (i.e., Belgium, Bulgaria, Czech Republic, Denmark, Germany, Estonia, Ireland, Greece, Spain, France, Croatia, Italy, Cyprus, Latvia, Lithuania, Luxembourg, Hungary, Malta, Netherlands, Austria, Poland, Portugal, Romania, Slovenia, Slovakia, Finland, and Sweden) and focused solely on terrestrial ecosystems as defined by the Corine land cover (CLC) classification system.

This index was developed through a systematic four-step methodological process designed to quantify multiple anthropogenic stressors affecting European terrestrial ecosystems. The process consisted of:

- Selection of Metrics: Identification and collection of relevant pressure indicators across the defined geographic extent.
- Data alignment and rescaling
- Scaling: Standardization of the diverse pressure metrics to ensure comparability across different measurement scales and units.
- Weighting: Assignment of relative importance to different pressure components based on their documented ecological impacts.
- Aggregation: We integrated the weighted metrics into a single comprehensive index.

This methodological approach allowed to create a spatially explicit measure of anthropogenic pressure that can be uniformly applied across different terrestrial ecosystem types within the study region.

Consideration for metrics selection

The pressure typology presented in Section 6.2.2 was used for selecting appropriate indicators. These indicators were chosen following several criteria:

- Responsiveness of ecosystem to change in biotic and/or abiotic state resulting from pressure changes,
- Validity (i.e., representability of the sub-category characteristics) and reliability (i.e., accuracy and reproducibility),
- Data availability simplicity and compatibility across different ecosystem types, and
- Spatial explicitness.

The final list of indicators should be parsimonious while comprehensively representing the range of human pressures. We based our selection on the participatory works performed within the SELINA project. Resource use focused on water use (i.e., Water Exploitation Index) and wood production was used as a proxy of forest land-use. For pesticide pressure, a pesticide risk score developed by Tang et al (2021) was used. The authors provided a global map on risk score based on pollution risk of active pesticide ingredients. This score was only used for agroecosystems as defined by CLC. The choice of these data was driven by the limitation of the data provided by the JRC. Although human activities may have direct impacts on climate change (IPCC 2023, Lynas 2021), indicators of climate change were not considered, as they often overlap and interact with human pressure indicators (e.g., air pollution, resources extraction). We also excluded indicators of pathogens and diseases, as no spatially explicit indicators were identified. Additionally, we omitted the water pollution for terrestrial ecosystems because freshwater pollution, such as nitrogen or phosphorus contamination, is usually linked to pollution coming from agricultural and urban areas. The final set of indicators is presented in Table 25.

Table 25. List of available variables selected to assess human pressure in terrestrial ecosystems in Europe (Sources of data: EEA: European Environment Agency; JRC: Joint

Research Center; ESDAC: European Soil Data Centre; EASIN: European Alien Species Information Network; EFI: European Forest Institute) (see Annex 5 for details).

Group	Class	Category	Variable	Source	Resolution	Reference
Abiotic pressures	AP1 - Physical	Water use	Water Exploitation Index (WEI+)	EEA	Sub-river basins	Faergemann (2012)
		Soil	Imperviousness	Copernicus	10 m	Copernicus (2018)
			Soil loss due to crop and roots harvesting (Soil erosion cropland)	JRC/ESDAC	1000 m	Borrelli et al. (2022)
			Soil loss due to harvesting and fire (Soil erosion forest)	JRC/ESDAC	100 m	Borrelli et al. (2016)
	AP2 - Chemical	Air pollution	AOT40 Ozone vegetation and crops	EEA	2000 m	Horálek et al. (2020)
			Exceedance of critical loads for eutrophication	EEA	Gridded	Posch et al. (2008)
		Soil pollution	N and P surplus	EEA	1000 m	De Vries et al. (2022)
			Pesticide risk score	Tang et al. (2021)	10000 m	Tang et al. (2021)
			Heavy metals	EEA	1000 m	De Vries et al. (2022)
Biotic pressure	BP1 - Compositional	Species	Pressure by invasive alien species (IAS)	JRC/EASIN	10000 m	Polce et al. (2023)
Landscape pressure	LP1 - Physical	Land-use	Forest product exploitation	EFI	1000 m	Verkerk et al. (2015)
			Intensity of agricultural management	JRC	1000 m	Rega et al. (2020)
	LP2 - Structural	Fragmentation	Mesh density	EEA	10000 m	Jaeger (2007)

Data alignment and rescaling

To ensure consistent spatial representation across diverse data sources and ecosystem types, a standardized resolution of 1 km^2 was implemented. All maps were reprojected to ETRS89-extended, the coordinate system for Europe (EPSG: 3035), and then resampled to a 1km^2-grid reference. Resolutions lower than 1 km^2 were upscaled using nearest neighbor criteria, while higher resolutions were downscaled using mean pixel values reduction.

Scaling the metrics

To ensure comparability across different metrics, we normalized each metric to a unitless score ranging from 0 (no pressure) to 1 (strongest pressure). The normalization was performed using the following formula:

$$x = ((\text{Metric}_x) - (\text{Lower anchor})) / ((\text{Upper anchor}) - (\text{Lower anchor}))$$

where x is the normalized score, Metric is the observed value of the metric, and the upper and lower anchors represent the range of the metric.

Here the lower anchor is the lower reference value of the pressure variable that is defined as zero, considering that no pressure is affecting ecosystems, and the upper anchor is the highest value found at the European continental scale used. Thus the final formula is:

$$x = (\text{Metric}_x) / (\text{Upper anchor})$$

Weighing the metrics

To address the varying impacts of different stressors on ecosystems, we aimed to create a weighting system, using both expert input and statistical analysis. Following the IPBES report (IPBES, 2019), we firstly categorized our pressure indicators into five primary drivers of biodiversity loss and ecosystem degradation, excluding climate change and species exploitation. We applied the weights assigned by IPBES to each driver based on their relative impact on six classes of Essential Biodiversity Variables (EBVs) (Pereira et al., 2013). Next, all co-authors of this study were asked to assign a relative score to each indicator within its respective driver category, based on its importance or relative impact. Finally, we multiplied the relative weight of each indicator by the total score of its category to determine the final weight of each indicator.

We also conducted a sensitivity analysis of the Human Pressure Index (HPI) to assess its responsiveness to changes in the input data. We modified the data by increasing and decreasing the mean values of each variable by 50%, while keeping the other variables constant. We adjusted each parameter individually and evaluated how much it deviated from the baseline HPI, using the standard set of parameters without weighting as a reference.

Aggregation of the metrics

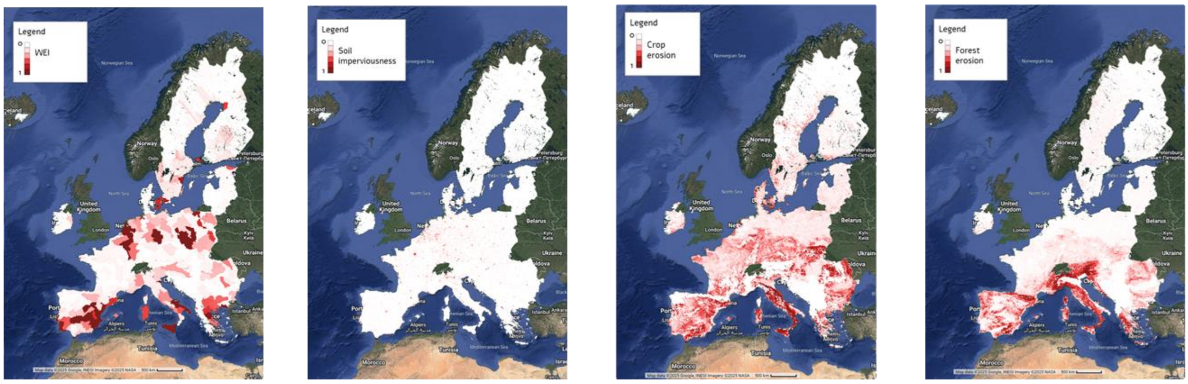
The final step consisted of aggregating the weighted, normalized scores into a single HPI. We used a weighted arithmetic mean to combine these scores, ensuring that each type of pressure was represented according to its impact on the ecosystem.

The resulting HPI ranges again from 0 to 1, with higher scores signifying greater human pressure and lower scores indicating minimal human disturbance. This standardized scale enables both spatial comparisons across different geographic regions and thematic analysis across various pressure components.

7.3. Results

Abiotic physical pressures

Water resources are under significant pressure (Fig. 14a). Regions highlighted in red represent zones with high Water Exploitation Index (WEI+) values, meaning water demand exceeds supply. These are primarily located in southern Europe, including Spain, Italy, and parts of Greece and France, reflecting regions prone to water scarcity. However it is worth noting that, in Belgium, Netherlands, north Germany and Poland also present high WEI+, which could be related to high agricultural activities. Soil sealing or impervious surfaces, representing high imperviousness, are notable around urban and densely populated areas, such as London, Paris, and parts of central Europe (Fig. 14b). These surfaces prevent water infiltration, thus affecting ecosystem services such as flood control (Vallecillo et al., 2020), and affect natural ecosystems. Significant erosion can be seen in central and southern European croplands, including parts of Italy, Spain, France, and eastern Europe, driven by factors such as rainfall, topography, and farming practices. (Fig. 14c). Forest soil erosion is prevalent in mountainous regions such as the Alps, the Apennines, and parts of the Balkans, probably driven by topography and higher rainfall, and in Mediterranean regions such as the Iberian Peninsula, Italy and Greece, prone to wildfires, especially in the summer months when water scarcity is high (Fig. 14d).



a) Water exploitation b) Imperviousness c) Soil erosion cropland d) Soil erosion forest

Figure 14: Individual maps of physical abiotic pressure across Europe: a) Water Exploitation Index plus (WEI+), b) Imperviousness, c) Soil erosion in cropland (i.e., soil loss due to tillage and roots harvesting) and d) Soil erosion in forest (i.e., loss loss due to harvesting and fire). (Larger maps can be found in Annex 6).

Abiotic chemical pressures

High level of ground-level ozone (O_3) pollution, which is harmful to human health, vegetation and various animal species including mammals,birds, reptiles and amphibians, are evident in southern and western Europe, especially Italy, France, and the Iberian Peninsula, reflecting the interactions between warm climates and high vehicle emissions (Fig. 15a). Atmospheric nitrogen pollution, often emissions of oxidized nitrogen (NO_2, nitric acid and nitrate-containing particles) are highest in Belgium, northern Germany, northern Italy, the Netherlands and Poland (Fig. 14b), indicating high nitrogen deposition and risk of eutrophication that can significantly disrupt nutrient balances and biodiversity. Fig. 15c and Fig. 15d displays nitrogen and phosphorus accumulation in soils. Central and southern Europe show high N surpluses, particularly Germany, Italy, and parts of France and eastern Europe and western Europe, including France and the Benelux region, along with northern Italy, show high phosphorus loads. These regions correspond to the major agricultural areas of Europe, highlighting over-fertilization. Pesticide risk score indicates areas under pressure from pesticide application, also typically linked to intensive agriculture (Fig. 15e). High scores in the Benelux region, France, northern Italy and eastern Europe, suggest widespread use. Finally, Fig. 15f shows regions with elevated concentrations of heavy metals, likely due to intensive industrial activities, agricultural practices, urbanisation and waste disposal. Prominent in central and southern Europe, including Germany, the Benelux region, northern Italy, and parts of France and Spain, these regions have long histories of intensive industry, mining, and agriculture, often combined with dense populations and infrastructure.

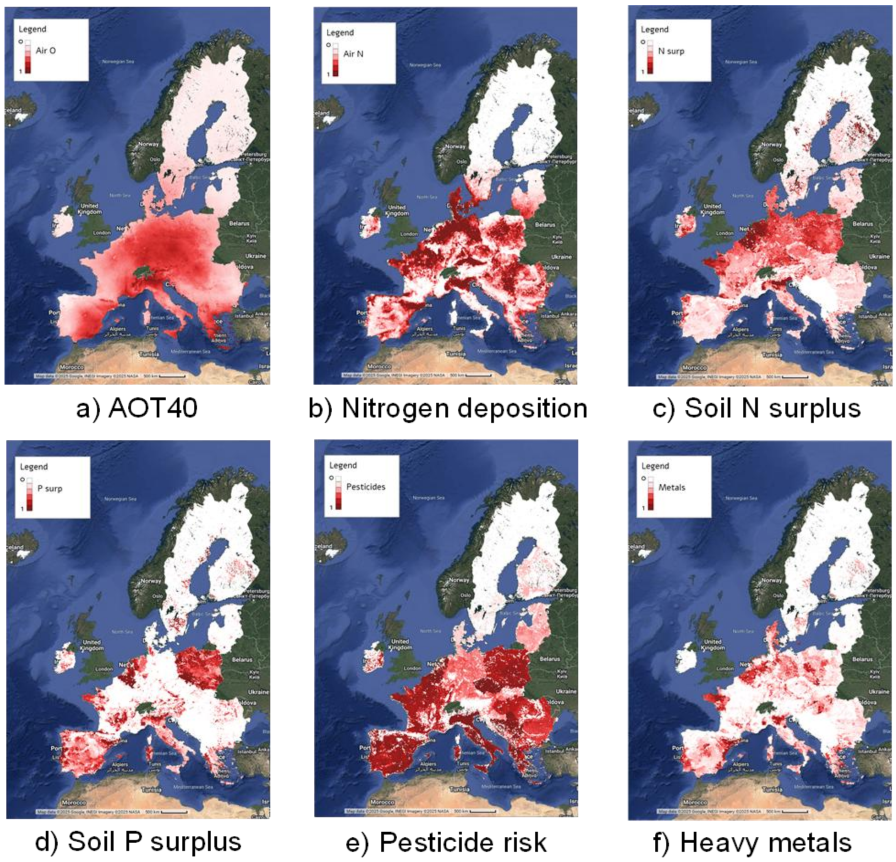


Figure 15: Individual maps of chemical abiotic pressure across Europe: a) Accumulated aeone exposure (AOT40), b) Risk of eutrophication (N deposition), c) N fertilizer surplus, d) P fertilizer surplus, e) Pesticide risk score and f) Exceedance of critical heavy metal inputs. (Larger maps can be found in Annex 6).

Biotic compositional pressure

This category only includes pressure by invasive alien species (Fig. 16). The map indicates the intensity of ecological pressure caused by the presence and spread of non-native species that are known to displace native flora and fauna, alter habitats, and disrupt ecological processes (Polce at al., 2023). The map highlights that western and central Europe face the highest pressure due to dense infrastructure, trade, and disturbed landscapes, which facilitates the introduction and spread of IAS. In contrast, northern and southeastern regions experience lower pressure, often corresponding to lower population density, harsh environmental conditions or remote/mountainous areas. This information is crucial for informing biodiversity protection strategies and IAS management policies.

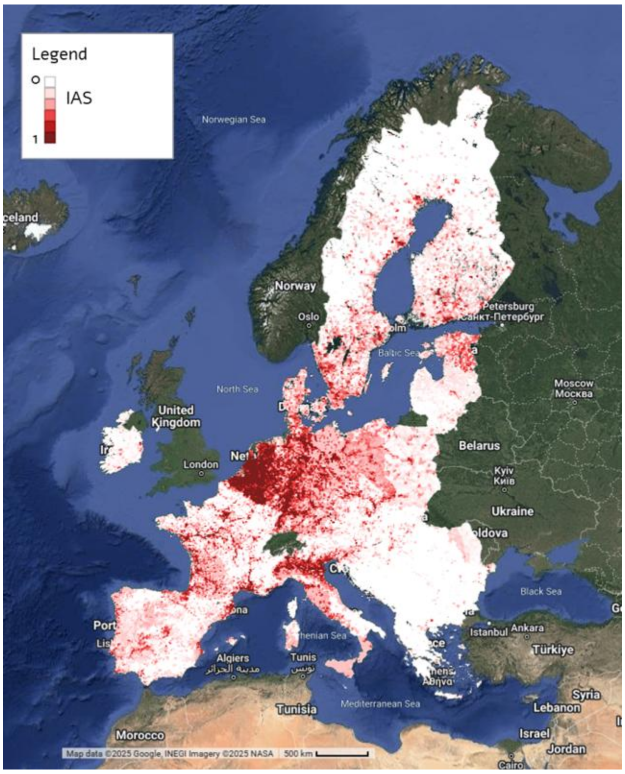
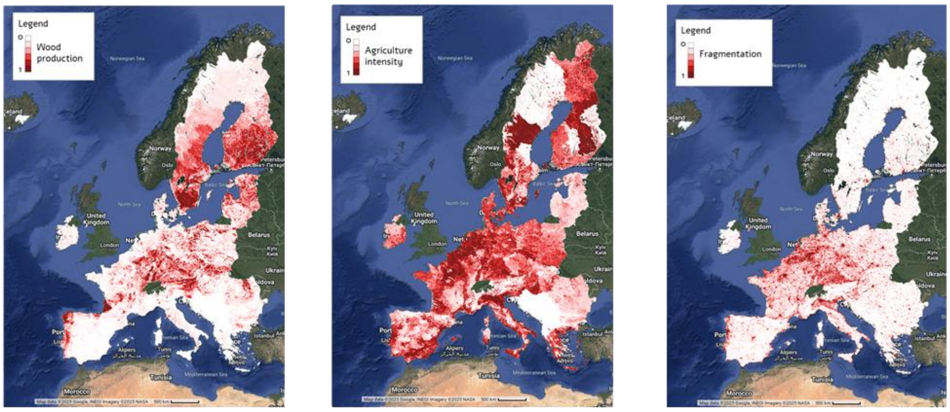


Figure 16. Pressure by invasive alien species (IAS) across Europe. (Larger map can be found in Annex 6).

Landscape pressures

Regions with high forest exploitation intensity are primarily located in Northern Europe, particularly in countries like Sweden and Finland (Fig. 17a). There are also significant areas of high intensity in Central Europe, including parts of Germany and France. The map also highlights Portugal, one of Europe's leading pulp producers, with a forest plantation area of fast-growing trees such as *Eucalyptus globulus* covering around 26% of the country. Tomé et al (2021) highlighted potential negative environmental issues (e.g., water use, loss of biodiversity) and vulnerability to hazards, such as wildfires that may increase forest erosion. High agricultural intensity is observed in Western Europe, particularly in northern France, Benelux region, Germany, northern Italy and Poland, corresponding to the major agricultural areas of Europe (Fig 17b). Finally, highly fragmented areas are scattered throughout Europe, with notable concentrations in Western and Central Europe, including parts of Germany, France, and the Benelux countries where population density is also higher. Fragmentation is less pronounced in Northern Europe and parts of Eastern Europe (Fig 17c).



a) Forest exploitation intensity

b) Agriculture intensity

c) Fragmentation

Figure 17: Individual maps of landscape pressures across Europe: a) forest land-use intensity, estimated through forest exploitation intensity (i.e., wood production), b) Agriculture intensity and c) fragmentation pressure (i.e., meshes density). (Larger maps can be found in Annex 6).

The aggregated Human Pressure Index

The map provides a visual and comprehensive representation of how human activities and pressures are distributed across Europe, highlighting areas of intense human impact and those with relatively lower pressures (Fig. 18). The map shows a clear geographical distribution with high pressure areas concentrated in Western and Central Europe. Countries such as the Netherlands, Belgium, Germany, western France, northern Italy and western Poland show high human pressure. These regions are densely populated, have strong infrastructure fragmenting the landscapes and have been subject to intense pressures due to agricultural and industrial development. Surrounding these high-pressure zones, there are areas with moderate human pressure in countries like Spain, Portugal, and parts of Eastern Europe. It is worth noting that coastal parts of eastern Spain, Portugal and southern Italy present higher pressure mainly due to high population density and touristic infrastructures. Finally, low pressure occurs in northern Europe, particularly Scandinavia, and parts of Eastern Europe, due to lower population densities and less intensive land use.

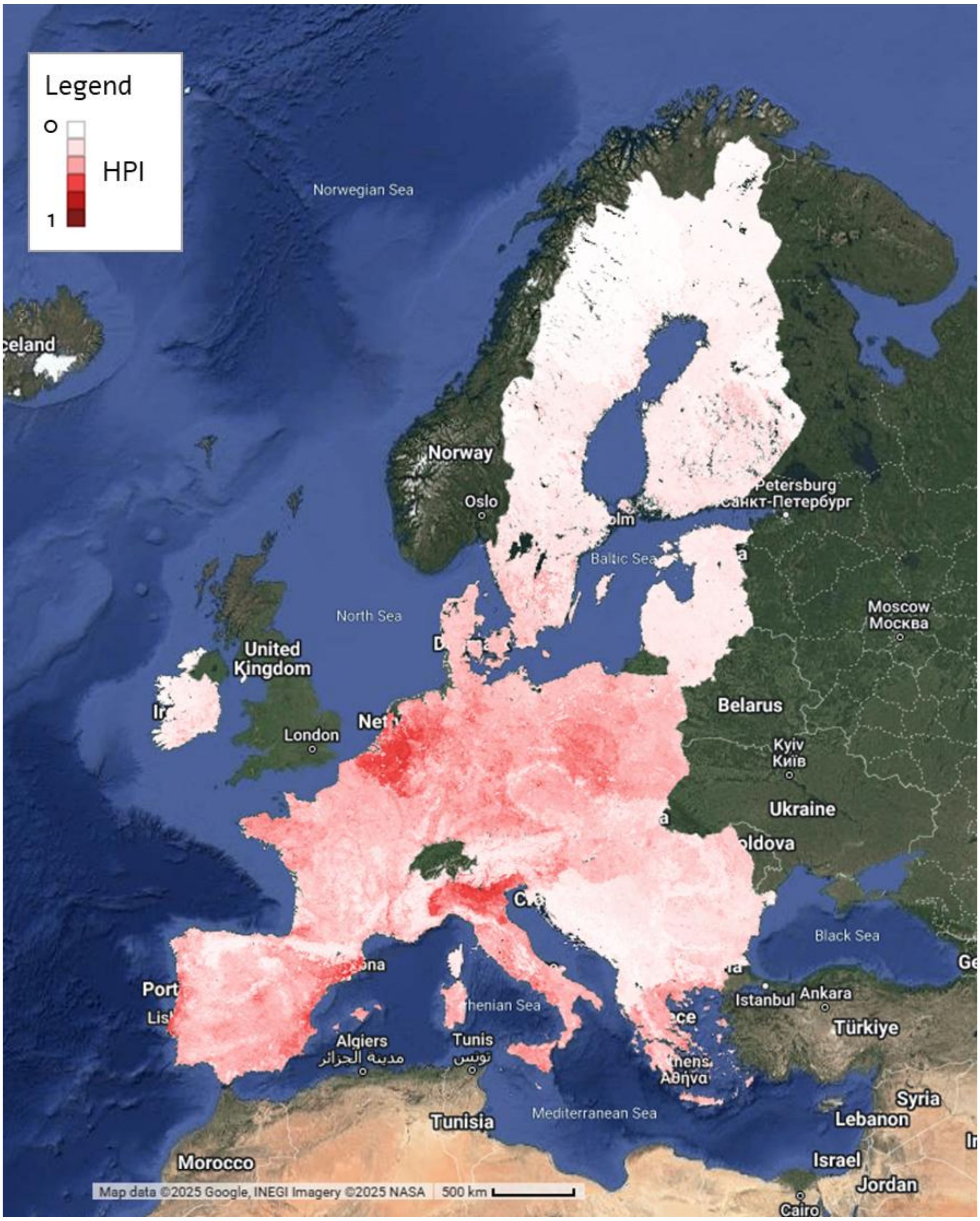


Figure 18. Aggregated Human Pressure Index (HPI) across Europe.

7.4. Perspectives

The Human Pressure Index (HPI) offers a potentially powerful and practical tool for translating environmental data into actionable insights for policy-making. Although not operating at fine plot-level resolution (e.g., parcel-level urban planning), the HPI's effective resolution of 1 km² appears highly appropriate for regional to sub-regional conservation planning and ecosystem restoration assessments. Indeed, the resolution is fine enough to support landscape-level intervention, especially for identifying pressure hotspots, and, in many cases, the resolution aligns with administrative units or ecological zones used for regional conservation programs (e.g., Natura 2000 sites, biogeographic regions). By integrating a wide range of anthropogenic stressors into a single, spatially explicit indicator, the HPI can guide where to mitigate pressures, invest in restoration, or monitor changes in ecosystem condition effectively. Strategic applications of the HPI for policy and planning can include:

Identifying Priority Areas for Conservation

While the Human Pressure Index (HPI) is not designed to identify pristine areas for strict conservation at the fine spatial scales used in local reserve planning, it offers a valuable continental and regional overview of cumulative human pressures. This helps highlight broad-scale patterns of pressure that can inform strategic conservation planning, such as:

- Identifying buffer zones or potential corridors between existing conservation areas
- Aligned with EU-wide frameworks like the *EU Biodiversity Strategy for 2030*, by informing where cumulative pressures may undermine conservation goals.
- Complementing fine-scale ecological assessments by identifying regions where pressure trends may require enhanced protection or management measures.
- Monitored over time to evaluate the effectiveness of site-based conservation actions or funding instruments (e.g., LIFE Programme, Natura 2000).

It is important to note that areas under high pressure are typically not suited for new conservation designations, unless the goal is to buffer existing sites, prevent further degradation, or support ecological connectivity in fragmented landscapes.

Guiding Ecological Restoration

When combined with ecosystem condition assessments, the HPI provides a foundation for targeted, effective restoration planning. HPI is critical to the implementation of the *EU Nature Restoration Regulation*, allowing restoration objectives to be tailored to real spatial and ecological challenges. More specifically, it can help:

- Identifying landscape-scale hotspots where restoration and pollution mitigation efforts may have the greatest regional benefit (e.g., high-intensity agricultural zones or heavily eroded catchments).
- Helping prioritize degraded areas under multiple pressures that align with *Nature Restoration Regulation* targets, such as soil erosion in Mediterranean croplands or forest degradation in mountainous regions.
- Supporting pressure-condition assessments by overlaying HPI data with national or regional condition indicators, enabling evidence-based restoration interventions. HPI may allow 1) highlighting resilient areas under pressure maintaining good ecological condition, which can serve as reference ecosystems or case studies for adaptive management, and 2) detecting areas of ecological collapse (i.e., chronic degradation) where restoration may need to be supported by additional measures, such as reducing upstream pressures or addressing legacy impacts.

Supporting Environmental Legislation and Policy

The HPI offers a harmonized, scientifically grounded tool that may improve coherence between European, national, and regional environmental policies, facilitating compliance and better regulatory outcomes. The HPI can contribute to policy coherence and legal compliance by:

- Increasing transparency and accountability of the *EU Environmental Impact Assessments* (EIAs): Although EIAs are generally conducted at the local, project-specific scale, HPI can provide a regional pressure baseline against which the potential cumulative impacts of new developments can be interpreted, particularly in *Strategic Environmental Assessments* (SEAs). Additionally, for transboundary or larger infrastructure projects, the HPI can guide planners to consider broader landscape pressures not visible in local datasets.
- Informing and justifying legislative action, such as expanding protected areas or regulating land-use intensification.
- Supporting reporting obligations under frameworks like SEEA-EA, IPBES, or the Convention on Biological Diversity.

