Global Ecology and Conservation 62 (2025) e03699

Contents lists available at ScienceDirect

Global Ecology and Conservation

journal homepage: www.elsevier.com/locate/gecco

Review article

Towards implementing workflows for essential biodiversity variables at a European scale

Maria Lumbierres[a,k,*], Marija Milanović[b], Pedro Beja[c,d,e], Aletta Bonn[f,g,h], Tom D. Breeze[i], Lluís Brotons[j,k,l], Néstor Fernández[f,m], Jessica Junker[n,o], Camino Liquete[p], Anne Lyche Solheim[q], Alejandra Morán Ordóñez[k,r,s], Francisco Moreira[c,d,e], Joana Santana[c,d,e], Stacy Shinneman[a], Bruno Smets[t], Henrique M. Pereira[d,f,m], Jose W. Valdez[f,m], Roy H.A. van Grunsven[u], W. Daniel Kissling[a]

[a] Institute for Biodiversity and Ecosystem Dynamics (IBED), University of Amsterdam, P.O. Box 94240, Amsterdam 1090 GE, the Netherlands
[b] Department of Community Ecology, Helmholtz Centre for Environmental Research – UFZ, Theodor-Lieser, Permoserstraße 15, Leipzig 04318, Germany
[c] CIBIO, Centro de Investigação Em Biodiversidade e Recursos Genéticos, InBIO Laboratório Associado, Campus de Vairão da Universidade do Porto, Vairão 4485-661, Portugal
[d] BIOPOLIS Program in Genomics, Biodiversity and Land Planning, Campus de Vairão da Universidade do Porto, Vairão 4485-661, Portugal
[e] CIBIO, Centro de Investigação em Biodiversidade e Recursos Genéticos, InBIO Laboratório Associado, Instituto de Agronomia, Universidade de Lisboa, Tapada da Ajuda, Lisboa 1349-017, Portugal
[f] German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig, Puschstrasse 4, Leipzig 04103, Germany
[g] Helmholtz Centre for Environmental Research – UFZ, Department of Biodiversity and People, Permoserstrasse 15, Leipzig 04318, Germany
[h] Institute of Biodiversity, Friedrich Schiller University Jena, Dornburger Strasse 159, Jena 07743, Germany
[i] Centre for Agri-Environmental Research (CAER), School of Agriculture, Policy and Development, University of Reading, Reading, UK
[j] CSIC, Consejo Superior de Investigaciones Científicas, Cerdanyola del Vallès, Spain
[k] CREAF, Centre de Recerca Ecològica i Aplicacions Forestals, Cerdanyola del Vallès, Spain
[l] CTFC, Centre de Ciència i Tecnologia Forestal de Catalunya, Solsona, Spain
[m] Institute of Biology/Geobotany and Botanical Garden, Martin Luther University Halle-Wittenberg, Am Kirchtor 1, Halle (Saale) 06108, Germany
[n] Re:wild, 500 N Capital of Texas Hwy Building 1, Suite 200, Austin, TX 78746, USA
[o] Senckenberg Museum for Natural History Görlitz, Senckenberg – Member of the Leibniz Association, Am Museum 1, Görlitz 02826, Germany
[p] European Commission, Joint Research Centre (JRC), Ispra, Italy
[q] Norwegian Institute for Water Research (NIVA), Økernveien 94, Oslo 0579, Norway
[r] Institute of Ecology and Evolution, Conservation Biology Division, Universität Bern, Baltzerstrasse 6, Bern 3012, Switzerland
[s] Institute of Earth Surface Dynamics (IDYST), Université de Lausanne, Quartier UNIL-Mouline, Bâtiment Géopolis, Lausanne 1015, Switzerland
[t] VITO Remote Sensing, Boeretang 200, Mol 2400, Belgium
[u] Dutch Butterfly Conservation, P.O. Box 506, Wageningen 6700 AM, the Netherlands

ARTICLE INFO

Dataset link: EuropaBON EBV workflow templates and Dataset supporting the implementation of workflows for Essential

ABSTRACT

Biodiversity is declining, prompting new multilateral treaties and environmental legislation. To track the progress of these efforts, a comprehensive monitoring network is essential. For the European Union (EU), the EuropaBON network has proposed a biodiversity observation network (BON) based on 84 Essential Biodiversity Variables (EBVs). These encompass species and habitats

* Corresponding author at: Institute for Biodiversity and Ecosystem Dynamics (IBED), University of Amsterdam, P.O. Box 94240, Amsterdam 1090 GE, the Netherlands.
E-mail address: m.lumbierres@creaf.cat (M. Lumbierres).

