



Research article

Ecosystem extent mapping in a global monitoring context

Polina Tregubova^{a,b}^{*}, Bruno Smets^c, Lars Hein^d, Ioannis P. Kokkoris^e,
 Michela Perrone^f, Vojtěch Barták^f, Jan Komárek^f, Vítězslav Moudrý^f, Ruben Remelgado^g,
 Stefano Balbi^h, Alessio Bulckaen^h, Ian McCallumⁱ, Myroslava Lesivⁱ, Marc Paganini^j,
 Carsten Meyer^{a,b,k}^{**}

^a German Centre for Integrative Biodiversity Research (iDiv), Leipzig, 04103, Germany

^b Leipzig University, Leipzig, 04109, Germany

^c Remote Sensing Unit, Flemish Institute for Technological Research NV (VITO), Mol, 2400, Belgium

^d Earth Systems and Global Change Group, Wageningen University, Wageningen, 6708 PB, Netherlands

^e University of Patras, Department of Sustainable Agriculture, Agrinio, 30131, Greece

^f Faculty of Environmental Sciences, Czech University of Life Sciences Prague, Prague–Suchbát, 165 00, Czechia

^g Agro-Ecological Modeling Group, Institute of Crop Science and Resource Conservation (INRES), University of Bonn, Bonn, 53113, Germany

^h BC3 Basque Centre for Climate Change, Leioa, 48940, Bizkaia, Spain

ⁱ International Institute for Applied Systems Analysis (IIASA), Laxenburg, A-2361, Austria

^j European Space Research Institute (ESRIN), European Space Agency, Frascati, Lazio, Italy

^k Durham University, Durham, DH1 3LE, United Kingdom

ARTICLE INFO

Keywords:

Ecosystem accounting
 Biodiversity monitoring
 Uncertainty assessment
 Classification systems
 Geospatial data
 Remote sensing

ABSTRACT

The vital role of ecosystems in maintaining biosphere stability is now recognized globally. Updates in policy frameworks on biodiversity and environmental decline include information on ecosystem extent (EE) as a core assessment indicator, e.g., the Global Biodiversity Framework indicator A2 ‘Extent of natural ecosystems’. The recently proposed System of Environmental-Economic Accounting – Ecosystem Accounting requires EE as the first pillar for assessing ecosystem condition and, ultimately, ecosystem services. Detailed and up-to-date information on ecosystem characteristics is increasingly achievable due to the unprecedented availability of Earth observation data, combined with advances in geospatial data analysis and high-performance computing, building on a long-established tradition of surface monitoring. However, consistent mapping and delineation of EE remains a challenge. This research aims to identify the role of EE mapping data in nature protection, environmental degradation, and climate agendas, and define components of the usability of geospatial data products as operational solutions. For that, we analyzed global and regional policy frameworks and corporate reporting standards to determine EE-related data needs, alongside bottlenecks shaped by domain-specific challenges, such as thematic complexity of ecosystem definitions, high costs of in-situ monitoring, and demands of data processing workflows to capture dynamic and complex entities. Finally, we translated these findings into a checklist to design policy- and reporting-ready products, covering relevance, thematic coherence, reliability of mapping outputs defined by validation and uncertainty quantification, and transparency of data and methods contributing to the achievement of shared policy targets.

1. Introduction

Ongoing human-driven environmental change entails drastic consequences for people and nature; among them biodiversity decline (IPBES, 2019; Secretariat of the Convention on Biological Diversity, 2022; Myers et al., 2025). Ecosystems are one key component of biodiversity. As fundamental regulators of climate, soil, water, and air quality, ecosystems provide vital services to humans (Wood et al., 2018;

Hein et al., 2020). Being in constant exchange of energy and matter with the surrounding environment, ecosystems are characterized by their conditions and dynamics. Ecosystem extent and condition determine both the capacity of ecosystems to supply services to people, and their resilience to pressures (Moore and Schindler, 2022). Yet, deterioration of ecosystems and the services they supply are observed worldwide (IPBES, 2019).

* Corresponding author at: German Centre for Integrative Biodiversity Research (iDiv), Leipzig, 04103, Germany.

** Corresponding author at: Durham University, Durham, DH1 3LE, United Kingdom.

E-mail addresses: polina.tregubova@idiv.de (P. Tregubova), carsten.meyer@durham.ac.uk (C. Meyer).

Achieving global nature-conservation targets, as defined under the Kunming-Montréal Global Biodiversity Framework (GBF), is fostered by national and regional efforts and necessitates consistent data collection and reporting. For that, the GBF relies on bottom-up national monitoring contributions and engages private sector, as part of impact assessments and reducing the negative effects of industries on nature (Secretariat of the Convention on Biological Diversity, 2022). A recent analysis of operationalizing the GBF's monitoring framework (Affinito et al., 2024) identified critical limitations to tracking progress on biodiversity targets. The most important constraints are data availability and methodological issues in consistent data collation, collection, and processing, hindering reliable assessments from indicators. These problems are amplified by the global extent, diversity, multiscale complexity, and dynamic nature of ecosystems.

The area and geographical distribution of individual ecosystem types – ecosystem extent (EE) – is an entry point for assessing ecosystem condition and functioning, underpinning ecosystem services. Monitoring their persistent change enables assessment of risks of biodiversity loss and ecosystem collapse (IUCN, 2024). Therefore, timely and detailed monitoring of EE is needed (Besson et al., 2022; Affinito et al., 2024).

The increasing availability of Earth observation data, combined with the rapid growth of data-analysis tools and accessible computational environments, makes spatial data applications increasingly widespread, yet still evolving. Spatial monitoring has a long tradition in land cover mapping, supported by a wide range of globally applicable geospatial products addressing different thematic levels and use cases (Buchhorn et al., 2020; Pickens et al., 2020; Brown et al., 2022; Tyukavina et al., 2025). However, EE is distinctly different from land cover. Land cover monitoring is largely defined by surface spectral signatures, which, in turn, reflect biotic composition and its structure, and abiotic surface properties. In comparison to land cover, ecosystems are defined as functional units characterized by complex dynamic interactions of plant, animal, and micro-organism communities and their environment (Secretariat of the Convention on Biological Diversity, 2004). Land cover is unable to capture important ecosystem complexities, as it does not reflect functional patterns or ecological factors (United Nations, 2024). For instance, in land cover data, savanna ecosystems are often misclassified as forests that are perceived as degraded due to sparse vegetation (Abdi et al., 2022). Generally, although land cover can in some cases be closely aligned to a single ecosystem type and thus be used as a surrogate, most land-cover classes represent multiple ecosystem types. Thus, there is a need for ecosystem-oriented monitoring that goes beyond land cover and is better aligned with biodiversity and ecosystem services assessments.

As for ecosystem-oriented solutions, spatial monitoring is a shared focus across many projects and initiatives, either as a direct objective or as a necessary foundation for assessing ecosystem services. Recent efforts (Mazur et al., 2023; Barton et al., 2024; Kokkoris et al., 2024; Webster et al., 2025) have delivered significant advances in mapping a wide range of ecosystem types and characteristics across diverse regions. An important evolution of this work, necessary for meeting global targets, is getting to harmonized, policy-aligned EE time series, compatible over spatial, temporal, and thematic scales (Group on Earth Observations, 2024). This target requires operational, policy-referenced criteria for the data to ensure usability across nature-related applications (Fig. 1).

This paper aims to define EE mapping data needs in intersecting targets in addressing biodiversity decline, environmental degradation, and climate change and translate policy-related demands into practical requirements for EE geospatial products. For that, we provide the following contributions:

1. We analyze relevant policies and corporate standards informed by ecosystem and environmental monitoring to identify the direct and complementary role of EE mapping data in tracking progress on cross-cutting public and industry commitments (Section 3).

