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ABSTRACT

Transnational monitoring frameworks are crucial for tracking progress and guiding biodiversity conservation policies at continental and global levels. Yet their development is constrained by the lack of comprehensive analyses of biodiversity monitoring gaps. Focusing on Europe, we quantified the shortfall between data integrated by transnational initiatives and the requirements for producing 48 Essential Biodiversity Variables (EBVs) identified with stakeholders for continent-wide monitoring. About 20% of EBVs lacked transnational data integration, and existing initiatives often covered fewer than 70% of countries. Even where integration occurred, major deficiencies remained in sampling standardization, taxonomic and ecosystem coverage, spatial and temporal resolution, data collection frequency, and data accessibility. Monitoring shortfalls varied widely across countries. Addressing monitoring gaps will require sustained funding for new transnational initiatives, stronger alignment between national and supranational efforts, improved sampling designs, novel technologies, and equitable open data sharing. Establishing such a framework could offer a model for global biodiversity monitoring.

1 | Introduction

Monitoring is a key component of biodiversity policy, including the Kunming-Montreal Global Biodiversity Framework (CBD 2022) and the European Union (EU) Biodiversity Strategy to 2030 (EC 2020). These policies call for strengthened monitoring systems capable of delivering transnational, standardized data to track progress and guide conservation at continental and global scales. While monitoring data are already being collected to support these goals (Dornelas et al., 2018; WWF/ZSL 2022; Smith and Edwards 2021; Brlík et al. 2021), major gaps persist, creating uncertainty in biodiversity trends (e.g., Valdez et al. 2023) and hindering effective policy and management (Pereira et al. 2012; Proença et al. 2017). Yet detailed information on the type and extent of these gaps remains limited (e.g., Takeuchi et al. 2021; Lindenmayer et al. 2022; Achieng et al. 2023; Moersberger et al. 2024).

Europe offers a valuable context to examine these challenges, given its policy commitments and established environmental data infrastructure. The EU is working to establish a coherent monitoring framework to support multiple legislative instruments, including the Habitats and Birds Directives, the Common Agricultural Policy, the Water Framework Directive (WFD), the Marine Strategy Framework Directive, and the Nature Restoration Law (Pereira et al. 2013, 2022). These efforts have been advanced through the Europa Biodiversity Observation Network (EuropaBON 2023; Pereira et al. 2022), with strong stakeholder engagement (Moersberger et al. 2024). EuropaBON identified a comprehensive set of EBVs required to monitor, report, assess, and manage biodiversity change (Junker et al. 2023). Covering genetic, species, community, and ecosystem levels across marine, freshwater, and terrestrial realms (Junker et al. 2023; Fernández et al. 2020), EBVs rely on field and remote sensing data, integrated through modeling to produce indicators of biodiversity change over time and space (Pereira et al. 2013; Kissling et al. 2018). Their implementation at scale would promote biodiversity data harmonization and help address systemic observation gaps, both within Europe and globally (Pereira et al. 2013; Gonzalez et al. 2023).

Biodiversity monitoring in Europe is largely implemented and funded through national and subnational programs, which vary widely in protocols, spatial coverage, and data accessibility (Moersberger et al. 2024). These efforts are essential (Moussy et al. 2022), but producing Europe-wide EBVs requires coordination through transnational initiatives—defined here as monitoring efforts where data from multiple countries are integrated using standardized methods and reporting structures (Kissling et al. 2018). While some national or subnational programs can contribute, data integration is only feasible when datasets are compatible in sampling design, taxonomic scope, temporal resolution, and sharing protocols (Kissling et al. 2018; Figure 1). Effective transnational monitoring also depends on spatially distributed sampling, long-term continuity, and compliance with FAIR (Findable, Accessible, Interoperable, and Reusable) and CARE (Collective Benefit, Authority to Control, Responsibility, and Ethics) principles, which promote transparent, equitable, and reusable data (Wetzel et al. 2018; Magurran et al. 2010). Few current initiatives fully meet the criteria for effective transnational monitoring, making it essential to identify where integration already occurs and where gaps persist to support a coordinated biodiversity monitoring framework in Europe (Moersberger et al. 2024).