https://doi.org/10.1016/j.gecco.2025.e03699
Received 16 December 2024; Received in revised form 28 May 2025; Accepted 19 June 2025
Available online 22 June 2025

Biodiversity Variables (EBVs) at a European scale

Keywords:
Biodiversity monitoring
Data flows
Essential Biodiversity Variables
Environmental policy
Model-based data integration
Novel monitoring methods
Stakeholder engagement

in the freshwater, marine, and terrestrial realms. Generating EBVs will require implementing workflows, including data collection, integration, and modelling. Here, we present the first conceptual representation of EBV workflows for guiding the future implementation of EBVs in a European BON based on insights from an EU-wide stakeholder consultation that engaged hundreds of experts in science, policy, and practice. Results suggest that implementing EBV workflows requires to incorporate advanced monitoring methods, enhance geographic, taxonomic, and temporal coverage, harmonize heterogeneous data, apply metadata standards, and develop new spatial models and quantitative indicators. Recommendations include enhancing monitoring techniques such as digital sensors, DNA-based methods and citizen science for species-focused EBVs, as well as satellite and aerial remote sensing for ecosystem-focused EBVs. For operationalizing a European BON, species-focused EBVs require better national, regional, and European data integration of different data types and data providers. In contrast, monitoring of ecosystem-focused EBVs would benefit from a centralized coordination of ground truth data collection and new Earth Observation products. The key components of the EBV workflows, along with the requirements and implementation needs identified here, together with emerging tools and projects, will help to shape the future implementation of EBV workflows at a European scale.

1. Introduction

Global biodiversity loss is a major threat to human wellbeing and has accelerated in recent decades (Díaz et al., 2019). To halt biodiversity loss, scientific and political institutions are responding with new multilateral agreements and environmental legislation. For instance, the COP15 of the Convention on Biological Diversity (CBD) convened in 2022 to the Kunming-Montreal Global Biodiversity Framework (GBF) with a set of goals for 2050 and milestones and targets for 2030 to reach a world living in harmony with nature. At the same time, the European Union (EU) recently adopted the EU Biodiversity Strategy for 2030 and the Nature Restoration Law, which aims to extend protected areas, increase the amount of strictly protected areas and restore at least 20 % of the EU land and sea. To effectively track the progress of policy targets, a robust biodiversity monitoring network is needed (Gonzalez et al., 2023; Moersberger et al., 2024). In Europe, existing monitoring networks suffer from taxonomic, spatial, and temporal gaps and biases, and lack of harmonisation and comparability, limiting their capacity to support and inform current and future legislation (Hermoso et al., 2017; Santana et al., 2023).

To improve monitoring efficiency and robustness, the Group on Earth Observations Biodiversity Observation Network (GEO BON) developed a framework based on the concept of Essential Biodiversity Variables (EBVs). EBVs are defined as a minimum set of measurements necessary to detect changes in biodiversity across time and space (Pereira et al., 2013). EBVs are classified into six classes: three classes focus on species (genetic composition, species populations and species traits) and three on communities and ecosystems (community composition, ecosystem functioning and ecosystem structure). GEO BON has also developed a globally coordinated strategy based on Biodiversity Observation Networks (BONs), which can be national, subnational, regional or thematic, to sustain an operational monitoring (Navarro et al., 2017). Following the principles of GEO BON, the EuropaBON network (Pereira et al., 2022), with the mandate from the European Commission, developed a proposal for an integrated biodiversity monitoring framework in the European Union (Kissling et al., 2024a). Through a participatory process, EuropaBON identified 84 EBVs to measure biodiversity across Europe's freshwater, marine, and terrestrial realms, encompassing all six EBV classes and a wide range of taxonomic groups and ecosystems (Junker et al., 2023). The network provided practical recommendations to boost the efficiency of the European biodiversity observation network and proposed the establishment of an EU Biodiversity Observation Coordination Centre (Liquete et al., 2024), all with the goal of fostering the generation and use of high-quality data to underpin the biodiversity knowledge-base used across EU policies. The proposed EBVs are measurable with existing technologies, but the details of how exactly to generate them still need to be specified.