Spatial Planning and Land-Use Decision Making

The HPI strengthens spatial planning by identifying zones where land use is intensifying in ways that threaten ecosystem health, supporting more resilient, climate-smart, and ecologically sustainable landscapes. Policymakers can:

- Limit urban expansion in high-pressure zones, avoiding ecologically sensitive areas in development plans.
- Guide green infrastructure investments in urban and peri-urban areas to reduce soil sealing and improve ecosystem function.
- Support regional zoning frameworks by highlighting cumulative pressure hotspots that warrant protective overlays, restoration targets, or infrastructure limits, balancing development with biodiversity protection and ecosystem service provision.

Monitoring and Evaluation of Environmental Policies

The HPI can enable long-term policy monitoring, allowing for a shift from reactive to proactive governance in environmental policy by providing:

- A baseline and tracking system for cumulative human pressures over time.
- A way to evaluate the effectiveness of policy interventions, including *CAP* greening measures, pollution reduction strategies under the *European Green Deal* (e.g., *EU Zero Pollution Action Plan*) and restoration programmes.
- Insight into where adaptive management is needed, especially in regions where pressures continue to increase or where ecosystem condition does not improve despite interventions.

Supporting Scientific Research and Identifying Knowledge Gaps

The HPI can support scientific evidence and policy learning by:

- Offering a standardized dataset to study how different pressures interact to drive ecosystem degradation or resilience.
- Helping detect discrepancies between pressure and ecosystem condition, indicating legacy effects, resilience, or unmeasured drivers (i.e., data gap in monitoring).

- Developing predictive models of ecosystem responses under different policy or climate scenarios, by offering harmonized baseline data.
- Stimulating cross-disciplinary collaboration on tipping points, thresholds, and restoration pathways by integrating ecological, social, and geospatial perspectives.

Public Awareness and Stakeholder Engagement

The HPI's visual outputs make complex environmental data understandable and relevant for non-specialist audiences. The HPI can support participatory environmental governance by:

- Communicating spatial risks and priorities to civil society, local authorities and businesses to build awareness and trust.
- Engaging stakeholders in shared responsibility for ecosystem stewardship by showing how local pressures affect broader ecological health and by promoting sustainable practices.
- Building public legitimacy and awareness of environmental priorities.

Human Health and Environmental Quality

Although the HPI is not a direct public health index, itI also has important applications for public health policy by identifying areas where environmental pressures pose risks to human well-being. This includes:

- Highlighting areas of high cumulative environmental pressure that may affect human well-being and health.
- Supporting planning decisions aimed at improving environmental quality and access to natural spaces.
- Ecosystem-based adaptation that supports long-term well-being and disease prevention.

7.5. Limitations, uncertainties and recommendations

While the Human Pressure Index (HPI) provides valuable insights into the anthropogenic pressures on terrestrial ecosystems across Europe, it is essential to acknowledge its limitations and uncertainties. Addressing these issues is crucial for improving the accuracy, applicability, and effectiveness of the HPI in guiding policy and conservation efforts.

Scalability and Resolution Constraints

The HPI’s resolution of 1 km^2, while adequate for landscape-level analysis, is insufficient for local-scale interventions, such as targeting specific wetland patches for restoration or designing urban green corridors. In peri-urban areas, where land-use patterns are highly fragmented, the HPI may also mask critical micro-variations due to spatial averaging. To overcome this issue, in contexts requiring granular decision-making, HPI applications should be complemented with high-resolution land cover and cadastral data, especially in urban planning or Natura 2000 management. Collaborations with national and regional environmental agencies and research institutions can facilitate data sharing and standardization, allowing for a more detailed and comprehensive analysis of human pressures on ecosystems.

Data gaps and spatio-temporal coverage

The HPI relies heavily on the availability and quality of spatially explicit data. However, there are significant data gaps, as described in this report (e.g., Pathogens and diseases), and inconsistencies due to limitations in data collection and the modeling approaches used for certain indicators (e.g., erosion, pesticide risk score), with potentially varying accuracy. In addition, differences in the reference years of datasets introduce temporal inconsistencies that may affect the reliability of the aggregated index. These limitations hinder accurate cross-regional comparisons and timely assessments. Addressing them requires strengthening national monitoring systems, standardising reporting obligations under existing EU frameworks, and increasing regular updates and spatial coverage.

Generalisation and Oversimplification

The process of normalizing, weighting, and aggregating diverse pressures into a single index inherently involves simplification and loss of information. This can obscure the complexity and interplay of stressors and their ecosystem-specific impacts. Supplementary disaggregated indicator dashboards, alongside the composite HPI, should be provided, for allowing more nuanced interpretation. The normative nature of weighting different pressures also presents a challenge. These weights may not reflect local ecological sensitivities or stakeholder priorities. Therefore, it is recommended to enable stakeholder-informed customization of weights, especially in participatory planning contexts, and to document all assumptions transparently.

Risk of Misinterpretation and Misuse

The intuitive nature of a composite score may lead to overreliance or incorrect assumptions about ecosystem condition. High HPI values indicate intense anthropogenic pressure, but not necessarily ecosystem degradation, as resilience or legacy effects may buffer or delay ecological responses. The HPI outputs should be embedded within interactive platforms or policy briefs that explain the index's meaning, limitations, and intended use cases.

By acknowledging these limitations and uncertainties taking proactive steps to mitigate their effects, the HPI can be more robustly and responsibly applied in support of ecosystem management, restoration, and policy formulation across Europe.

7.6. HPI testing and development

The Human Pressure Index is not just an environmental monitoring tool: It is a cross-cutting policy asset. It can inform where and how to intervene, support evidence-based governance, and connect biodiversity, climate resilience, and human well-being and health into a unified framework. For policymakers, the HPI can offer the spatial intelligence needed to implement smarter, more coherent, and more sustainable policies across Europe's landscapes. However, testing the HPI against ecosystem condition indicators is needed to ensure its effectiveness as a tool for environmental management, conservation planning, and policy development. It will not only validate the methodological soundness of the index but will also confirm its ecological relevance and practical applicability, ensuring it reflects real conservation needs. First, it will ensure validation and accuracy, confirming that the HPI reflects real ecological degradation and not just modeled pressure levels. Second, it will help identify cause-and-effect relationships between specific pressures and ecosystem responses, enabling more effective and targeted conservation strategies. Third, it will support calibration and refinement of the HPI, improving its predictive power by adjusting weights, identifying missing drivers, and correcting biases. Fourth, it will enhance policy relevance, allowing policymakers to prioritize areas for intervention, guide restoration planning, and track the effectiveness of environmental measures over time. Finally, a validated HPI will become a powerful communication and awareness tool, helping stakeholders and the public understand where human impacts are most critical and how ecosystems are responding.

8. Alignment of D3.2 Ecosystem Condition Framework with Global Biodiversity and Ecosystem Service Frameworks

The framework presented in D3.2 is grounded in global efforts to harmonize biodiversity and ecosystem-service monitoring, notably the Essential Biodiversity Variables (EBVs) of GEO BON (Pereira et al., 2013), the Essential Ecosystem Service Variables (EESVs) (Balvanera et al., 2022), and the Nature Positive Initiative. These frameworks provide a common foundation for tracking ecological change and human–nature interactions across scales. D3.2 operationalizes these approaches in the European context, integrating ecological and biophysical data at both local and landscape levels under SEEA-EA and aligning its indicators with major EU policies such as the Biodiversity Strategy for 2030, the Nature Restoration Law, and the Marine Strategy Framework Directive. By doing so, D3.2 bridges the gap between conceptual frameworks and practical implementation, ensuring comparability, policy relevance, and scientific rigor in ecosystem assessments.

8.1. Alignment with GEO BON's Essential Biodiversity Variables (EBVs)

GEO BON (Group on Earth Observations Biodiversity Observation Network) is a global network dedicated to improving the acquisition, coordination, and delivery of biodiversity and ecosystem data (https://geobon.org/). GEO BON aims to provide robust, interoperable biodiversity observation data to support effective management and policy decisions for biodiversity and ecosystem services worldwide.

The ecosystem-specific indicators directly correspond to four EBV classes defined by GEO BON: species populations and community composition (i.e., taxonomic diversity), ecosystem structure, and ecosystem function (Pereira et al., 2013). Genetic composition was not included by D3.2 expert groups, due to the lack of available data, as well as functional traits, although some species have been included on the basis of their functional role (e.g. bumblebees as pollinators). For example:

- **Species Populations:** D3.2 focused on specific indicators relevant for each ecosystem type, as bird diversity specific to farmland, wetland or forest; bumblebee diversity in agroecosystems, heathlands & shrublands or natural grasslands. Community composition could be assessed only for certain types of ecosystems, for which several species were identified.

- **Ecosystem Structure:** In forests, D3.2 focuses on canopy height and tree cover density corresponding to the *ecosystem structure* EBV class. By leveraging high-resolution Copernicus data, D3.2 ensures spatial continuity and comparability across European forests, addressing gaps in spatial resolution (Kissling et al., 2018).
- **Ecosystem Function:** For wetlands, D3.2's use of the Water-Wetness Probability Index (WWPI) and flooding frequency reflects the *ecosystem function* EBV class, particularly hydrological dynamics. These indicators are derived from open-access datasets (e.g., Copernicus, EEA), ensuring transparency and accessibility.

Significant monitoring gaps remain for EBVs, as identified by Santana et al. (2025). The authors provide a comprehensive, multi-dimensional analysis of biodiversity monitoring gaps in Europe, linked to the production and implementation of EBVs. The study underscores that these gaps hinder reliable, policy-relevant assessments, calling for sustained funding, harmonized sampling, open data sharing, and equitable transnational coordination to bridge deficiencies.

D3.2 contributes to addressing these gaps:

- **Transnational Integration:** D3.2 leverages EU-wide datasets (e.g., Copernicus, EEA, EMODnet) to ensure comparability across borders.
- **Taxonomic and Spatial Biases:** D3.2 includes understudied but relevant taxa for all ecosystem types (e.g., benthic species, pollinators).
- **Temporal Gaps:** D3.2 integrates multi-year datasets (e.g., Copernicus time series) and prioritizes repeated measurements (e.g., SOC, canopy cover). However, not all indicators are available for the same reference year across the EU, reflecting the broader challenge of irregular data collection cycles.
- **Data Accessibility:** D3.2 promotes open-access platforms (e.g., GBIF, JRC ESDAC) and FAIR-compliant data sharing to ensure transparency and reusability, addressing the restricted access to raw data (e.g., WFD monitoring data stored nationally).

While D3.2 focuses on the above areas, Santana et al. (2025) also highlights protocol standardization and geographic disparities (e.g., non-EU regions) gaps. To fully address these, D3.2 recommends strengthening standardized protocols (e.g., for citizen science or field surveys), expand coverage to non-EU regions (e.g., the Balkans and Caucasus regions) to reduce geographic disparities and deepen temporal alignment by synchronizing indicator updates and partnering with long-term monitoring networks (e.g., the Long-Term Ecological Research (LTER) network, national forest inventories).

8.2. Alignment with Essential Ecosystem Service Variables (EESVs)

The EESV framework (Balvanera et al., 2022) defines six dimensions for monitoring nature-society interactions: ecological supply, anthropogenic contribution, demand, use, instrumental values, and relational values. The minimum sets of indicators contribute to these dimensions as follows:

- **Ecological Supply** refers to the ecosystem structures and functions that underlie the potential capacity of ecosystem services provisioning: Indicators such as SOC, NPP, canopy cover and seagrass cover measure the capacity of ecosystems to provide services like carbon sequestration and habitat provision.
- **Anthropogenic Contribution** refers to the human investments to enhance ecological supply and to make use of ecosystem services: For example, D3.2 tracks land management intensity and pollinator diversity, that can quantify human efforts to enhance or degrade ecosystem services, such as food provisioning.
- **Demand and Use:** D3.2's indicators for pollination-dependent crop area, fisheries yield, and recreational access to green spaces illustrate how societies benefit from and rely on healthy ecosystems.
- **Instrumental and Relational Values:** Indicators measuring green (and blue) infrastructure and spatial connectivity align with the EESV framework's focus on human-nature interactions.

By aligning with EESVs, D3.2 supports the assessment of progress toward the UN Sustainable Development Goals (SDGs), particularly those related to biodiversity (SDG 15), sustainable cities (SDG 11), and ocean health (SDG 14).

8.3. Contribution to the Nature Positive Initiative

The Nature Positive Initiative (NPI) is a coalition of nature conservation organisations, businesses, financial institutions, governance bodies, which has set itself the goal of 'Nature Positive by 2030', i.e. to "halt and Reverse Nature Loss by 2030 on a 2020 baseline, and achieve full recovery by 2050" (https://www.naturepositive.org/). The NPI, which aligns with the Kunming-Montreal Global Biodiversity Framework (GBF), calls for universal metrics to track progress toward halting and reversing biodiversity loss and improving natural processes. However, the NPI is still looking for a consensus on a set of credible metrics that measure the state of nature that should be universally applicable, credible, practical and affordable across scales, users and geographies. D3.2 aims to fill these gaps by integrating robust and standardized indicators at European level and for all ecosystem types. Its dual-index framework, separating human pressure and ecosystem condition, also aligns with the NPI's focus on baseline assessments and impact tracking, following the pressure-state-response framework:

- **Ecosystem Condition Indicators:** D3.2 aimed to develop a set of indicators for assessing ecosystem health, enabling the detection of improvements or degradation over time. As with the NPI, these indicators encompass both local and landscape levels and cover abiotic and biotic characteristics, following the SEEA EA framework. For example, indicators of biodiversity, ecosystem productivity or fragmentation were identified by both the NPI and D3.2.
- **Pressure Indicators:** D3.2 has identified a wide range of indicators of human pressures, including land-use change, pollution and invasive alien species, supporting the Nature Positive Initiative's goal. D3.2 goes further by proposing the Human Pressure Index (HPI) (D3.2, section 7) that aims to integrate these indicators into a single index to quantify such anthropogenic impacts.

9. General D3.2 Conclusion

The work undertaken in this Deliverable D3.2 supports the broader effort of systematic EC assessments, through proposing a structured and practical approach grounded in the SEEA-EA framework. It provides a comprehensive framework for identifying and proposing a minimum set of operational and spatially explicit indicators across a wide range of terrestrial, freshwater, marine, and coastal ecosystems. Building upon the SEEA-EA accounting system and insights from the MAES framework, the report offers both conceptual refinements and practical methodologies for distinguishing condition from pressure indicators, addressing a persistent challenge in environmental monitoring and policy application. A major advancement presented in this work is the proposal to clearly separate condition and pressure indicators, not only for conceptual clarity, but also for enhancing causal analysis and targeted policy intervention. The proposed dual-index framework, comprising a condition index representing intrinsic ecosystem characteristics and a pressure index representing anthropogenic stressors, offers an analytically rigorous and operationally feasible structure for ecosystem accounting.

Whilst not exhaustive, the work presented here provides a step toward more integrated and scalable EC assessments. The extensive expert-based evaluation across nine ecosystem types revealed significant commonalities in challenges, including data limitations, the contextual interpretation of indicators, and the tension between minimum and comprehensive indicator sets. Despite these shared issues, ecosystem-specific insights underscored the importance of tailoring indicators to the functional, structural, and compositional nuances of each ecosystem type. The review also highlighted a continued bias toward structural and physical indicators, with limited coverage of functional and compositional attributes, especially due to data scarcity and monitoring gaps. Another key constraint is the quality of spatially explicit data, with the unbalanced coverage identified during the review echoed in the process of populating indicator lists, where the inclusion of ecologically relevant variables was often limited by data gaps. These gaps restrict consistent representation across ecosystem types and may obscure important patterns or trends. In addition, the classification of indicators, particularly the separation of condition and pressure, remains a subject of ongoing discussion.

The indicator sets proposed for each ecosystem type are intended as a minimum operational set of indicators to be assessed. While they prioritize existing data availability and pan-European applicability, they also recognize the importance of flexibility, allowing for ecosystem-specific adaptations and future refinement as data infrastructure improves. Importantly, the report stresses that this minimum set is not a static endpoint, but a starting point for iterative improvement, aligned with evolving scientific knowledge, policy needs, technological capacities, and emerging environmental dynamics. These minimum sets of indicators remain conceptual and have not yet been systematically tested across different ecosystem contexts. Applying them in a range of geographical and ecological settings would provide critical insight into their suitability for representing broad ecosystem types and whether refinements are needed to reflect internal variation. Such testing would also help to evaluate the practical adequacy of the selected indicators. Crucially, meaningful application requires the use of reference levels to assess ecosystem quality, for which the methodology developed in Deliverable D3.3 provides a relevant basis.

For this purpose of applicability, we have developed a new Human Pressure Index (HPI) for terrestrial ecosystems across Europe based on the minimum sets proposed here. The HPI could prove to be a powerful tool for assessing and visualizing the cumulative impact of human activities. By integrating multiple stressors into a single framework, it supports evidence-based policy, targeted conservation, and public awareness. Its combination with ecosystem condition data will enhance our understanding of pressure-response dynamics and reveal knowledge gaps, making it valuable for both decision-making and scientific research.

In conclusion, the deliverable supports the EU's ambitions under the Biodiversity Strategy for 2030 and the Nature Restoration Regulation by offering a harmonized yet adaptable framework for evidence-based ecosystem assessment and management. It lays the groundwork for consistent and comparable ecosystem condition reporting while ensuring ecological relevance and policy utility across Europe’s diverse ecosystems and their condition and pressures.

The results of Task 3.2 will provide input for SELINA Task 3.4, which will propose a scientifically robust decision framework to support the designation of ecosystem condition levels, through providing reliable data and indicator suggestions to be integrated into this framework. Indeed, while the various forms of EU-wide ecosystem assessment have highlighted that reduced pressures don’t always lead to immediate ecosystem recovery due to time lags and complex responses, our framework allows accounting for interactions between pressures and EC. Separating pressure from EC may clarify cause-effect relationships and enable early detection of degradation. It will balance the trade-off between site-specific accuracy and broader regulatory needs to support timely, precautionary restoration and management.

This work is also particularly relevant for the SELINA task 6.2 that aims to integrate the findings from ecosystem condition (WP3) and ecosystem services (WP4) assessments to identify the minimum conditions required in different ecosystem types to support specific ecosystem services. This interrelationships analysis between EC and ES will generate robust, evidence-based insights that are directly applicable to regulatory and policy design, particularly for ecosystem restoration, sustainable management, and the planning of use and non-use options. The outcomes will support more targeted, site-specific, and effective implementation of ecosystem-related policies and strategies. Additionally, it is expected that the insights of this report, including the minimum indicator sets, will be integrated in the unified SELINA Framework for Integrated Ecosystem Assessment (FIEA) developed in Task 6.4. Specifically, the step ‘Assess’ which involves quantifying, mapping and accounting ecosystem condition. Finally, the findings presented in this report will shape key products related to the assessment of ecosystem condition, through two scientific papers in which the results of Section 6.1 and Section 7 will be presented.

10. Final Recommendations

The work conducted under SELINA Deliverable D3.2 represents a significant step toward establishing a harmonized, scientifically grounded, and operational framework for assessing ecosystem condition across Europe. Drawing from extensive expert consultation, literature review, and alignment with the SEEA-EA framework, we offer the following final recommendations to guide future implementation, policy integration, and methodological refinement:

1. Implement the Dual-Index Framework for Condition and Pressure

- **Adopt a clear conceptual separation** between ecosystem condition (natural characteristics) and ecosystem pressure (anthropogenic drivers) across EU ecosystem accounting and monitoring frameworks.
- This distinction improves analytical rigor, supports targeted policy interventions, and enhances clarity in communication to stakeholders

2. Operationalize the Proposed Minimum Indicator Sets

- Use the **ecosystem-specific minimum indicator sets** presented in this report as a **starting point** for consistent and comparable ecosystem condition assessments.
- Ensure that the selected indicators reflect the key abiotic, biotic, and landscape characteristics as defined in the SEEA-EA typology, while remaining sensitive to data availability and ecosystem-specific priorities.

3. Address Critical Data Gaps and Monitoring Needs

- **Invest in expanding biodiversity monitoring**, especially for compositional and functional state indicators (e.g., pollinators, soil biota, wetland dynamics).
- **Allow the disclosure of EU sensitive pollution data** (e.g. pesticides, heavy metals) in order to effectively assess the condition of ecosystems
- **Invest in monitoring plastic and emerging pollutants** (e.g., PFAS) to capture chronic and persistent contamination.
- **Enhance the spatial and temporal resolution** of key indicators, particularly in data-poor ecosystems such as wetlands, grasslands, and marine/coastal environments.
- **Support the development of spatially explicit, Europe-wide datasets** that capture underrepresented condition variables.

4. Promote Ecosystem-Specific Flexibility within a Harmonized Framework

- While comparability across ecosystems is crucial, allow **adaptive refinement of indicators** to reflect ecological realities, management contexts, and regional specificities.
- Consider supplemental indicators in areas where the minimum set may not sufficiently capture ecological condition (e.g., peatland hydrology, marine food webs).

5. Integrate Findings into EU Policy and Reporting Mechanisms

- Align the minimum indicator framework with existing initiatives such as the **EU Biodiversity Strategy, Nature Restoration Regulation, Water Framework Directive,** and **Marine Strategy Framework Directive**.

- Support member states and local governments in using the framework for **baseline condition assessment, restoration planning, and progress reporting** under legal and voluntary biodiversity commitments.

6. Maintain an Iterative and Transparent Development Process

- Treat the minimum set as a **dynamic baseline**, to be revisited and revised as new data, methods, and policy priorities emerge.
- Encourage **multi-stakeholder collaboration** and regular expert engagement to ensure continued relevance, usability, and legitimacy of the indicator framework.

7. Leverage Technological Innovations

- Continue to utilize and refine **remote sensing technologies** for structural and functional indicators, while promoting integration with **field-based and citizen science data**.
- Support methodological innovation in **data fusion, big data analyses and modelling** to enhance ecological interpretability and forecasting capacity.

These recommendations will better equip decision-makers and practitioners to assess and restore ecosystems in a scientifically credible, policy-relevant, and operationally feasible manner, advancing both environmental and societal goals toward 2030 and beyond.

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13. Annexes

Annex 1

Selection criteria for ecosystem condition characteristics and their metrics (Czúcz et al., 2021b; UN et al., 2024).

Criterion	Short description
Conceptual criteria	
Intrinsic relevance	Characteristics and metrics should reflect existing scientific understanding of ecosystem integrity, supported by the ecological literature
Instrumental relevance	Characteristics and metrics should be related to the availability of ecosystem services (characteristics that provide most information about the highest number of services should be favoured)
Directional meaning	Characteristics and metrics need to have a potential for a consensual normative interpretation (it should be clear if a change is favourable or unfavourable)
Sensitivity to human influence	Characteristics and metrics should be responsive to known socio-ecological leverage points (key pressures, management options)
Framework conformity	Characteristics and metrics should be differentiated from other components of the SEEA ecosystem accounting framework
Practical criteria	
Validity	Metrics need to represent the characteristics they address in a credible and unbiased way
Reliability	Metrics need to be accurate, reliable, and reproducible, with potential sources of error explored and documented
Availability	Metrics covering the studied spatial and temporal extents with the required resolution need to be achievable in terms of the resources and time available
Simplicity	Metrics should be as simple as possible
Compatibility	The same characteristics should be measured with the same (compatible) metrics in the different ecosystem types and/ or different ecosystem accounting areas (countries)
Ensemble criteria	
Comprehensiveness	The final set of metrics, as a whole, should cover all of the relevant characteristics of the ecosystem
Parsimony	The final set of metrics should be free of redundant (correlated) variables

Annex 2

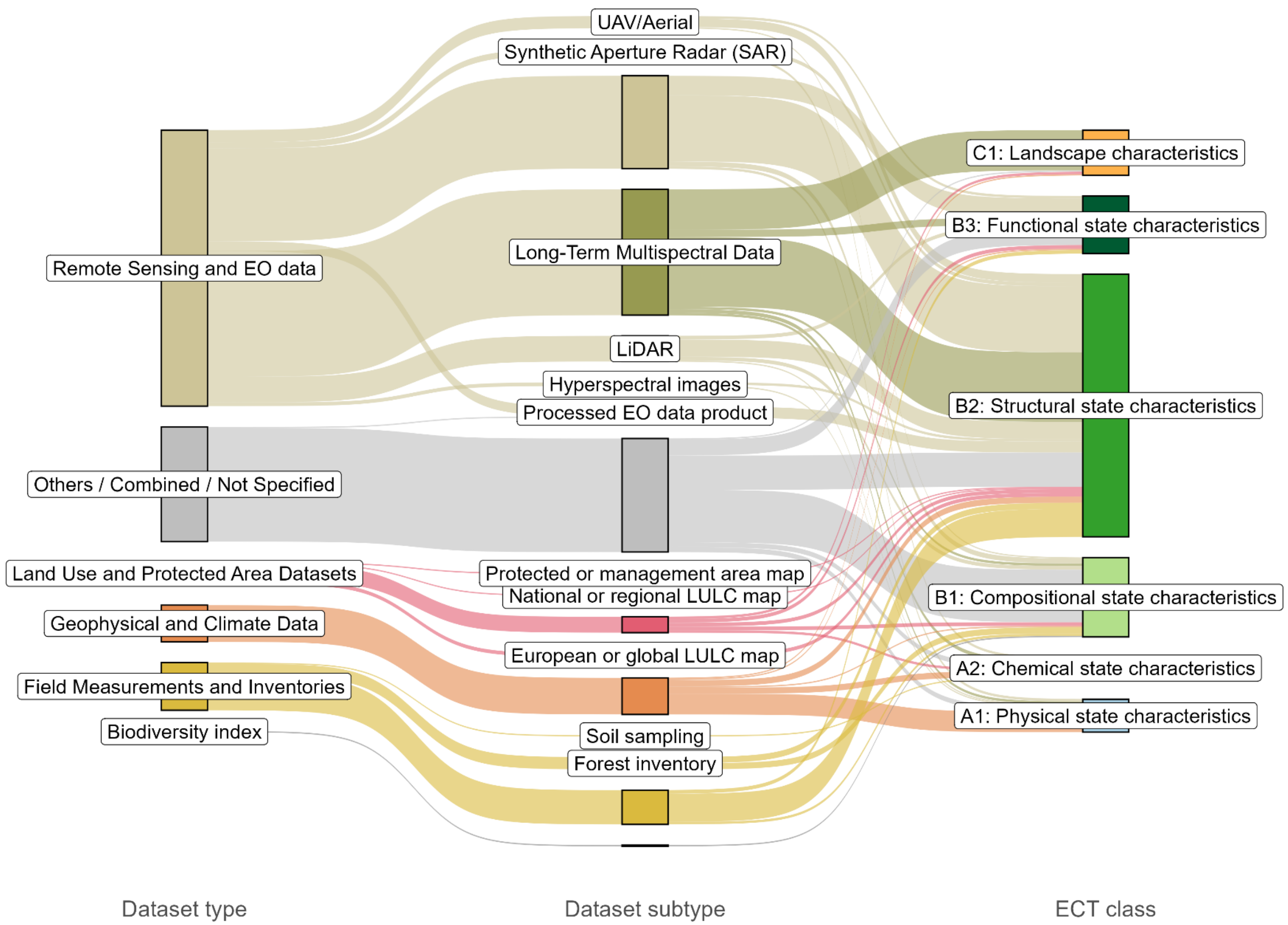
Detailed description of ECT and 'ECT+' classes (Czúcz et al., 2021)