To evaluate current limitations in biodiversity monitoring, we analyzed gaps across Europe by comparing data integrated by transnational monitoring initiatives with the requirements for producing EBVs across the three realms and all EBV classes. Gaps were identified based on data integration, country coverage, taxonomic and ecosystem representation, sampling protocols, spatial and temporal design, and data accessibility (Figure 1), following EBV-specific minimum criteria (Kissling et al. 2018). Our findings inform the development of a coordinated European biodiversity monitoring framework and support the EU Biodiversity Observation Coordination Centre (Moersberger et al. 2024; Liquete et al. 2024), while also offering insights for global monitoring efforts.

2 | Methods

Gaps were evaluated for 48 EBVs (Table S1), out of 84 previously identified in collaboration with stakeholders for Europe-wide monitoring (Junker et al. 2023; EuropaBON 2023). We focused on EBVs that primarily require in situ, field-based data collection, which aligns with most current biodiversity monitoring initiatives (Morán-Ordóñez et al. 2023) and typically demands transnational coordination. EBVs derived mainly from satellite remote sensing were excluded, as they rely on globally available data and do not require harmonized field monitoring efforts among countries. The selected EBVs span all six EBV classes and represent a wide range of taxa and ecosystems across terrestrial, freshwater, and marine realms (Pereira et al. 2013; Junker et al. 2023) (Figure 2). For each EBV, we extracted information on the biological entity addressed (taxonomic group, ecosystem type) and the target sampling design (minimum and maximum spatial and temporal resolution), as defined with stakeholders (Junker et al. 2023; EuropaBON 2023).

The main sources of information were the EuropaBON (Morán-Ordóñez et al. 2023) and MarBioME (Jessop et al. 2022) databases, complemented with expert consultation. We matched each EBV with European monitoring initiatives potentially generating suitable data for its production (Table S1). This process considered whether the EBV and the monitoring initiative targeted the same biological entity or a subset of it, and whether the initiative involved transnational integration, meaning that it covered multiple countries across Europe or within a region (e.g., Baltic Sea). For each transnational initiative, we gathered the information necessary to estimate monitoring gaps relative to the corresponding EBVs (Figure 1). This included details on countries involved, sampling methods, focal entities, temporal and spatial sampling design, and data accessibility.

We focused on the 27 EU Member States (MS) and 20 non-EU MS (Figure 3). Gaps were evaluated for each EBV by comparing the type, quality and quantity of biodiversity data required for its production (Junker et al. 2023) with the data provided by the corresponding initiative(s). When more than one initiative potentially contributed to an EBV, we selected the