Generating EBVs requires workflows that specify the procedures for data collection (e.g. species distributions, community composition, or habitat structure), integration (e.g. cleaning, standardising, harmonising, and merging the data), and spatially explicit models (Boyd et al., 2023; Fernández et al., 2020; Kissling et al., 2018a). For the collection of raw data, monitoring programs in the EU often focus on structured field-based monitoring programs for species and communities, and on satellite remote sensing for ecosystems and land cover monitoring (Santana et al., 2023). However, since monitoring data remain incomplete and fragmented, building an effective BON in Europe would benefit from the integration of additional data obtained from other sources and monitoring techniques (Kühl et al., 2020; Liquete et al., 2024; Proença et al., 2017). The monitoring community in Europe is actively advancing the adoption of techniques that augment data coverage and cost-effectiveness (Dornelas et al., 2023; van Klink et al., 2022). For instance, DNA-based methods such as amplified fragment length polymorphism (AFLP), microsatellites and environmental DNA (eDNA), along with digital sensors like camera traps, audio devices, and GPS tags, can provide data for species-focused EBVs (Hoban et al., 2022; Steenweg et al., 2017). Airborne remote sensing methods with drones, airplanes, and weather radar provide additional data on communities, ecosystems, and habitats. Overall, citizen science initiatives provide important additional observations through unstructured or semi-structured programs (Pocock et al., 2018), especially for species-focused EBVs (Jetz et al., 2019). However, the integration of data from these diverse monitoring techniques into EU reporting streams still needs to be fully realised (Moersberger et al., 2024).

Data integration and modelling are essential for EBV workflows because they allow incorporating heterogeneous data and filling gaps in data cubes (Fernández et al., 2020; Kissling et al., 2018a). Achieving this requires a coordinated effort to standardise metadata, harmonise different data formats, develop model-based data integration, ensure data accessibility and interoperability, establish nodes to coordinate monitoring, and develop and assess the uncertainty of spatial models (Hardisty et al., 2019; Kissling et al., 2018a; Isaac et al., 2020). In Europe, the degree of data integration, data sharing, and modelling varies among biodiversity initiatives with significant gaps and bottlenecks in the availability and accessibility of raw data, the automatisation of dataflows, and the development of spatially-explicit models, user-friendly software, and open-access code (Morán-Ordóñez et al., 2023a; Santana et al., 2023). Currently, most biodiversity monitoring in Europe that is connected to various nature legislations, such as the Birds Directive, the Habitats Directive, the Water Framework Directive, and the Marine Strategy Framework Directive, only produces qualitative indicators of the status and trends of species and habitats (European Environment Agency., 2020). Some quantitative indicators exist, such as the Grassland Butterfly Index and the Farmland Bird Index, and are now being used to support the EU Nature Restoration Law. Nevertheless, the underlying raw data used for EU-wide assessments are often not openly accessible. The scientific community addresses these challenges by developing innovative techniques and methods for improving data integration and modelling (Dornelas et al., 2023). Despite these efforts, there is currently no comprehensive overview for how data integration and modelling for implementing EBVs in a European BON could be conducted and advanced for the marine, freshwater, and terrestrial realms.

Here, we present the first conceptual representation of workflows to guide the future implementation of EBVs in the EU. We outline EBV workflows that highlight the current capacities and needs for implementing and standardising transnational and transinstitutional data streams covering data collection, data integration and modelling. Using a comprehensive stakeholder consultation, we identify specific areas where workflows can be improved to support EBV generation for a new European BON. Specifically, we (1) assess the potential use of various monitoring techniques (structured field-based monitoring, citizen science, DNA-based methods, digital sensors, satellite remote sensing, and aerial or other remote sensing techniques) for complementing the collection of EBV-relevant data at the EU scale; (2) exemplify marine, terrestrial and freshwater EBV workflows of current monitoring initiatives in the EU; and (3) identify specific needs and requirements for advancing EBV workflows and how this aligns with tools and projects currently in developement. Leveraging these insights, we visualise workflows for both species-focused and ecosystem-focused EBVs and discuss how emerging tools and projects in Europe are currently being developed to support them. These results can help to advance the implementation of EBV workflows and guide actions for establishing a European BON.