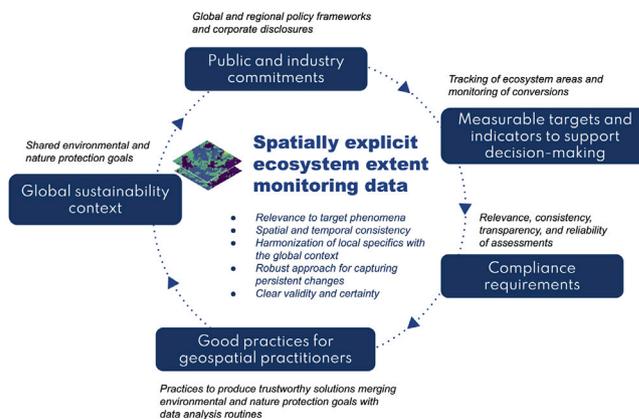


Fig. 1. Conceptual scheme of compliance drivers for ecosystem extent data in a global monitoring context. Global sustainability goals in environmental and nature protection define public and industry commitments, formalized through policy frameworks and obligations in corporate reporting. Corresponding monitoring and decision-making are operated via measurable targets and indicators. Ecosystem extents and their conversions are among the most informative cross-cutting information source, directly and implicitly. Policy demand in relevant, consistent, and reliable assessments defines compliance requirements for geospatial data compilation. In turn, corresponding good practices are yet to be established, considering specifics of ecosystem monitoring.

2. Based on that, we derive essential data quality dimensions that ensure applicability of geospatial products in operational policy-oriented monitoring, and discuss challenges and new opportunities relevant to EE (Section 4).
3. We synthesize these findings into a checklist with targets for data developers to produce policy-compatible outputs (Section 5).

2. Methods

Two central questions guided this research:

1. How do policy-driven applications explicitly require or otherwise leverage EE mapping data to track shared nature and environmental sustainability goals?
2. What needs to be ensured so that EE geospatial products are operationally usable for policy and corporate monitoring and decision-making?

To address these questions, we focused on cross-national commitments featuring operational nature- and environment-oriented monitoring and reporting, covering terrestrial, freshwater, coastal, and marine domains. Thus, we analyzed global policy frameworks and multilateral environmental agreements (MEAs), primarily coordinated under the United Nations (UN), alongside relevant international statistical and methodological standards. The analysis further covers European Union (EU) policy instruments for environmental and biodiversity protection, including those supporting the EU Green Deal and the EU Biodiversity Strategy for 2030 (Table 1).

To evaluate how EE monitoring supports corporate reporting, we analyzed standards of the Global Reporting Initiative (GRI), the Taskforce on Nature-related Financial Disclosures (TNFD), and the European Sustainability Reporting Standards (ESRS). GRI and TNFD are the leading global frameworks guiding companies in communicating their impacts on nature and protection efforts, which is ensured by ESRS at European level (Table 2). Given high development dynamics, we looked for mentions of expected updates to these standards. We analyzed primary texts and official guidance/implementation documents to identify ecosystem-relevant indicators, mandatory disclosures, and

Table 1

Analyzed global and EU policy frameworks and instruments with ecosystem-related operational monitoring and reporting requirements. The table provides acronyms for policy frameworks and instruments used further in the text.

Framework/instrument	Short name	Primary topic	Geography	Framework/instrument type
Kunming-Montreal Global Biodiversity Framework (adopted under Convention on Biological Diversity)	GBF	Biodiversity protection	Global	Policy framework
UN convention to Combat Desertification	UNCCD	Land degradation	Global	International treaty (MEA)
UN framework convention on climate change	UNFCCC	Climate action	Global	International treaty (MEA)
Ramsar convention on Wetlands	Ramsar convention	Wetland conservation	Global	International treaty (MEA)
Sustainable development goals (as targets and indicators)	SDG	Economic and environmental sustainability	Global	Policy framework
UN strategic plan for forests 2017–2030	UNSPF	Forest management	Global	Policy framework
UN environment programme regional seas programme	UNEP RSP	Marine and coastal environments protection	Global	Policy framework
Regulation (EU) No 691/2011 on European environmental economic accounts (as amended by 2024/3024)	Regulation (EU) 691/2011 (as amended by 2024/3024)	Nature capital accounting	EU	Legal act
Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora	Habitats directive	Habitat conservation	EU	Legal act
Directive 2009/147/EC on the conservation of wild birds	Birds directive	Species protection	EU	Legal act
Regulation (EU) 2024/1991 on nature restoration	NRR	Nature restoration	EU	Legal act
Directive 2000/60/EC on water policy (Water Framework Directive)	WFD	Water management	EU	Legal act
Directive 2008/56/EC for community action in the field of marine environmental policy (Marine Strategy Framework Directive)	MSFD	Marine biodiversity protection	EU	Legal act
Regulation (EU) 2018/841 on the inclusion of greenhouse gas emissions and removals from land use, land use change and forestry	LULUCF regulation	Climate action	EU	Legal act
Regulation (EU) 2021/2115 (Common Agricultural Policy)	CAP	Sustainable agriculture	EU	Legal act
System of Environmental-Economic Accounting – Ecosystem Accounting	SEEA EA	Ecosystem accounting	Global	Statistical standard
Intergovernmental panel on climate change guidelines for national greenhouse gas inventories	IPCC guidelines	Greenhouse gas emissions reporting	Global	Methodological standard

the principles underpinning standardized assessments. Specifically, we focused on the following dimensions:

- Mentioning of EE – either directly or through related phenomena, such as land use/cover and habitats,
- Accounting logics or indicator structures,
- Mentioning of a recommended or required ecosystem classification system (typology), and
- Stated requirements for data to ensure applicability in monitoring and decision-making.

Based on the extracted information, we defined the role of EE mapping data in cross-cutting applications and general and specific data requirements.

3. Ecosystem extent monitoring in the policy landscape

3.1. Ecosystem extent as a self-standing monitoring and reporting target and the role of SEEA EA

The complex context of natural capital on a global level needs a robust assessment approach, which is now shaped by the System

of Environmental Economic Accounting - Ecosystem Accounting, or SEEA EA, aiming to inform actions on global nature degradation and environmental change (United Nations, 2024). SEEA EA is a central accounting framework and its principles align with the common accounting structure requiring opening/closing extents and recorded changes.

The Ecosystem extent account, or EE account, is the first core SEEA EA account, as it structures the assessment of ecosystem condition and ecosystem services supply by ecosystem type. For each accounting period, EE data should be shared as the opening and closing extent, with additions and reductions between individual ecosystem types (i.e., net change from one ecosystem type to another), reported in a conversion matrix. Where feasible, changes should be disaggregated into managed and unmanaged ones. Importantly, ecosystems are classified in a mutually exclusive way (United Nations, 2024). This logic underpins indicators and reporting elements aligned with SEEA EA and provides a common basis for other policy-driven spatial-temporal assessments.

The policy demand to include EE in natural capital assessment is global. A major global policy framework, the GBF, requires signatories to report on the state of biodiversity in their territories, explicitly requesting EE information (Indicator A2). This is grounded in the rationale that natural ecosystems enable and sustain the coexistence

and thriving of a wide range of life forms. For reporting, the data on EE should be organized according to SEEA EA (GBF Indicators, 2024). At European level, following biodiversity commitments and environmental objectives, EU Member States shall produce and report ecosystem accounts, including EE, according to the recent amendment of Regulation (EU) 2024/3024, which, again, advises providing measurements based on the SEEA EA (European Parliament and the Council, 2024b). Outside the EU, ecosystem accounting is not yet mandatory in any state, but uptake is advancing. For example, natural capital accounts following SEEA EA have been published by China (National Bureau of Statistics of China, 2021), India (MoSPI, 2021), and Latin American countries, including Brazil, Colombia, Costa Rica, and Peru, among others (GOAP, 2024; Inácio et al., 2025).

In addition to frameworks that require monitoring the full suite of ecosystems, there are also policies targeting particular groups of ecosystems, given their critical role in sustaining life on Earth and the observed large decline in extent. For example, wetlands are targeted by the Ramsar Convention and SDG Target 6.6, requiring monitoring of wetland extent and, where possible, recent change (SDG Indicators, 2025). Another example is forests, targeted by UNSPF and monitored through the Global Forest Resources Assessment. The latter compiles data on forest and other wooded land, with the very first reporting element as “Forest extent, characteristics and changes” (Food and Agriculture Organization of the United Nations, 2023).

3.2. Ecosystem extent data in supporting cross-cutting nature-related targets

A range of international and regional initiatives focused on climate change mitigation, sustainable natural resource management, environmental degradation, and species protection can benefit from spatially explicit information on ecosystem types. In principle, assessing land use impacts mirrors the need for spatial EE data as an informative proxy of patterns and shifts in landscape functioning (Scherzinger et al., 2024).

