Highlights

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- EE monitoring supports tracking cross-cutting progress on nature-related goals.
- SEEA EA serves as a main statistical framework for harmonized reporting.
- Ecosystems' thematic complexity and dynamic nature limit assessments' coherence.
- Tracking ecosystem changes and transitions is key for practical applications.
- Transparency in methods, validation, estimated uncertainty define EE map reliability.

Ecosystem extent mapping in a global monitoring context

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ABSTRACT

The vital role of ecosystems in maintaining biosphere stability is now recognised 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 data products as operational solutions. For that, we analyzed the landscape of 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

Ecosystems are central to environmental functioning and change, and are a key dimension of biodiversity. By one official definition, an ecosystem is a dynamic complex of plant, animal and micro-organism communities and their non-living environment, operating as a functional unit (Secretariat of the Convention on Biological Diversity, 2004). Their fundamental role in nature as regulators of climate, soil, water, and air quality, is defined by the feedback loop with the environment: being open, ecosystems are in constant exchange of energy with the surrounding environment, reflecting external conditions and their dynamics, while retaining the capacity to adapt to change (Moore and Schindler, 2022).

The attempt to comprehensively value the vital importance of ecosystems is currently shaped by the concept of ecosystem services, which links human well-being to natural capital through the assessment of ecosystem condition and functioning (Wood et al., 2018; Hein et al., 2020). Extent of ecosystems (EE), i.e., areas under ecosystem types

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and their distribution, is a key dimension for assessing ecosystem composition and functioning and capturing their persistent change. Accordingly, a practical approach to evaluating and tracking ecosystem types and condition relies on timely, detailed monitoring of EE, which is only achievable if supported by coordinated spatial-temporal analysis and mapping (Besson et al., 2022; Affinito et al., 2024).

Reaching global targets is underpinned by harmonised national and regional efforts, necessitating consistent data collection and reporting. This is crucial for agreements like the Global Biodiversity Framework (GBF), relying on bottom-up monitoring contributions from not only the public, but also the 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 progress towards developing and operationalizing the GBF's monitoring framework (Affinito et al., 2024) identified critical limitations, including data availability and methodological issues in consistent data collation, collection, and calculation of corresponding indicators, amplified by the global extent, diversity, multiscale complexity, and dynamic nature of ecosystems. Addressing these barriers is urgent for the development of robust monitoring tools.

The increasing availability of Earth observation (EO) data, combined with the rapid growth of data-analysis tools and accessible computational environments, makes spatial data applications increasingly widespread. Spatial monitoring has a long tradition of tracking conditions and changes in the closely related land cover (LC) domain, resulting in a suite of globally applicable products supporting different thematic levels and use scenarios (Buchhorn et al., 2020; Pickens et al., 2020; Brown et al., 2022). LC types, largely defined by surface spectral signatures, correspond to the biotic composition and its structure; thus, LC serves as crucial input information for capturing EE. However, by definition, LC does not reflect functional patterns or interconnection with the adjacent environments, and therefore does not fully reflect ecosystem complexities as functional units at finer scales.

As for ecosystem-oriented solutions, spatial ecosystem 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 of products across nature-related applications (Figure 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 the landscape of 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).
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 does policy-driven monitoring 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?

To evaluate how cross-national commitments can benefit from EE mapping data, we focused on global and EU frameworks featuring operational nature- and environment-oriented monitoring and reporting (Figure 2), covering terrestrial, freshwater, coastal and marine domains:

- Major global multilateral environmental agreements and coordinating instruments.
- Major European Union (EU) policies for protecting the environment and biodiversity, including those supporting the EU Green Deal and Biodiversity Strategy for 2030.