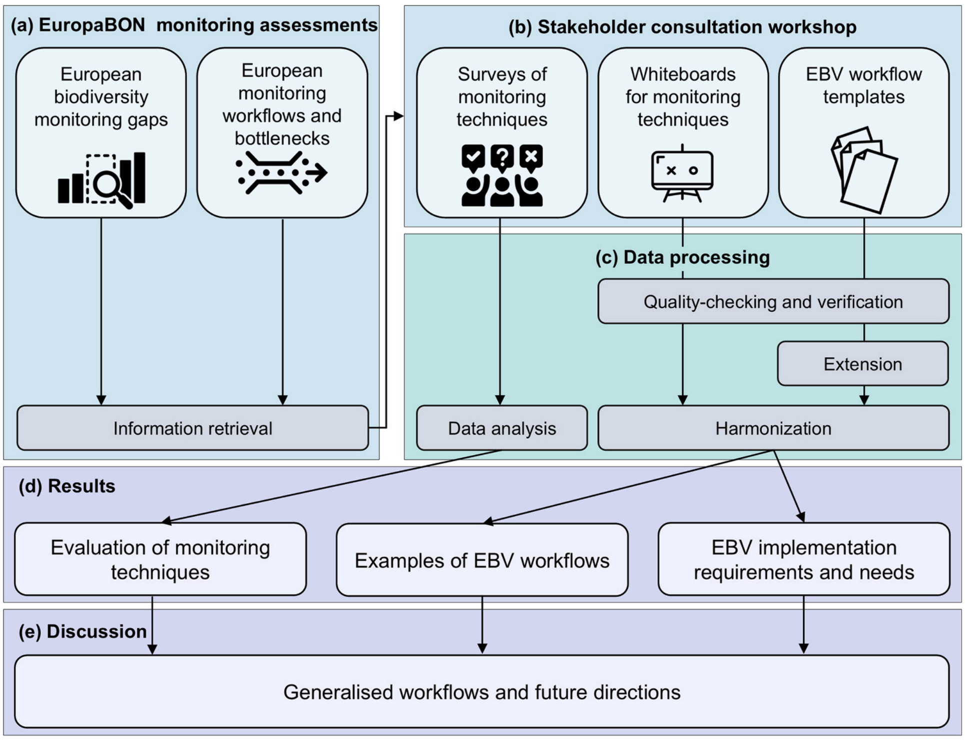

Fig. 1. Methodological framework for this study, including data collection through (a) EuropaBON assessments and (b) a stakeholder workshop, with (c) subsequent data processing, (d) results parts, and (e) discussion.

2. Materials and methods

2.1. Methodological approach

Our analysis is based on two main inputs (Fig. 1): a review of the EuropaBON monitoring gaps and bottlenecks assessments (Fig. 1a) and a stakeholder consultation workshop (Fig. 1b). The information was processed (Fig. 1c) to derive three main analyses, namely (1) an evaluation of monitoring techniques, (2) examples of EBV workflows, and (3) a summary of requirements and needs for implementing EBV workflows at a European scale (Fig. 1d). In the discussion, we then visualise generalised workflows for species-focused and ecosystem-focused EBVs and discuss future directions (Fig. 1e). Details of each of these steps are provided below.

2.2. EuropaBON monitoring assessments status

We retrieved preliminary information on the status of workflows for the European biodiversity monitoring from two EuropaBON monitoring assessments (Fig. 1a). The first assessment was a comprehensive gap analysis (Santana et al., 2023) which summarised the potential of using current biodiversity monitoring data to produce EBVs across Europe at a spatial and temporal resolution and taxonomic and ecosystem scope as identified by EuropaBON (Junker et al., 2023). It specified the geographic, temporal and taxonomic gaps in data collection for each EU member state using criteria such as country coverage, taxonomic and ecosystem coverage, standardised sampling protocols, temporal replication, length of time series, existing monitoring capacities, sampling frequency and density, and accessibility of raw data (Santana et al., 2023). This assessment covered 44 (63 %) of the 70 EBVs identified by EuropaBON at that point in time (Junker et al., 2023), focusing on EBVs for which transnational integration initiatives exist and which rely on data derived from structured field-based monitoring programmes.

The second EuropaBON assessment was an analysis of EBV workflow bottlenecks in Europe (Morán-Ordóñez et al., 2023a). It identified limitations in the current data flows of EU biodiversity monitoring programmes using sixteen criteria related to data collection and sampling, modelling, interoperability, IT infrastructure, and data integration (Morán-Ordóñez et al., 2023a). This analysis included 36 EBVs (51 %) of the 70 EBVs identified by EuropaBON at that point in time, representing initiatives that had developed transnational workflows based on structured field-based monitoring data.

From these two assessments, we retrieved preliminary information about the current implementation of workflows for ~50–60 % of the EBVs. The gap analysis (Santana et al., 2023) provided information on data collection and sampling efforts, whereas the workflow bottleneck analysis (Morán-Ordóñez et al., 2023a) provided information on data integration and modelling activities at transnational and European level. We entered the information from the two assessments into EBV workflow templates that were specifically designed for our stakeholder workshop (Fig. 1b). The information available from the two assessments thus served as a baseline input for the expert consultation in the workshop.