Greenhouse gas emissions and removals inventories under the Agriculture, Forestry and Other Land Use sector, as defined by the IPCC guidelines supporting UNCCC, quantify anthropogenic emissions from year-to-year changes, driven by land use and management, across forest, cropland, grassland, wetland, settlement, and other lands. In turn, estimation of corresponding carbon stocks is based on ecosystems' composition and functional characteristics (IPCC, 2019). To date, countries are not required to submit carbon stock maps, however, related legislations at national and regional levels increasingly require spatial assessments. For instance, recently revised LULUCF Regulation obliges Member States to implement geographically-explicit annual monitoring supported by detailed spatial datasets. Use of spatial data is expected to raise policy relevance of assessments through the use of the highest-quality data and methods. In turn, spatial data need to accurately capture inventory inputs, including key processes such as deforestation and disturbance, as well as landscape characteristics such as natural ecosystem areas, settlement areas, forest and agriculture patches (European Environment Agency, 2024). Thus, although the mentioned examples are framed around land use and land-use change, demand for spatially and thematically detailed data creates a direct opportunity for integration of EE information. Potential benefits are driven not only by enhanced landscape structural context, but also by contribution to data harmonization, needed to improve tracking of multifaceted Earth system changes.

EE data can inform action on land degradation by providing more details than land cover and land use data. EE can be systematically associated with degradation status linked to composition and condition assessments for individual ecosystem types. Tracking change in EE can help distinguish temporary and persistent changes over the landscape, defining gains and losses (United Nations, 2024). As an example, the UNCCD and corresponding Land Degradation Neutrality target, linked to SDG Target 15.3, practically rely on land-use and land cover monitoring. Corresponding Indicator 15.3.1 operates with

changes in sub-indicators such as trends in land cover, land productivity, and carbon stocks. However, land degradation itself is defined as a loss of ecosystem services. Thus, countries are strongly encouraged to use complementary information because current sub-indicators are explicitly recognized as insufficient to fully capture land degradation processes, while information and consistency lack leads to degradation underestimation (Schillaci et al., 2023; SDG Indicators, 2025). Still, the balance between the complexity associated with a large number of thematic classes and the level of detail required to represent areas of national significance must be ensured (Teich et al., 2025). At the European level, sustainable agriculture and food security are framed by the CAP. Accordingly, agricultural practices should be aligned with environmental protection, biodiversity, and climate action. Currently, the performance of the CAP Strategic Plans is evaluated through a framework operationalized by impact and context indicators (European Commission, Directorate-General for Agriculture and Rural Development, 2024). These indicators include landscape features and land cover as information to support objectives in preserving biodiversity and ecosystem services. Detailed data on EE, both spatially and thematically, could fill the existing gap in a consistent data source bridging landscape features with ecosystem services.

Extent of individual ecosystem types and their composition, structure, function characteristics is a necessary basis for conservation and restoration action, while fine-resolution spatial data enable effective long-term planning and investment (Allan et al., 2022). Documenting EE change is, therefore, critical for the EU Habitats and Birds Directives, the NRR, and, more broadly, the IUCN Red List (Council of the European Communities, 1992; European Parliament and the Council, 2010, 2024a; IUCN, 2024). In coastal and marine domains, the UNEP RSP promotes regional coordination of indicators on the extent and distribution of key habitats, e.g., seagrass meadows, mangroves, coral reefs (United Nations Environment Programme, 2023). Similarly, the MSFD (European Parliament and the Council, 2008) at the EU level requires assessing and monitoring habitat extent and condition under the biodiversity and seafloor integrity descriptors. For inland and coastal waters, EE data can inform the WFD aim to protect the quality of aquatic ecosystems. Related assessments include defining ecological status by surface water body type, including rivers, lakes, transitional and coastal waters, and artificial and heavily modified types, for which geospatial data delineating water bodies are required (European Parliament and Council of the European Union, 2000).

EE mapping thus emerges as a cross-cutting enabler across policy agendas, from climate reporting to conservation planning (Fig. 2).

3.3. Ecosystem extent monitoring as a globally recognized target in corporate reporting

Target 15 of the GBF encourages businesses to assess, disclose, and reduce biodiversity-related risks and negative impacts. In response, widely used reporting standards GRI, TNFD and ESRS (Table 2) provide instruments to organizations to align their activities with global biodiversity goals by assessing and addressing their impacts on ecosystems.

GRI standards (Global Reporting Initiative, 2024) are among the most widely used sustainability frameworks globally, guiding disclosure of economic, environmental, and social impacts, including those related to ecosystems and ecosystem services. TNFD Recommendations (Taskforce on Nature-related Financial Disclosures, 2023) focus on nature-related risks and opportunities, aiming to shift financial flows toward nature-positive outcomes, generating business benefits and strengthening corporate value (Smith et al., 2024). The ESRS operationalizes the Corporate Sustainability Reporting Directive (CSRD) (European Commission, 2023). Companies subject to the CSRD must disclose risks and opportunities related to society and environment, with the ESRS providing reporting guidelines. While primarily focused on information disclosure, these standards also stress actions such as ecosystem restoration as part of broader corporate responsibility.

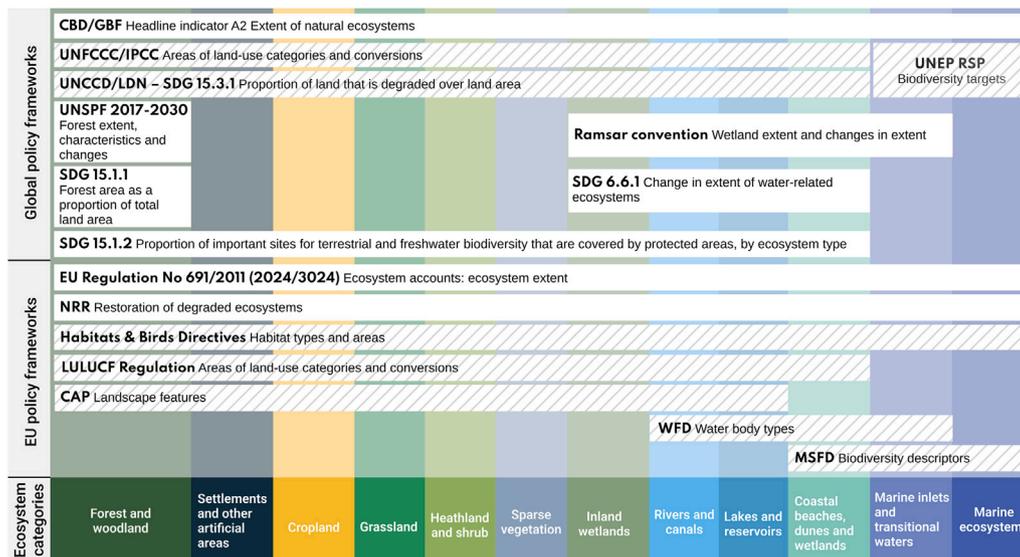


Fig. 2. Contribution of ecosystem extent and ecosystem-extent change data to key global and European policy frameworks. Frameworks for which ecosystem extent data are not yet formally required are indicated by diagonal hatching. Policy acronyms are explained in Table 1. The ecosystem categories shown in the Figure represent the main high-level ecosystem classes used in European ecosystem accounting as an example to illustrate overlapping data needs and applications. It should be noted that each policy framework operates its own classification system, which is discussed further in Section 4.1.

Table 2
Overview of selected sustainability reporting frameworks and standards scoping environmental and ecosystem monitoring.

Corporate initiative family	Target users	Target geography	Specific standards related to EE data
GRI standards	Any organization	Any	GRI 101: Biodiversity 2024
TNFD	Any organization	Any	Recommendations of the Taskforce on Nature-related Financial Disclosures
NPI	Any organization	Any	NPI 1 and 2 metrics
ESRS	Companies under the Corporate Sustainability Reporting Directive (CSRD)	EU (primarily)	ESRS E4 Biodiversity and ecosystems

All three frameworks acknowledge ecosystem monitoring, however, they differ in scope: GRI offers broad sectoral applicability with explicit biodiversity disclosures; TNFD embeds it in risk–opportunity assessments for investors; ESRS integrates ecosystem monitoring more tightly into mandatory EU sustainability reporting. These differences create overlaps and gaps that practitioners must navigate. A consolidated pathway for addressing these inconsistencies is increasingly framed by the emerging Nature Positive Initiative, NPI (Nature Positive Initiative, 2024; Luxton et al., 2024), aimed at linking together standard setters, businesses, and conservation organizations, to achieve the global goal to halt and reverse biodiversity loss by 2030 set by GBF.