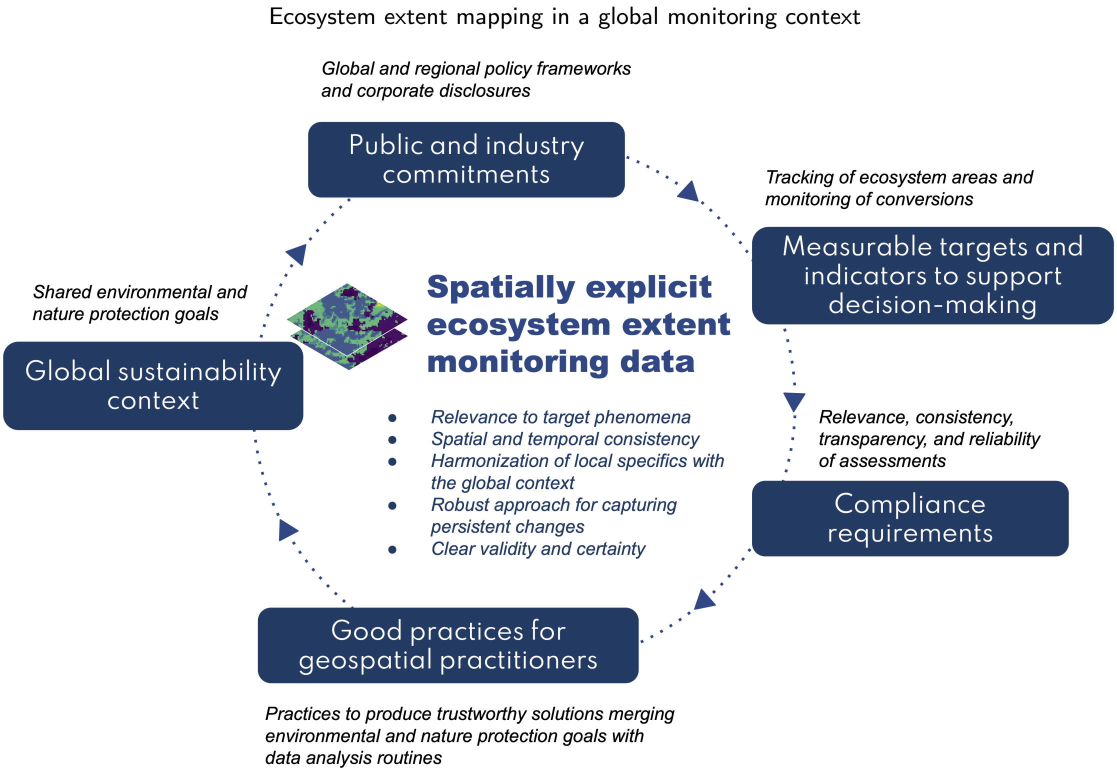

Figure 1: EE data for meeting joint environmental and nature protection goals: as the global sustainability context drives governmental and industry commitments, the efficiency of tracking progress using relevant indicators relies heavily on the informativeness of the data. The latter, therefore, needs to follow appropriate compilation practices to provide meaningful insights.

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 1). 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 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 (SEEA EA), aiming to inform actions on global nature degradation and environmental change (United Nations, 2024).

EE 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 reported as the opening and closing extent, with additions and reductions by ecosystem type reported as a conversion matrix. Where feasible, changes should be disaggregated into managed and unmanaged ones. Importantly, and in contrast to habitats, 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.

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 underpin 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) No 691/2011 (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 of broad EE diversity, there are also policies focusing on specific ecosystems, given their high role in sustaining life on Earth and urgent decline. For example, wetlands are targeted by the Ramsar Convention and Sustainable Development Goals (SDG) Target 6.6, which require monitoring of wetland extent and, where possible, recent change (SDG Indicators, 2023). Another example is forests, targeted by United Nations (UN) Strategic Plan for Forests 2030 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).

The policy demand to include EE in natural capital assessment is global. SEEA EA is central accounting frame and, even when not used explicitly, its principles align with the common reporting structure requiring opening/closing extents and recorded changes.

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).

Carbon stock inventories under the Agriculture, Forestry and Other Land Use (AFOLU) sector, as defined by the Intergovernmental Panel on Climate Change (IPCC) under the UN Framework Convention on Climate Change, quantify anthropogenic emissions from year-to-year changes across forest, cropland, grassland, wetland, settlement, and other lands, while carbon sinks and reservoirs are estimated from related ecosystems’ composition and structure (IPCC, 2019). To date, countries are not required to submit carbon stock maps; however, inventories must rely on transparent, time-consistent data. At national and regional levels, related initiatives increasingly require spatial assessments, e.g., the revised EU Land Use, Land Use-Change, and Forestry (LULUCF) Regulation obliges Member States to implement geographically explicit annual monitoring with detailed spatial datasets to improve accuracy, resolution, and policy relevance (European Environment Agency, 2024). Although framed around land use and land-use change, this creates a direct opportunity to integrate EE data, adding spatial detail, functional context, and supporting data harmonization.

EE data can inform action on land degradation, enhancing LC data. The UN Convention to Combat Desertification (UNCCD) and corresponding Land Degradation Neutrality (LDN) target, linked to SDG Target 15.3, practically rely on LC and land-use monitoring, as changes in arable and other lands reflect degradation (Sims et al., 2021). At the European level, sustainable farming and food security are among the objectives of the Common Agricultural Policy (CAP), which tracks progress through long-term observation of agricultural practices and environmental impacts, including landscape features indicators, that can be expressed as spatial data on human-affected ecosystems (European Commission, Directorate-General for Agriculture and Rural Development, 2024).