2.3. Stakeholder consultation workshop

We conducted an online stakeholder workshop on 22–24 February 2023 with the aim to co-design the future freshwater, marine and terrestrial EBV workflows for a European BON. The workshop had 520 self-enrolled participants from 49 countries, with diverse expertise across terrestrial, marine, and freshwater realms, covering all EBV classes, various monitoring techniques, and the three workflow components (data collection, data integration and modelling) (Lumbierres and Kissling, 2023). Most workshop participants (67 %) had expertise in in-situ monitoring while 24–37 % had experience in citizen science, DNA-based methods, digital sensors, satellite remote sensing, and aerial or other remote sensing. The majority (85 %) had experience with data collection, whereas about half (40–50 %) were familiar with data integration and modelling (Lumbierres and Kissling, 2023). Before the workshop, an input document was provided to the registered participants containing background on the 70 EBVs as identified by EuropaBON together with some examples of EBV workflows (Kissling and Lumbierres, 2023). In the workshop, participants were then asked to provide EBV-specific information on workflow components, and the use of monitoring techniques for collecting EBV-relevant data. Additionally, participants identified EU or national initiatives that can generate EBV-relevant data, and were asked to highlight emerging tools and specify future needs and requirements for operationalising EBVs at a EU scale.

Three different online documents were used to obtain information from the participants: (1) surveys of monitoring techniques, (2) whiteboards for monitoring techniques, and (3) EBV description tables (workflow templates) (Fig. 1b). During the workshop, we conducted a set of online surveys to assess the relevance of different monitoring techniques for collecting data for each EBV (see example survey in Appendix A). The online surveys consisted of six separate questionnaires, i.e. one for each monitoring technique (structured field-based monitoring, citizen science, DNA-based methods, digital sensors, satellite remote sensing, and aerial remote sensing). The survey respondents had to indicate the importance of a specific monitoring technique for each of the 70 EBVs, with possible responses being "yes," "partially," "no," or "I don’t know". Participants were asked to reply to the questionnaire that contained the monitoring technique in their field of expertise. The number of responses per survey varied for each questionnaire, ranging from 14 to 41.

Structured whiteboards (provided as online Miro Boards) were used to obtain information on the overarching needs and requirements for implementing specific biodiversity monitoring techniques at the European scale (see Miro Boards in Appendix B). Six Miro Boards were used, one for each of the following monitoring techniques: structured field-based monitoring, unstructured citizen-science observations, DNA-based methods (e.g. microsatellites and metabarcoding), digital sensors (e.g. cameras and acoustic devices), satellite remote sensing, and aerial and other remote sensing (including drones, airplane remote sensing surveys and weather radar). The boards were structured to represent the three different EBV workflow components (data collection, data integration, modelling) and aspects of interoperability and IT infrastructure. Participants were allocated to a breakout group according to their expertise in a monitoring technique and asked to add their suggestions for implementation requirements into the whiteboard. An online discussion was fostered amongst the participants of each break-out group to aggregate the identified needs into broader thematic topics (Lumbierres and Kissling, 2023).

A collection of EBV workflow templates (provided as Google Docs) was further used to gather information on workflow descriptions for each EBV (see example of EBV workflow template in Appendix C). At the time of the workshop, 70 EBVs had been identified (see EBV list in Appendix D). The templates were organised in three rows to capture information about the different workflow components, i.e. data collection, data integration, and modelling (Lumbierres et al., 2024). Additionally, each workflow component was described in three columns to represent different implementation levels. The first column ('Current initiatives') aimed to capture information on workflows as they are currently implemented, e.g. for European-level integration initiatives of biodiversity monitoring schemes or the current regulatory reporting under EU policies such as the Water Framework Directive (WFD), the Land Use and Coverage Area frame Survey (LUCAS), or the European Butterfly Monitoring Scheme (eBMS). Before the workshop, some information on current initiatives was pre-filled with information from the EuropaBON assessments. The second column ('Emerging tools and projects') captured emerging tools and EU projects that are developing new data collection, data integration, and modelling tools, but which still need to become operational for EU regulatory policies reporting. The third column ('Future needs') captured the requirements and needs for future EBV workflow implementation, i.e., what is additionally needed to operationalise EBVs across Europe.

Table 1
Harmonised categories to describe expert-derived requirements and needs for implementing and enhancing EBV workflows and monitoring techniques consistently and comparably. The categories are separated into three EBV workflow components (data collection, data integration, and modelling).