Code	Class	Description	Examples
XENV	Stable environmental characteristics	Climatic and other environmental variables which in general change slowly and are largely external to the ecosystems	Climate (precipitation or temperature), slope, aspect, geology
XES	Ecosystem services	Measurable parameters or metrics used to assess and monitor provision or demand of ES.	Specific services or broad categories (cultural services, provisioning services etc)
XEE	Ecosystem extent	The area/cover/share of the main (=MAES) ETs (in the landscape).	Area (specified for ET recorded in B.08, or generic)
XAG	Pre-aggregated indicators	Data collected and processed for various policies are often available in the form of (highly) aggregated indices.	WFD ecological condition index, or the Art17 structure & function parameters. We would also include EC indices such as 'ecosystem health', 'ecosystem condition'
XMA	Natural resource management	Ecosystem management (grazing, felling, fishing, agriculture...) characterized with its intensity. This class may include indicators/densities of the infrastructure for management/extraction (e.g. forest road density...). Indicators for stocks (that are being extracted, e.g. fish, game, timber...) should be considered as B1, B2, or A1 (where it best fits).	Grazing, felling, fishing, agriculture, forest road density
XAC	Accessibility	Accessibility for humans typically for ES "extraction" activities.	Road (or channel) density, human population density, distance from roads or human population centres.
XPA	Protected areas	Indicators highlighting administrative land designations	Status/degree of nature protection

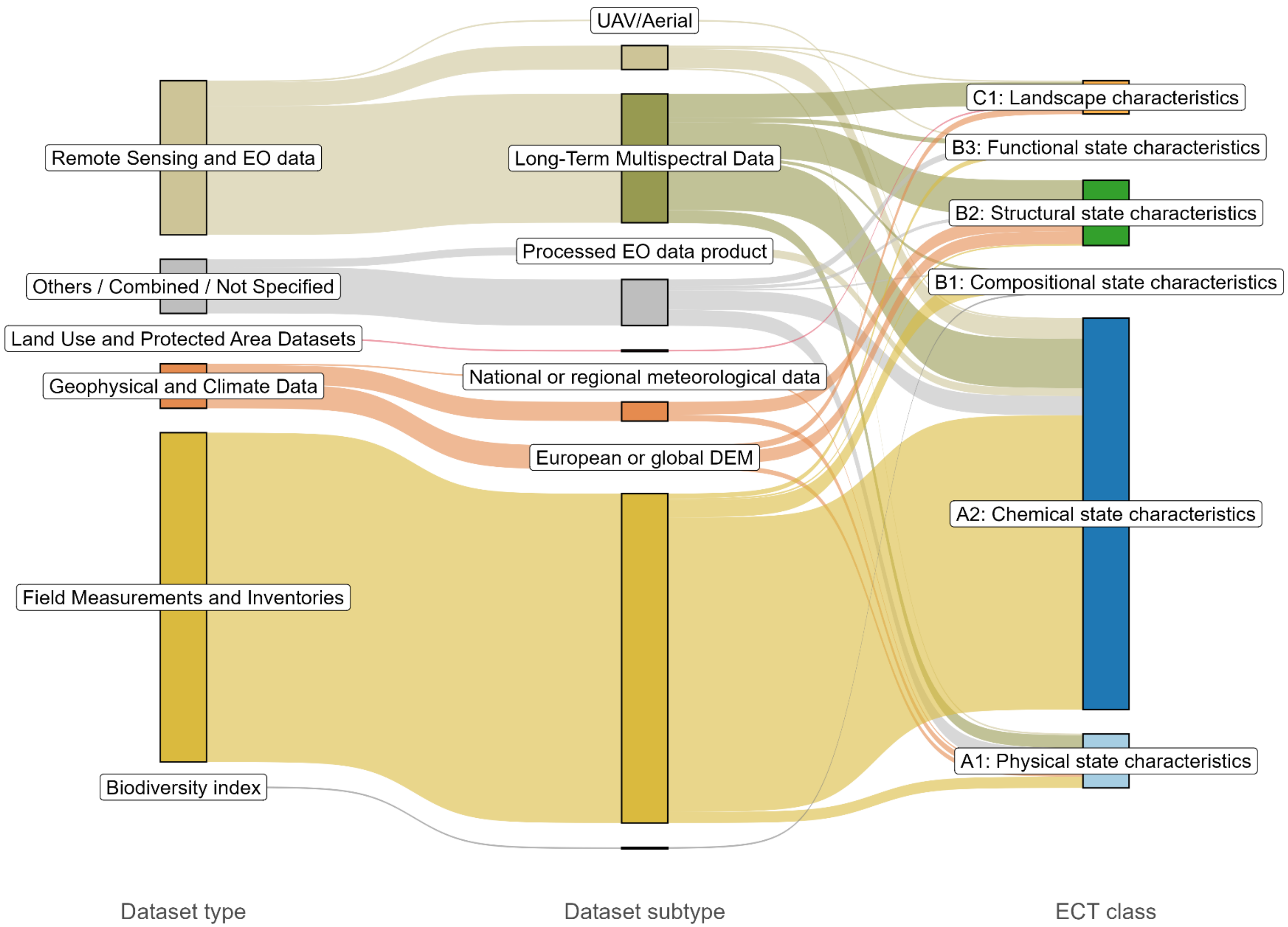
Code	Class	Description	Examples
XPR	Pressures	‘Raw’ pressure indicators given as human extraction/ emission/ immission/ transformation (=change) rates. (The related stocks (e.g. pollutant concentrations, impervious surfaces, hunted species, etc.) should be assigned to its main class (typically A2, A1 or B2, or possibly also B1, XEE)	Pollutant loads/in-flows, habitat loss
B2/C1	Embedded (sub)types	The abundance of embedded "subgrid" fragments of other ETs in an embedding ET	Hedgerows in an agricultural ET
O	Other	Indicator is clear but does not fit in any of the above classes	
U	Unclear	Indicator name is insufficiently clear for classification	

Annex 3

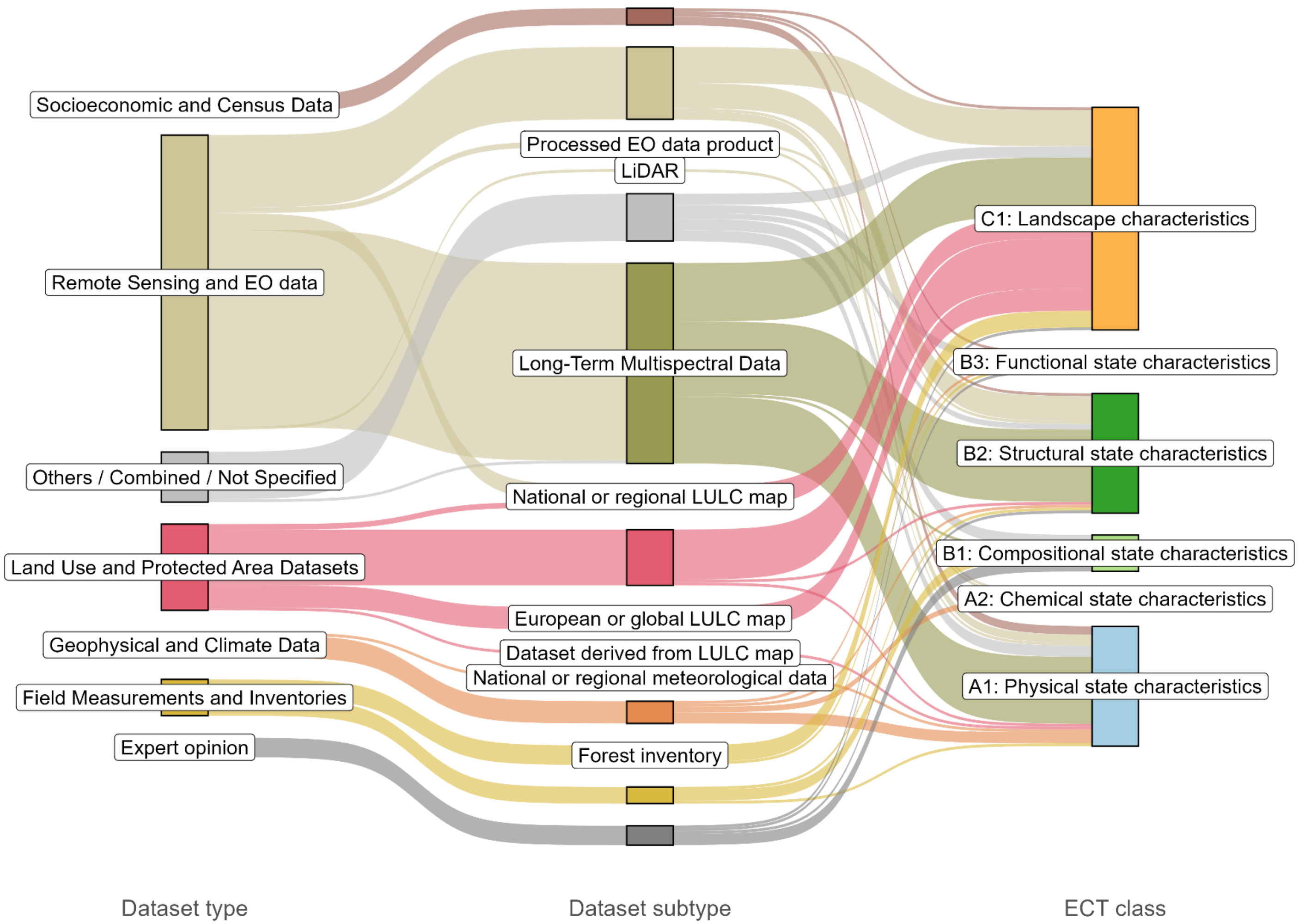
Sankey diagrams in full size



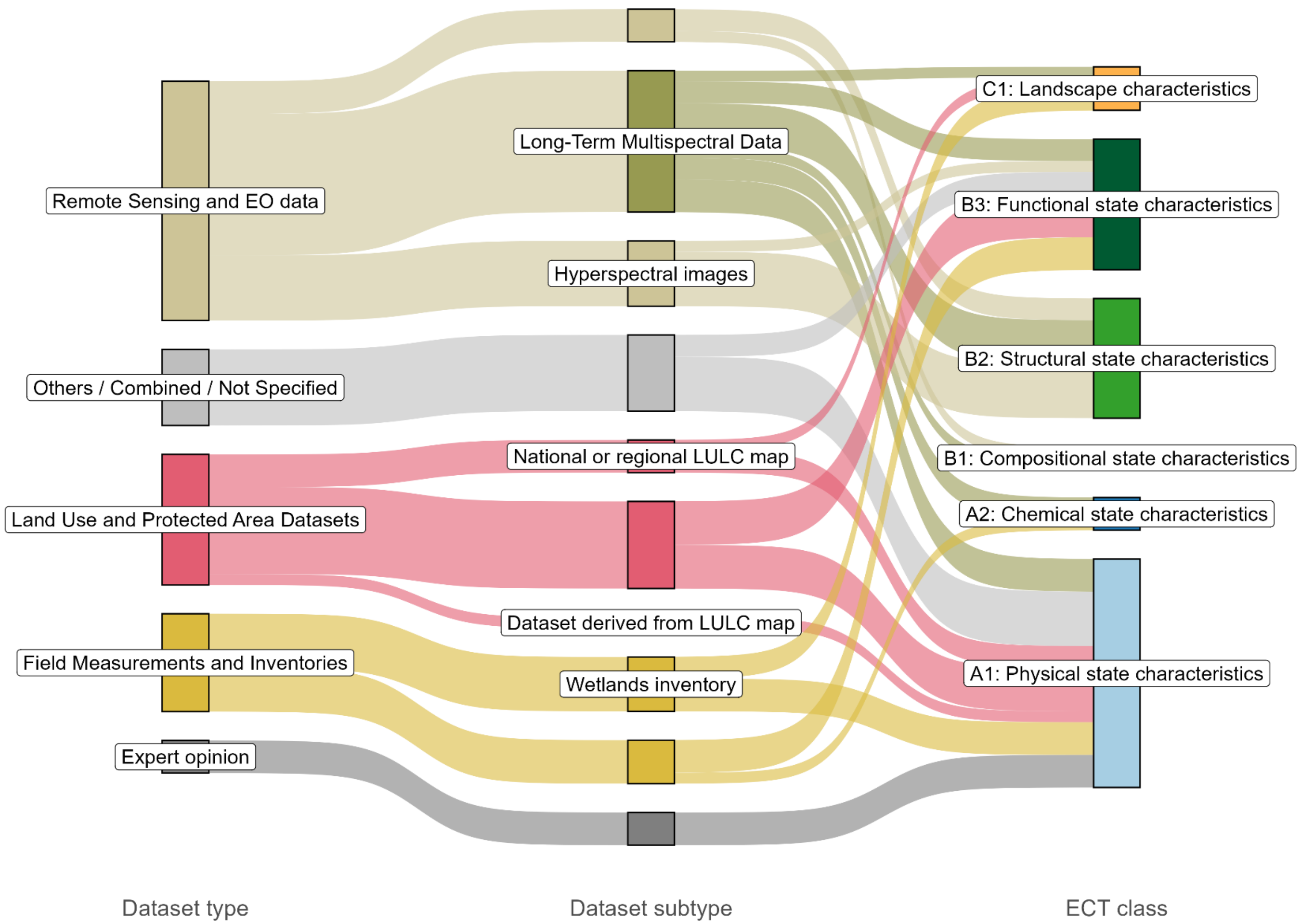
Sankey diagram showing the data types and subtypes used in developing the different classes of indicators used in EC studies in forests



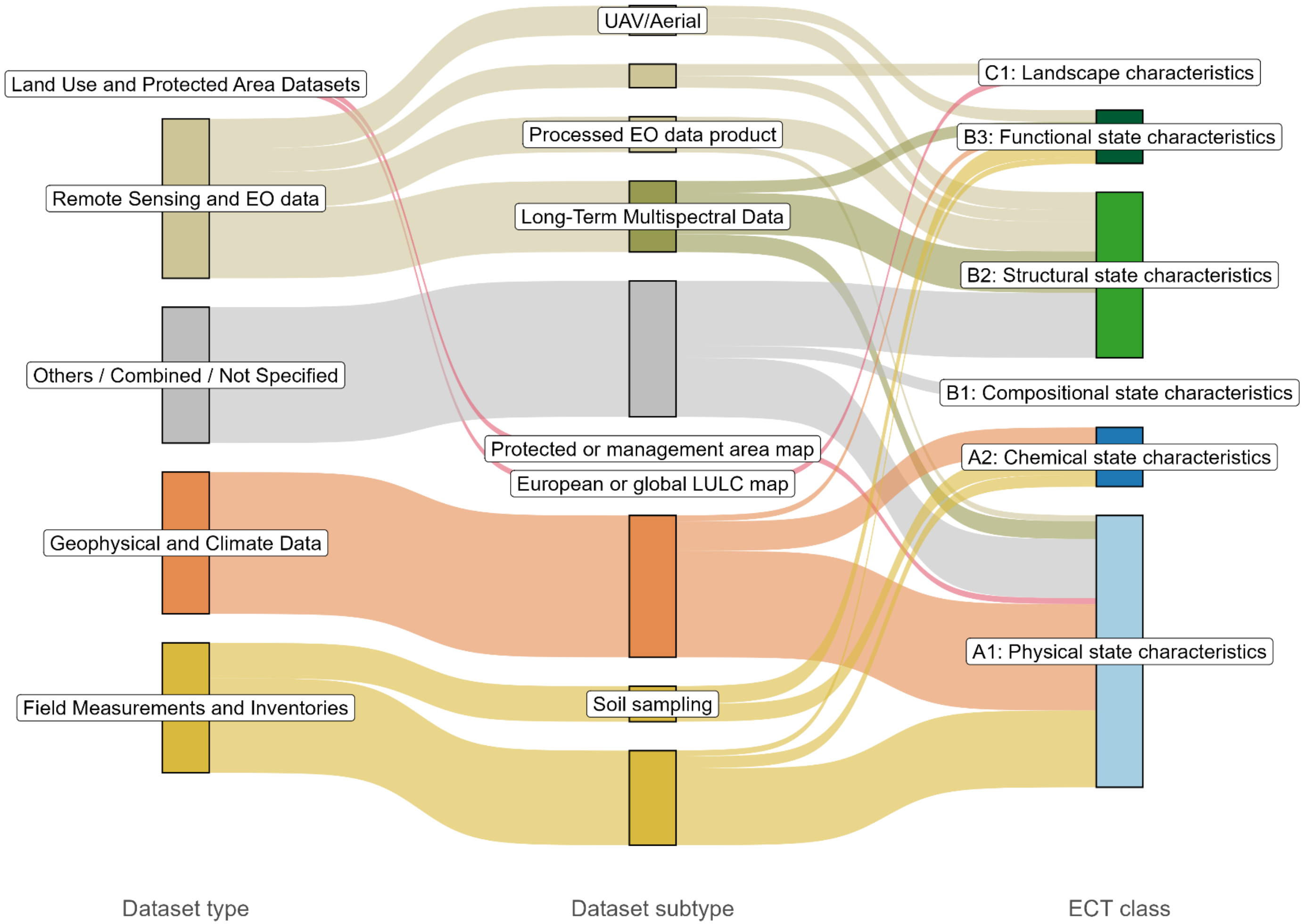
Sankey diagram showing the data types and subtypes used in developing the different classes of indicators used in EC studies in rivers and lakes



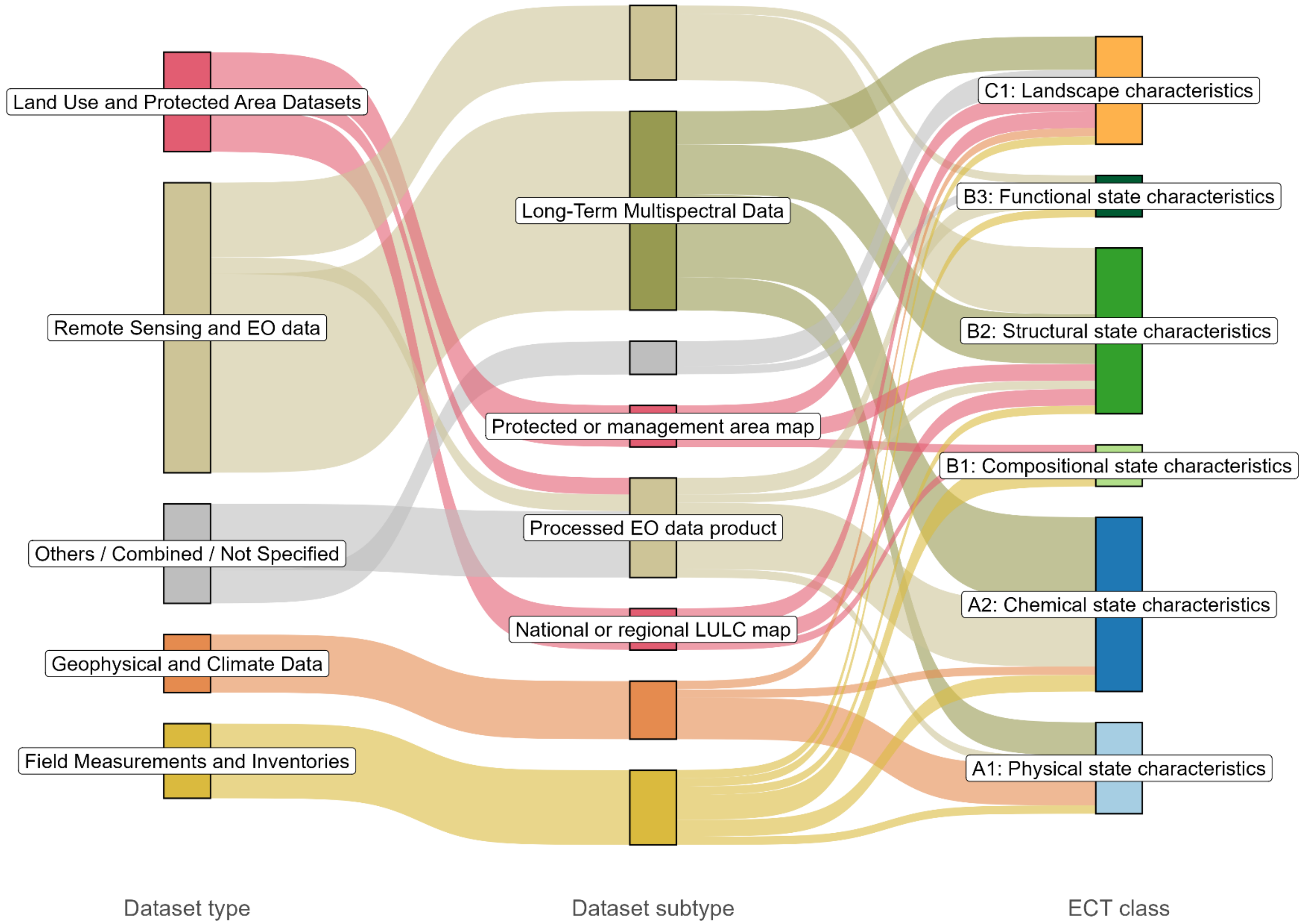
Sankey diagram showing the data types and subtypes used in developing the different classes of indicators used in EC studies in urban ecosystems



Sankey diagram showing the data types and subtypes used in developing the different classes of indicators used in EC studies in wetland ecosystems



Sankey diagram showing the data types and subtypes used in developing the different classes of indicators used in EC studies in agroecosystems



Sankey diagram showing the data types and subtypes used in developing the different classes of indicators used in EC studies in heathland and grassland ecosystems

Annex 4

Evaluation results by ecosystem type

1) Evaluation results for indicators of Agroecosystems

<u>Condition</u>

Class	Category	Indicator	Good indicator	Data availability	Importance	Directional meaning	Framework conformity	Instrumental relevance	Intrinsic relevance	Parsimony	Reliability	Sensitivity to human influence	Simplicity	Validity
AS1	Soil state	Bulk density	Strongly agree	Yes	8	4.3	4.7	5.0	2.5	1.0	2.0	4.0	4.0	4.5
AS1	Soil state	Soil erodibility	Strongly agree	Yes	9	4.3	2.0	5.0	2.0	2.0	2.0	5.0	3.0	4.5
AS1	Soil state	Soil packing density	Agree	Yes	7	4.3	4.7	4.0	2.5	1.0	2.0	4.0	4.0	4.0
AS1	Water availability	Soil moisture deficit	Agree	Yes	7	5.0	5.0	4.0	2.5	5.0	3.0	4.0	4.0	3.5
AS2	Soil quality	C:N ratio	Strongly agree	Yes	9	4.0	4.7	4.0	2.5	4.0	4.0	5.0	5.0	4.5
AS2	Soil quality	SOC	Strongly agree	Yes	9	4.3	4.0	5.0	2.0	2.0	2.0	5.0	4.0	4.5
BS1	Species	Crop diversity	Agree											
BS1	Species	Functional diversity	Strongly agree	No	10									
BS1	Species	Species richness (of key species, e.g. farmland birds)	Strongly agree	Yes	9	5.0	4.0	4.0	3.0	2.0	3.0	5.0	4.0	3.5
BS1	Species	Taxonomic diversity (of key species)	Strongly agree	Yes	10	4.7	4.7	4.0	4.0	4.0	1.0	5.0	4.5	4.5

Class	Category	Indicator	Good indicator	Data availability	Importance	Directional meaning	Framework conformity	Instrumental relevance	Intrinsic relevance	Parsimony	Reliability	Sensitivity to human influence	Simplicity	Validity
BS2	Vegetation Cover	Livestock Density	Disagree											
BS2	Vegetation Cover	NDVI	Agree	Yes	6	1.7	3.7	2.0	1.5	2.0	3.0	4.0	5.0	3.5
BS2	Vegetation Cover	Share of cover crops	Agree	Yes	8	4.0	4.0	4.0	2.0	2.0	3.0	5.0	5.0	3.5
BS3	Productivity	Net Primary Production	Agree	Yes	8	3.0	4.0	4.0	3.0	2.0	2.0	5.0	4.0	4.0
CS1	Connectivity	Connectivity index (contagion)	Agree	Yes	8	2.3	4.0	3.0	2.5	4.0	2.0	5.0	3.0	4.0
CS1	Fragmentation	Mesh density	Agree	Yes	7	4.0	4.0	4.0	2.5	2.0	3.0	5.0	4.0	3.5
CS1	Semi-natural habitats	Density of semi-natural areas	Strongly agree	Yes	10	4.3	4.0	5.0	2.5	2.0	3.0	5.0	5.0	4.5
CS2	Species flow	Beta diversity	Agree	No	5									

Pressure

Class	Category	Indicator	Good indicator	Data availability	Importance	Directional meaning	Framework conformity	Instrumental relevance	Intrinsic relevance	Parsimony	Reliability	Sensitivity to human influence	Simplicity	Validity
AP1	Soil	Soil imperviousness	Agree	Yes	8	4.3	3.7	5.0	3.0	5.0	2.0	5.0	4.0	4.5
AP1	Water	Water extraction	Neither agree nor disagree	Yes	6	4.0	5.0	4.0	2.5	5.0	4.0	5.0	4.0	2.5
AP2	Air pollutants	Carbon monoxide (CO)	Disagree											

Class	Category	Indicator	Good indicator	Data availability	Importance	Directional meaning	Framework conformity	Instrumental relevance	Intrinsic relevance	Parsimony	Reliability	Sensitivity to human influence	Simplicity	Validity
AP2	Air pollutants	Nitrogen deposition: Eutrophication risk (N load exceedance)	Strongly agree	Yes	7	4.0	4.0	4.0	2.0	2.0	2.0	4.0	3.5	4.0
AP2	Air pollutants	Nitrogen dioxide (NO2)	Neither agree nor disagree	No	4									
AP2	Air pollutants	Ozone (O_3)	Neither agree nor disagree	No	4									
AP2	Air pollutants	Particulate matter (PMx)	Neither agree nor disagree	No	5									
AP2	Air pollutants	Sulphur dioxide (SO2)	Neither agree nor disagree	No	2									
AP2	Soil pollutants	Fertilizers (NP surplus) 4	Strongly agree	Yes	8	4.0	4.7	4.0	4.0	4.0	3.0	4.0	3.5	4.0
AP2	Soil pollutants	Heavy metals (Cd, Pb, Cu, Zn exceedances)	Agree	Yes	7	4.7	4.7	3.0	4.0	4.0	3.0	4.0	4.0	4.0
AP2	Soil pollutants	PFAS (S)	Agree	No	3									
AP2	Soil pollutants	Pesticides residues	Strongly agree	Yes	8	4.3	4.7	3.0	4.0	4.0	3.0	4.0	4.0	4.0
BP1	Species	Pest and diseases	Agree	No										
BP1	Species	Pressure by Invasive alien species	Agree	Yes		4.0	3.3		3.0	4.0	2.0	4.0	3.5	4.0
CP1	Disturbance	Intensity	Agree	Yes	8	4.7	4.0	4.0	2.0	4.0	2.0	4.0	4.0	4.0
CP2	Encroachment	Human population	Neither agree nor disagree	Yes	8	3.7	3.0	4.0	2.5	4.0	2.0	4.0	3.5	3.0
CP2	Fragmentation	Fragmentation pressure of urban and transport infrastructure expansion	Neither agree nor disagree	Yes	9	4.0	4.0	4.0	3.0	4.0	2.0	4.0	3.5	3.0