When nature-related impacts are material, i.e., significant for the environment and/or financially significant for the company, they must be measured and reported to provide both qualitative and quantitative insights for monitoring and mitigating the ecological footprint. With that, all frameworks recognize monitoring of EE and corresponding change as a core of impact assessments and restoration actions. In all cases, EE definitions correspond to spatial area of a specific ecosystem type and compatible with SEEA EA.

In the GRI, EE is directly required by the new GRI 101:Biodiversity 2024 standard as part of the disclosures on natural ecosystem conversion as one of the direct biodiversity loss drivers, and on biodiversity state changes themselves. Thus, the ecosystem type before conversion, after conversion, and the converted area shall be reported, similarly applicable for intensively used or modified ecosystems. Current sector standards (Oil and Gas sector, Coal sector, Agriculture, Aquaculture and Fishing Sectors, and Mining sector) all contain biodiversity as a material topic and are being revised to align with GRI 101:Biodiversity 2024 (Global Reporting Initiative, 2024; Global Sustainability Standards Board, 2025).

Under the TNFD, EE shapes one of the core global disclosure metrics and the corresponding indicator “Extent of land/freshwater/ocean-use change”, alongside the disclosures on impacting activities, and area conservation, restoration, or management status. As part of core disclosure metrics, this indicator is relevant to the majority of sectors and, therefore, is incorporated into general or cross-sector standards (Taskforce on Nature-related Financial Disclosures, 2023).

Disclosure Requirement E4-5 of ESRS “Impact metrics related to biodiversity and ecosystems change” calls for measuring the area of particular ecosystems. Thus, material impacts on biodiversity and ecosystems (especially in or near biodiversity-sensitive areas) should be disclosed through metrics that reflect changes in EE and condition, for example, the area of natural, semi-natural, or artificial ecosystems affected, converted, or restored due to the undertaking’s operations or value chain activities (European Commission, 2023).

Within NPI, a set of State of Nature Metrics has been designed for integration across various disclosure frameworks. Ecosystem Extent (Change and Classification) is defined as the first indicator (Nature Positive Initiative, 2024). Currently, this initiative is in a pilot phase, testing the metrics applicability with companies and financial institutions.

All frameworks advise following SEEA EA as an assessment approach. Ongoing developments in corporate reporting indicate that companies will increasingly need spatial data to quantify and disclose impacts.

4. Applicability of geospatial products for operational policy-oriented ecosystem extent monitoring

As the importance and applications of EE data are defined, detailed maps are the most significant source of information. The question, therefore, is: what makes geospatial data compatible with policy use?

The GBF Indicator A2 broadly requires maps of ecosystem types using appropriate ecosystem classifications and time-series maps showing changes in EE, however, supporting data-compilation guidelines are to be developed (GBF Indicators, 2024). At the same time, the SEEA EA framework communicates more explicitly expectations about data quality. Furthermore, IPCC Guidelines and requirements to Essential Climate Variables operating well-established fields of land use and land cover monitoring, closely related to EE, provide more detailed principles of data compilation (IPCC, 2019; World Meteorological Organization, 2022). Thus, operational data should ensure relevance, accuracy, consistency, reliability of assessments, and support transparency of evaluation process and outcomes (United Nations, 2024). For data developers, all of these aspects present both challenges and new opportunities linked to the complexity of ecosystem monitoring.

4.1. Thematic relevance over the diversity of definitions of ecosystem types

Given ecosystems' multi-scale differences in composition, structure, and functioning, monitoring of different ecosystem types depends heavily on classification. While specifying ecosystem definitions is a fundamental first step, the local knowledge embedded in national and regional typologies also needs to be aligned with a global context. Furthermore, consistency in definitions is necessary for cross-jurisdictional comparison of assessments and for aggregating them to global level time series to track progress on shared targets in nature conservation. To enable this, the Global Ecosystem Typology by International Union for Conservation of Nature (IUCN GET) was proposed, defining ecosystem types hierarchically, based on dominant ecosystem processes and key biotic and abiotic properties (Keith et al., 2020). IUCN GET has six levels, the most relevant one from an international policy perspective being Level 3, called 'ecosystem functional groups'. These are groups of related ecosystem types, defined within a biome, that share common ecological drivers and ecosystem properties. Finer levels of IUCN GET, 4 to 6, are designed to incorporate specific local knowledge on ecosystem compositional properties. Thus, while remaining within the global classification system, these levels can be aligned with targets at national or subnational levels, ensuring consistent tracking of ecosystems and species under threat of extinction (IUCN, 2025). IUCN GET is focused initially on natural ecosystems, but efforts are underway to further define strongly human-modified ecosystems.

For tracking EE, SEEA EA suggests that countries either use IUCN GET Level 3 or a national classification supported with a cross-walk to IUCN GET (IUCN, 2025), and, consequently, the same is advised under observed corporate standards (United Nations, 2024). Accordingly, IUCN GET Level 3 is proposed for reporting under the GBF (GBF Indicators, 2024). Currently, there are 110 ecosystem functional groups, including 98 (semi-)natural and 12 anthropogenic classes.

As the IUCN GET is still new and supports limited disaggregation to local environmental and operational contexts, regional/national typologies continue to complement it. For instance, the EU ecosystem typology was developed by Eurostat (2024) for use in ecosystem accounting across Europe. To ensure relevance to ecosystems of EU countries while also facilitating international comparisons, the classes of EU ecosystem typology are broadly aligned with the MAES ecosystem typology and the EUNIS habitat classifications, and are organized into a hierarchical structure at three levels. Currently, Member States shall report EE at Level 1 of EU ecosystem typology, including 12 natural and human-influenced ecosystem categories (Fig. 2), with the first reporting year 2024. A crosswalk is available to translate the EU classes to IUCN GET Level 3, the reporting classes proposed in the SEEA EA.

Alignment of EE with cross-cutting reporting targets requires thematic harmonization. Specifics of the data supporting climate-related, nature, and land-management monitoring are defined by use of generally broader classes and importance of land management (IPCC, 2019). Additionally, monitoring and reporting for ecosystem-oriented policies, may operate their own classification systems, beyond already

mentioned, such as, for instance, wetland inventories under the Ramsar Convention (Ramsar Convention, 2019), or forest-extent monitoring under the Forest Resource Assessments supporting UNSPF, UNCCD, SDG targets and GBF (Food and Agriculture Organization of the United Nations, 2023). Both examples incorporate land management information. However, for assessments based on target indicators, ecosystem characteristics, reflecting ecosystem composition and functioning, are also required, as discussed in Section 3.2. As EE data can serve as a more detailed form of land cover and land use data (United Nations, 2024), preserving land management and ecosystem characteristics information is the foundation for thematic harmonization, contributing to the consistency of cross-cutting assessments.

On a national level, ecosystem monitoring may use its own classifications, capturing the local context and perception of influencing factors. Direct translation of local classes to classes of regional and global frameworks can be limited because of different thematic resolutions and lack of information needed to unambiguously establish the relationships between the concepts listed in the different classifications. This results in "one-to-many" or "many-to-many" crosswalk choices or even complete absence of potential fit (Sprague and Wiser, 2024). A general approach to overcoming this challenge, as proposed in recent guidelines for cross-referencing ecosystem classifications to IUCN GET, is detailed documentation of diversified ecosystem properties (IUCN, 2025). Whereas this requires significant effort in additional data mobilization, it opens a path to filling EE data needs across different domains and scales, enabling robust and consistent harmonization.

4.2. Accuracy of mapping products

Map accuracy assessments are particularly important in the policy context and are defined as a validation procedure. Validation is a concise measurement of the quality of classified maps based on their comparison against independent reference data (Justice et al., 2000). Validation thus enables quick evaluations of data product errors, enhancing the reliability of assessments for a given application. Therefore, the accuracy of geospatial products used for policy purposes is expected to be documented, although not specified as numeric thresholds (IPCC, 2019; United Nations, 2024; IUCN, 2024; Teich et al., 2025).