Harmonized categories	Definition
Data collection	
Development of data collection protocols	Development of systematic procedures for data collection tailored for EBV production at the EU scale and adapted to the social and ecological characteristics of EU member states.
Utilisation of advanced data collection methods	Use of monitoring methods other than structured field-based monitoring schemes, i.e. monitoring methods such as citizen science, DNA-based methods, digital sensors, satellite remote sensing and aerial remote sensing.
Improvement of raw data	Enhancement of raw data through additional measurements, e.g. to improve accuracy, detail, or resolution, including additional measurements or augmenting the number of replicates at each monitoring site.
Increase or adjustment of the taxonomic scope	Modify the sampling design to increase or adjust the included biological entities, such as species or ecosystem types.
Expansion of geographical coverage	Expand the spatial extent and resolution of monitoring, including the location and density of sampling sites or monitoring in additional countries, ecosystems, and regions.
Increase temporal coverage	Increase sampling frequency and promote the creation of denser time series.
Data integration	
Integration and harmonisation of multi-source data	Combine data collected using different methods and sources.
Implementation of metadata and data standards	Development and adoption of controlled vocabularies, ontologies, and consistent structure that describes data and their metadata systematically.
Improvement of data availability and accessibility	Improve the availability and accessibility of raw data under the FAIR guiding principles (Wilkinson et al., 2016). This includes mobilising data and creating legal data agreements for data sharing.
Establishment and improvement of databases	Set up and manage databases, including both data repositories and reference databases. Data repositories are platforms to store and share raw and processed data, using a persistent taxa record identifier. Reference databases compile annotated data for training and validation, with relevance for taxonomy, AI species recognition, metabarcoding, and remote sensing image analysis.
Automatization of data streams	Improve the automation of data handling, including automated data collection, automatization of data transfers, and automated harmonisation of EBV-relevant data.
Creation, support, or improvement of coordination and integration nodes	Strengthen the organisations or institutions at national, regional, or European scale that are responsible for coordinating the sampling and integration of biodiversity monitoring data
Strengthening of capacity building	Develop programs to enhance the skills of monitoring practitioners, including training in the EBV framework, sampling methods, and taxonomic expertise.
Modelling	
Identification and prioritisation of metrics	Select the best metrics for an EBV to effectively capture the spatial and temporal change of the targeted taxa, community, or ecosystem status.
Addition and improvements of predictors	Expand the set of predictor variables to enhance model predictions and improve the accessibility and accuracy of variables.
Development of spatial models	Develop or improve models to produce spatially explicit EBVs, including SDMs, classification algorithms, spatial interpolation or upscaling algorithms. This allows to derive continuous probability surfaces (i.e., wall-to-wall estimates) for species and habitats. Tailor models to specific areas and taxonomic groups.
Development of data pre-processing models	Develop models for preparing and refining data before EBV production, such as AI species identification models and imputation models to fill data gaps.
Development of indicators	Develop indicators for quantifying ecological or biodiversity change, and other decision support tools, including trend analysis and attribution to drivers of biodiversity change.
Assessment of uncertainties and biases	Better assess the potential errors, biases, and uncertainties inherent in EBV-relevant models.
Improvement of model accessibility, software, and code	Improve the availability and accessibility of models through the development of user-friendly interfaces, promotion of open-source code, and training for programming and modelling.

2.4. Data processing

After the workshop, the three types of documents were processed (Fig. 1c). For the monitoring techniques surveys, we analysed the data by computing the percentages of positive, partial, and negative responses for each combination of EBV and monitoring technique. These results were summarised by EBV class, separately summing the "yes," "partially," and "no" responses of EBVs in the same EBV class for each survey. Subsequently, the percentages of positive, partial, and negative responses were calculated for each EBV class and monitoring technique.

For the EBV workflow templates and the whiteboards, information was first quality-checked and verified by proofing that each listed integration initiative or project was part of an active monitoring scheme and pertinent to the specific EBV, using the initiatives' websites, a reference database on European monitoring initiatives (Morán-Ordóñez et al., 2023b), and other data on biodiversity data workflows collected in the previous EuropaBON assessments (Morán-Ordóñez et al., 2023a; Santana et al., 2023). We ensured that the requirements and needs for implementation which were listed in the EBV workflow templates were correctly placed for each workflow component (data collection, data integration and modelling) and implementation level ('Current initiatives', 'Emerging tools and projects' or 'Future needs'). We further completed missing information in the EBV workflow templates, e.g. initiative names or sources if workshop participants had not provided sufficient details by reviewing the sources provided by the participants and other online information. We then summarised the initiatives' primary workflow tasks, stating the data collection methods and geographical or taxonomical coverage and identifying the types of modelling and databases utilised. The cleaned and quality-checked EBV workflow templates are available on Zenodo (Lumbierres et al., 2024). For both the EBV workflow templates and the whiteboards, we also harmonised the information on the requirements and needs for EBV implementation. We developed categories and definitions to describe the information provided by the participants in a consistent way (Table 1) and assigned each requirement or need listed by the