Ecosystem type information is an entry point for conservation and restoration actions, 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 Nature Restoration Regulation (NRL), and, more broadly, the

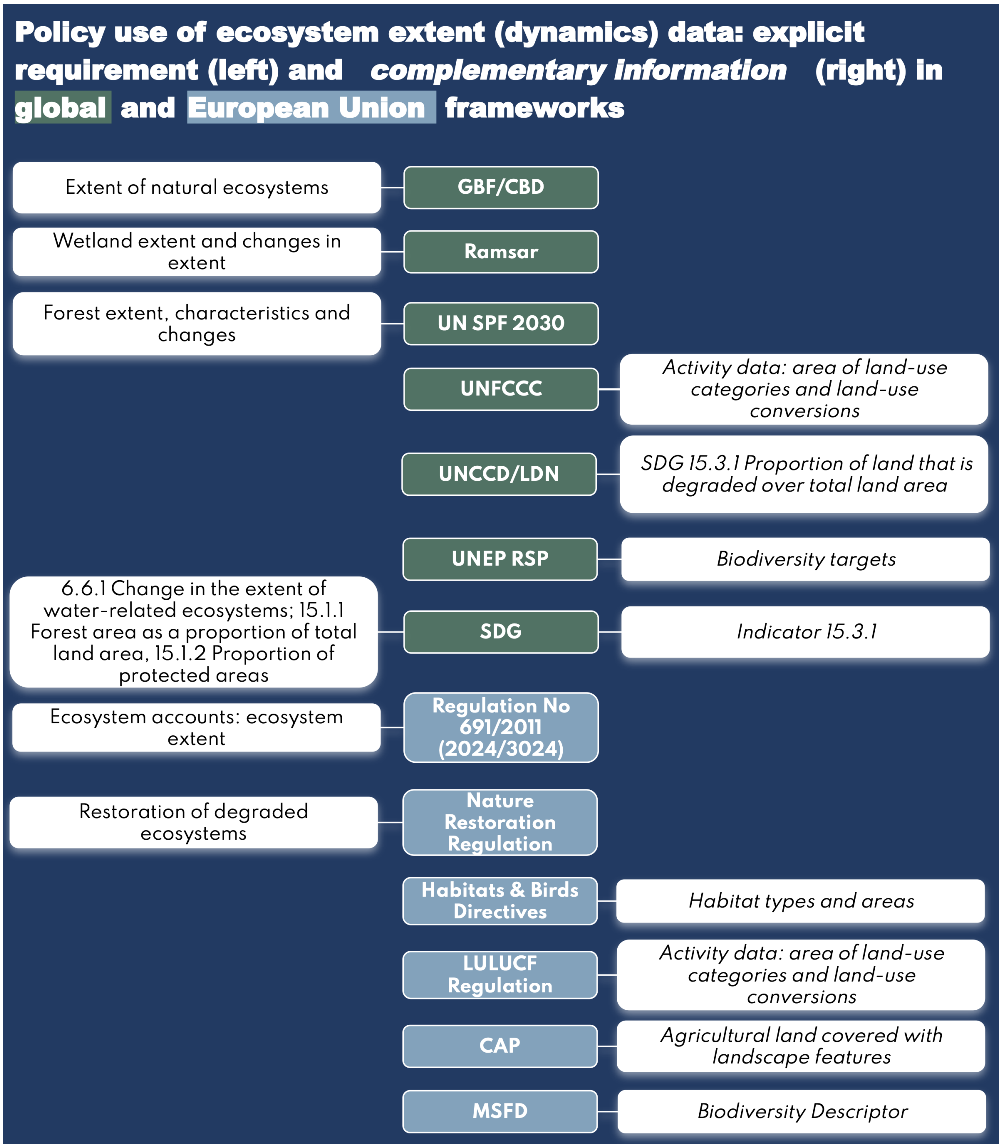

Figure 2: EE data for meeting joint environmental and nature protection goals: as the global sustainability context drives governmental and industry commitments, the efficiency of tracking progress using relevant indicators relies heavily on the informativeness of the data. The latter, therefore, needs to follow appropriate compilation practices to provide meaningful insights.

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 Regional Seas Programme (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 Marine Strategy Framework Directive (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.

Figure 2 summarizes global and European frameworks that benefit from up-to-date EE data, distinguishing those that explicitly require EE from those for which EE can provide valuable insights. EE mapping thus emerges as a cross-cutting enabler across policy agendas, from climate reporting to conservation planning.

Table 1
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 organisation	Any	GRI 101: Biodiversity 2024
TNFD	Any organisation	Any	Recommendations of the Taskforce on Nature-related Financial Disclosures
ESRS	Companies under the Corporate Sustainability Reporting Directive (CSRD)	EU (primarily)	ESRS E4 *Biodiversity and ecosystems*

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 1) 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.

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. EE-related information is recognised by frameworks as a core part of such assessments.