Approaches to validation of spatial monitoring data are extensively described in the recently updated Good Practices Protocol for land cover maps (Tyukavina et al., 2025). These guidelines discuss product maturity stages based on the provided accuracy assessments. Without validation, a map can be considered only as a prototype and not a product applicable for decision-making. More mature versions differ based on the statistical soundness of the validation design, and on enabling regular updates of accuracy assessment for time-series releases. Based on these principles, in the best-case scenario, mappers should plan for independent validation following probability-based sampling to calculate and report class-specific accuracy, and consequently, estimate class areas and corresponding uncertainties, as well as extend accurate assessments for new map versions. While designs of sampling campaigns are established, the main limitation is the reference data.

To ensure robust validation, high-quality reference data are essential. At a minimum, these must comprise all target classes, be regionally representative to avoid bias (Skakun, 2025), and include site-level and temporal descriptions. *In-situ* observations (e.g., vegetation plots) following standardized monitoring schemes and on-site vetting by thematic experts are often preferred. However, collecting these data is time-consuming and costly, demanding extensive consultations with local experts, and sometimes cross-checking with historical reports, to assure cross-scales consistency (Xu et al., 2024). To reduce costs, visual interpretations of high-resolution imagery may be a solution, but carries its own caveats. These data require thorough quality checks and advanced contextual knowledge, making the image-interpretation process susceptible to biases. Alternatively, Volunteered Geographic

Information may be used. These data originate from various measurement tools (e.g., surveys, social media), and are created, assembled, and shared for public use, both by professional and citizen scientists, enabling growing reference-data pools (See et al., 2025). Yet, such observations unlikely follow a probabilistic sampling design, requiring specialized models to enable their meaningful use for validation and careful standardization of information to gather (Stehman et al., 2018).

Accuracy assessments of EE and related mapping products, including time-series, have traditionally focused on validating the thematic accuracy of pixel values. From a monitoring perspective, however, temporal consistency and accuracy of pixels' time-series are even more important, as they determine the comparability of data between years and the reliability of inferred changes. Nevertheless, temporal accuracy and consistency assessments remain challenging due to comparatively underdeveloped protocols and the global rarity of reference data suitable for validating changes, even for small number of classes (Xu et al., 2024).

Thematic consistency is another dimension of data accuracy, which brings advanced challenges in the conceptually complex domain of ecosystem monitoring, where terminology and methodologies can vary depending on acquisition purposes and authorities. For instance, thematic inconsistencies in field-based ecosystem mapping can reach up to 51% (Naas et al., 2023). A significant barrier to cross-product comparability arises from the use of different thematic legends and definitions for similar classes, such as "wetland" and "flooded vegetation" (Wang et al., 2023). As standardized guidelines for collecting reference data for EE mapping are yet to be developed, again, an envisioned data-collection protocol could involve documentation of both species and environmental factors, to describe a more detailed ecological context.

Validation is a critical component for a data product to be considered suitable for operational use. Here, described practices from the long-established field of land-cover monitoring are, as well, relevant for the development of EE products. It can be expected that substantial efforts need to be invested in establishing routines defining consistent and continuously updated reference data collection, as well as their actual acquisition. Following the very definition of ecosystems as natural bodies, accompanying information on environment, biotic communities, structure, and functioning is important to document to ensure multiscale thematic consistency. Organizing sustained global networks of calibration and validation sites, as previously done for land cover, is thus equally important for EE monitoring.

4.3. Reliability of mapping products built on imperfect data with imperfect models

Geospatial products, though providing spatially explicit information, are built on imperfect data and modeling techniques. This extends validation to the estimation of uncertainty, defined as a parameter associated with a measurement that characterizes the dispersion of values that could reasonably be attributed to it (JCGM (2012)). Uncertainty arises from aleatoric sources (natural variability, not manageable) and epistemic sources (limited knowledge, potentially reducible) (Hüllermeier and Waegeman, 2021). Both need to be communicated, either through measurement or description.

Policy frameworks set clear expectations for uncertainty estimation. For example, the IPCC guidelines emphasize not only the measurement of uncertainty but also call for the use of data suitable for understanding uncertainties, and the LULUCF Regulation echoes this demand (European Environment Agency, 2024). The UNCCD/LDN emphasizes documenting uncertainties, including those arising from generalizations used to harmonize national data with international standards (United Nations Convention to Combat Desertification, 2022). The IUCN Red List of Ecosystems requires documentation of uncertainties in ecosystem risk assessments, including those related to mapped distributions (IUCN, 2024). Following IPCC principles, assessors should evaluate evidence type, quality, and consistency; assess agreement

among sources; estimate the likelihood of alternative outcomes; and report both the most likely result and plausible bounds. Across these cases, reporting uncertainty is essential for transparency, reproducibility, and credibility of spatial assessments using both Earth observation and other data sources.

Requirements for land cover products as Essential Climate Variables treat uncertainty as part of the validation process, expressing it in terms of omission and commission errors and error in area estimates, with 95% confidence intervals (World Meteorological Organization, 2022). This aligns technical evaluation with policy needs by quantifying both classification performance and errors in area estimates. A step further involves shifting from uncertainty quantification for aggregate areas to spatially explicit uncertainty measures.

Data-driven approaches produce confidence scores alongside predicted classes, but these reflect model choice rather than real-world accuracy: a model may be confident but incorrect, or unconfident and correct (Guo et al., 2017). Yet, for practical choices based on spatial planning, one needs to know how the map actually reflects real-world distributions. Spatially explicit evaluation of the model performance against reference data can be a solution (Valle et al., 2023).

Uncertainty reporting is thus essential. At minimum, products should provide area estimates with confidence intervals, class-wise omission/commission errors, and document main uncertainty contributors such as data limitations, thematic coherence, mapping choices, and harmonization steps. This makes outputs interpretable and auditable, while extending quantification to the pixel level supports more robust spatial planning.

4.4. Challenges in capturing ecosystem extents from spatial monitoring data

Earth observation data currently serves as the primary, most important, and powerful source for producing classified products for environmental and ecosystem monitoring (Brown et al., 2022, 2025; Kokkoris et al., 2024). However, satellite-based mapping faces limitations when it comes to fine ecosystem distinctions.

First, the accurate classification of Earth observation data is limited due to ambiguous spectral signals, sensor constraints, and poor capture of ecosystem functional patterns, as ecosystem functioning is driven by multiple influencing factors, as discussed earlier. The ambiguity of spectral signals impedes remote monitoring of transitional areas due to factors like seasonality, requiring additional environmental context (Murray et al., 2022). Another example is mapping of subtidal seagrass where detection from remote sensing data is limited by light attenuation, turbidity, sunglint, and sea surface roughness, so complementary data (e.g., high-resolution bathymetry) are needed (Roca et al., 2025). Furthermore, for some ecosystem types, integrating socio-economic context, such as land-use history or management data, is required. This is the case for human-influenced/semi-natural ecosystems or when distinguishing between managed and unmanaged changes (Yin et al., 2021; Fassnacht et al., 2024).

Second, whereas Earth observation data are increasingly vast and open access, there are still limitations in data coverage, quality, spatial and temporal resolution, and required data volumes (Kokkoris et al., 2024). In terms of spatial resolution, again, transitional zones and fragmented areas such as urban greenspaces or naturally complex landscapes, in principle, require higher resolution imagery for the assessments (<5 m/pixel), available mostly from commercial products (Guo et al., 2023; Hong et al., 2024). On the other hand, Earth observation data may fall short in adequately representing target phenomena due to limitations in temporal resolution. For instance, weather conditions may limit monitoring from open-source data from passive sensors due to irregular clear-sky observation frequencies, especially for northern latitudes and regions subject to seasonal rainfall (Rahimi and Jung, 2024).

Acknowledgment of these limitations is required in data-production efforts. Solutions lie in approaches that enrich spatial context, enhance data coverage, and capture influencing factors, both

natural and anthropogenic, which are fundamentally important for ecosystem monitoring (de Koning et al., 2023; Brown et al., 2025). Using more diverse information sources, however, adds hurdles related to storage, management, and processing.