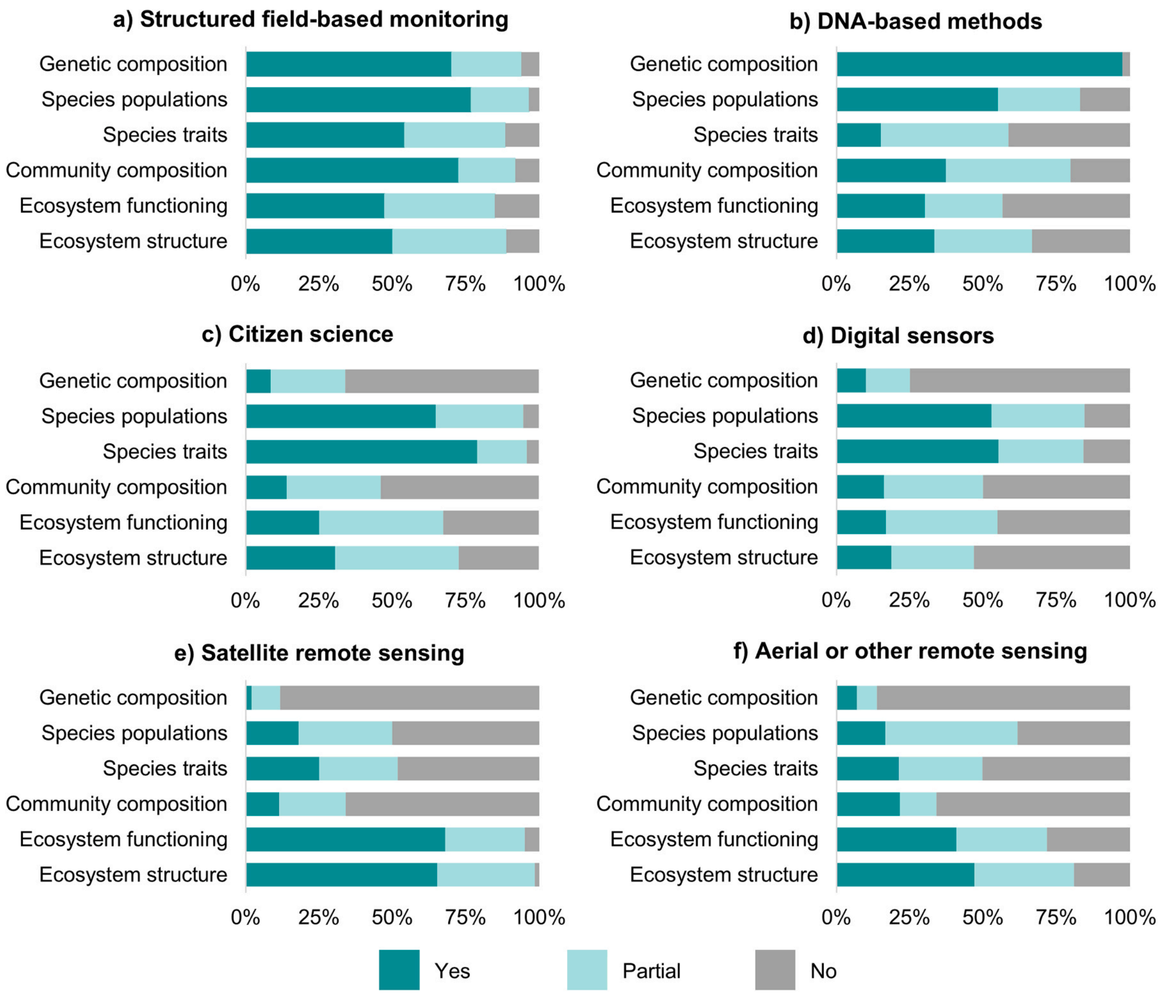

Fig. 2. Relative importance of different monitoring techniques for data collection by EBV class. Results show the % answers (yes, partial, no) from online surveys conducted during the stakeholder workshop, asking whether a monitoring technique is of central importance for an individual EBV. Answers for individual EBVs were aggregated by EBV class.

participants to one of these categories (see the list of all requirements and needs classified into harmonised categories in 'Data availability'). We matched the emerging tools listed in the EBV workflow templates with the harmonised categories (see the list of emerging tools and projects classified into harmonised categories in 'Data availability').