2) Evaluation results for indicators of Forests

Condition

Class	Category	Indicator	Good indicator	Data availability	Importance	Directional meaning	Framework conformity	Instrumental relevance	Intrinsic relevance	Parsimony	Reliability	Sensitivity to human influence	Simplicity	Validity
AS1	Soil	Soil type condition	Agree	Yes	9	3.3	3.3	3	3	4	3	4	2.5	3
AS1	Soil state	Soil packing density	Neither agree nor disagree	Yes	8	3	4	3	2	4	2	4	3	3.5
AS1	Water availability	Frequency of drought events over a defined length of time period	Agree	Yes	10	3.3	3.7	4	2	4	2	4	4	3.5
AS2	Soil quality	C:N ratio	Agree	Yes	9	2.3	4	3	2.5	4	2	4	3.5	3
AS2	Soil quality	SOC	Agree	Yes	8	3	4	4	2.5	4	2	4	3.5	4
BS1	Species	Endemic species	Agree	Yes	8	4	4	3	3	4	2	4	3.5	4
BS1	Species	Functional diversity	Agree	Yes	10	4	3.7	4	4	3	2	4	3	4
BS1	Species	Presence / percentage of allochtonous (non-native) species	Agree	No	7									
BS1	Species	Proportion of native tree species	Strongly agree	No	7									
BS1	Species	Taxonomic diversity (of key species)	Agree	Yes	9	3.7	4	4	3	4	2	4	3.5	4
BS2	Vegetation Cover	Above ground biomass	Agree	Yes	7	4	4	4	3	2	3	4	3.5	4

Class	Category	Indicator	Good indicator	Data availability	Importance	Directional meaning	Framework conformity	Instrumental relevance	Intrinsic relevance	Parsimony	Reliability	Sensitivity to human influence	Simplicity	Validity
BS2	Vegetation Cover	Basal area	Neither agree nor disagree	Yes	5	4	4	3	3	2	3	4	4	4
BS2	Vegetation Cover	Canopy or forest height	Agree	Yes	3	3.7	4	4	3.5	3	2	4	4	4
BS2	Vegetation Cover	Dead wood	Strongly agree	No	8									
BS2	Vegetation Cover	Enhanced Vegetation Index (EVI)	Agree	Yes	8	4	4	3	4	4	3	4	4	3
BS2	Vegetation Cover	Forest age	Agree	Yes	10	4	4	4	4	3	2	4	3.5	4
BS2	Vegetation Cover	Forest cover density	Strongly agree	Yes	8	3.3	4	3	4	2	3	4	5	4
BS2	Vegetation Cover	Leaf Area Index	Neither agree nor disagree	Yes	4	3.7	3.7	4	3	2	2	4	3	3.5
BS2	Vegetation Cover	Leaf mass per area	Neither agree nor disagree	No	1									
BS2	Vegetation Cover	NDVI	Agree	Yes	6	3.7	3.3	4	2.5	2	2	4	3	3
BS2	Vegetation Cover	Number of age/size groups	Strongly agree	No	9									
BS2	Vegetation Cover	Plant senescence reflectance index (PSRI)	Neither agree nor disagree	Yes	2	3.3	3.7	3	3.5	3	2	3	3.5	3
BS2	Vegetation Cover	Presence of large trees	Strongly agree	No	8									
BS2	Vegetation Cover	Soil Adjusted Vegetation Index (SAVI)	Neither agree nor disagree	Yes	1	3.7	3.7	3	2	2	3	4	3	3.5
BS2	Vegetation Cover	Tree cover	Agree	Yes	9	4	4	4	4	4	3	4	4	4
BS2	Vegetation Cover	Tree height (average)	Agree	Yes	8	3.7	4	4	4	3	2	4	4	4

Class	Category	Indicator	Good indicator	Data availability	Importance	Directional meaning	Framework conformity	Instrumental relevance	Intrinsic relevance	Parsimony	Reliability	Sensitivity to human influence	Simplicity	Validity
BS2	Vegetation Cover	Variability (standard deviation?) of tree height	Strongly agree	No	7									
BS2	Vegetation Cover	Variability of size (e.g number of diameter classes)	Strongly agree	No	9									
BS2	Vegetation Cover	Variance in forest canopy height	Strongly agree	Yes	8	4	4	3	4	2	3	4	4	4
BS3	Productivity	Leaf N:P ratio	Agree	No	9									
BS3	Productivity	Leaf nitrogen	Agree	No	7									
BS3	Productivity	Leaf phosphorus	Agree	No	6									
BS3	Productivity	Net Primary Production	Agree	Yes	10	4	4	4	4	4	2	4	3.5	4
BS3	Productivity	Normalised Difference Infrared Index	Neither agree nor disagree	Yes	8	4	4	3	4	3	2	4	3	4
CS1	Connectivity	Connectivity index (contagion)	Agree	Yes	9	4	4	3	4	4	3	4	4	3.5
CS1	Connectivity	Largest patch index	Neither agree nor disagree	Yes	7	4	4	3	3	4	2	4	4	3.5
CS1	Connectivity	Mean patch size	Agree	Yes	10	4	4	3	3.5	4	2	4	4	4
CS1	Connectivity	Variance in forest patch size	Agree	Yes	10	4	4	3	4	4	4	3	3.5	4
CS2	Species flow	Beta diversity	Agree	No	8									

<u>Pressure</u>

Class	Category	Indicator	Good indicator	Data availability	Importance	Directional meaning	Framework conformity	Instrumental relevance	Intrinsic relevance	Parsimony	Reliability	Sensitivity to human influence	Simplicity	Validity
AP1	Climate	Increase in air temperature (e.g relation amount of heat days amount of freezing days)	Strongly agree	Yes	7	4	4	3	4	3	2	4	5	4
AP1	Climate	Number (or changes in the number) of extreme heat days	Agree	No	6									
AP1	Soil	Soil imperviousness	Neither agree nor disagree	Yes	9	4	2.7	3	4	4	2	4	4	3.5
AP1	Water	Proportion of drainage systems	Neither agree nor disagree	No	8									
AP1	Water	Water extraction	Neither agree nor disagree	No	10									
AP2	Air pollutants	Carbon monoxide (CO)	Neither agree nor disagree	Yes	7	3.7	4	3	2.5	4	2	4	3.5	3.5
AP2	Air pollutants	Nitrogen deposition: Eutrophication risk (N load exceedance)	Disagree											
AP2	Air pollutants	Nitrogen dioxide (NO2)	Agree	Yes	6	3.7	4	3	3	4	2	4	3.5	3.5
AP2	Air pollutants	Ozone (O_3)	Neither agree nor disagree	Yes	8	4	4	3	2.5	4	2	4	3.5	3.5
AP2	Air pollutants	Particulate matter (PMx)	Neither agree nor disagree	Yes	5	4	4	3	2.5	4	2	4	3.5	3.5

Class	Category	Indicator	Good indicator	Data availability	Importance	Directional meaning	Framework conformity	Instrumental relevance	Intrinsic relevance	Parsimony	Reliability	Sensitivity to human influence	Simplicity	Validity
AP2	Air pollutants	Sulphur dioxide (SO2)	Agree	Yes	9	4	4	3	3.5	4	2	4	3.5	3.5
AP2	Natural chemical processes	Increase of soil acidity (e.g. allochthonous needle-leavec species)	Agree	Yes	10	4	3.5	3	3	4	3	4	4	4
AP2	Soil pollutants	Fertilizers (NP surplus) 4	Disagree											
AP2	Soil pollutants	Heavy metals (Cd, Pb, Cu, Zr exceedances)	Agree	Yes	8	4	4	3	4	4	2	4	3.5	4
AP2	Soil pollutants	Pesticides residues	Disagree											
AP2	Water pollution	Dissolved NP	Disagree											
AP2	Water pollution	Nitrate (NO_3-)	Disagree											
AP2	Water pollution	Nitrite (NO_2-)	Disagree											
AP2	Water pollution	Pesticides	Disagree											
AP2	Water pollution	Phosphate (PO43-)	Disagree											
AP2	Water pollution	PFAS	Disagree											
BP1	Species	Game	Agree	No	8									
BP1	Species	Pest and diseases	Agree	No	10									
BP1	Species	Pressure by Invasive alien species	Agree	Yes	9	4	3.7	4	4	4	2	4	3	4
CP1	Disturbance	Burn severity (dNBR)	Agree	Yes	9	4	2.7	2	4	2	2	4	4	4

Class	Category	Indicator	Good indicator	Data availability	Importance	Directional meaning	Framework conformity	Instrumental relevance	Intrinsic relevance	Parsimony	Reliability	Sensitivity to human influence	Simplicity	Validity
CP1	Disturbance	Intensity	Agree	No	10									
CP1	Disturbance	Management intensity	Agree	No	9									
CP1	Disturbance	Number of disturbance events within a period	Agree	No	10									
CP1	Waste deposits	Proportion of waste deposits landfills	Strongly agree	No	8									
CP2	Encroachment	Human population	Disagree											
CP2	Fragmentation	Fragmentation pressure of urban and transport infrastructure expansion	Neither agree nor disagree	No	10									
CP2	Land consumption	Proportion of forest are lost by artificial soil sealing in time	Strongly agree	Yes	9	4	4	3	4.5	3	2	4	4.5	4

3) Evaluation results for indicators of Urban ecosystems

Condition

Class	Category	Indicator	Good indicator	Data availability	Importance	Directional meaning	Framework conformity	Instrumental relevance	Intrinsic relevance	Parsimony	Reliability	Sensitivity to human influence	Simplicity	Validity
AS1	Air	Temperature (deviation from air temperature)	Disagree											

Class	Category	Indicator	Good indicator	Data availability	Importance	Directional meaning	Framework conformity	Instrumental relevance	Intrinsic relevance	Parsimony	Reliability	Sensitivity to human influence	Simplicity	Validity
AS1	Flood	Flood risk	Strongly disagree											
AS1	Soil state	Imperviousness	Strongly agree	Yes	1	4.0	4.0	4.0	4.0	2.0		5.0	4.5	4.5
AS1	Soil state	Normalised Difference Bare Soil Index/Normalised Difference Soil Index	Disagree											
AS1	Soil state	Normalised Difference Built-up Index (NDBI)	Disagree											
AS1	Soil state	Soil packing density	Agree	No	5									
AS1	Water availability	NDMI/Wetness	Neither agree nor disagree	Yes	3	3.7	4.3	3.0	3.0	4.0			3.0	3.5
AS2	Air quality	NO2	Agree	Yes	2	4.0	5.0	4.0	4.0	4.0			3.0	4.0
AS2	Air quality	PM10	Agree	Yes	3	4.0	5.0	4.0	4.0	3.0			3.0	4.0
AS2	Air quality	PM2.5	Agree	Yes	1	4.0	5.0	4.0	4.0	3.0			3.0	4.0
AS2	Air quality	SO2	Agree	Yes	4	4.0	5.0	4.0	4.0	4.0			3.0	4.0
AS2	Soil quality	C:N ratio	Disagree											
AS2	Soil quality	SOC	Agree	Yes	5	4.0	5.0	4.0	3.0	5.0		4.0	4.0	4.0
BS1	Species	Functional diversity	Neither agree nor disagree	No	2									
BS1	Species	National pollinator monitoring	Strongly disagree											

Class	Category	Indicator	Good indicator	Data availability	Importance	Directional meaning	Framework conformity	Instrumental relevance	Intrinsic relevance	Parsimony	Reliability	Sensitivity to human influence	Simplicity	Validity
BS1	Species	Naturalness of vegetation	Neither agree nor disagree	No	3									
BS1	Species	Taxonomic diversity (of key species)	Neither agree nor disagree	No	1									
BS2	Natural elements	Blue Green Factor	Disagree											
BS2	Natural elements	Share of green (and blue) space	Agree	Yes	3	4.3	4.3	4.0	4.0	2.0			4.5	4.5
BS2	Vegetation Cover	NDVI	Agree	Yes	2	4.3	4.0	4.0	3.0	2.0			4.0	3.0
BS2	Vegetation Cover	Soil Adjusted Vegetation Index	Neither agree nor disagree	Yes	4	4.3	4.0	4.0	3.0	2.0			4.0	3.0
BS2	Vegetation Cover	Tree canopy cover	Strongly agree	Yes	1	4.3	4.7	4.0	4.0	2.0			4.5	4.5
BS3	Productivity	Net Primary Production	Agree	Yes		4.3	4.7	5.0	4.0	4.0			3.0	4.0
CS1	Composition	Landscape Fragmentation Index	Neither agree nor disagree	Yes	2	4.0	3.7	2.0	3.0	2.0			3.5	2.5
CS1	Composition	Landscape diversity	Disagree											
CS1	Composition	Patch Cohesion Index	Neither agree nor disagree	Yes	3	3.0	3.7	2.0	3.0	2.0			3.0	3.0
CS1	Composition	Shannon's Diversity Index	Disagree											
CS1	Connectivity	Connectivity index (contagion)	Neither agree nor disagree	Yes	1	3.0	4.3	2.0	3.0	2.0			3.0	3.0
CS1	Species flow	Beta diversity	Agree	No	4									

Pressure

Class	Category	Indicator	Good indicator	Data availability	Importance	Directional meaning	Framework conformity	Instrumental relevance	Intrinsic relevance	Parsimony	Reliability	Sensitivity to human influence	Simplicity	Validity
AP1	Soil	Annual rate of net soil sealing	Agree	Yes	1	4.0	3.0		4.0	3.0			4.5	4.0
AP1	Soil	Soil imperviousness	Strongly agree	Yes		4.0	2.3	4.0	4.0	2.0			4.5	4.5
AP1	Waste	Waste generated per inhabitant	Disagree											
AP1	Water	Water extraction	Disagree											
AP2	Air pollutants	Carbon monoxide (CO)	Neither agree nor disagree	Yes	3	4.3	4.7	2.0	3.0	3.0			3.5	3.0
AP2	Air pollutants	Heavy metals	Neither agree nor disagree	Yes	9	4.3	4.7	2.0	3.0	3.0			3.5	3.0
AP2	Air pollutants	Nitrogen deposition: Eutrophication risk (N load exceedance)	Agree	No	8									
AP2	Air pollutants	Nitrogen dioxide (NO2)	Neither agree nor disagree	Yes	2	4.3	4.7	2.0	3.0	3.0			3.5	3.0
AP2	Air pollutants	Ozone (O_3)	Agree	Yes	5	4.3	4.7		3.0	4.0			3.5	3.5
AP2	Air pollutants	Particulate matter (PMx)	Neither agree nor disagree	Yes	1	4.3	4.7	2.0	3.0	3.0			3.5	3.0
AP2	Air pollutants	Sulphur dioxide (SO2)	Neither agree nor	Yes	4	4.3	4.7	2.0	3.0	3.0			3.5	3.0

Class	Category	Indicator	Good indicator	Data availability	Importance	Directional meaning	Framework conformity	Instrumental relevance	Intrinsic relevance	Parsimony	Reliability	Sensitivity to human influence	Simplicity	Validity
			disagree											
AP2	Soil pollutants	Fertilizers (NP surplus)	Neither agree nor disagree	No	8									
AP2	Soil pollutants	Fertilizers input	Agree	No										
AP2	Soil pollutants	Heavy metals (Cd, Pb, Cu, Zn exceedence)	Neither agree nor disagree	No	10									
AP2	Soil pollutants	Pesticide residues	Neither agree nor disagree	No	6									
AP2	Soil pollutants	Pesticides input	Agree	No										
BP1	Species	Density of street dogs and feral cats	Neither agree nor disagree	No	2									
BP1	Species	Pest and diseases	Neither agree nor disagree	No	3									
BP1	Species	Pressure by Invasive alien species	Neither agree nor disagree	No	1									
CP1	Intensity	Intensity	Neither agree nor disagree	No										
CP1	Intensity	Light pollution levels	Agree	Yes	2	4.0			4.0	5.0			3.5	4.0
CP1	Intensity	Noise pollution levels (Lden / Lnight)	Agree	Yes	1	4.3			4.0	5.0			4.0	4.0
CP2	Encroachment	Human population	Disagree											

Class	Category	Indicator	Good indicator	Data availability	Importance	Directional meaning	Framework conformity	Instrumental relevance	Intrinsic relevance	Parsimony	Reliability	Sensitivity to human influence	Simplicity	Validity
CP2	Fragmentation	Fragmentation pressure of urban and transport infrastructure expansion	Neither agree nor disagree	No										

4) Evaluation results for indicators of Wetlands

<u>Condition</u>

Class	Category	Indicator	Good indicator	Data availability	Importance	Directional meaning	Framework conformity	Instrumental relevance	Intrinsic relevance	Parsimony	Reliability	Sensitivity to human influence	Simplicity	Validity
AS1	Soil state	Soil packing density	Disagree											
AS1	Water availability	Soil moisture anomalies	Agree	Yes	2	3.0	4.3	3.0	4.0	3.0	2.0	5.0	2.5	3.0
AS2	Soil quality	C:N ratio	Agree	Yes	7	3.7	5.0	4.0	3.0	4.0	3.0	4.0	4.0	4.0
AS2	Soil quality	SOC	Agree	Yes	7	3.7	4.0	3.0	3.0	4.0	3.0	4.0	4.0	4.0
AS2	Water quality	Water salinity	Strongly disagree											
BS1	Species	Functional diversity	Strongly agree	Yes	9	4.0	5.0	4.0	3.5	4.0	2.0	4.0	3.0	4.5

Class	Category	Indicator	Good indicator	Data availability	Importance	Directional meaning	Framework conformity	Instrumental relevance	Intrinsic relevance	Parsimony	Reliability	Sensitivity to human influence	Simplicity	Validity
BS1	Species	Taxonomic diversity (of key species)	Strongly agree	Yes	9	2.7	5.0	4.0	3.5	4.0	2.0	4.0	3.0	4.5
BS2	Vegetation Cover	NDVI	Agree	Yes	6	2.7	2.7	4.0	3.5	2.0	2.0	4.0	3.5	3.5
BS3	Productivity	Net Primary Production												
CS1	Connectivity	Connectivity index (contagion)	Strongly agree	Yes	9	4.7	5.0	4.0	4.0	5.0	2.0	5.0	3.5	5.0
CS1	Soil state	Imperviousness	Agree	Yes	6	5.0	2.3	2.0	3.0	3.0	2.0	5.0	4.0	2.5
CS2	Species flow	Beta diversity	Agree	No	7	5	4	3	3	4	4	4	3	3

Pressure

Class	Category	Indicator	Good indicator	Data availability	Importance	Directional meaning	Framework conformity	Instrumental relevance	Intrinsic relevance	Parsimony	Reliability	Sensitivity to human influence	Simplicity	Validity
AP1	Soil	Soil imperviousness	Agree	Yes	6	4.0	2.7	4.0	3.0	4.0	4.0	4.0	4.0	3.5
AP1	Water	Water extraction	Agree	Yes	7	4.3	4.0	5.0	3.0	4.0	4.0	4.0	4.0	3.0
AP2	Air pollutants	Carbon monoxide (CO)	Strongly disagree											
AP2	Air pollutants	Nitrogen deposition: Eutrophication risk (N load exceedance)	Strongly agree	Yes	9	4.0	4.0	4.0	3.0	4.0	2.0	3.0	3.5	3.0

Class	Category	Indicator	Good indicator	Data availability	Importance	Directional meaning	Framework conformity	Instrumental relevance	Intrinsic relevance	Parsimony	Reliability	Sensitivity to human influence	Simplicity	Validity
AP2	Air pollutants	Nitrogen dioxide (NO2)	Agree	Yes	8	4.0	4.0	4.0	3.0	3.0	2.0	4.0	3.5	2.5
AP2	Air pollutants	Ozone (O_3)	Neither agree nor disagree	Yes	5	4.0	4.0	4.0	4.0	3.0	2.0	4.0	3.5	2.5
AP2	Air pollutants	Particulate matter (PMx)	Neither agree nor disagree	Yes	7	4.0	4.0	4.0	3.0	3.0	2.0	4.0	3.5	2.5
AP2	Air pollutants	Sulphur dioxide (SO2)	Agree	Yes	7	4.0	4.0	4.0	4.0	4.0	2.0	3.0	3.5	3.0
AP2	Soil pollutants	Fertilizers (NP surplus)	Agree	Yes	8	4.0	4.0	5.0	3.0	4.0	2.0	4.0	4.0	3.0
AP2	Soil pollutants	Heavy metals (Cd, Pb, Cu, Zn exceedances)	Agree	Yes	9	4.0	4.0	4.0	4.0	4.0	2.0	4.0	4.0	3.0
AP2	Soil pollutants	Pesticides residues	Agree	Yes	9	4.0	4.0	4.0	4.0	4.0	2.0	4.0	4.0	3.0
AP2	Soil pollutants	PFAS (S)	Strongly agree	No										
AP2	Water pollution	Nitrate (NO_3-)	Strongly agree	Yes	9	4.0	4.0	5.0	3.0	4.0	2.0	4.0	4.0	3.0
AP2	Water pollution	Nitrite (NO_2-)	Strongly agree	Yes	9	4.0	4.0	5.0	3.0	4.0	2.0	4.0	4.0	3.0
AP2	Water pollution	Pesticides	Strongly agree	Yes	9	4.3	4.0	5.0	4.0	4.0	2.0	4.0	4.0	3.0
AP2	Water pollution	Phosphate (PO43-)	Strongly agree	Yes	9	4.0	4.0	5.0	3.0	4.0	2.0	4.0	4.0	3.0
AP2	Water pollution	PFAS (W)	Strongly agree	No	9									
AP2	Water pollution	Pressure by Invasive alien species	Agree	Yes	9	2.0	4.0	4.0	4.0	4.0	2.0	4.0	3.5	3.0

Class	Category	Indicator	Good indicator	Data availability	Importance	Directional meaning	Framework conformity	Instrumental relevance	Intrinsic relevance	Parsimony	Reliability	Sensitivity to human influence	Simplicity	Validity
BP1	Species	Pest and diseases	Disagree		1									
CP1	Disturbance	Intensity	Agree	No	6									
CP2	Encroachment	Human population	Strongly disagree	No	1									
CP2	Encroachment	Threat factors	Strongly disagree	No	1									
CP2	Fragmentation	Fragmentation pressure of urban and transport infrastructure expansion	Agree	Yes		4.0	4.0	5.0	4.0	2.0	2.0	4.0	2.0	2.0
CP2	Fragmentation	Road density	Agree	Yes		4.0	4.0	4.0	4.0	2.0	2.0	4.0	2.0	2.0

5) Evaluation results for indicators of Heath- and Shrubland

<u>Condition</u>

Class	Category	Indicator	Good indicator	Data availability	Importance	Directional meaning	Framework conformity	Instrumental relevance	Intrinsic relevance	Parsimony	Reliability	Sensitivity to human influence	Simplicity	Validity
AS2	Soil quality	C:N ratio	Agree	Yes	9	3.7	4.0	3.0	3.5	4.0	4.0	4.0	4.0	4.0
AS2	Soil quality	Crude protein concentration	Disagree											

Class	Category	Indicator	Good indicator	Data availability	Importance	Directional meaning	Framework conformity	Instrumental relevance	Intrinsic relevance	Parsimony	Reliability	Sensitivity to human influence	Simplicity	Validity
AS2	Soil quality	SOC (topsoil, predicted from LUCAS)	Agree	Yes	9	2.7	4.0	3.0	3.5	4.0	4.0	4.0	4.0	4.0
AS1	Soil state	Soil bulk density	Agree	Yes	7	3.3	4.0	4.0	4.0	4.0	3.0	3.0	4.0	4.0
AS1	Water availability	Surface Soil Moisture	Neither agree nor disagree	Yes	7	2.3	3.7	2.0	4.0	4.0	2.0	2.0	4.0	4.0
BS1	Species	Functional diversity	Strongly agree	No	10									
BS1	Species	Taxonomic diversity (of key species)	Strongly agree	No	10									
BS2	Vegetation Cover	NDVI or EVI	Agree	Yes	8	4.0	4.7	5.0	4.0	4.0	4.0	4.0	5.0	4.5
BS2	Vegetation Cover	Tree cover density	Strongly agree	Yes	8	3.7	4.7	3.0	4.0	4.0	4.0	4.0	5.0	4.0
BS3	Productivity	Net Primary Production	Agree	Yes	9	4.0	4.7	4.0	4.0	2.0	2.0	4.0	5.0	3.5
CS1	Connectivity	Connectivity index (contagion)	Neither agree nor disagree	Yes	5	3.3	4.0	2.0	3.5	4.0	3.0	3.0	4.0	2.0
CS2	Species flow	Beta diversity	Agree	No	7									

<u>Pressure</u>

Class	Category	Indicator	Good indicator	Data availability	Importance	Directional meaning	Framework conformity	Instrumental relevance	Intrinsic relevance	Parsimony	Reliability	Sensitivity to human influence	Simplicity	Validity
AP1	Soil	Soil imperviousness	Strongly agree	Yes	10	4.3	4.7	3.0	4.0	4.0	2.0	5.0	4.0	4.0
AP1	Water	Water extraction	Disagree											
AP2	Air pollutants	Carbon monoxide (CO)	Disagree											
AP2	Air pollutants	Nitrogen deposition: Eutrophication risk (N load exceedance)	Strongly agree	Yes	10	4.0	4.0	2.0	4.0	4.0	3.0	2.0	4.0	4.0
AP2	Air pollutants	Nitrogen dioxide (NO_2)	Neither agree nor disagree	Yes	4	4.0	4.0	2.0	4.0	4.0	3.0	2.0	4.0	3.5
AP2	Air pollutants	Ozone (O_3)	Strongly agree	Yes	9	4.0	4.0	2.0	4.0	4.0	3.0	2.0	4.0	4.0
AP2	Air pollutants	Particulate matter (PMx)	Disagree											
AP2	Air pollutants	Sulphur dioxide (SO2)	Neither agree nor disagree	Yes	4	4.0	4.0	2.0	4.0	4.0	3.0	2.0	4.0	3.5
AP2	Soil pollutants	Fertilizers (NP surplus) 4	Disagree											
AP2	Soil pollutants	Heavy metals (Cd, Pb, Cu, Zn exceedances)	Disagree											
AP2	Soil pollutants	PFAS (S)	Disagree											
AP2	Soil pollutants	Pesticides residues	Disagree											
AP2	Water pollution	Dissolve NP	Disagree											
AP2	Water pollution	Nitrate (NO_3^-)	Disagree											
AP2	Water pollution	Nitrite (NO_2^-)	Disagree											

Class	Category	Indicator	Good indicator	Data availability	Importance	Directional meaning	Framework conformity	Instrumental relevance	Intrinsic relevance	Parsimony	Reliability	Sensitivity to human influence	Simplicity	Validity
AP2	Water pollution	PFAS (W)	Disagree											
AP2	Water pollution	Pesticides	Disagree											
AP2	Water pollution	Phosphate (PO43-)	Disagree											
BP1	Species	Pest and diseases	Neither agree nor disagree	No										
BP1	Species	Pressure by Invasive alien species	Agree	Yes	7	4.3	4.0	2.0	4.0	4.0	2.0	4.0	3.5	4.5
CP1	Disturbance	Intensity	Agree	Yes	8	3.7	4.0	2.0	4.0	4.0	3.0	3.0	3.5	3.5
CP1	Encroachment	Human population	Agree	Yes	9	4.0	3.3	2.0	4.0	2.0	2.0	5.0	4.0	3.0
CP1	Fragmentation	Fragmentation pressure of urban and transport infrastructure expansion	Agree	Yes	4	4.0	4.0	2.0	4.0	4.0	2.0	4.0	4.0	2.5