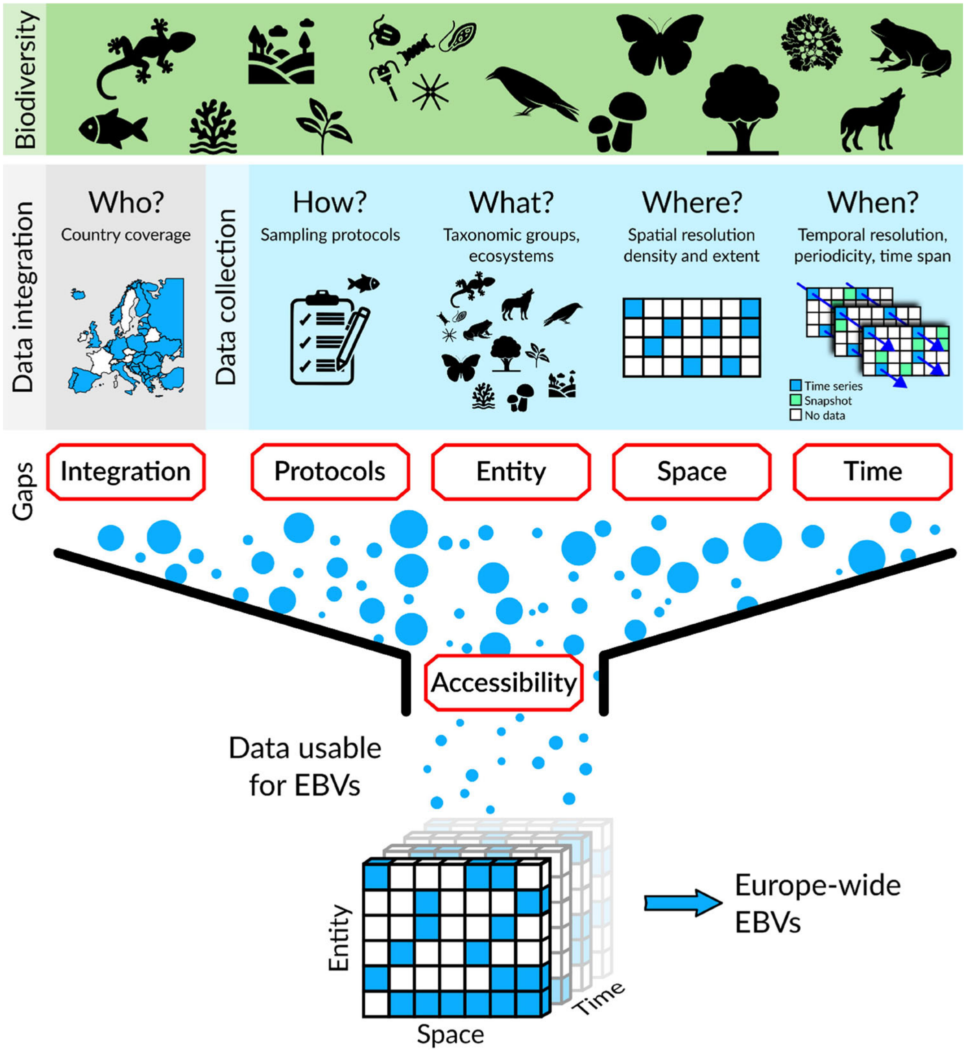

FIGURE 1 | Schematic representation of key monitoring gaps that hinder the production of Essential Biodiversity Variables (EBVs) for European-scale monitoring. For a given EBV, data collection and "Integration" should be made across countries (Who?), using standardized sampling "Protocols" (How?), that cover the target biological "Entity" (taxonomic groups, ecosystems; What?). Moreover, data need to be collected over "Space" at sufficient extent and resolution (Where?), and over sufficiently long and frequent "Time" frames (When?). Finally, mechanisms should be put in place to ensure the "Accessibility" of the data for potential users (see Table 1 for details). Figure designed with resources from Flaticon.com—Gecko, landscape, and insect: Freepik; frog and bird: Anditii Creative; mushroom: Tanah Basah; wolf: PLANBSTUDIO; fish: DinosoftLabs; seaweed: Danki Design; tree: VectorPortal; herb: Mayor Icons; micro-algae: metamiseptiana and Freepik.

initiative with the lowest degree of mismatch relative to EBV requirements. We considered six types of gaps (G#) (Figure 1) evaluated according to the ten criteria (C#) described in Table 1 (Kissling et al. 2018).

To assess gaps for each EBV, we applied the ten criteria on a per-country basis, using the procedures outlined in Table 1 (Supporting Information S1: Appendix II). We evaluated whether the criterion was not met (gap), partially met (partial gap), or fully met (no gap). We then aggregated information across criteria to assess the presence of each gap category per country. For the gap types with more than one criterion (i.e., G4 and G5), we applied the one-out-all-out principle, whereby, if at least one criterion was not met, or only partially met, a total or partial gap was recorded, respectively. Although conservative (Borja and Rodríguez 2010), this method recognizes that failing to meet a single criterion implies that the corresponding EBV cannot be produced with the required characteristics.

Information from each country-level gap type was aggregated across countries to produce Europe-wide estimates. We tallied all countries with a gap (or partial gap) of a given type and expressed the value as a proportion of the European countries ($n = 47$). For marine EBVs, only coastal countries ($n = 32$) were considered. The coarse categorization used to evaluate gaps was necessary because the information for monitoring initiatives was often scarce and inconsistent. Therefore, our approach was designed based on the minimum set of information that was generally available, allowing comparability across EBVs and gap types. This broad categorization offers a preliminary identification of current monitoring gaps, which can be refined as more information becomes available.