5. Conclusions and recommendations

EE is recognized as one of the core indicators required by biodiversity conservation policies while also serving as an important information source for sustainable resource management and climate action. While demand for detailed, up-to-date EE data is growing, geospatial products should satisfy important criteria to be policy-compliant. Importantly, although current policy and corporate standards still permit entry-level monitoring and reporting based on coarse or aggregated inputs (both thematically and spatially), a shift toward greater detail is expected, as already evidenced by evolving guidance for climate-related inventories. Taking that into consideration, we provide the following summary of targets for geospatial data-product developers:

- The product should correctly represent the dynamic, multiscale diversity of ecosystems and be suitable for identifying persistent change between ecosystem types.
- It should allow building summary information in form of opening and closing extents for reporting periods, and track both additions and reductions.
- It should be accompanied by sufficient information to distinguish between managed and unmanaged changes.
- It should be supported by information that enables cross-walks between local and global/regional typologies used in ecosystem-oriented and cross-cutting policy frameworks (e.g., such as IUCN GET, EU Ecosystem Typology, and categories of land use, and others).
- It should be built using well-described, reliable, up-to-date data sources with sufficient spatial resolution (e.g., certain ecosystem types and transition areas require spatial resolutions <5 m/pixel).
- It should be supported by a detailed description of the used methods to gather, process and produce the data.
- To be applicable for monitoring, it should be supported by an accuracy assessment through independent validation of both areas and changes and the communication of corresponding uncertainties.
- To be applicable for spatial planning, it should be supported by spatially explicit uncertainty quantification.
- It should allow further refinement through preservation of local context (e.g., as ensured by engaging local communities).
- It should contribute to global commitments by making data, including ground-truth, openly accessible and adhering to FAIR and CARE principles.

Each point implies a direction for new processing tools, but technical progress depends on input data, methods, and infrastructure, all of which have their specifics in the context of EE.

Lack of ground-truth observations remains the main bottleneck for EE monitoring. Along with reliable georeferencing and thematic assignment, it is essential to support ground-truth observations with richer contextual information. Earth observation data is the main input for classified maps, providing readily available spatial details at 10–30 m resolution. Yet, often, delineating ecosystems requires even finer resolutions. Moreover, even at coarse thematic levels, some ecosystems cannot be reliably delineated without socio-economic context (e.g., land management) or environmental conditions. Identifying the origin of changes, likewise, requires such information. This calls for context-aware, multi-modal data integration, thematic harmonization, and sufficient infrastructure to support large-scale processing.

Ultimately, EE data sit at the intersection of ecological knowledge, data analysis, and policy practice. Stronger alignment across these domains is essential for EE monitoring to move from a technical task to a practical foundation for coordinated global action on biodiversity, climate, and resource management.

CRediT authorship contribution statement

Polina Tregubova: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Bruno Smets:** Writing – original draft, Project administration, Methodology, Funding acquisition, Conceptualization. **Lars Hein:** Writing – original draft, Conceptualization. **Ioannis P. Kokkoris:** Writing – original draft, Conceptualization. **Michela Perrone:** Writing – original draft, Investigation. **Vojtěch Barták:** Writing – original draft, Investigation. **Jan Komárek:** Writing – original draft, Investigation. **Vítězslav Moudrý:** Writing – original draft, Investigation. **Ruben Remelgado:** Writing – original draft, Conceptualization, Funding acquisition. **Stefano Balbi:** Writing – original draft, Funding acquisition, Conceptualization. **Alessio Bulckaen:** Writing – original draft, Conceptualization. **Ian McCallum:** Writing – original draft, Methodology, Funding acquisition, Conceptualization. **Myroslava Lesiv:** Writing – review & editing. **Marc Paganini:** Writing – original draft, Resources, Methodology. **Carsten Meyer:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization.

Permission to reproduce material from other sources

No material was taken from other sources that need permission to publish.

Consent to publish

All authors consent to publish.

Funding

The research and preparation of this paper was supported by the World Ecosystem Extent Dynamics project, funded by the European Space Agency (ESA) (Contract Number: 000144495/24/I-NS) and the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy – EXC 2070 – 390732324.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data were used to conduct the research is openly available.

References

- Abdi, A.M., Brandt, M., Abel, C., Fensholt, R., 2022. Satellite remote sensing of savannas: Current status and emerging opportunities. *J. Remote. Sens.* <http://dx.doi.org/10.34133/2022/9835284>.
- Affinito, F., Williams, J.M., Campbell, J.E., Londono, M.C., Gonzalez, A., 2024. Progress in developing and operationalizing the monitoring framework of the global biodiversity framework. *Nat. Ecol. Evol.* 8 (12), 2163–2171. <http://dx.doi.org/10.1038/s41559-024-02566-7>.
- Allan, J.R., Possingham, H.P., Atkinson, S.C., Waldron, A., Di Marco, M., Butchart, S.H., Adams, V.M., Kissling, W.D., Worsdell, T., Sandbrook, C., et al., 2022. The minimum land area requiring conservation attention to safeguard biodiversity. *Science* 376 (6597), 1094–1101. <http://dx.doi.org/10.1126/science.abl9127>.
- Barton, D.N., Immerzeel, B., Brander, L., Grêt-Regamey, A., Kato Huerta, J., Kretsch, C., Le Clech, S., Rendón, P., Seguin, et al., 2024. Increasing uptake of ecosystem service assessments: best practice check-lists for practitioners in Europe. *One Ecosyst.* 2024, 1–25. <http://dx.doi.org/10.3897/oneeco.9.e111425>.
- Besson, M., Alison, J., Bjerge, K., Gorochowski, T.E., Høye, T.T., Jucker, T., Mann, H.M., Clements, C.F., 2022. Towards the fully automated monitoring of ecological communities. *Ecol. Lett.* 25 (12), 2753–2775. <http://dx.doi.org/10.1111/ele.14123>.