6) Evaluation results for indicators of Grassland

Condition

Class	Category	Indicator	Good indicator	Data availability	Importance	Directional meaning	Framework conformity	Instrumental relevance	Intrinsic relevance	Parsimony	Reliability	Sensitivity to human influence	Simplicity	Validity
AS1	Soil state	Soil bulk density	Agree	Yes	7	3.0	4.0	4.0	3.0	4.0	3.0	4.0	4.5	3.5
AS1	Soil state	Soil packing density	Neither agree nor disagree	No										
AS1	Water availability	Surface Soil Moisture	Agree	Yes	9	4.0	4.7	5.0	4.0	5.0	3.0	3.0	4.5	4.5
AS2	Soil quality	C:N ratio	Strongly agree	Yes	9	3.7	4.7	4.0	4.0	4.0	3.0	4.0	4.0	4.0
AS2	Soil quality	Crude protein concentration	Disagree											
AS2	Soil quality	SOC (topsoil, predicted from LUCAS)	Strongly agree	Yes	8	2.7	4.7	4.0	3.5	4.0	3.0	4.0	4.0	4.0
BS1	Species	Functional diversity	Strongly agree	No	10									
BS1	Species	Taxonomic diversity (of key species)	Strongly agree	No	10									
BS2	Vegetation Cover	NDVI	Agree	Yes	7	4.0	4.0	4.0	4.0	2.0	3.0	4.0	5.0	3.5
BS2	Vegetation Cover	Proportion of woody vegetation (using Normalized Difference Infrared Index (NDII)?	Strongly agree	No	8									
BS3	Productivity	Net Primary Production	Agree	Yes	9	4.3	4.0	4.0	3.0	2.0	3.0	4.0	4.0	3.5

Class	Category	Indicator	Good indicator	Data availability	Importance	Directional meaning	Framework conformity	Instrumental relevance	Intrinsic relevance	Parsimony	Reliability	Sensitivity to human influence	Simplicity	Validity
BS3	Productivity	Soil Biomass Productivity in grassland	Agree	Yes	7	3.7	4.0	4.0	3.5	3.0	3.0	4.0	4.0	3.0
CS1	Connectivity	Connectivity index (contagion)	Agree	No	9									
CS2	Species flow	Beta diversity	Neither agree nor disagree	No	7									

Pressure

Class	Category	Indicator	Good indicator	Data availability	Importance	Directional meaning	Framework conformity	Instrumental relevance	Intrinsic relevance	Parsimony	Reliability	Sensitivity to human influence	Simplicity	Validity
AP1	Soil	Soil imperviousness	Strongly agree	Yes	9	4.0	4.0	3.0	4.0	4.0	2.0	4.0	5.0	4.5
AP1	Water	Water extraction	Neither agree nor disagree	Yes	6	2.7	4.0	2.0	2.5	4.0	2.0	3.0	4.0	3.5
AP2	Air pollutants	Carbon monoxide (CO)	Disagree											
AP2	Air pollutants	Nitrogen deposition Eutrophication risk (N load exceedance)	Strongly agree	Yes	10	4.0	4.7	4.0	4.0	4.0	3.0	2.0	4.0	4.0
AP2	Air pollutants	Nitrogen dioxide (NO_2)	Neither agree nor disagree	Yes	4	3.3	4.0	4.0	4.0	4.0	3.0	2.0	4.0	3.5
AP2	Air pollutants	Ozone (O_3)	Strongly agree	Yes	9	4.0	4.0	4.0	4.0	4.0	3.0	2.0	4.0	4.0

Class	Category	Indicator	Good indicator	Data availability	Importance	Directional meaning	Framework conformity	Instrumental relevance	Intrinsic relevance	Parsimony	Reliability	Sensitivity to human influence	Simplicity	Validity
AP2	Air pollutants	Particulate matter (PMx)	Disagree											
AP2	Air pollutants	Sulphur dioxide (SO2)	Neither agree nor disagree	Yes	4	3.7	4.0	4.0	4.0	4.0	3.0	2.0	4.0	3.5
AP2	Soil pollutants	Fertilizers (NP surplus) 4	Agree	No	8									
AP2	Soil pollutants	Heavy metals (Cd, Pb, Cu, Zn exceedances)	Disagree											
AP2	Soil pollutants	Pesticides residues	Disagree											
AP2	Soil pollutants	PFAS_S	Disagree											
BP1	Species	Pest and diseases	Neither agree nor disagree	No	6									
BP1	Species	Pressure by Invasive alien species	Strongly agree	Yes	10	4.3	4.0	4.0	4.0	4.0	2.0	4.0	4.0	4.0
	Disturbance	Intensity	Agree	No	8									
CP1	Disturbance	Livestock density	Agree	Yes	8	3.7	3.0	4.0	3.0	4.0	3.0	4.0	4.0	4.0
CP2	Encroachment	Human population	Neither agree nor disagree	No	4									
CP2	Fragmentation	Fragmentation pressure of urban and transport infrastructure expansion	Agree	Yes	10	4.0	4.0	4.0	4.0	4.0	2.0	4.0	4.0	3.5

7) Evaluation results for indicators of Rivers and Lakes

Condition

Class	Category	Indicator	Good indicator	Data availability	Importance	Directional meaning	Framework conformity	Instrumental relevance	Intrinsic relevance	Parsimony	Reliability	Sensitivity to human influence	Simplicity	Validity
AS1		Water availability	Strongly agree	Yes	10	3.7	4.3	3	2	3	3	5	3.5	4
AS1	Soil state	Soil packing density	Strongly agree	Yes	8	3.7	4.3	3	1.5	3	3	5	3	3.5
AS1	Water state	Water surface temperature	Strongly agree	Yes	5	3.7	4	3	1.5	3	2	3	4	3.5
AS2	Soil quality	C:N ratio	Strongly agree	Yes	8	3.7	4.3	3	1	3	3	5	3	4
AS2	Soil quality	SOC	Strongly agree	Yes	8	3.7	4.3	3	1	3	3	5	3	4
AS2	Water quality	Ammonium	Agree	No	6									
AS2	Water quality	Chlorophyll-a	Strongly agree	No	8									
AS2	Water quality	Dissolved oxygen	Strongly agree	Yes	10	3.7	4.3	3	1.5	3	3	4	3	4
AS2	Water quality	Nitrates	Agree	Yes	7	3.7	4.3	3	1.5	3	3	4	3	4
AS2	Water quality	Nitrite	Agree	Yes	6	3.7	4.3	3	1.5	3	3	5	3	4
AS2	Water quality	Phosphates	Agree	Yes	6	3.7	4.3	3	1.5	3	3	5	3	4
AS2	Water quality	Secchi depth	Neither agree nor disagree	No	2									
AS2	Water quality	Sulfates	Agree	Yes	6	3.7	4.3	3	1.5	3	3	5	3	4
AS2	Water quality	Total Nitrogen	Strongly agree	Yes	8	3.7	4.3	3	1.5	3	3	4	3	4
AS2	Water quality	Total Phosphorus	Strongly agree	Yes	8	3.7	4.3	3	1.5	3	3	4	3	4

AS2	Water quality	Total dissolved solids	Agree	Yes	5	3.7	4	3	1	3	3	5	3	4
AS2	Water quality	Total suspended solids	Agree	Yes	5	3.7	4.3	3	1.5	3	3	4	3	4
	Water quality	Turbidity	Agree	Yes	5	3.7	4.3	3	1.5	3	3	4	3	4
AS2	Water quality	Water Quality Index	Strongly agree	No	10									
AS2	Water quality	pH	Strongly agree	Yes	8	3.7	4.3	3	1.5	3	3	5	3	4
BS1	Species	Functional diversity	Agree	No	5									
BS1	Species	Taxonomic diversity (of key species)	Agree	No	5									
BS2	Vegetation Cover	Enhanced Vegetation Index	Strongly agree	Yes	7	3.7	4	3	1.5	3	3	4	4	3.5
BS2	Vegetation Cover	NDVI	Strongly agree	Yes	8	3.7	4.3	3	1	3	3	5	4	4
BS2	Vegetation Cover	Tree cover	Strongly agree	Yes	7	3.7	4	3	1	3	3	4	3.5	3.5
BS3	Productivity	Net Primary Production	Strongly agree	Yes	8	2.7	4.3	3	1	3	3	4	3.5	3.5
BS3	Productivity	Trophic state index	Agree	Yes	5	3.67	4	3	1.5	3	3	4	3.5	3.5
CS1	Connectivity	Connectivity index (contagion)	Agree	No	7									
CS2	Species flow	Beta diversity	Agree	No	4									

Pressure

Class	Category	Indicator	Good indicator	Data availability	Importance	Directional meaning	Framework conformity	Instrumental relevance	Intrinsic relevance	Parsimony	Reliability	Sensitivity to human influence	Simplicity	Validity
AP1	Soil	Soil imperviousness	Agree	Yes	7	4.3	4	4	2	4	2	5	4	4
AP1	Water	Water extraction	Strongly agree	Yes	7	4.3	4.7	4	2.5	4	1	4	4.5	4
AP2	Air pollutants	Carbon monoxide (CO)	Agree	Yes	5	3.3	4	3	3.5	4	2	3	4	4
AP2	Air pollutants	Nitrogen deposition: Eutrophication risk (N load exceedance)	Strongly agree	Yes	8	4	4	4	3	4	2	4	4	4
AP2	Air pollutants	Nitrogen dioxide (NO_2)	Strongly agree	Yes	7	4	4	4	2	4	2	4	4	4
AP2	Air pollutants	Ozone (O_3)	Strongly agree	Yes	5	4	4	4	2	4	2	4	4	4
AP2	Air pollutants	Particulate matter (PMx)	Strongly agree	Yes	7	4	4	4	2	4	2	4	4	4
AP2	Air pollutants	Sulphur dioxide (SO2)	Strongly agree	Yes	7	4	4	4	3	4	2	4	4	3
AP2	Soil pollutants	Fertilizers (NP surplus) 4	Strongly agree	No	7									
AP2	Soil pollutants	Heavy metals (Cd, Pb, Cu, Zn exceedances)	Strongly agree	Yes	9	4	4	4	4	4	2	4	4	4
AP2	Soil pollutants	PFAS (S)	Strongly agree	Yes	9	4	4	4	4	4	2	4	4	4
AP2	Soil pollutants	Permanganate Index (CODMn)	Strongly disagree											
AP2	Soil pollutants	Pesticides residues	Strongly agree	Yes	8	4	4	4	4	4	2	4	4	4

Class	Category	Indicator	Good indicator	Data availability	Importance	Directional meaning	Framework conformity	Instrumental relevance	Intrinsic relevance	Parsimony	Reliability	Sensitivity to human influence	Simplicity	Validity
AP2	Water pollution	Dissolve NP	Strongly disagree											
AP2	Water pollution	Nitrate (NO_3-)	Strongly agree	Yes	9	4	4.7	4	3	4	2	4	4	4
AP2	Water pollution	Nitrite (NO_2-)	Strongly agree	Yes	9	4	4.7	4	3	4	2	4	4	4
AP2	Water pollution	PFAS (W)	Strongly agree	Yes	9	4	4	4	3	4	2	4	4	4
AP2	Water pollution	Pesticides	Strongly agree	Yes	9	4	4.7	4	3	4	2	4	4	4
AP2	Water pollution	Phosphate (PO43-)	Strongly agree	Yes	9	4	4.7	4	3	4	2	4	4	4
BP1	Species	Pest and diseases	Disagree											
BP1	Species	Risk of invasion of alien species	Strongly agree	Yes	9	4	4	4	4	4	2	4	3	4
CP1	Disturbance	Intensity	Agree	Yes	6	3.333333	2.666667	4	4	2	2	4	3	2
CP2	Encroachment	Human population	Strongly disagree											
CP2	Fragmentation	European river water bodies with significant pressures from barriers	Agree	Yes	10	2.666667	4	4	2	4	2	4	4	4
CP2	Fragmentation	Number of barriers	Strongly agree	Yes	10	2.666667	4	4	2	4	2	4	4	4

8) Evaluation results for indicators of Marine

Condition

Class	Category	Indicator	Good indicator	Data availability	Importance	Directional meaning	Framework conformity	Instrumental relevance	Intrinsic relevance	Parsimony	Reliability	Sensitivity to human influence	Simplicity	Validity
AS2	Oxygen availability	Dissolved oxygen	Strongly agree	Yes	9	5.0	4.0	5.0	5.0	5.0	4.0	4.0	5.0	5.0
BS1	Species	Marine species richness of conservation concern	Agree	Yes	8	5.0	5.0	4.0	1.5	4.0	4.0	5.0	4.5	3.0
BS1	Species	Percentage of marine species with good population status	Agree	Yes	8	5.0	5.0	5.0	1.5	4.0	2.0	5.0	4.5	3.0
BS1	Species	Spawning stock biomass (SSB) of commercially important fish species	Strongly agree	Yes	10	5.0	5.0	5.0	2.0	4.0	4.0	5.0	3.0	4.5
BS1	Species	State of breeding and wintering seabirds	Agree	Yes	7	4.0	3.0	3.0	2.5	2.0	3.0	4.0	4.0	3.0
BS2	Phytoplankton	Chlorophyll-a concentration	Agree	Yes	7	2.7	3.0	4.0	3.0	2.0	4.0	4.0	4.0	3.0
BS2	Productivity	Maximum depth of habitat-forming vegetation	Agree	Yes	8	5.0	3.3	4.0	3.0	4.0	2.0	4.0	4.0	4.0
CS2	Species flow	Benthic community indices	Strongly agree	Yes	10	4.0	3.3	3.0	3.0	4.0	4.0	4.0	3.5	4.0
CS2	Species flow	Beta diversity	Agree	No	8									

Pressure

Class	Category	Indicator	Good indicator	Data availability	Importance	Directional meaning	Framework conformity	Instrumental relevance	Intrinsic relevance	Parsimony	Reliability	Sensitivity to human influence	Simplicity	Validity
AP1	Climate change	Acidification	Agree	No	4									
AP1	Climate change	Sea level anomaly	Agree	Yes	3	4.0	4.0	2.0	3.0	4.0	4.0	4.0	5.0	2.5
AP1	Climate change	Sea water salinity	Agree	Yes	6	2.0	4.0	4.0	2.0	4.0	4.0	4.0	4.5	3.0
AP1	Climate change	Temperature increase	Agree	Yes	5	4.0	4.0	5.0	4.0	4.0	4.0	4.0	5.0	2.0
AP1	Pollution	Marine litter (macro & micro)	Neither agree nor disagree	No	3									
AP1	Pollution	Underwater noise	Agree	Yes	6	4.0	4.0	2.0	4.0	4.0	2.0	5.0	1.5	4.0
AP2	Air pollution	Nitrogen deposition (Eutrophication risk (N load exceedance))	Disagree											
AP2	Sediment pollution	Contaminants in sediment	Agree	Yes	3	4.0	4.0	4.0	3.0	4.0	4.0	5.0	4.0	3.0
AP2	Water pollution	Dissolve NP	Disagree											
AP2	Water pollution	Nitrate (NO_3-)	Disagree											
AP2	Water pollution	Nitrite (NO_2-)	Disagree											
AP2	Water pollution	PFAS	Disagree											
AP2	Water pollution	Pesticides	Disagree											
AP2	Water pollution	Phosphate (PO43-)	Disagree											

Class	Category	Indicator	Good indicator	Data availability	Importance	Directional meaning	Framework conformity	Instrumental relevance	Intrinsic relevance	Parsimony	Reliability	Sensitivity to human influence	Simplicity	Validity
BP1	Species	Frequency and intensity of harmful algal blooms	Agree	Yes	7	4.0	4.0	4.0	3.5	4.0	4.0	4.0	3.0	4.0
BP1	Species	IAS: Number of (newly-introduced) non-indigenous species	Agree	Yes	4	3.3	4.0	3.0	2.0	4.0	4.0	4.0	4.0	2.0
BP1	Species	Pest and diseases	Strongly disagree											
BP2	Land-use	Fish mortality (f) of commercially exploited fish and shellfish exceeding fishing mortality at maximum sustainable yield (fmsy)	Agree	Yes	8	5.0	1.0	5.0	2.0	4.0	2.0	5.0	3.5	3.0
CP1	Disturbance	Adversely affected benthic habitats	Strongly agree	Yes	10	5.0	1.0	5.0	2.5	2.0	2.0	5.0	2.0	3.0
CP1	Disturbance	Intensity	Agree	No	6									
CP2	Fragmentation	Barrier density	Disagree											
CP3	Pollutant flow	Riverine litter	Neither agree nor disagree	No	2									

Annex 5

Indicator descriptions and links

Terrestrial ecosystems. (A: Agro, F: Forest, U: Urban, W: Wetland, H&S: Heathland and Shrubland, G: Grassland, C: Coastal, R&L: Rivers and Lakes)

Class	Category	Variable	Ecosystem types	Description	Data source
AC1	Water availability	Soil water index	A, F, H&S, G, C	Measures soil moisture levels at different depths, a critical factor for vegetation health, productivity, and resilience. SWI is relevant for describing ecosystem condition by reflecting water availability for plants, detecting drought stress, and supporting assessments of land degradation.	Soil Water Index 2015-present (raster 1km), Europe, daily - version 1. European Union's Copernicus Land Monitoring Service Information, https://land.copernicus.eu/en/products/soil-moisture/daily-soil-water-index-europe-v1-0-1km (Accessed on 27.05.2025).
		Surface Water Occurrence (SWO)	R&L	SWO measures how often and persistently water is present on the Earth's surface over a specific time period, using satellite imagery. It captures the frequency of water detection relative to the total observations at a location, providing insights into the dynamics and changes of surface water bodies like lakes and rivers (Pekel et al. 2016).	Global surface water data set (30m) - JRC & Copernicus Programme https://data.jrc.ec.europa.eu/dataset/jrc-gswe-global-surface-water-explorer-v1
		Water and Werness Probability	W	WWPI represents the likelihood or extent of surface water presence and wetness conditions in a specific	Water and Wetness status 2018 (raster 10 m and 100 m), Europe, 3-yearly. European Union's Copernicus Land Monitoring

Class	Category	Variable	Ecosystem types	Description	Data source
		Index (WWPI)		area. It captures variations in soil moisture, surface water and wet vegetation	Service Information, https://land.copernicus.eu/en/products/high-resolution-layer-water-and-wetness
	Soil condition	Soil erodibility	F	Expressed as the K-factor, represents the susceptibility of soil to erosion. It is a key soil characteristic linked to properties such as organic matter content, texture, structure, and permeability. (Panagos et al., 2014)	Soil Erodibility (K- Factor) High Resolution dataset for Europe. JRC European Soil Data Centre (ESDAC), https://esdac.jrc.ec.europa.eu/content/soil-erodibility-k-factor-high-resolution-dataset-europe. (Accessed on 27.05.2025).
		Bulk density	A, F, H&S, G, C , R&L	Reflects the level of compaction of soil, and so the degree of water infiltration and the capacity to support vegetation.	Soil Bulk Density in Europe. JRC European Soil Data Centre (ESDAC), https://esdac.jrc.ec.europa.eu/content/soil-bulk-density-europe. (Accessed on 27.05.2025).
AC2	Water	Dissolved oxygen	R&L	Used to assess ecological condition under the WFD as it reflects pollution levels and habitat quality. Low concentrations may indicate organic pollution or poor flow, impacting fish and macroinvertebrate communities.	Heinle, M., Lisniak, D. and Saile, P. (2024). UNEP GEMS/Water Global Freshwater Quality Archive [Data set]. Zenodo. https://doi.org/10.5281/zenodo.14230628
		pH	R&L	Used to assess condition under the WFD and MSFD, reflecting the acidity of surface water.	Heinle, M., Lisniak, D. and Saile, P. (2024). UNEP GEMS/Water Global Freshwater

Class	Category	Variable	Ecosystem types	Description	Data source
					Quality Archive [Data set]. Zenodo. https://doi.org/10.5281/zenodo.14230628
	Soil	Soil Organic Carbon (SOC)	A, F, H&S, G	Derived from belowground plant material, SOC plays a key role in regulating ecosystem functions. It supports soil microorganisms, influences soil structure, and controls the availability of organically bound nutrients. (Billings et al., 2021)	Soil Bulk Density in Europe. JRC European Soil Data Centre (ESDAC), https://esdac.jrc.ec.europa.eu/content/topsoil-soil-organic-carbon-lucas-eu25. (Accessed on 27.05.2025).
		C:N ratio	F	Represents the ratio of carbon content to nitrogen content within organic matter.	Soil Bulk Density in Europe. JRC European Soil Data Centre (ESDAC), https://esdac.jrc.ec.europa.eu/content/chemical-properties-european-scale-based-lucas-topsoil-data. (Accessed on 27.05.2025).
BC1	Species diversity	Farmland/ Forest/ bird diversity	A, F	Birds are high in the food chain and therefore are considered good indicators for the overall state of biodiversity. Aggregated indicators based on species of interest are used across multiple ecosystems.	Diverse sources including Population trend of bird species: datasets from Article 12, Birds Directive 2009/147/EC reporting, EEA, (https://www.eea.europa.eu/en/datahub/datahubitem-view/96e1b9b1-ee94-4547-ad61-8059df7240bf, Accessed 28.05.2025;)
		Percentage of wetland	W	proportion of assessed wetland-dependent species whose populations are considered to be in good status, based on criteria such as stable or increasing	Population trend of bird species: datasets from Article 12, Birds Directive 2009/147/EC reporting, EEA,

Class	Category	Variable	Ecosystem types	Description	Data source
		species with good population status		trends, adequate population size, and favorable habitat conditions	(https://www.eea.europa.eu/en/datahub/datahubitem-view/96e1b9b1-ee94-4547-ad61-8059df7240bf, Accessed 28.05.2025)
		Bumblebee diversity	A, H&S, G	Bumblebees are key pollinators, pollinating a wide range of flora and supporting multiple ecosystem services and biodiversity. They are considered keystone species in multiple habitats (MacLeod et al., 2024)	Polce C, Maes J, Rotllan-Puig X, Michez D, Castro L, Cederberg B, Dvorak L, Fitzpatrick Ú, Francis F, Neumayer J, Manino A, Paukkunen J, Pawlikowski T, Roberts S, Straka J, Rasmont P (2018) Distribution of bumblebees across Europe. One Ecosystem 3: e28143. https://doi.org/10.3897/oneeco.3.e28143
		Crop diversity	A	Crop diversity, derived from EU crop type maps, reflects the variety and distribution of crop types across agricultural landscapes. It serves as an indicator of agroecosystem condition, with higher diversity often linked to greater resilience, pest control, and sustainable land use.	EUCROPMAP 2022. European Commission, Joint Research Centre (JRC) [Dataset] doi: 10.2905/555e5d1d-1aae-4320-a716-2e6d18aa1e7c PID: http://data.europa.eu/89h/555e5d1d-1aae-4320-a716-2e6d18aa1e7c. (Accessed on 27.05.2025).
		Proportion of native tree species	F	The proportion of native tree species is a, with a high proportion of native tree species associated with high value from a biodiversity perspective (Marín et al., 2021). The indicator is derived from the European Atlas of Forest Tree Species.	de Rigo, D., Caudullo, G., Houston Durrant, T., San-Miguel-Ayanz, J., 2016. The European Atlas of Forest Tree Species: modelling, data and information on forest tree species. In: San-Miguel-Ayanz, J., de

Class	Category	Variable	Ecosystem types	Description	Data source
					Rigo, D., Caudullo, G., Houston Durrant, T., Mauri, A. (Eds.), European Atlas of Forest Tree Species. Publications Office of the European Union, Luxembourg, pp. e01aa69+. https://w3id.org/mtv/FISE-Comm/v01/e01aa69
		Fish diversity in rivers	R&L	The RivFISH database documents the presence of all native freshwater-dependent fish species across 1,554 European river basins, integrating data using both accepted scientific names and their synonyms. It includes a total of 707 scientific names, with 667 currently recognized as valid. RivFISH will be periodically updated (Mameri et al., 2025).	Fishspotting: freshwater fish species presence in European river basins – RivFISH database
BC2	Vegetation	Share of cover crops	A	Refers to the proportion of land planted with cover crops during fallow periods. These crops protect soil from erosion and enhance soil structure, infiltration, and water-holding capacity. (Fendrich et al., 2023).	Cover Crops across Europe. JRC European Soil Data Centre (ESDAC), https://esdac.jrc.ec.europa.eu/content/cover-crops-accross-europe. (Accessed on 27.05.2025).
		Small Woody Features	A, G, C	Small woody features (SWF) include landscape elements such as hedgerows, shrubs, and small clusters of trees. They offer ecological benefits by serving as habitat bases and enhancing biodiversity in otherwise suboptimal environments. In agricultural areas, they also help regulate water	Small Woody Features 2018 (vector/raster 5 m and 100 m), Europe, 3-yearly. European Union's Copernicus Land Monitoring Service Information, https://land.copernicus.eu/en/products/high-resolution-layer-small-woody-

Class	Category	Variable	Ecosystem types	Description	Data source
				cycles and prevent soil erosion, supporting soil health. (Copernicus)	features/small-woody-features-2018 (Accessed on 27.05.2025).
		Normalised Difference Vegetation Index (NDVI)	F, R&L	NDVI is a common and widely used remote sensing index representing vegetation greenness, used to quantify the presence and health of vegetation.	Normalised Difference Vegetation Index 1999-2020 (raster 1 km), global, 10-daily – version 3. European Union's Copernicus Land Monitoring Service Information, Normalised Difference Vegetation Index 1999-2020 (raster 1 km), global, 10-daily – version 3 — Copernicus Land Monitoring Service (Accessed on 27.05.2025).
		Above-ground biomass	F	Refers to the total mass of living plant material above the soil surface, typically measured in dry weight per unit area. It includes stems, branches, leaves, and reproductive structures of vegetation, excluding below-ground components such as roots. AGB reflects the productivity, carbon storage capacity, and structural complexity of ecosystems.	Santoro, M.; Cartus, O. (2025): ESA Biomass Climate Change Initiative (Biomass_cci): Global datasets of forest above-ground biomass for the years 2007, 2010, 2015, 2016, 2017, 2018, 2019, 2020, 2021 and 2022, v6.0. NERC EDS Centre for Environmental Data Analysis, 17 April 2025. doi:10.5285/95913ffb6467447ca72c4e9d8cf30501. https://dx.doi.org/10.5285/95913ffb6467447ca72c4e9d8cf30501
		Tree cover density/Tr	F, U, C	"The amount and density of trees in forest is a fundamental trait of ecosystem structure, which underpin, among other processes, biogeochemical	High Resolution Layer Tree Cover and Forests. European Union's Copernicus Land Monitoring Service Information,

Class	Category	Variable	Ecosystem types	Description	Data source
		ee canopy cover		processes, habitat for biodiversity, productivity and carbon storage." (Vallecillo et al., 2022)	https://land.copernicus.eu/en/products/high-resolution-layer-forests-and-tree-cover (Accessed on 27.05.2025).
		Canopy height	F, H&S	"Canopy-top height is an important indicator of biomass and the associated, global aboveground carbon stock. At high spatial resolution, canopy height models (CHMs) directly characterize habitat heterogeneity" (Lang et al, 2024)	P. Potapov, X. Li, A. Hernandez-Serna, A. Tyukavina, M.C. Hansen, A. Kommareddy, A. Pickens, S. Turubanova, H. Tang, C.E. Silva, J. Armston, R. Dubayah, J. B. Blair, M. Hofton (2021) Mapping and monitoring global forest canopy height through integration of GEDI and Landsat data. Remote Sensing of Environment, 112165. https://doi.org/10.1016/j.rse.2020.112165
		Enhanced Vegetation Index	H&S, G	The Enhanced Vegetation Index is a vegetation index, similar to NDVI but with a higher sensitivity in areas of dense vegetation	MODIS NDVI and EVI, 16-day time series for Europe at 1 km resolution. Open Data Science Europe (2021), https://data.opendatascience.eu/geonetwork/srv/api/records/4ea3b1e9-d3d0-4c3f-afb1-6445cec3a89d. Accessed 29.05.2025
		Share of green (and blue) space	U	Urban green and blue spaces (UGBS) refer to the variety of natural areas such as parks, open areas, forests, rivers, lakes, and wetlands present within the urban fabric. UGBS are viewed as key components in urban ecosystems on account of their ability to support biodiversity and provide	CLC plus Backbone 2021 (raster 10 m), Europe, 3-yearly. EU Copernicus Land Monitoring Service information. https://land.copernicus.eu/en/products/clc-backbone/clc-backbone-2021. (Accessed on 27.05.2025).