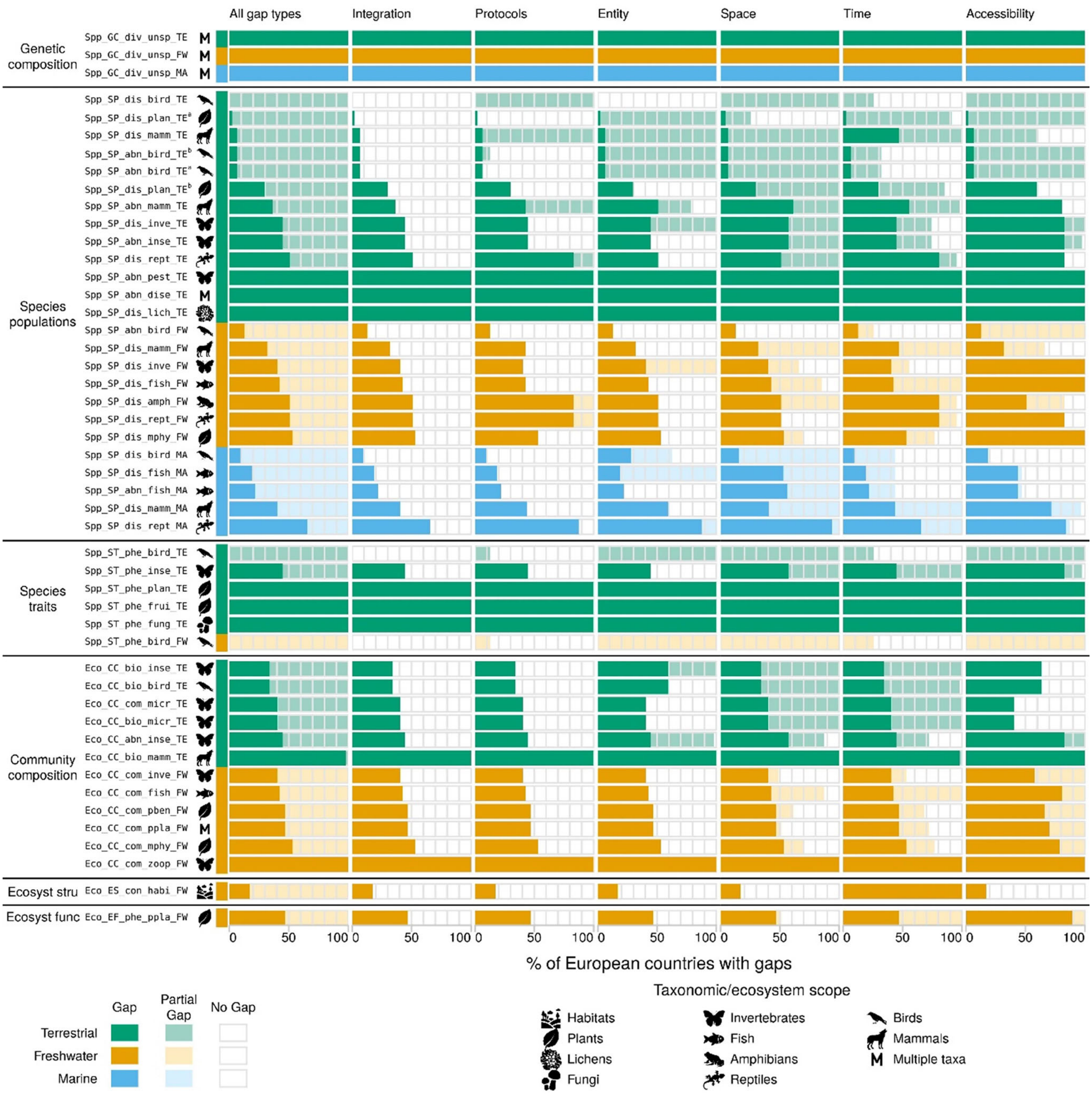

FIGURE 2 | Monitoring gaps per EBV. Gaps are expressed by the proportion (%) of European countries that do not fulfill (gap) and partially fulfill (partial gap) criteria for each EBV. EBVs are grouped by EBV classes and realms (see Section 2 for details), and are coded following a coding system available on GitHub (https://github.com/EuropaBON/EBV-Descriptions/wiki) (see Table S1). For marine EBVs, calculations were restricted to the 22 countries with a coastline. Figure designed with resources from Flaticon.com—Plant: SeyfDesigner; gecko, landscape, and insect: Freepik; frog and bird: Anditii Creative; mushroom: Tanah Basah; wolf: PLANBSTUDIO; fish: DinosoftLabs.