- Brown, C.F., Brumby, S.P., Guzder-Williams, B., Birch, T., Hyde, S.B., Mazzariello, J., Czerwinski, W., Pasquarella, et al., 2022. Dynamic world, near real-time global 10 m land use land cover mapping. *Sci. Data* 9 (1), 251. <http://dx.doi.org/10.1038/s41597-022-01307-4>.
- Brown, C.F., Kazmierski, M.R., Pasquarella, V.J., Rucklidge, W.J., Samsikova, M., Zhang, C., Shelhamer, E., Lahera, E., et al., 2025. AlphaEarth foundations: An embedding field model for accurate and efficient global mapping from sparse label data. arXiv preprint [arXiv:2507.22291](https://arxiv.org/abs/2507.22291).
- Buchhorn, M., Lesiv, M., Tsendbazar, N.-E., Herold, M., Bertels, L., Smets, B., 2020. Copernicus global land cover layers—collection 2. *Remote. Sens.* 12 (6), 1044. <http://dx.doi.org/10.3390/rs12061044>.
- Council of the European Communities, 1992. Council Directive 92/43/EEC of 21 May 1992 On the Conservation of Natural Habitats and of Wild Fauna and Flora. Vol. L 206, Official Journal of the European Communities, pp. 7–50, (Habitats Directive). URL <http://data.europa.eu/eli/dir/1992/43/oj>.
- de Koning, K., Broekhuijsen, J., Kühn, I., Ovaskainen, O., Taubert, F., Endresen, D., Schigel, D., Grimm, V., 2023. Digital twins: Dynamic model-data fusion for ecology. *Trends Ecol. Evolut.* 38 (10), 916–926. <http://dx.doi.org/10.1016/j.tree.2023.06.005>.
- European Commission, 2023. Commission Delegated Regulation (EU) 2023/2772 of 31 July 2023 Supplementing Directive 2013/34/EU of the European Parliament and of the Council as Regards Sustainability Reporting Standards. Official Journal of the European Union, OJ L 2023/2772, 22.12.2023, URL <http://data.europa.eu/eli/reg/del/2023/2772/oj>.
- European Commission, Directorate-General for Agriculture and Rural Development, 2024. Context and Impact Indicators. Technical Report, European Commission, Version 10.0, 25 October 2024.
- European Environment Agency, 2024. Handbook On the Updated LULUCF Regulation EU 2018/841: Guidance And Orientation for the Implementation of the Updated Regulation. Handbook, European Environment Agency; European Commission, DG CLIMA, URL <https://climate-energy.eea.europa.eu/topics/climate-change-mitigation/land-and-forests/reports/handbook-on-the-update-lulucf-regulation-v2>. Version 2, 15 May 2024.
- European Parliament and Council of the European Union, 2000. Directive 2000/60/EC of the European parliament and of the council of 23 october 2000 establishing a framework for community action in the field of water policy. *Off. J. Eur. Communities* 327, 1–73, URL <http://data.europa.eu/eli/dir/2000/60/oj>.
- European Parliament and the Council, 2008. Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 Establishing a Framework for Community Action in the Field of Marine Environmental Policy (Marine Strategy Framework Directive). Official Journal of the European Union, OJ L 164, 25.6.2008, pp. 19–40, URL <http://data.europa.eu/eli/dir/2008/56/oj>.
- European Parliament and the Council, 2010. Directive 2009/147/EC Of the European Parliament and of the Council of 30 November 2009 on the Conservation of Wild Birds (Codified Version). Official Journal of the European Union, OJ L 20, 26.1.2010, pp. 7–25, URL <http://data.europa.eu/eli/dir/2009/147/oj>.
- European Parliament and the Council, 2024a. Regulation (EU) 2024/1991 of the European Parliament and of the Council of 24 June 2024 on Nature Restoration and Amending Regulation (EU) 2022/869. Official Journal of the European Union, OJ L 2024/1991, 29.7.2024, URL <http://data.europa.eu/eli/reg/2024/1991/oj>. Text with EEA relevance.
- European Parliament and the Council, 2024b. Regulation (EU) 2024/3024 of the European Parliament and of the Council of 27 November 2024 Amending Regulation (EU) No 691/2011 As Regards Introducing New Environmental Economic Account Modules. Official Journal of the European Union, OJ L 2024/3024, 6.12.2024, URL <http://data.europa.eu/eli/reg/2024/3024/oj>. Text with EEA relevance.
- Eurostat, 2024. EU Ecosystem Typology. Technical Note, Eurostat.
- Fassnacht, F.E., White, J.C., Wulder, M.A., Næsset, E., 2024. Remote sensing in forestry: Current challenges, considerations and directions. *Forestry* 97, 11–37. <http://dx.doi.org/10.1093/forestry/cpad024>.
- Food and Agriculture Organization of the United Nations, 2023. Guidelines And Specifications: FRA 2025. Technical Report, FAO, Rome.
- GBF Indicators, 2024. Extent of natural ecosystems: Metadata factsheet. URL <https://www.gbf-indicators.org/metadata/headline/A-2>. Retrieved from website.
- Global Reporting Initiative, 2024. Consolidated set of the GRI Standards 2024.
- Global Sustainability Standards Board, 2025. GRI Standards project for alignment of sector standards with new and revised topic standards – Exposure draft. URL <https://www.globalreporting.org>. Exposure draft.
- GOAP, 2024. Status of Ocean Accounting in Latin America and the Caribbean. Technical Report, Global Ocean Accounts Partnership Secretariat, UNSW, Sydney, Australia.
- Group on Earth Observations, 2024. Global Ecosystems Atlas. URL <https://globalecosystemsatlas.org>.
- Guo, C., Pleiss, G., Sun, Y., Weinberger, K.Q., 2017. On calibration of modern neural networks. In: Precup, D., Teh, Y.W. (Eds.), *Proceedings of the 34th International Conference on Machine Learning*. In: *Proceedings of Machine Learning Research*, vol. 70, PMLR, pp. 1321–1330.
- Guo, J., Xu, Q., Zeng, Y., Liu, Z., Zhu, X.X., 2023. Nationwide urban tree canopy mapping and coverage assessment in Brazil from high-resolution remote sensing images using deep learning. *ISPRS J. Photogramm. Remote Sens.* 198, 1–15. <http://dx.doi.org/10.1016/j.isprsjrs.2023.02.007>.
- Hein, L., Bagstad, K.J., Obst, C., Edens, B., Schenau, S., Castillo, G., Soular, F., Brown, C., Driver, A., et al., 2020. Progress in natural capital accounting for ecosystems. *Science* 367 (6477), 514–515. <http://dx.doi.org/10.1126/science.aaz8901>.
- Hong, Y., Que, X., Wang, Z., Ma, X., Wang, H., Salati, S., Liu, J., 2024. Mangrove extraction from super-resolution images generated by deep learning models. *Ecol. Indic.* 159, 111714. <http://dx.doi.org/10.1016/j.ecolind.2024.111714>.
- Hüllermeier, E., Waegeman, W., 2021. Aleatoric and epistemic uncertainty in machine learning: An introduction to concepts and methods. *Mach. Learn.* 110 (3), 457–506. <http://dx.doi.org/10.1007/s10994-021-05946-3>.
- Inácio, M., Baltranaite, E., Valença Pinto, L., Meisutovic-Akhtarieva, M., Barceló, D., Pereira, P., 2025. A systematic literature review on the implementation of the system of environmental-economic accounting—ecosystem accounting in forests, cities and marine areas. *Ecosyst. Serv.* 74, 101752. <http://dx.doi.org/10.1016/j.ecoser.2025.101752>.
- IPBES, 2019. Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the intergovernmental science-policy platform on biodiversity and ecosystem services. <http://dx.doi.org/10.5281/zenodo.3553579>.
- IPCC, 2019. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Volume 4, Agriculture, Forestry and Other Land Use — Chapter 3: Consistent Representation of Lands. Technical Report, Intergovernmental Panel on Climate Change, Geneva, Switzerland.
- IUCN, 2024. Guidelines for the Application of IUCN Red List of Ecosystems, Categories and Criteria. IUCN, Gland, Switzerland, Version 2.0.
- IUCN, 2025. Standards, methods and guidelines for cross-referencing ecosystem classifications and maps to the IUCN Global Ecosystem Typology.
- JCGM, 2012. International Vocabulary of Metrology – Basic and General Concepts and Associated Terms (VIM). Guidance JCGM 200:2012, Bureau International des Poids et Mesures (BIPM), 3rd ed., corrected version 2012.
- Justice, C., Belward, A., Morissette, J., Lewis, P., Privette, J., Baret, F., 2000. Developments in the validation of satellite sensor products for the study of the land surface. *Int. J. Remote Sens.* 21 (17), 3383–3390. <http://dx.doi.org/10.1080/014311600750020000>.
- Keith, D.A., Ferrer-Paris, J.R., Nicholson, E., Kingsford, R.T. (Eds.), 2020. The IUCN Global Ecosystem Typology 2.0: Descriptive Profiles for Biomes and Ecosystem Functional Groups. IUCN, Gland, Switzerland.
- Kokkoris, I.P., Smets, B., Hein, L., Mallinis, G., Buchhorn, M., Balbi, S., Černeček, J., Paganini, M., Dimopoulos, P., 2024. The role of Earth observation in ecosystem accounting: A review of advances, challenges and future directions. *Ecosyst. Serv.* 70, 101659. <http://dx.doi.org/10.1016/j.ecoser.2024.101659>.
- Luxton, S.J., Smith, G.S., Williams, K.J., Ferrier, S., Bond, A.J., Prober, S.M., 2024. An introduction to key ecological concepts, financial opportunities, and risks underpinning aspirations for nature positive. *BioScience* 74 (7), 450–466. <http://dx.doi.org/10.1093/biosci/biae040>.
- Mazur, E., Sims, M., Goldman, E., Schneider, M., Stolle, F., Daldoss Pirri, M., Beatty, C.R., 2023. SBTN natural lands map. Science Based Targets Network (SBTN), dataset.
- Moore, J.W., Schindler, D.E., 2022. Getting ahead of climate change for ecological adaptation and resilience. *Science* 376 (6600), 1421–1426. <http://dx.doi.org/10.1126/science.abo3608>.
- MoSPI, 2021. Ecosystem Accounts for India – Report of the NCAVES Project. Technical Report, Government of India, Ministry of Statistics and Programme Implementation, New Delhi, India.
- Murray, N.J., Worthington, T.A., Bunting, P., Duce, S., Hagger, V., Lovelock, C.E., Lucas, R., Saunders, M.I., et al., 2022. High-resolution mapping of losses and gains of Earth's tidal wetlands. *Science* 376 (6594), 744–749. <http://dx.doi.org/10.1126/science.abm9583>.
- Myers, S.S., Masztalerz, O., Ahdoot, S., Gabrysch, S., Gupta, J., Haines, A., Kleineberg-Massuthe, H., Lambrecht, N.J., Landrigan, P.J., Mahmood, J., et al., 2025. Connecting planetary boundaries and planetary health: A resilient and stable Earth system is crucial for human health. *Lancet* 406 (10501), 315–319.
- Naas, A.E., Halvorsen, R., Horvath, P., Wollan, A.K., Bratli, H., Brynildsrud, K., Finne, E.A., Keetz, L.T., et al., 2023. What explains inconsistencies in field-based ecosystem mapping? *Appl. Veg. Sci.* 26 (1), e12715. <http://dx.doi.org/10.1111/avsc.12715>.
- National Bureau of Statistics of China, 2021. Ecosystem Accounts for China: Results of the NCAVES Project. Technical Report, National Bureau of Statistics of China.
- Nature Positive Initiative, 2024. Building consensus on state of nature metrics to drive nature positive outcomes: Supporting information for consultation brief. URL <https://www.naturepositive.org/>, PDF.
- Pickens, A.H., Hansen, M.C., Adusei, B., Potapov, P., 2020. Sentinel-2 Forest Loss Alert. Global Land Analysis and Discovery (GLAD), University of Maryland, College Park, MD, Dataset.
- Rahimi, E., Jung, C., 2024. Evaluating the applicability of landsat 8 data for global time series analysis. *Front. Remote Sens.* 5, 1492534. <http://dx.doi.org/10.3389/frsen.2024.1492534>.
- Ramsar Convention, 2019. Guidance on Information on National Wetland Extent: Target 8 “National Wetlands Inventory” of the Ramsar National Report for COP14. Guidance, Ramsar Convention Secretariat, Gland, Switzerland.