Class	Category	Variable	Ecosystem types	Description	Data source
				multiple benefits for human health. (Guinaudeau et al., 2023)	https://doi.org/10.2909/71fc9d1b-479f-4da1-aa66-662a2fff2cf7
BC3	Productivity	Net Primary Production (NPP)	A, F, U, WH&S, G, R&L	Represents the net amount of carbon assimilated by plants through photosynthesis after accounting for plant respiration losses. It serves as a key indicator of ecosystem productivity, energy flow, and carbon cycling.	Net Primary Production 2023-present (raster 300 m), global, 10-daily – version 1. . European Union's Copernicus Land Monitoring Service Information, https://land.copernicus.eu/en/products/vegetation/net-primary-production-v1-0-300m. (Accessed on 27.05.2025).
		Soil biomass productivity	A, F, G	Biomass production is a key element of soil function and one of two soil functions, along with raw material provision, which has a direct use by humans (Tóth et al., 2013)	Soil Biomass Productivity maps of grasslands and pasture, of croplands and of forest areas in the European Union (EU27). JRC European Soil Data Centre (ESDAC), https://esdac.jrc.ec.europa.eu/content/soil-biomass-productivity-maps-grasslands-and-pasture-coplands-and-forest-areas-european. (Accessed on 27.05.2025).
LC	Connectivity	Density/connectivity of Semi-	A, F,U, W,	Semi-natural Habitats that have been shaped by traditional, low-intensity human land use over long periods, but which still support a high diversity of	CLC plus Backbone 2021 (raster 10 m), Europe, 3-yearly. EU Copernicus Land Monitoring Service information.

Class	Category	Variable	Ecosystem types	Description	Data source
		natural areas	H&S, G, C	native species and ecological processes. This indicator is calculated from high-resolution land cover data.	https://land.copernicus.eu/en/products/clc-backbone/clc-backbone-2021. (Accessed on 27.05.2025). https://doi.org/10.2909/71fc9d1b-479f-4da1-aa66-662a2fff2cf7
AP1	Water use	Water Exploitation Index (WEI+)	A	Measures the ratio of total freshwater abstraction to the long-term average of available renewable freshwater resources. Values above 20% indicate water stress; above 40% indicate severe stress (EEA, 2021).	Seasonal water scarcity conditions across Europe, measured by the water exploitation index plus (WEI+) for sub river basins, 2019. European Environment Agency (EEA) https://www.eea.europa.eu/en/analysis/maps-and-charts/seasonal-water-exploitation-index-plus-4
	Soil	Imperviousness	A, F, U, H&S, G	Refers to the proportion of land covered by impermeable surfaces (e.g., roads, buildings), which disrupts natural water infiltration and increases runoff, affecting forest hydrology and soil erosion (EEA, 2019).	High Resolution Layer Imperviousness. EU Copernicus Land Monitoring Service information. https://land.copernicus.eu/en/products/high-resolution-layer-imperviousness. (Accessed on 27.05.2025).
		Soil loss due to harvesting and fire	F	Quantifies soil degradation from logging and wildfires, which reduces soil fertility and affects forest regeneration (Panagos et al., 2015).	Soil erosion in forestland in Europe (using RUSLE2015). European Soil Data Centre (ESDAC), Soil erosion in forestland in Europe (using RUSLE2015) - ESDAC - European Commission (Accessed on 27.05.2025).

Class	Category	Variable	Ecosystem types	Description	Data source
		Soil loss due to harvesting and tillage	(Used for HPI)	Quantifies soil degradation from harvesting and tillage, which reduces soil fertility and affects cropland (Panagos et al., 2019).	Soil erosion in cropland in Europe (using RUSLE2015). European Soil Data Centre (ESDAC), https://esdac.jrc.ec.europa.eu/content/soil-loss-due-crop-harvesting-european-union (Assessed on 29.05.2025)
AP2	Air pollution	Exceedance of critical loads for acidification	F	Indicates areas where atmospheric deposition of acidifying substances (e.g., sulfur, nitrogen) surpasses the ecosystems buffering capacity, leading to soil and water acidification (Hettelingh et al., 2017)	Exceedance of critical loads for acidification by deposition of nitrogen and sulphur compounds in 2020 under Current Legislation to reduce national emissions. European Environment Agency (EEA), https://www.eea.europa.eu/en/analysis/maps-and-charts/exceedance-of-critical-loads-for-acidification-by-deposition-of-nitrogen-and-sulphur-compounds-in-2020-under-current-legislation-to-reduce-national-emissions
		Exceedance of critical loads for eutrophication	F, H&S	Measures nitrogen deposition exceeding ecological thresholds, causing nutrient imbalances and biodiversity loss (Posh et al., 2017).	Risk of eutrophication measured as exceedance of critical loads of nitrogen deposition in Europe, in 2022. European Environment Agency (EEA), https://www.eea.europa.eu/en/analysis/indicators/eutrophication-caused-by-atmospheric-nitrogen/risk-of-eutrophication-measured

Class	Category	Variable	Ecosystem types	Description	Data source
		AOT40	A, F, G	Accumulated Ozone exposure over a Threshold of 40 ppb. It quantifies the cumulative exposure of vegetation to harmful ozone levels during the growing season (Mills et al., 2011).	Rural concentration of the ozone indicator AOT40 for vegetation, 2018. European Environment Agency (EEA), https://www.eea.europa.eu/en/analysis/maps-and-charts/rural-concentration-map-of-the-ozone-indicator-aot40-for-crops-year-14
		Annual average concentration of PM2.5	U	Fine particles, also referred to as PM2.5, are a key air pollutant leading to detrimental effects on both human health and the environment. (EEA, 2023)	European air quality data (interpolated data)- Series. European Environment Agency (EEA). https://www.eea.europa.eu/en/datahub/datahubitem-view/82700fbd-2953-467b-be0a-78a520c3a7ef?activeAccordion=1092391%2C1092385.
	Water pollution	Nutrients concentrations (N and P)	R&L	Represent the concentration of nitrogen (N) and phosphorus (P) that are naturally present or introduced into the river system. When present in excessive amounts, often due to runoff from agriculture, wastewater, or other human activities, they can lead to nutrient pollution, causing problems like algal blooms and eutrophication, which harm water quality and aquatic life.	Waterbase WISE State of Environment (SoE). European Environment Agency (EEA) https://www.eea.europa.eu/en/datahub/datahubitem-view/208518d1-ffe3-4981-9cae-13264cd9c32c

Class	Category	Variable	Ecosystem types	Description	Data source
		Pesticides concentrations	R&L	Refer to chemicals that can enter rivers through agricultural runoff, industrial discharge, or urban stormwater. The concentration indicates how much pesticide is dissolved or suspended in the water and is important for assessing the potential impact on aquatic ecosystems and human health	Waterbase WISE State of Environment (SoE). European Environment Agency (EEA) https://www.eea.europa.eu/en/datahub/datahubitem-view/208518d1-ffe3-4981-9cae-13264cd9c32c
		Pesticide risk score	(Used for HPI)	Environmental pollution risk caused by 92 active ingredients (i.e., herbicides, insecticides and fungicides) in groundwater, surface water, soil and atmosphere, using a spatially explicit modelling approach.	Tang, F.H.M., Lenzen , M., McBratney , A. and Maggi, F. (2021). Risk of pesticide pollution at global scale. Nature Geoscience, 14: 206 210. https:// doi.org/10.1038/s41561021007125
	Soil pollution	N and P surplus	A, G	N and P surplus represents the total inputs of N and P to land from sources including fertilizers and atmospheric deposition minus the offtake from crop removal (EEA, 2022)	Spatial variation in N surplus (left) and P surplus (right) for the year 2010 in the EU-27. European Environment Agency (EEA) https://www.eea.europa.eu/en/analysis/maps-and-charts/spatial-variation-in-n-surplus?activeTab=570bee2d-1316-48cf-adde-4b640f92119b
		Heavy metals	A	Represents the exceedance of critical heavy metals, including cadmium (Cd), copper (Cu), lead (Pb) and zinc (Zn). "Cu and Zn are minor nutrients but at high inputs, they may cause adverse impacts on soil biodiversity, whereas Cd and Pb are toxic metals that may lead to soil degradation, by both affecting soil biodiversity and food quality." (EEA, 2020)	Concentrations of heavy metals in European agricultural soils, Oct. 2020. European Environment Agency (EEA) https://sdi.eea.europa.eu/catalogue/srv/api/records/f23391fd-2524-42be-91cb-27d930d6a099

Class	Category	Variable	Ecosystem types	Description	Data source
		Soil acidity	F	Reflects the pH level of forest soils, influencing nutrient availability, microbial activity, and tree health. Acidic soils can limit forest productivity (European Commission, 2005). Calculated from the dominant leaf type information and pH measurements	Soil pH in Europe. European Soil Data Centre (ESDAC), https://esdac.jrc.ec.europa.eu/content/soil-ph-europe (Accessed on 27.05.2025). High Resolution Layer Tree Cover and Forests. European Union's Copernicus Land Monitoring Service Information, https://land.copernicus.eu/en/products/high-resolution-layer-forests-and-tree-cover (Accessed on 27.05.2025).
BP1	Species	Insect and disease disturbances	F	Tracks the frequency and severity of pest and pathogen outbreaks, which can cause tree mortality and alter forest structure (USDA Forest Service, 2020).	Forzieri, G., Dutrieux, L., Elia, A., Eckhardt, B., Caudullo, G., Álvarez Taboada, F., Andriolo, A., Bălăcenoiu, F., Bastos, A., Buzatu, A., Castedo Dorado, F., Dobrovolný, L., Duduman, M., Fernandez-Carrillo, A., Hernández-Clemente, R., Hornero, A., Ionuț, S., Lombardero, M.J., Junttila, S., Lukes, P., Marianelli, L., Mas, H., Mlčoušek, M., Mugnai, F., Nețoiu, C., Nikolov, C., Olenici, N., Olsson, P., Paoli, F., Paraschiv, M., Patočka, Z., Pérez-Laorga, E., Quero, J.L., Rüetschi, M., Stroheker, S., Nardi, D., Ferenčík, J., Battisti, A., Hartmann, H., Nistor, C., Cescatti, A. and Beck, P. (2023).

Class	Category	Variable	Ecosystem types	Description	Data source
					The Database of European Forest Insect and Disease Disturbances: DEFID2, GLOBAL CHANGE BIOLOGY, ISSN 1354-1013, 29 (21): 6040-6065, JRC134202
		Pressure by IAS	A, F, H&S, G	Assesses the impact of non-native species that disrupt native ecosystems, outcompete local flora and fauna, and alter forest dynamics (EEA, 2021). The indicator represents cumulative potential pressure by 66 IAS of Union concern across terrestrial and freshwater ecosystems, using a trait-based approach to estimate the potential pressure.	Polce, C., Cardoso, A.C., Deriu, I. et al. (2023). Invasive alien species of policy concerns show widespread patterns of invasion and potential pressure across European ecosystems. Sci Rep 13, 8124. https://doi.org/10.1038/s41598-023-32993-8 (https://easin.jrc.ec.europa.eu/easin)
CP1		Light pollution levels	U	Represents the level of nighttime light, captured by SDGSAT-1.	SDGSAT Level-4 products. See https://www.sdgsat.ac.cn/satellite/data; SDGSAT EU Visual
		Livestock density	G	Represents the number of livestock units per unit area of grassland. The presence of livestock on grassland influences the function and diversity of plant and vertebrate communities (Filazzola et al., 2020)	Gridded livestock density (Global - 2020 - 10 km) - GLW4. UN Food and Agriculture Organisation (FAO), https://data.apps.fao.org/catalog//iso/9d1e149b-d63f-4213-978b-317a8eb42d02. (Accessed 28.05.2025).
		Agricultural land cover in	R&L	This computed indicator is related to agricultural activities that may directly affect rivers and lakes, in terms of environmental assessment (i.e., Water	CLCplus Backbone 2021 (raster 10 m), Europe, 3-yearly. EU Copernicus Land Monitoring Service information.

Class	Category	Variable	Ecosystem types	Description	Data source
		catchment area		quality and biodiversity) and resources management (i.e., water resource and soil conservation). (e.g., Szpakowska et al, 2022)	https://land.copernicus.eu/en/products/clc-backbone/clc-backbone-2021. (Accessed on 27.05.2025). https://doi.org/10.2909/71fc9d1b-479f-4da1-aa66-662a2fff2cf7
	Disturbance	Number of disturbance events	F	Counts natural or anthropogenic events (e.g., storms, fires, pest outbreaks) that disrupt forest ecosystems (Senf et al., 2021).	Viana-Soto, A. and Senf, C.: The European Forest Disturbance Atlas: a forest disturbance monitoring system using the Landsat archive, Earth Syst. Sci. Data Discuss. [preprint], https://doi.org/10.5194/essd-2024-361, in review, 2024.
		Wood production	(Used for HPI)	Predicted wood production (2000-2010) using location factors (i.e., forest resources, environmental conditions and socio-economic data)	Verkerk, P.J., Levers, C., Kuemmerle, T., Lindner M.,,Valbuena, R., Verburg, P.H. and Zudin, S. (2015). Mapping wood production in European forests. For. Ecol. Manage., 357: 228-238, 10.1016/j.foreco.2015.08.007
		Intensity of agricultural	(Used for HPI)	Anthropogenic energy for the primary crop production, using entrants inputs and activities (using the CAPRI model)	Rega, C., Short, C., Pérez-Soba, M. and Paracchini, M.L.(2020). A classification of European agricultural land using an energy-based intensity indicator and detailed crop description. Landsc. Urban Plan., 198:

Class	Category	Variable	Ecosystem types	Description	Data source
		management			103793. 10.1016/j.landurbplan.2020.103793
CP2	Fragmentation	Mesh density	A, F, H&S, G	A measure of the degree to which movement between different parts of the landscape is interrupted by impervious surfaces or roads	Landscape fragmentation Effective Mesh Density time series. European Environment Agency (EEA), https://www.eea.europa.eu/en/datahub/datahubitem-view/9d0b51f9-047d-4af1-89eb-3756e46ff.

Marine ecosystems

Class	Category	Variable	Description	Data source
AC2	Water	Dissolved Oxygen	Used to assess ecological condition under the MSFD, as it reflects pollution levels and habitat quality. Low concentrations may indicate organic pollution or poor flow, impacting fish and macroinvertebrate communities.	https://portal.gemstat.org/applications/public.html?publicuser=PublicUser#gemstat/Stations; https://zenodo.org/records/14230628

Class	Category	Variable	Description	Data source
		Nutrient concentrations	Refers to the concentrations of Dissolved inorganic nitrogen, Total Nitrogen, Total Phosphorus, Dissolved inorganic phosphorus in water.	https://emodnet.ec.europa.eu/en/chemistry; https://www.ices.dk/data/dataset-collections/Pages/default.aspx
		Concentration of total suspended matter	Total suspended matter (TSM) measures particles in the water that reduce light, affect photosynthesis, and alter habitat quality. It reflects natural processes and human impacts.	https://emodnet.ec.europa.eu/en/chemistry; https://www.ices.dk/data/dataset-collections/Pages/default.aspx
BC1	Species diversity	Bird, mammal, cephalopod and turtle abundances	Reflects population trends of key marine fauna groups.	https://indicators.helcom.fi/indicator/grey-seal-abundance/; https://medqsr2023.info-rac.org/biodiversity-fisheries/#E01; https://oap.ospar.org/en/ospar-assessments/quality-status-reports/qsr-2023/thematic-assessments/marine-mammals/
		Seagrass cover	distribution of Seagrass meadows in European waters	https://emodnet.ec.europa.eu/geonetwork/srv/eng/catalog.search#/metadata/39746d9c-4220-425c-bc26-7cb3056c36a5

Class	Category	Variable	Description	Data source
BC2	Structural	Spawning stock biomass (SSB) of commercially important fish species (tonne per spp)	Spawning stock biomass (SSB) is the total weight of mature, reproductive individuals in a fish population. For commercially important species, it indicates the stock's ability to replenish and sustain harvests.	WISE-Marine(https://water.europa.eu/marine); https://www.ices.dk/advice/Pages/Latest-Advice.aspx; https://www.fao.org/gfcm/en/; https://www.iccat.int/en/
BC3	Productivity	Chlorophyll-a concentration	Reflects the level of primary production in water, influenced by nutrient and light availability. High concentrations can indicate adverse effects of nutrient enrichment.	https://marine.copernicus.eu/access-data/ocean-monitoring-indicators/chlorophyll-and-primary-production
		Frequency and intensity of harmful algal blooms	Tracks the occurrence and severity of algal bloom events in coastal water bodies that disrupt marine ecological balance and threaten biodiversity. It reflects changes in environmental conditions, such as nutrient pollution and climate variability, that promote the growth of harmful algae.	https://marine.copernicus.eu/services/use-cases/harmful-algae-bloom-monitoring-aquaculture-farms-spain https://indicators.helcom.fi/indicator/cyanobacterial-blooms/ https://dataspace.copernicus.eu/gallery/2023-6-14-algae-blooms-north-sea
		Coverage of habitat forming vegetation (e.g. Maximum depth of habitat-forming vegetation) (%)	Measures key vegetative habitats such as seagrasses or macroalgae in coastal water bodies. It reflects ecosystem health and water clarity, as reduced coverage or depth often indicates environmental degradation.	WISE freshwater (https://water.europa.eu/freshwater/resources/metadata/wfd-dashboards/surface-water-bodies-quality-elements-status-table)

Class	Category	Variable	Description	Data source
LC2	Compositi onal	Benthic community indices (AMBI, BQI)	Assesses the structure and health of seabed communities based on species composition and sensitivity to disturbance.	WISE freshwater (https://water.europa.eu/freshwater/resources/metadata/wfd-dashboards/surface-water-bodies-quality-elements-status-table); HELCOM (https://helcom.fi/wp-content/uploads/2019/08/State-of-the-soft-bottom-macrofauna-community-HELCOM-core-indicator-2018.pdf)
AP1	Water	Underwater noise	An important pressure indicator for mammals, and also possibly seabirds and fish, due to its influence masking biological signals	https://maritime-forum.ec.europa.eu/contents/map-week-underwater-noise-indicator-0_en
		Marine macro- & micro-litter	Represents the density of floating litter per net, normalized in grams per km^2	European Marine Observation and Data Network (EMODnet) https://emodnet.ec.europa.eu/geonetwork/srv/eng/catalog.search#/search?from=1&to=30
AP2	Water pollution	Antifoulants	Concentration of Antifoulants (Tributyltin, Triphenyltin) in water at sampling stations	European Marine Observation and Data Network (EMODnet) https://emodnet.ec.europa.eu/en/chemistry#contaminants
		Heavy metals	Concentration of Heavy metals (Cadmium, Lead, Mercury, Nickel) in water at sampling stations	European Marine Observation and Data Network (EMODnet) https://emodnet.ec.europa.eu/en/chemistry#contaminants

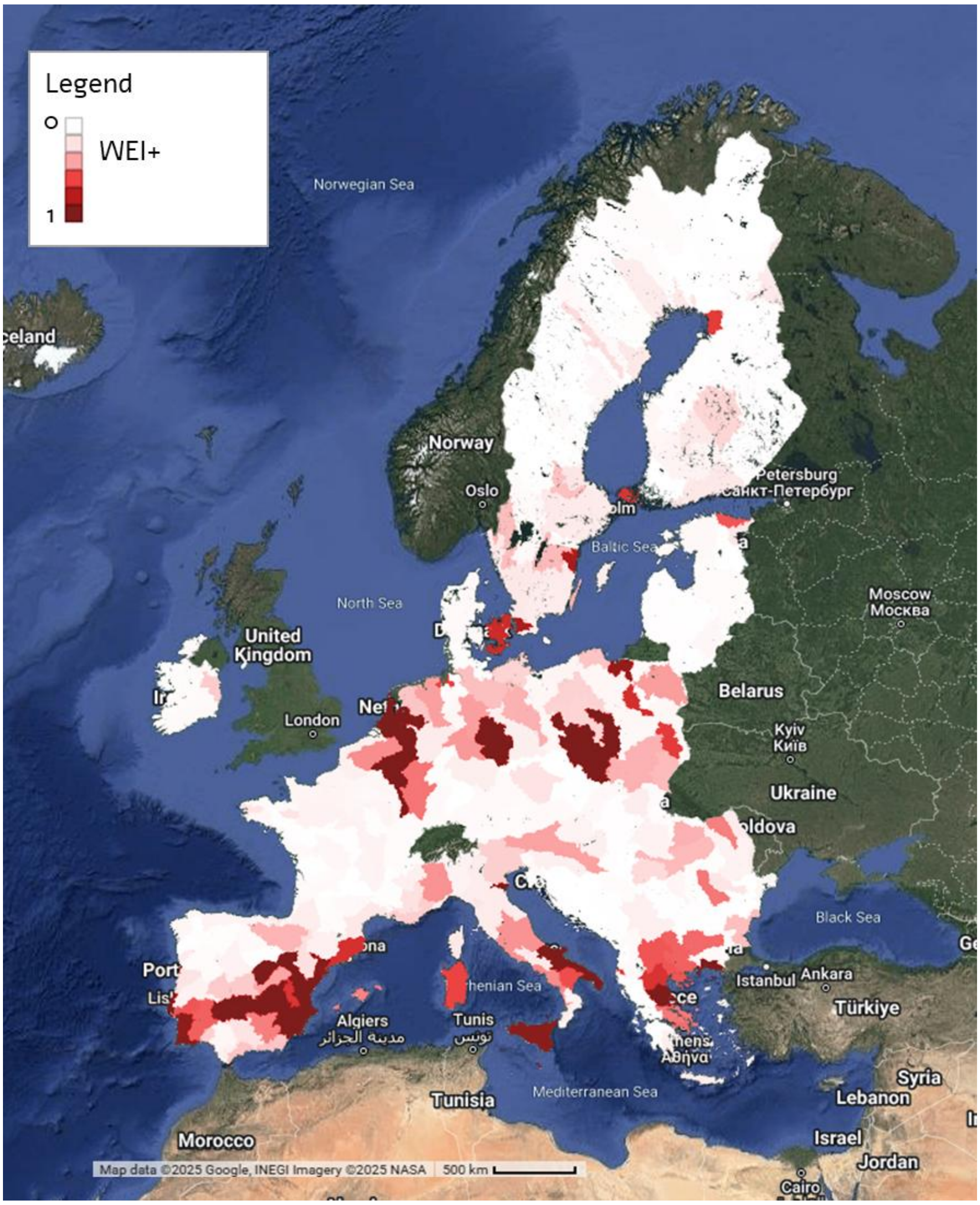
Class	Category	Variable	Description	Data source
		Hydrocarbons	Concentration of Hydrocarbons (Anthracene, Benzo(A)Pyrene, Fluoranthene, Naphthalene) in water et sampling stations	European Marine Observation and Data Network (EMODnet) https://emodnet.ec.europa.eu/en/chemistry#contaminants
		Pesticides and biocides	Concentration of pesticides and biocides (DDT-DDE-DDD, and Hexachlorobenzene) in water at sampling stations	European Marine Observation and Data Network (EMODnet) https://emodnet.ec.europa.eu/geonetwork/srv/eng/catalog.search#/search?from=1&to=30
		Nitrogen and Phosphorus loads	Annual nutrient loads and source apportionments for 1990-2018 estimated at the outlets of freshwater river basins with model GREEN (November 2021 version; Vigiak et al. 2022). Sources of nutrients comprise agriculture (mineral and organic fertilization), atmospheric nitrogen deposition, phosphorus releases from natural areas, scattered dwellings, and point sources (domestic and industrial discharges).	Joint Research Centre Data Catalogue - Nitrogen and phosphorus loads to the sea (1990-201... - European Commission
	Sediment pollution	Antifoulants	Concentration of Antifoulants (Tributyltin, Triphenyltin) in sediment at sampling stations	European Marine Observation and Data Network (EMODnet) https://emodnet.ec.europa.eu/en/chemistry#contaminants

Class	Category	Variable	Description	Data source
		Heavy metals	Concentration of Heavy metals (Cadmium, Lead, Mercury, Nickel) in sediment at sampling stations	European Marine Observation and Data Network (EMODnet) https://emodnet.ec.europa.eu/en/chemistry#contaminants
		Hydrocarbons	Concentration of Hydrocarbons (Anthracene, Benzo(A)Pyrene, Fluoranthene, Naphthalene) in sediment et sampling stations	European Marine Observation and Data Network (EMODnet) https://emodnet.ec.europa.eu/en/chemistry#contaminants
		Pesticides and biocides	Concentration of pesticides and biocides (DDT-DDE-DDD, and Hexachlorobenzene) in sediment at sampling stations	European Marine Observation and Data Network (EMODnet) https://emodnet.ec.europa.eu/geonetwork/srv/eng/catalog.search#/search?from=1&to=30
	Biota	Contaminants in fish and shellfish (CHASE)	Concentration of contaminants (Heavy metals, hydrocarbons and pesticides and biocide) in marine organisms such as molluscs, fish and crustaceans.	https://emodnet.ec.europa.eu/en/chemistry; https://www.ices.dk/data/dataset-collections/Pages/default.aspx
BP1	Species	Introduced Invasive alien species	Tracks the presence and spread of non-native species that establish, proliferate, and cause ecological or economic harm in marine ecosystems. It reflects pressures from human activities such as shipping, aquaculture, and climate-driven range shifts.	Marine non-indigenous species in Europe's seas. European Environment Agency (EEA). https://www.eea.europa.eu/en/analysis/indicators/marine-non-indigenous-species-in