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, while specific data-compilation guidelines are to be developed (GBF Indicators, 2024). At the same time, the SEEA EA framework, a main assessment tool for many policies and related applications, and climate-related IPCC Guidelines and requirements to Essential Climate Variables, operationalizing relevant and well-established fields of land use and LC monitoring, provide more detailed principles for data compilation (IPCC, 2019; World Meteorological Organization, 2022).

Organizational details, such as reporting periods, dates for opening and closing extents, and units of measurement, can be derived directly from information on indicators. As for data quality, it should ensure relevance, accuracy, consistency, reliability, transparency, and accessibility (United Nations, 2024). For data developers, all of these 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 definitions is an essential first step, the local knowledge embedded in national and regional typologies also needs to be linked with a global context. To enable this, the International Union for Conservation of Nature Global Ecosystem Typology (IUCN GET) was proposed, defining ecosystem types hierarchically, based on dominant ecosystem processes and key biotic and abiotic properties (Keith et al., 2020). It has six levels, the most relevant one from an international policy perspective being Level 3, called 'ecosystem functional groups' (EFGs). EFGs are groups of related ecosystem types within a biome that share common ecological drivers and ecosystem properties.

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, 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 EFGs, including 98 (semi-)natural and 12 anthropogenic ones.

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 (Eurostat, 2024) for use in ecosystem accounting across Europe. It has three hierarchical levels. To ensure relevance to ecosystems of EU countries while also facilitating international comparisons, it is aligned with the MAES ecosystem typology, EUNIS habitat classifications, and IUCN GET. Currently, Member States shall report EE at Level 1, including 12 natural and human-influenced ecosystem categories.

Alignment of EE with cross-cutting reporting targets requires thematic harmonization. As discussed, climate-related inventory uses broader land-use classes than EE mapping (IPCC, 2019). However, EE can serve as an enhanced form of land-use and LC contexts if adjusted to the core principles of land-use definitions through clear identification of the management status (United Nations, 2024). Likewise, land management status is essential for informing inventories of ecosystem-specific policies, such as wetland inventories under the Ramsar Convention or forest-extent monitoring under the Forest Resource Assessments, each operating its own classification system (Ramsar Convention, 2019; Food and Agriculture Organization of the United Nations, 2023).

The diversity of typologies poses challenges to harmonization of EE data needs across different domains and scales. National-level ecosystem monitoring typically utilizes local classification systems, capturing the dynamic local context and perception of influencing factors, which can not always be directly and unambiguously translated into unified global frameworks (Nedd et al., 2021). Thus, the challenge is not only building crosswalks, but designing a robust approach for 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 products' potential fitness-for-purpose for a given application.

Approaches to validation of spatial monitoring data are extensively described in the recently updated Good Practices Protocol for LC maps (Tyukavina et al., 2025). Guidelines establish product maturity stages based on the availability of validation. With that, no validation corresponds to a map that is just 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 image-interpretation expertise, making the image-interpretation process susceptible to biases.

Alternatively, Volunteered Geographic Information (VGI) 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, VGI is unlikely to 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. Although important, 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 standardised 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. 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 LC, 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 mapping 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 EU LULUCF 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 EO and non-EO data.

Requirements for LC 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

EO 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, EO-based mapping faces limitations when it comes to fine ecosystem distinctions.

First, accurate classification of EO data is limited by ambiguous spectral signals and sensor constraints. For instance, for human-influenced/semi-natural ecosystems or when distinguishing between managed and unmanaged changes, mapping of extents cannot rely on spectral information alone and requires integrating socio-economic context, such as land-use history or management data (Yin et al., 2021; Fassnacht et al., 2024). The ambiguity of spectral signals constrains the 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 EO detection 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).

Second, whereas EO 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, EO 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).

Acknowledgement 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 recognised 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 <5m/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. EO 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: Conceptualization, Methodology, Formal analysis, Investigation, Visualization, Writing – original draft; **Bruno Smets**: Conceptualization, Methodology, Writing – original draft, Funding acquisition, Project administration; **Lars Hein**: Conceptualization, Writing – original draft; **Ioannis P. Kokkoris**: Conceptualization, Writing – original draft; **Michela Perrone**: Investigation, Writing – original draft; **Vojtěch Barták**: Investigation, Writing – original draft; **Jan Komárek**: Investigation, Writing – original draft; **Vítězslav Moudrý**: Conceptualization; **Ruben Remelgado**: Conceptualization, Writing – original draft, Funding acquisition; **Stefano Balbi**: Conceptualization, Writing – original draft, Funding acquisition; **Alessio Bulckaen**: Conceptualization, Writing – original draft; **Ian McCallum**: Conceptualization, Methodology, Writing – original draft, Funding acquisition; **Myroslava Lesiv**: Writing – review & editing; **Marc Paganini**: Writing – original draft, Methodology, Resources; **Carsten Meyer**: Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Funding acquisition.

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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.

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