- Roca, M., Lee, C.B., Pertiwi, A.P., Blume, A., Caballero, I., Navarro, G., Traganos, D., 2025. Subtidal seagrass and blue carbon mapping at the regional scale: A cloud-native multi-temporal Earth observation approach. *GIScience Remote Sens.* 62 (1), 2438838. <http://dx.doi.org/10.1080/15481603.2024.2438838>.
- Scherzinger, F., Schädler, M., Reitz, T., Yin, R., Auge, H., Merbach, I., Roscher, C., Harpole, W.S., et al., 2024. Sustainable land management enhances ecological and economic multifunctionality under ambient and future climate. *Nat. Commun.* 15 (1), 4930. <http://dx.doi.org/10.1038/s41467-024-48830-z>.
- Schillaci, C., Jones, A., Vieira, D., Munafò, M., Montanarella, L., 2023. Evaluation of the united nations sustainable development goal 15.3. 1 indicator of land degradation in the European union. *Land Degrad. Dev.* 34 (1), 250–268.
- SDG Indicators, 2025. SDG indicator metadata. URL <https://unstats.un.org/sdgs/metadata/>.
- Secretariat of the Convention on Biological Diversity, 2004. *The Ecosystem Approach (CBD Guidelines)*. Secretariat of the Convention on Biological Diversity, Montreal.
- Secretariat of the Convention on Biological Diversity, 2022. *Decision 15/4: Kunming–montreal global biodiversity framework (CBD/COP/DEC/15/4)*.
- See, L., Olteanu-Raimond, A.-M., Fonte, C.C., 2025. Recent advances in volunteered geographic information (VGI) and citizen sensing. *Int. J. Digit. Earth* 18 (1), 2480220. <http://dx.doi.org/10.1080/17538947.2025.2480220>.
- Skakun, S., 2025. The impact of map accuracy on area estimation with remotely sensed data within the stratified random sampling design. *Remote Sens. Environ.* 326, 114805. <http://dx.doi.org/10.1016/j.rse.2025.114805>.
- Smith, G.S., Ascui, F., O'Grady, A.P., Pinkard, E., 2024. Indicators for measuring and reporting corporate nature-related impacts, dependencies, and risks. *Environ. Sustain. Indic.* 22, 100351. <http://dx.doi.org/10.1016/j.indic.2024.100351>.
- Sprague, R.I., Wisner, S.K., 2024. *Investigating a Unifying Ecosystem Typology for All of New Zealand*. Report, Manaaki Whenua – Landcare Research.
- Stehman, S.V., Fonte, C.C., Foody, G.M., See, L., 2018. Using volunteered geographic information (VGI) in design-based statistical inference for area estimation and accuracy assessment of land cover. *Remote Sens. Environ.* 212, 47–59. <http://dx.doi.org/10.1016/j.rse.2018.04.014>.
- Taskforce on Nature-related Financial Disclosures, 2023. *Recommendations of the Taskforce on Nature-related Financial Disclosures*. Technical Report, TNFD.
- Teich, I., Zvoleff, A., Minelli, S., O'Connor, B., Carranza, C., 2025. *Good Practice Guidance Addendum. SDG Indicator 15.3.1: Proportion of Land That Is Degraded Over Total Land Area*. Technical Report, United Nations Convention to Combat Desertification (UNCCD), Bonn, Germany, In collaboration with WOCAT and Centre for Development and Environment (CDE), University of Bern, Switzerland.
- Tyukavina, A., Stehman, S.V., Foody, G.M., Bontemps, S., See, L., Olofsson, P., Tsendbazar, N.E., et al., 2025. *Land Cover and Change Map Accuracy Assessment and Area Estimation Good Practices Protocol*. Technical Report, Land Product Validation Subgroup (WGCV/CEOS), p. 187. <http://dx.doi.org/10.5067/doc/ceoswgcv/lpv/lc.00>, Version 1.0.
- United Nations, 2024. *System of Environmental-Economic Accounting: Ecosystem Accounting*. United Nations, New York.
- United Nations Convention to Combat Desertification, 2022. *PRAIS4 Reporting Manual*. Technical Report, United Nations Convention to Combat Desertification, Bonn, Germany.
- United Nations Environment Programme, 2023. *Harmonized Reporting between Regional Seas Programmes National Reporting and the Convention on Biological Diversity National Reporting (NBSAP)*. Technical Report, United Nations Environment Programme, Nairobi.
- Valle, D., Izbicki, R., Leite, R.V., 2023. Quantifying uncertainty in land-use land-cover classification using conformal statistics. *Remote Sens. Environ.* 295, 113682. <http://dx.doi.org/10.1016/j.rse.2023.113682>.
- Wang, Y., Sun, Y., Cao, X., Wang, Y., Zhang, W., Cheng, X., 2023. A review of regional and global scale land use/land cover (LULC) mapping products generated from satellite remote sensing. *ISPRS J. Photogramm. Remote Sens.* 206, 311–334. <http://dx.doi.org/10.1016/j.isprsjprs.2023.11.014>.
- Webster, K.L., Strack, M., Balliston, N., Davies, M.A., Hettinga, E.K., Hunter, M., Kleinke, K., Schmidt, M., et al., 2025. Data and knowledge needs for improving science and policy for peatlands in Canada in a changing world: Insights from global peatlands initiative workshop, June 2023. 10, pp. 1–19. <http://dx.doi.org/10.1139/facets-2025-0011>.
- Wood, S.L., Jones, S.K., Johnson, J.A., Brauman, K.A., Chaplin-Kramer, R., Fremier, A., Girvetz, E., et al., 2018. Distilling the role of ecosystem services in the sustainable development goals. *Ecosyst. Serv.* 29, 70–82. <http://dx.doi.org/10.1016/j.ecoser.2017.10.010>.
- World Meteorological Organization, 2022. *2022 GCOS ECVs Requirements*. Technical Report, World Meteorological Organization, Geneva, Switzerland, Updated in 2025.
- Xu, P., Tsendbazar, N.-E., Herold, M., De Bruin, S., Koopmans, M., Birch, T., Carter, S., Fritz, S., et al., 2024. Comparative validation of recent 10 m-resolution global land cover maps. *Remote Sens. Environ.* 311, 114316. <http://dx.doi.org/10.1016/j.rse.2024.114316>.
- Yin, J., Dong, J., Hamm, N.A., Li, Z., Wang, J., Xing, H., Fu, P., 2021. Integrating remote sensing and geospatial big data for urban land use mapping: A review. *Int. J. Appl. Earth Obs. Geoinf.* 103, 102514. <http://dx.doi.org/10.1016/j.jag.2021.102514>.