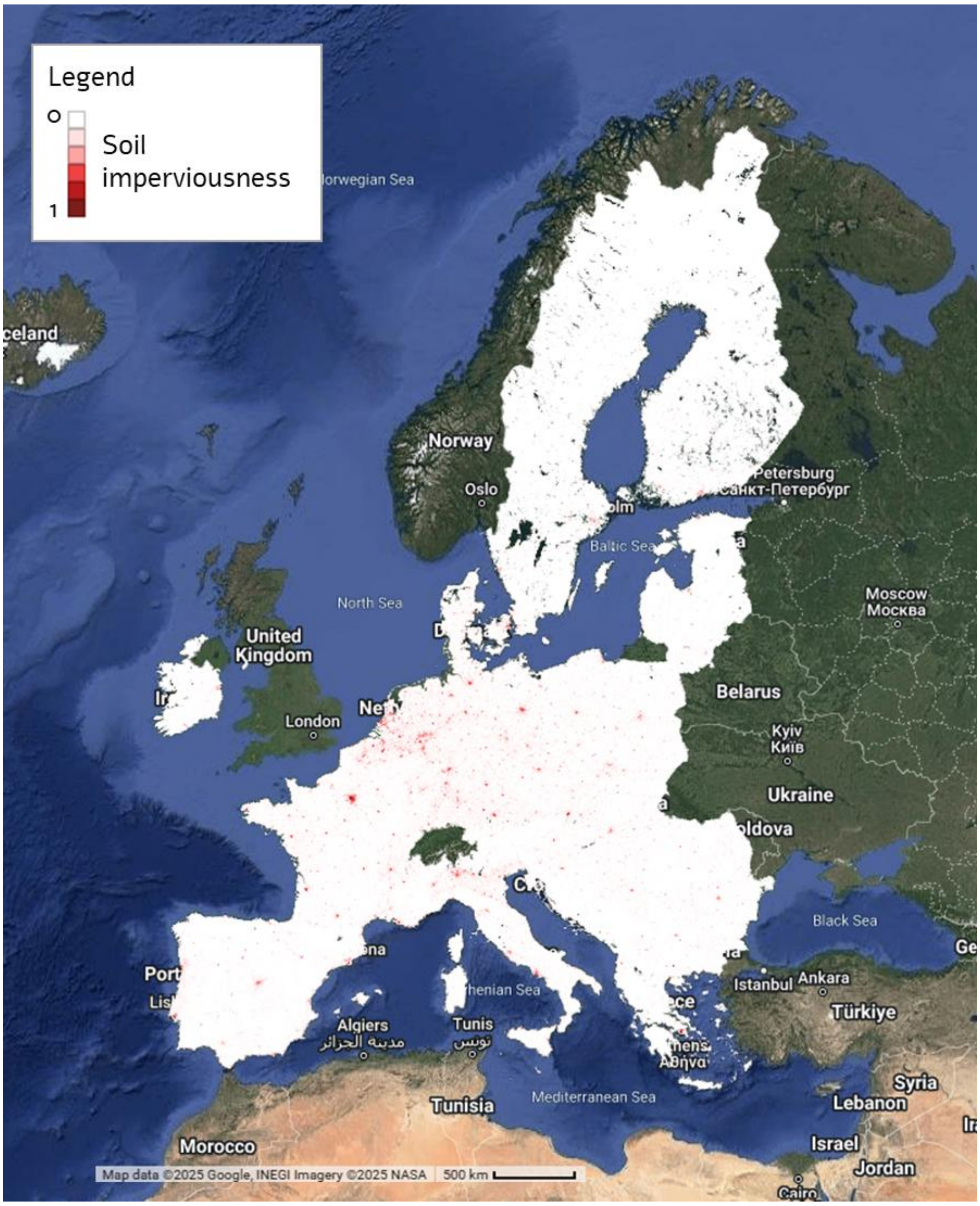
Class	Category	Variable	Description	Data source
CP1	Sea-use	Fish mortality (f) of commercially exploited fish and shellfish exceeding fishing mortality at maximum sustainable yield (fmsy)	Indicates that fishing pressure on commercially exploited fish and shellfish is unsustainable. It means harvest rates surpass the level that allows populations to replenish, risking stock depletion.	WISE-Marine(https://water.europa.eu/marine); https://www.ices.dk/advice/Pages/Latest-Advice.aspx; https://www.fao.org/gfcm/en/; https://www.iccat.int/en/
CP2	Fragment ation	Adversely affected benthic habitats	Reflects the condition of seabed areas degraded by human activities such as trawling, dredging, or pollution	ISE-Marine(https://water.europa.eu/marine); EEA (https://www.eionet.europa.eu/etcs/etc-icm/products/etc-icm-reports/etc-icm-report-4-2019-multiple-pressures-and-their-combined-effects-in-europes-seas); HELCOM (https://stateofthebalticsea.helcom.fi/findings/distribution/baltic-sea-pressure-and-impact-indices/)

Annex 6

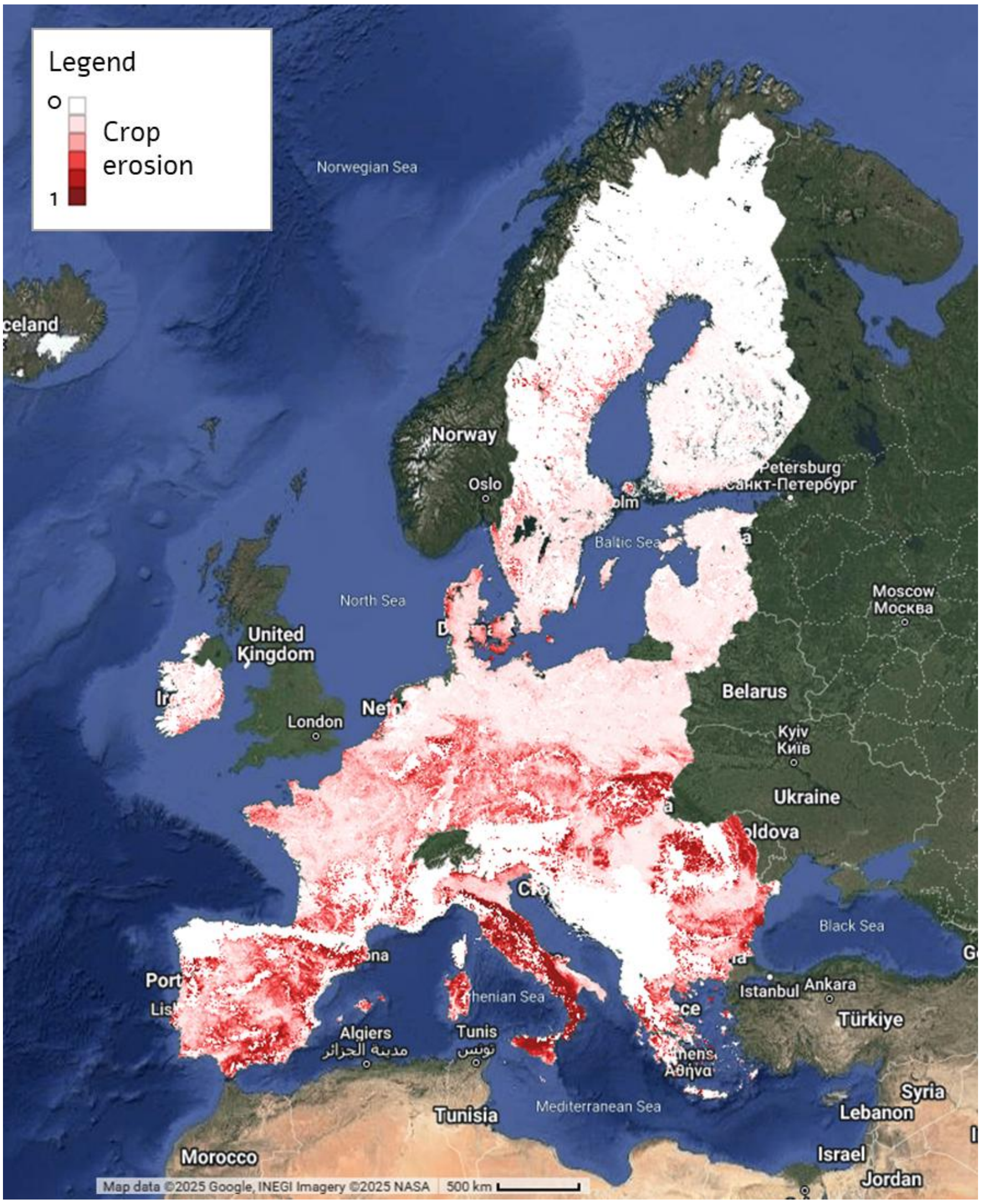
Individuals maps used for the HPI development



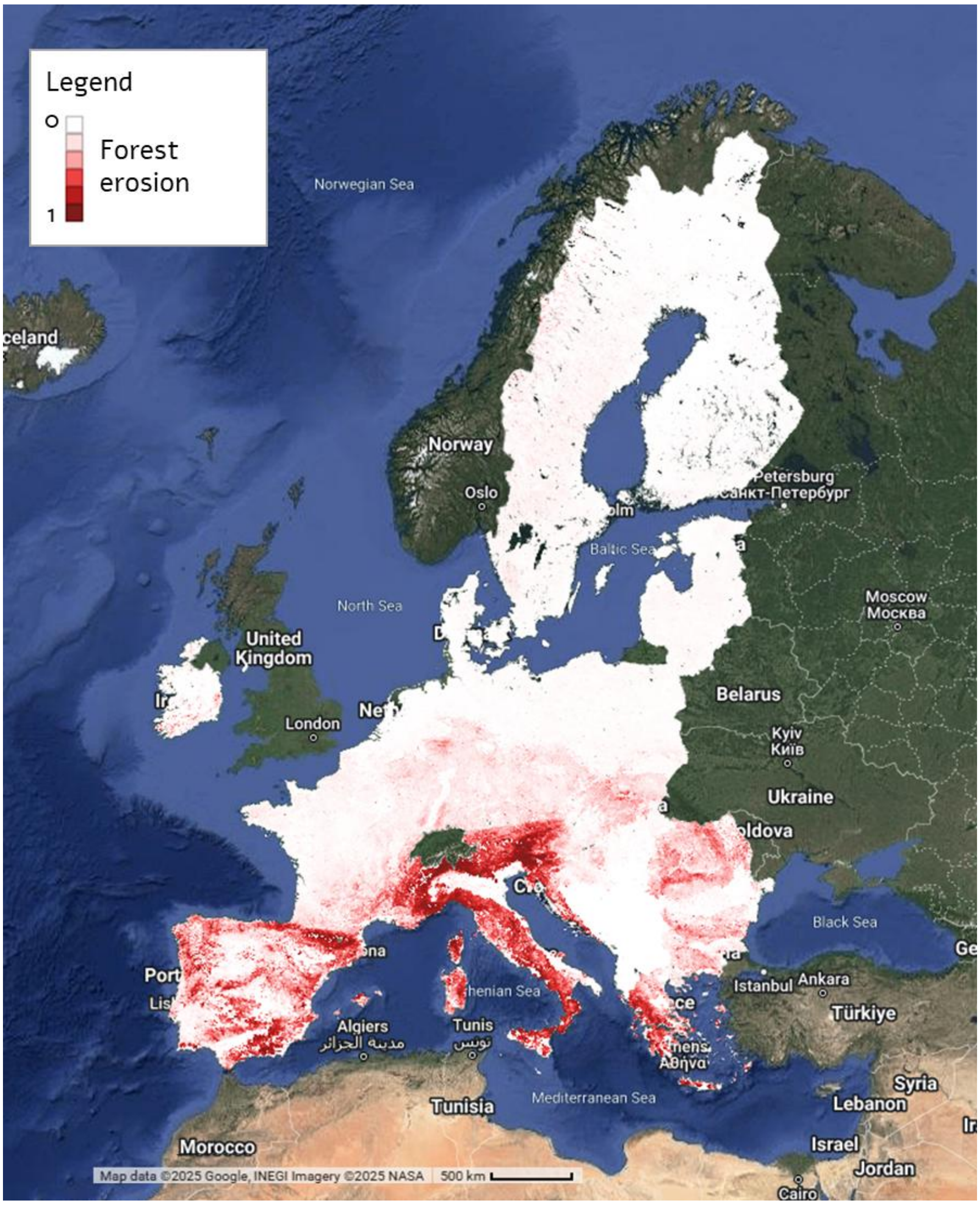
Water Exploitation Index (WEI+)



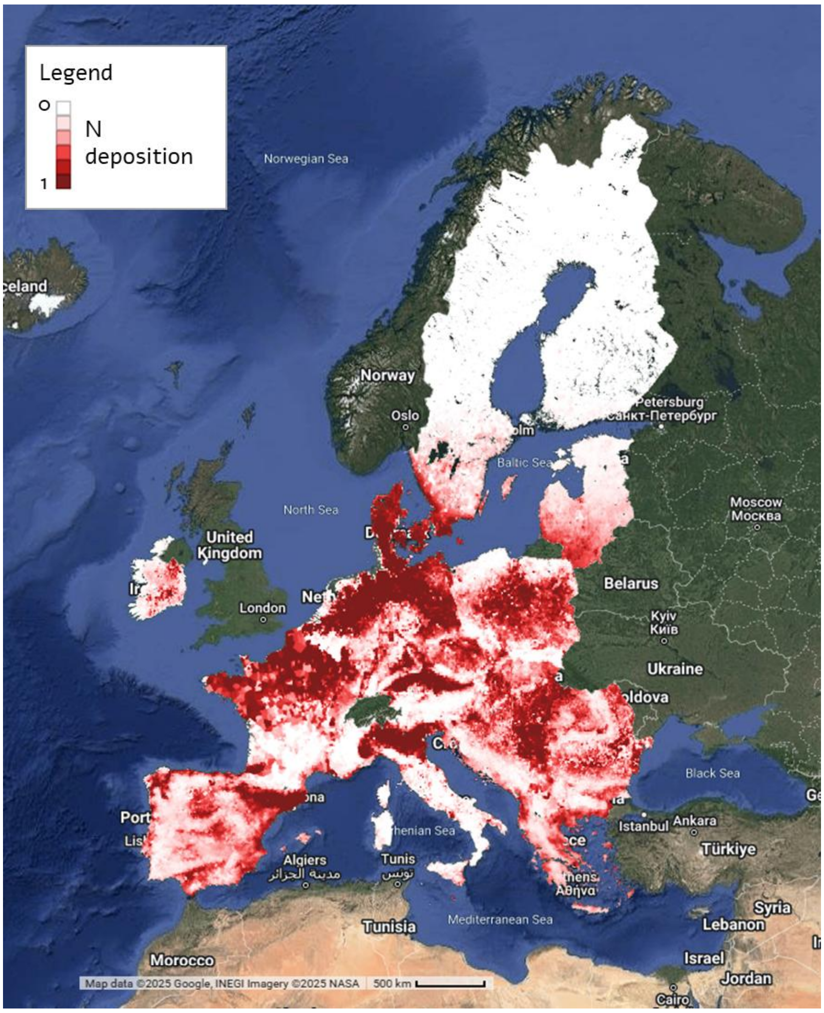
Soil Imperviousness



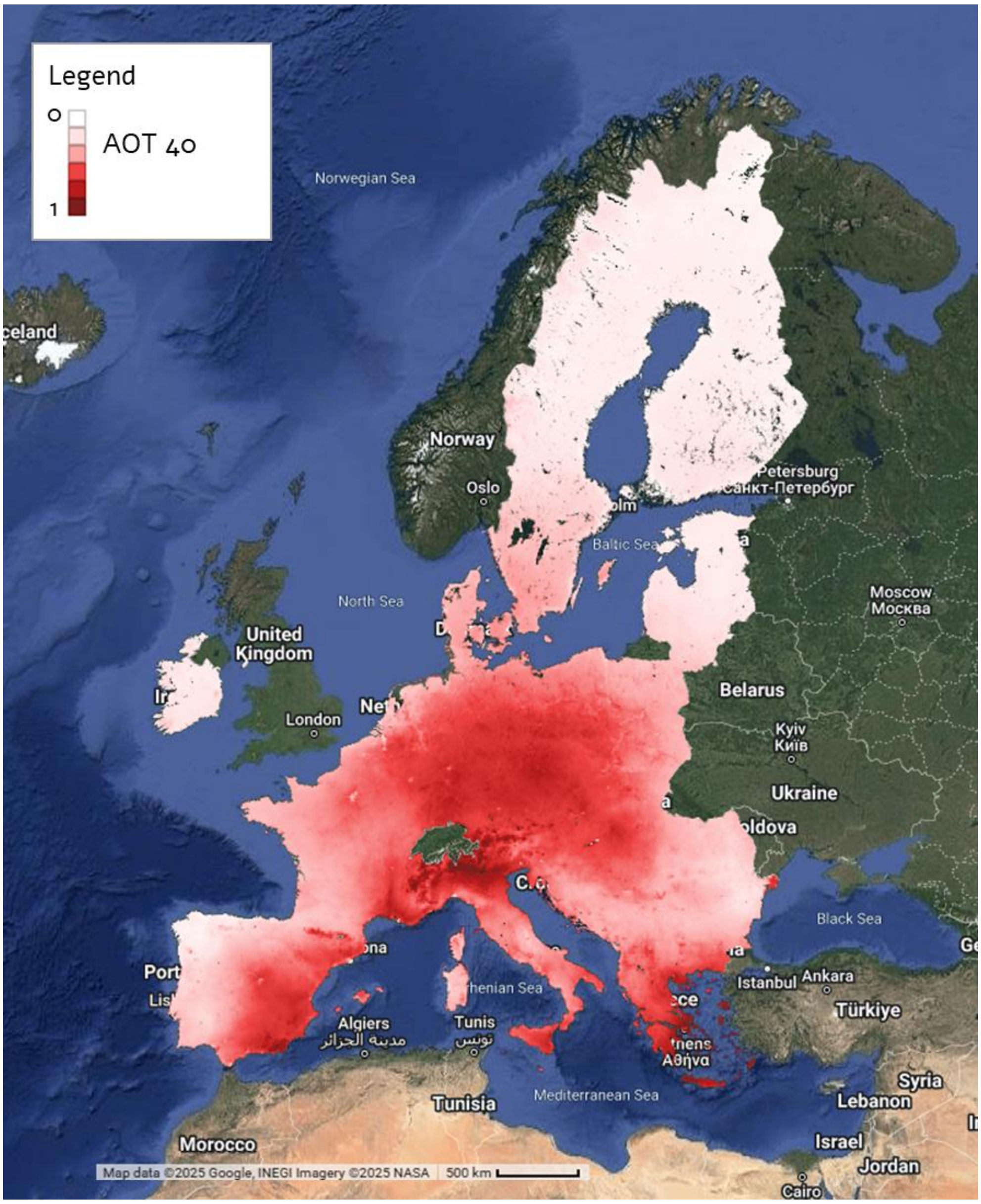
Soil erosion cropland



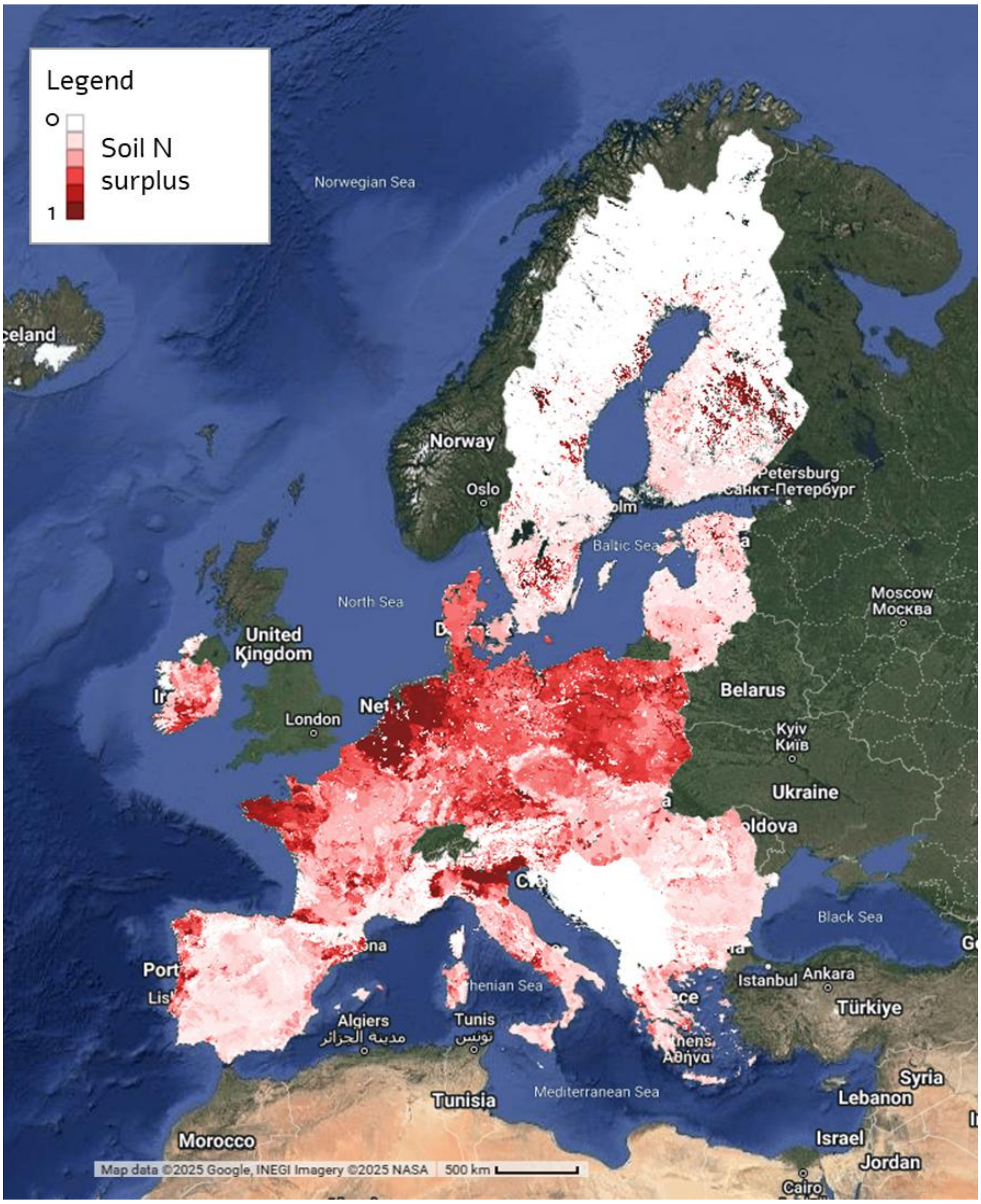
Soil erosion Forest



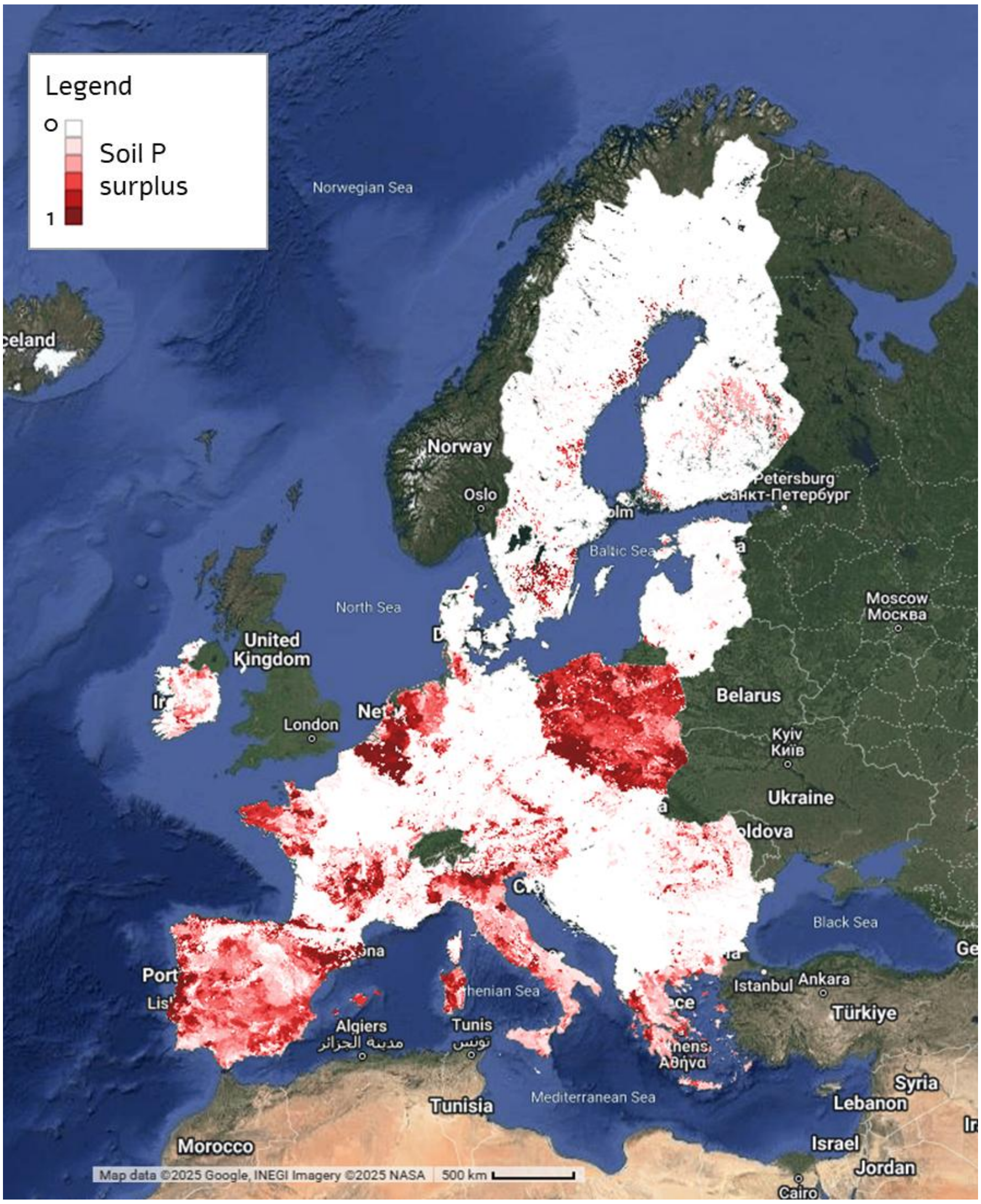
Legend
0
N
deposition
1
Norwegian Sea
Norway
Oslo
North Sea
United Kingdom
London
Baltic Sea
Belarus
Kyiv
Київ
Ukraine
Moscow
Москва
Black Sea
Istanbul
Ankara
Türkiye
Algiers
Tunis
Tunisia
Mediterranean Sea
Morocco
Syria
Lebanon
Israel
Jordan
Cairo
Map data ©2025 Google, INEGI Imagery ©2025 NASA
500 km



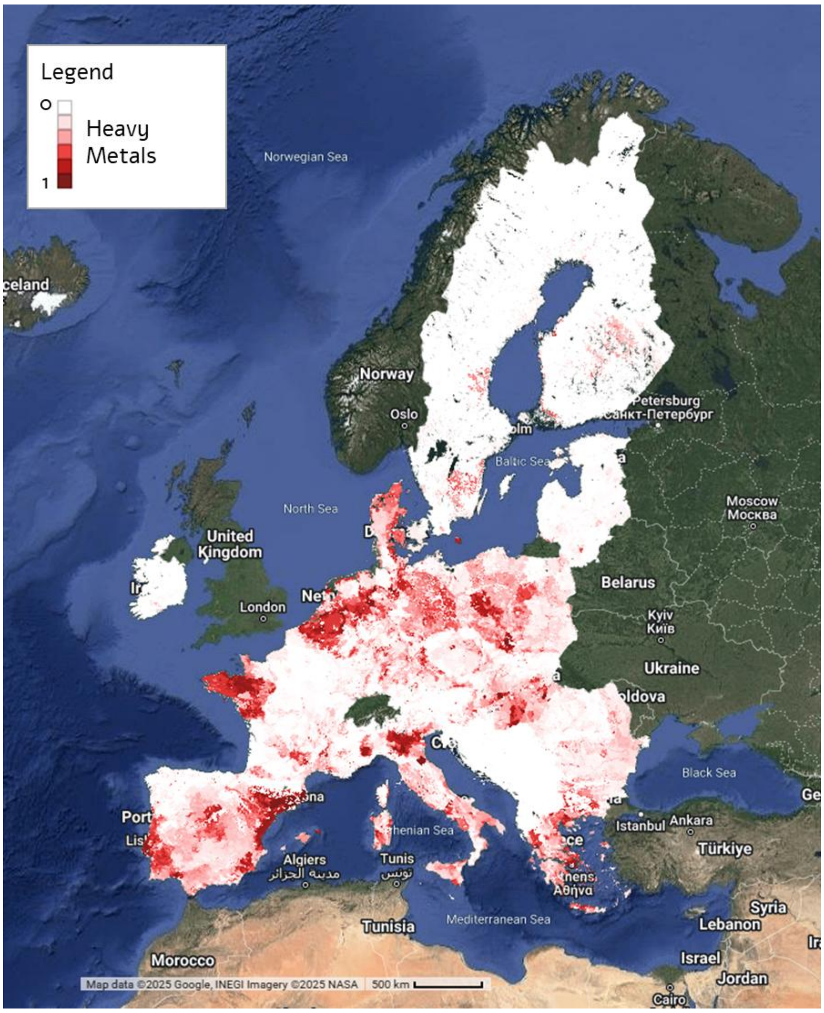
Accumulated ozone exposure for vegetation and crops