3 | Results

Data for 11 out of the 48 EBVs examined were not integrated at the transnational level, resulting in complete monitoring gaps (Figure 2). These included three EBVs describing genetic composition; one on freshwater zooplankton; three on lichens, disease vectors, and crop pests; three on fungi and plant phenology; and one on aerial biomass of bats. For the remaining EBVs, data were potentially produced by more than 25 transnational initiatives, with some achieving broad integration across Europe (Table S1), such as the European atlases of vertebrates, the African-Eurasian Waterbird Census, and the EURING monitoring of migratory birds, while others involve integration mostly at the EU level, including WFD monitoring and the Pan-European Common Bird Monitoring Scheme (PECBMS). Other initiatives integrate data from a smaller subset of countries, such as the European Butterfly Monitoring Scheme (eBMS) and the National Forest Inventories (ENFIN). For marine EBVs, data are generally integrated at regional levels such as North Sea, Baltic Sea, Northeast Atlantic, Black Sea, and Mediterranean Sea. Consequently, there is wide

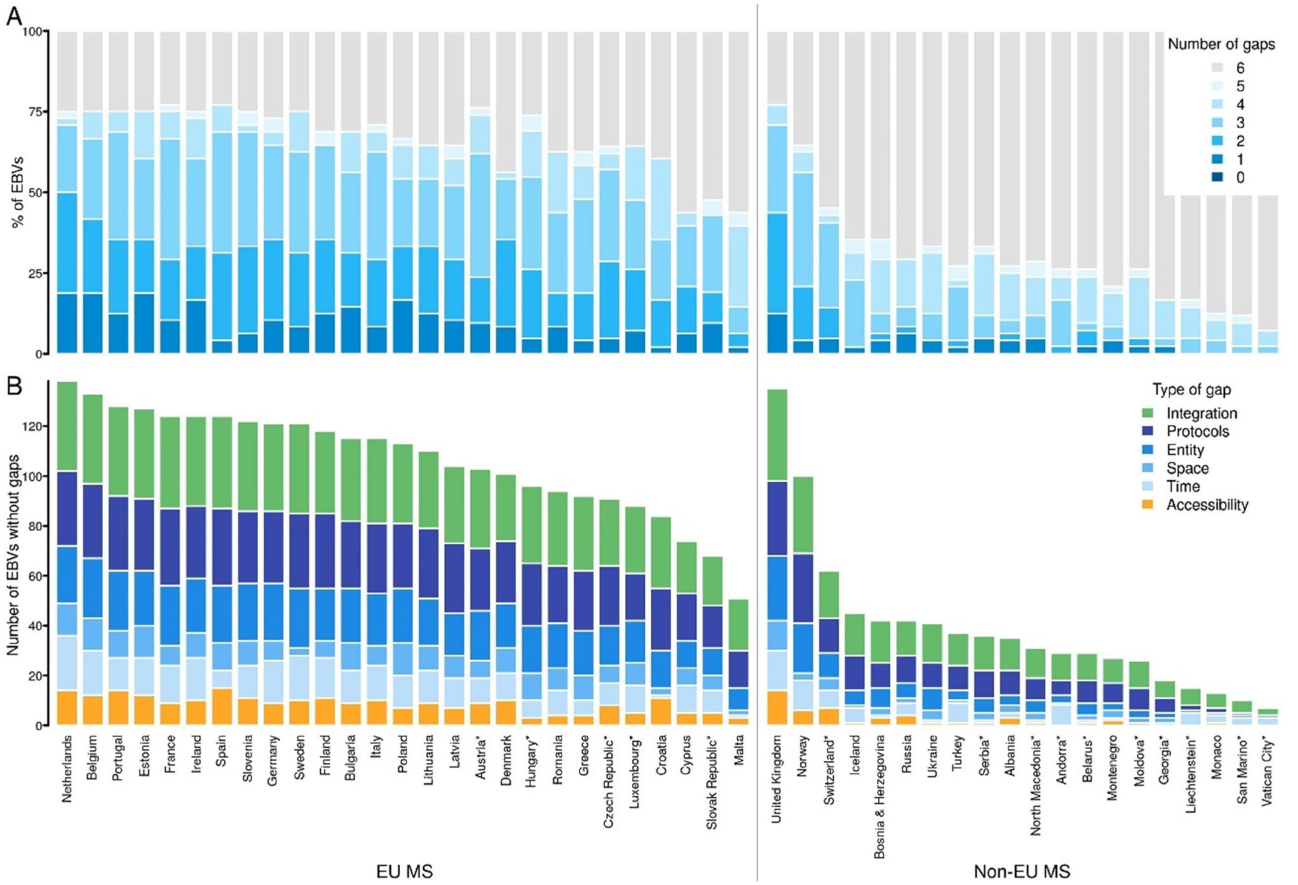

FIGURE 3 | Geographic patterns of monitoring gaps across Europe. (A) The proportion (%) of EBVs with 0 to 6 types of gaps for each European country (including microstates). (B) The number of EBVs without any gap for each country, and that for each gap type. *Marine EBVs were not considered for inland countries. MS = Member State.

variation in the integration gap across EBVs (Figure 2), with integration for 79% of the analyzed EBVs involving <70% of countries, which in most cases are EU-MS (Figure 3, Supporting Information S1: Appendix II).