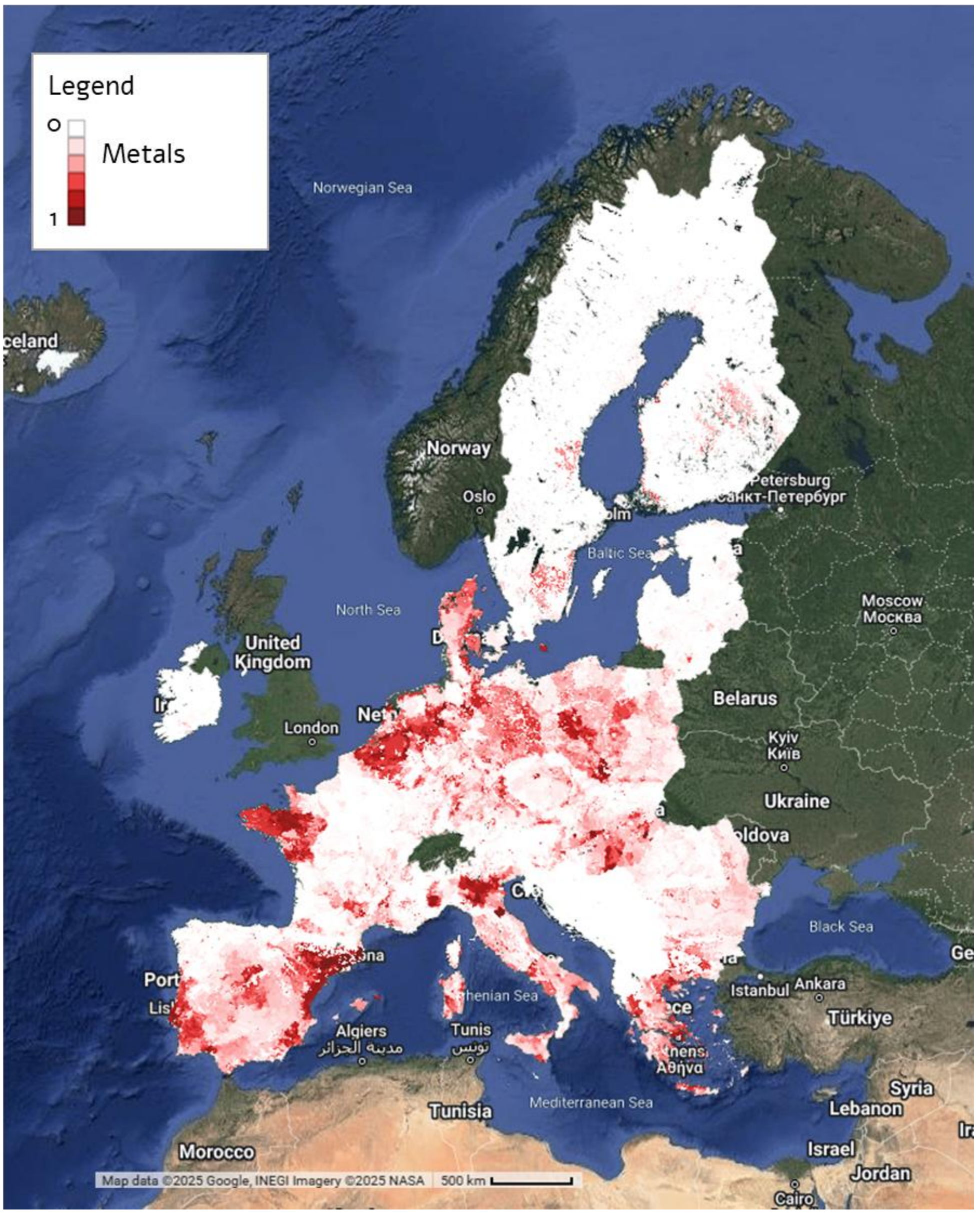


Soil Nitrogen surplus

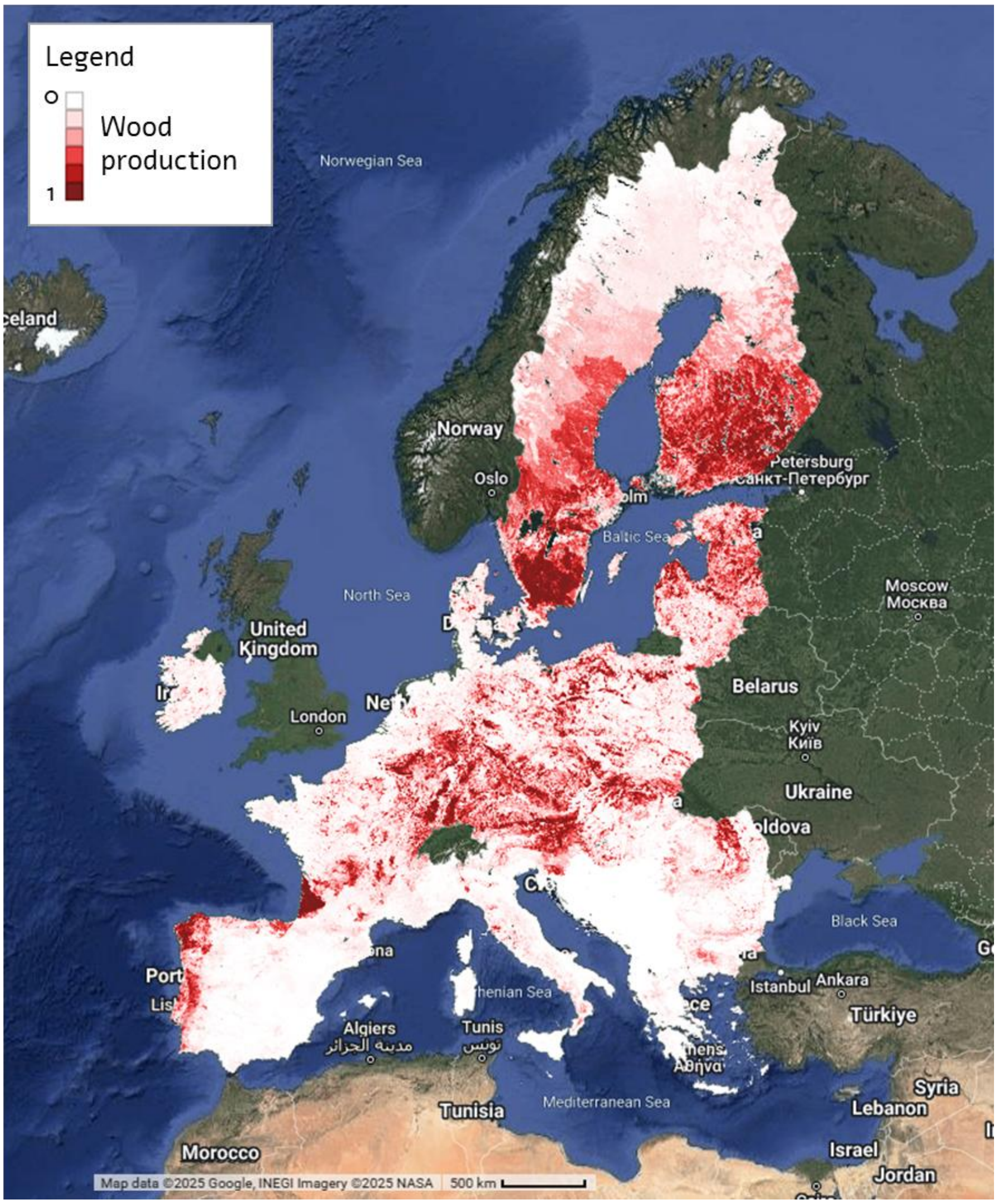


Soil Phosphorus surplus

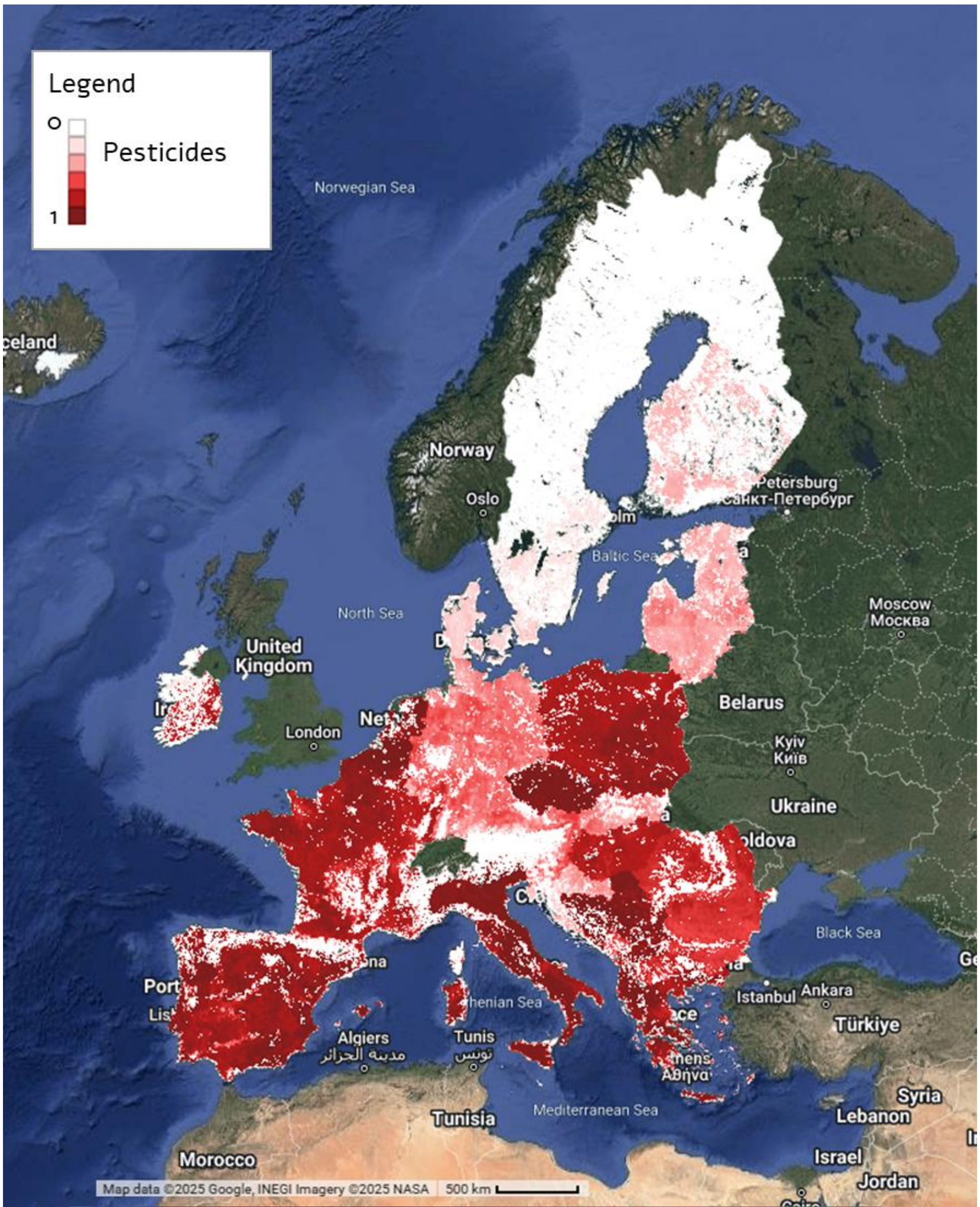

Legend
0
Heavy
Metals
1
Norwegian Sea
Norway
Oslo
North Sea
United Kingdom
London
Baltic Sea
Belarus
Ukraine
Black Sea
Istanbul
Ankara
Türkiye
Syria
Lebanon
Israel
Jordan
Cairo
Mediterranean Sea
Tunisia
Morocco
Algiers
Tunis
Moscow
Москва
Kyiv
Київ
Map data ©2025 Google, INEGI Imagery ©2025 NASA
500 km

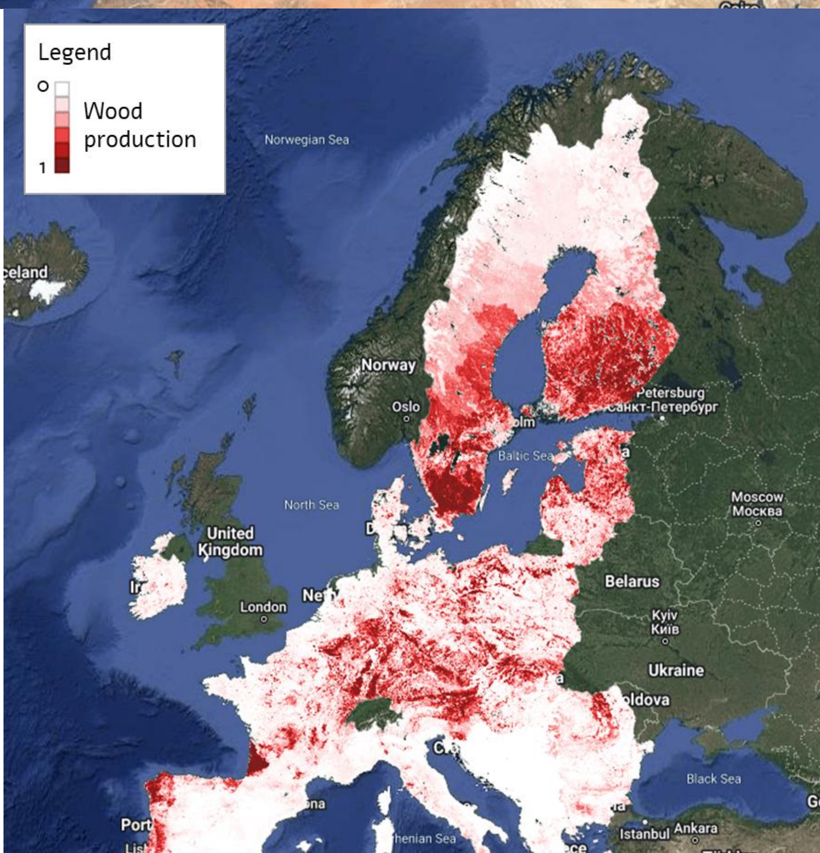


Exceedance of critical inputs of heavy metal in soil

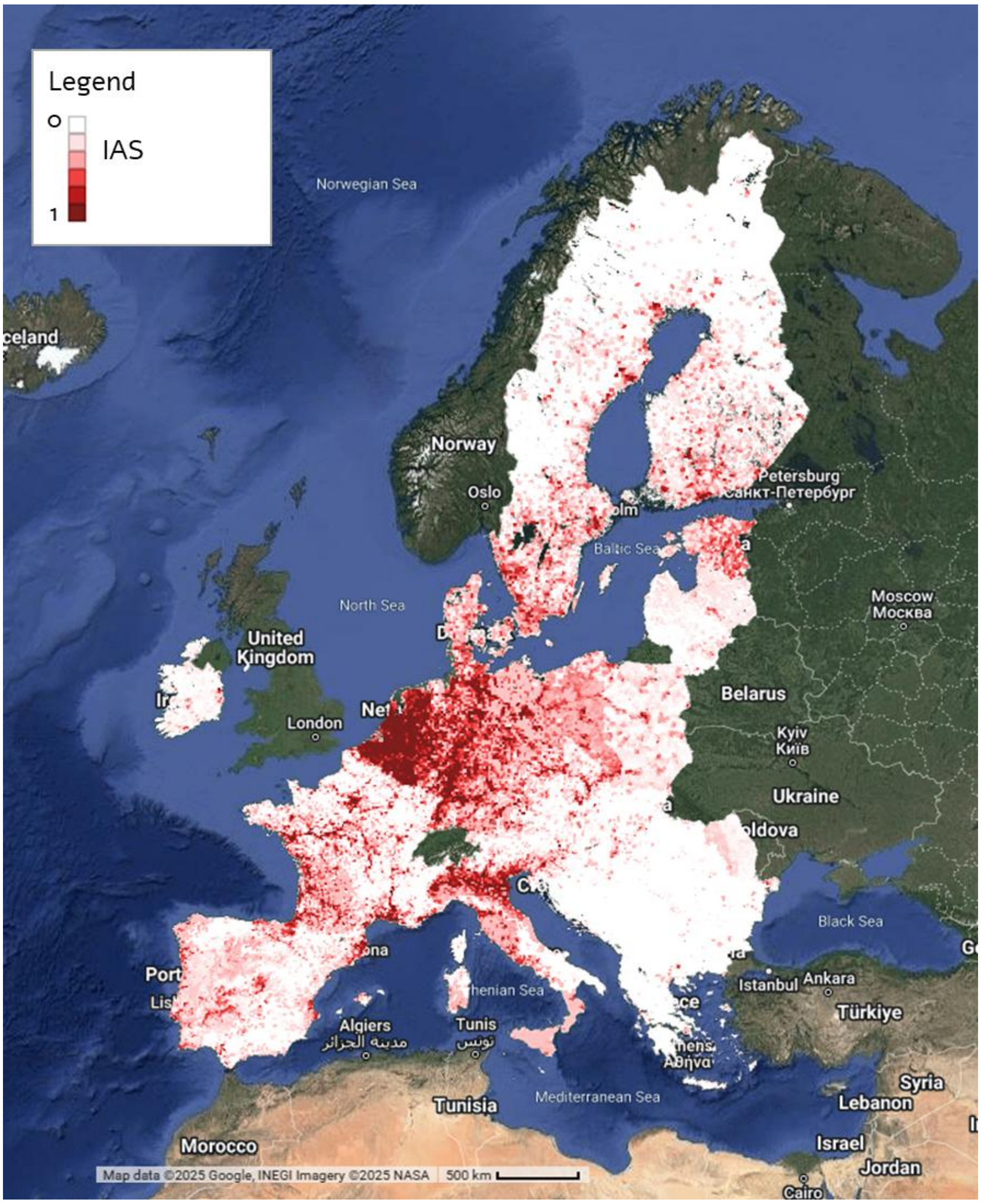


Forest land-use intensity (estimated as wood production)

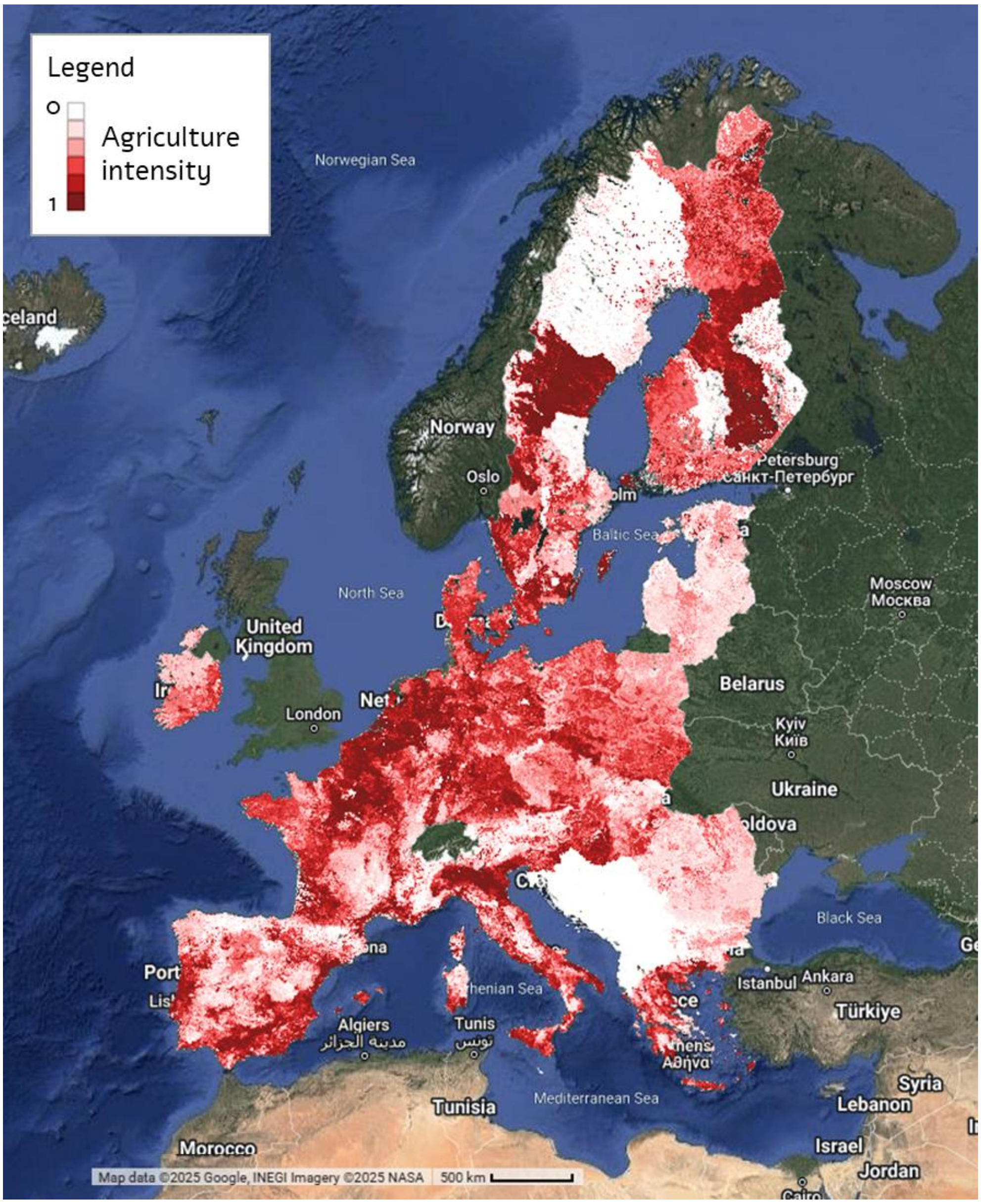

Legend
0
Pesticides
1
Norwegian Sea
Norway
Oslo
North Sea
United Kingdom
London
Baltic Sea
Moscow
Москва
Belarus
Kyiv
Київ
Ukraine
Black Sea
Istanbul
Ankara
Türkiye
Algiers
Tunis
Tunisia
Mediterranean Sea
Morocco
Syria
Lebanon
Israel
Jordan
Map data ©2025 Google, INEGI Imagery ©2025 NASA
500 km


Legend
0
Wood production
1
Norwegian Sea
Norway
Oslo
North Sea
United Kingdom
London
Baltic Sea
Moscow
Москва
Belarus
Kyiv
Київ
Ukraine
Black Sea
Istanbul
Ankara

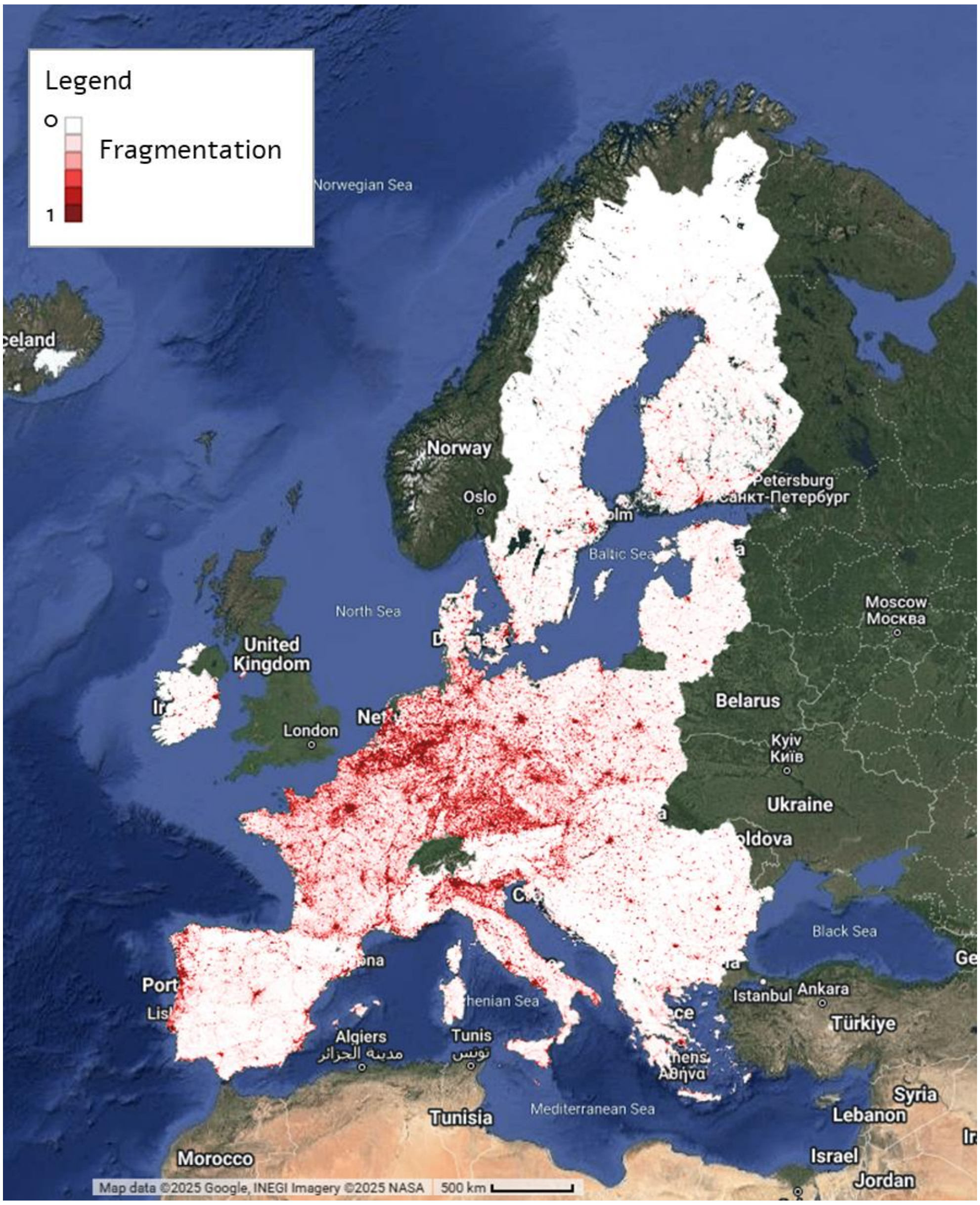
Pesticide risk score



Pressure by invasive alien species (IAS)



Agriculture land-use intensity



Landscape fragmentation