Most transnational initiatives involved standardized methods applied at the country level (Table S1), resulting in similar gaps in integration and sampling protocol (Figure 2). The exceptions included monitoring using atlas methodologies, for which data on species occurrences were mostly collected opportunistically (Supporting Information S1: Appendix II). Regarding the taxonomic/ecosystem entities, the data produced by most supranational initiatives covered only part of the taxonomic or ecosystem scope defined for each EBV (Figure 2). For instance, some transnational initiatives produce and integrate standardized data for the eight bird EBVs, but five had partial gaps in taxonomic coverage. The largest monitoring gaps were found for spatial and temporal sampling designs. The sampling-site density was generally too low, and the sampling unit too coarse (Figure S1). Likewise, the data were generally insufficient, mostly because sampling was too infrequent and there were few long-term data series (Figure S1). Many atlas initiatives rely heavily on non-standardized, opportunistic data collection and often lack the consistent temporal replication needed for trend analysis (Figure 2, Supporting Information S1: Appendix II). Finally, there were major total or partial gaps in data accessibility, with few initiatives generating data readily accessible for external users (Figure 2). In many cases, accessing data require a request to the owners and may involve fees (Supporting Information S1: Appendix II).

Gaps varied widely across Europe and were typically smaller for EU-MS than for non-EU MS (Figure 3). The main exceptions were the United Kingdom and Norway, which had gaps comparable to the EU-MS. However, the quality of the collected information varied across countries; for instance, obtaining accurate data for some non-EU MS such as Russia, Belarus, Ukraine, Turkey, and the Caucasus region, was challenging, potentially leading to an overestimation of gaps.

4 | Discussion

Wefound significant gaps in biodiversity monitoring to produce Europe-wide EBVs. About one-fifth of the EBVs lacked transnational monitoring initiatives. For others, initiatives existed but often had limited country coverage, as well as gaps in sampling protocols, taxonomic and ecosystem coverage, spatial and temporal designs, and data accessibility. These gaps were widespread but varied among countries. Understanding the drivers of this variation would require further analysis beyond the scope of this study. Our findings underscore the need for coordinated efforts

TABLE 1 | Types of monitoring gaps and criteria for their identification at the country level across Europe. We considered six main types of gaps (Figure 1, G#), each of which is categorized according to one to four criteria (C#). Each criterion is described by a question, the answer to which determines whether there exists a complete ("No") or partial ("Partially") monitoring gap, or whether the criteria are fulfilled with no monitoring gap ("Yes"). For some criteria, the partial gap category was not considered and is therefore marked as not applicable (NA).

Types of Gap	Criterion	Evaluation
G1. Integration (Who?)	**C1**. Country coverage Does the country aggregate national-level monitoring data into a transnational monitoring initiative?	**Gap**: Monitoring data are missing or not integrated transnationally. **Partial gap**: NA.
G2. Sampling protocols (How?)	**C2**. Standardized monitoring Does the monitoring follow a specific sampling protocol (i.e., are sites sampled using the same methods)?	**Gap**: Data collection is based on non-standardized methodologies (i.e., opportunistic observations). Partial gap: Only part of the data is collected following standardized sampling protocols.
G3. Entity (What?)	**C3. Taxonomic/ ecosystem coverage** Does the monitoring encompass all the target taxonomic or ecosystem types needed for producing the EBV as described in its taxonomic/ecosystem scope specifications (Junker et al. 2023; EuropaBON 2023)?	**Gap**: Monitoring only focused on part of the taxonomic (or ecosystem) scope of the EBV (e.g., some fish species vs. the whole fish community). **Partial gap**: Species-level identification only for some taxa, although data/ samples are collected for all taxa.
G4. Spatial sampling (Where?)	**C4. Spatial coverage** Is the spatial coverage of the network of sites sufficient to meet the requirements for the target EBV specifications (Junker et al. 2023; EuropaBON 2023)?	**Gap**: Baseline data have already been used to produce atlases/maps with national coverage with spatial resolution lower than the lower spatial resolution of the EBV; <20% of the WFD water bodies were actually monitored. **Partial gap**: The spatial resolution of the maps/atlases produced was higher than or equal to the lower spatial resolution of the EBV but not the higher spatial resolution of the EBV; >20% of the WFD water bodies were actually monitored for rivers or lakes but not both.
	C5. Minimum sampling unit Is the accuracy at which the sampling location is registered (e.g., exact site, grid cell) higher than or equal to the required EBV spatial resolution, meeting the requirements for the target EBV specifications (Junker et al. 2023; EuropaBON 2023)?	**Gap**: The minimum sampling unit is lower than the EBV desired spatial resolution. **Partial gap**: The minimum sampling unit is lower than or equal to the lower spatial resolution of the EBV but not the higher spatial resolution of the EBV.
G5. Temporal sampling (When?)	**C6. Baseline data** Were there past baseline data (did sampling start before 2012, >10 years), enabling to uncover changes in biodiversity over time?	**Gap**: Monitoring started after 2012, regardless of whether it was a time-series or one-off monitoring. **Partial gap**: NA.
	C7. Ongoing monitoring Was monitoring ongoing by 2021?	**Gap**: The monitoring initiative is no longer being implemented. **Partial gap**: NA.
	C8. Time-series data Does the monitoring sample for at least two different years?	**Gap**: The sampling was conducted in a single year (snapshot, one-off monitoring). **Partial gap**: NA
	C9. Sampling frequency Is the sampling frequency higher than or equal to the EBV desired temporal resolution, being sufficient to meet the EBV specifications (Junker et al. 2023; EuropaBON 2023)?	**Gap**: The sampling frequency is lower than or equal to the lowest desired temporal resolution for the EBV. **Partial gap**: The sampling frequency is lower than the highest desired temporal resolution for the EBV, but not the lowest.

(Continues)

Types of Gap	Criterion	Evaluation
G6. Accessibility (Usable?)	**C10. Data accessibility** Is the monitoring data openly accessible or accessible upon request, and thus available to external users?	**Gap**: The monitoring data collected is not open access nor accessible upon request. **Partial gap**: Raw data are accessible upon request, but payment is required; open access only covers part of the data; data request requires authorization of individual data owners; data are available but only at the EBV spatial resolution (e.g., atlases). Only derived data are accessible (e.g., EQR-values).

to fill these gaps and establish a robust European biodiversity monitoring framework.

A major constraint on EBV production is the absence of transnational monitoring initiatives. For genetic composition EBVs, no such initiatives were found, despite numerous population genetic studies, underscoring a critical gap between research and operational monitoring (Hoban et al., 2022; Pearman et al. 2023). Likewise, we found no initiatives integrating data for lichens, despite their use in environmental monitoring (Rocha et al. 2022); for both disease vectors and crop pests, despite their relevance to human health and agriculture; and for fungi, despite the economic interest of some species. These gaps reflect a broader lack of monitoring for less-charismatic taxa and species that are difficult to identify. No initiative collected data on freshwater zooplankton, likely due to a lack of WFD reporting obligations. Information was also scarce for marine taxa such as deep-sea corals, turtles, pelagic fauna, and microbes, especially in southern and eastern Europe (Jessop et al. 2022). The limited data on the deep sea further underscores the monitoring challenges associated with ecosystems that are difficult to sample. Finally, there were large gaps for EBVs describing species traits, even for charismatic groups such as birds (Weisshaupt et al. 2021).

The most common monitoring gaps involved spatial and temporal sampling designs. Sampling networks were frequently too sparse, and the spatial resolution of sampling units too coarse (Kissling et al. 2018). This affected even the relatively intensive WFD monitoring, which in many countries covers <20% of freshwater waterbodies. Also, while Europe-wide vertebrates atlases generate valuable data, their spatial resolution is often too coarse (e.g., 50 × 50 km; Keller et al. 2020). Temporal gaps were mainly related to the lack of long time-series and low sampling frequency, reflecting insufficient funding for long-term monitoring (Moersberger et al. 2024). For example, information from species distribution atlases often reflects aggregated data over 3–5 years and updated only every 20–30 years, while EBVs generally require data collected at shorter intervals (Junker et al. 2023; EuropaBON 2023). Finally, there are often trade-offs between spatial and temporal replication, with monitoring sometimes involving frequent sampling at a few sites to estimate temporal trends, and a low sampling frequency at many sites to estimate spatial trends (Moe et al. 2023). It is important to note that these spatial and temporal gaps were assessed against EBV-specific requirements defined by stakeholders during the EuropaBON consultation process (Junker et al. 2023), which are often more demanding than the standards applied in other monitoring contexts, such as general species trend assessments.

Gaps were smaller for EBVs based on data from long-standing European monitoring initiatives. The most complete data involved charismatic taxa such as birds and butterflies, supported by decades of work from professionals, citizen scientists, and NGOs (e.g., Keller et al. 2020). Smaller gaps were also found for EBVs produced from WFD monitoring, with data collected by experts, often following European standards, and funded by government agencies and centralized by the European Environment Agency (Moe et al. 2023). A comparable, albeit less structured initiative involves the national data integration by the European National Forest Inventory Network (ENFIN; Vidal et al. 2016). Despite these efforts, none of the corresponding EBVs is free from monitoring gaps. For instance, with some exceptions, data are generated and/or integrated for only a subset of countries, often EU-MS, and there are differences in sampling methods hindering full harmonization. More often, only part of the taxonomic or ecosystem scope of the EBVs is covered, and the spatial and temporal sampling designs adopted are insufficient.

Limited access to raw biodiversity data remains a major obstacle to EBV production, hindering both reuse and independent verification (Kissling et al. 2018; Morán-Ordóñez et al. 2023). Often, only aggregated or synthesized data products are publicly available, while access to the raw data is virtually impossible. This applies to WFD monitoring, where the raw data underlying ecological status classes and Ecological Quality Ratios are stored at national or sub-national levels, with restricted access (Moe et al. 2023). In many cases, data are not readily available and must be requested from owners, such as observers or organizations coordinating fieldwork, typically reliant on volunteers. Additionally, data handling fees may be required to support the long-term maintenance of these biodiversity observation networks. Some marine monitoring initiatives provide processed data through databases such as the Ocean Biodiversity Information System (OBIS), European Marine Observation and Data Network (EMODnet), Database of Trawl Surveys, and Seabirds At Sea, but the raw data are often difficult to access (Jessop et al. 2022).

Addressing current biodiversity monitoring gaps will require coordinated action across multiple levels. First, transnational monitoring initiatives must be expanded to include underrepresented taxa and ecosystems; to cover genetic composition and species traits variables; and to improve participation by countries outside the EU. Secondly, national monitoring programs should be better integrated, particularly those with well-established field networks, thereby contributing to meet both national and supranational policy needs. Most biodiversity data are still generated through these national or subnational programs, but fragmented protocols and limited accessibility hinder their integration into Europe-wide EBVs. Promoting integration will therefore require investment in methodological harmonization, interoperable data infrastructures, and data-sharing practices. Third, more ambitious sampling designs are needed, involving denser spatial coverage and shorter observation intervals, supported by sustained, multi-level funding. Emerging technologies such as eDNA (Ruppert et al. 2019), remote sensing (Reddy 2021), AI-assisted automation (Besson et al., 2022), and citizen science can help reduce costs and increase data collection efficiency. Models can also be used to fill gaps in the network of sites (Fernández et al. 2020), but the extent to which this can be done without compromising results remains understudied. Finally, open access to data following FAIR and CARE principles should be promoted, to ensure justice and data sovereignty, ideally through public repositories (Wetzel et al. 2018; Morán-Ordóñez et al. 2023; Liquete et al. 2024).

Meeting these challenges will require increased investment and more coherent governance of biodiversity monitoring across Europe. Although most monitoring is conducted and funded at the national level, producing Europe-wide EBVs requires coordination, harmonization of methodologies, and integration of data across countries. Without dedicated funding mechanisms and institutions to support transnational alignment, it will be difficult to close the integration gaps we identified. This highlights the strategic importance of initiatives such as the EU Biodiversity Observation Coordination Centre (Liquete et al. 2024), which could provide the necessary infrastructure and policy coherence to enable data integration, methodological standardization, and long-term continuity. Similarly, aligning marine monitoring with Essential Ocean Variables would enable greater synergy with global efforts such as the Global Ocean Observation System (Révelard et al. 2022) and the European Ocean Observation Initiative. Ultimately, a functional and equitable monitoring framework will require transnational funding instruments, interoperable data platforms, and stronger institutional linkages between data collection and conservation decision-making.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The sources of data that support the findings of this study are provided in the Supporting Information.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supplementary Materials: conl13134-sup-0001-SupMat.docx. **Supplementary Materials**: conl13134-sup-0002-SupMat.xlsx. **Supplementary Materials**: conl13134-sup-0003-SupMat.docx.