2.5. Outputs

The processed information from the three types of documents of the stakeholder workshop led in three main results (Fig. 1d). First, we present an evaluation of monitoring techniques by quantifying their potential to support EBV data collection across Europe. The surveys were aggregated into EBV classes for each monitoring technique. Second, we present visualisations of EBV workflows as described in the 70 EBV workflow templates (Lumbierres et al., 2024). Since not all the EBV workflows could be visualised here, we selected three examples that represent the marine, freshwater and terrestrial realms as well as species-focused and ecosystem-focused EBVs. Third, we present the requirements and needs for implementing EBV workflows at the EU scale. This was derived from the 70 EBV workflow templates and the six whiteboards for monitoring techniques, i.e., summarising needs and requirements as identified by the workshop participants. The needs and requirements were compared to how emerging tools and projects in the EU initiatives address these challenges. We present this by comparing the number of EBVs associated with each need and requirement with the number of EBVs that have initiatives dedicated to these needs.

3. Results

3.1. Evaluation of monitoring techniques

The online surveys showed that monitoring techniques vary in their importance for each EBV class (Fig. 2). Structured field-based monitoring was considered of central importance for monitoring all EBV classes (Fig. 2a). However, the highest importance was identified for species populations and community composition, with > 90 % of the survey answers considering structured field-based monitoring to be at least partially relevant (Fig. 2a). DNA-based methods were regarded as the primary method for genetic composition, with 98 % of the survey answers seeing it as centrally important (Fig. 2b). With 83 %, DNA-based methods were also considered at least partially relevant for species populations EBVs (Fig. 2b). Citizen science was considered a central data collection method for species populations and species traits EBVs, with 95 % of the survey answers viewing it as at least partially important (Fig. 2c). Digital sensors were most relevant for monitoring species populations and species traits (Fig. 2d), with 85 % of the survey answers considering it at least of partial use. Satellite and aerial remote sensing techniques were judged to be especially important for monitoring ecosystem functioning and ecosystem structure, with satellite remote sensing being of higher relevance than aerial or other remote sensing (Fig. 2e,f). Remote sensing was considered less relevant for the other four EBV classes.

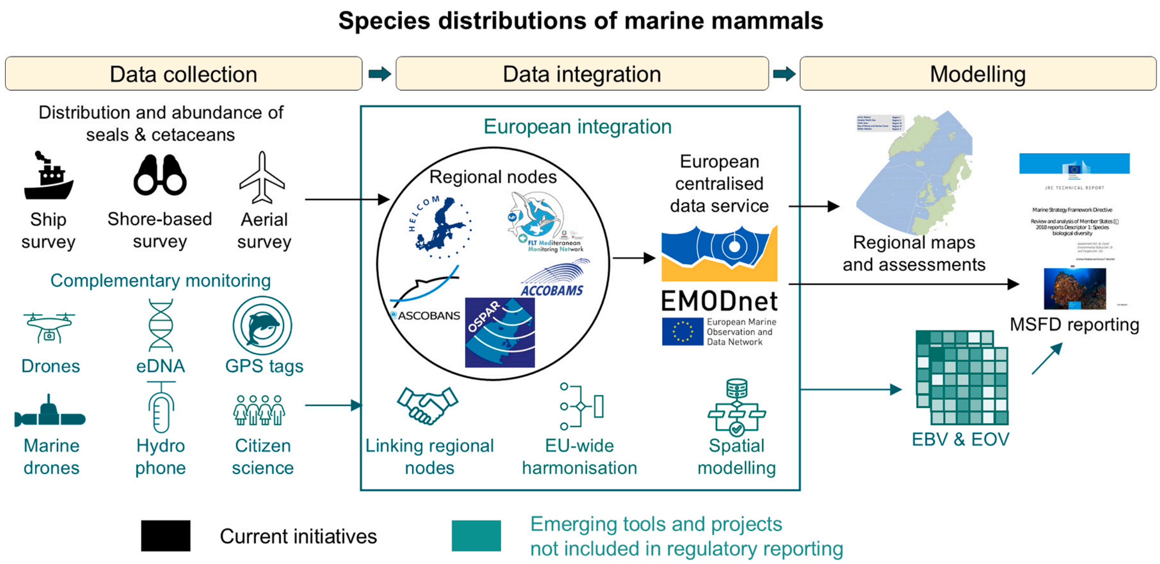

Fig. 3. EBV workflow for species distributions of marine mammals. Currently existing parts of the workflow are shown in black while emerging tools from new projects are shown in green. Additional details can be found in the EBV workflow template (Lumbierres et al., 2024). Abbreviations: HELCOM = Helsinki Commission or Baltic Marine Environment Protection Commission, ACCOBAMS = Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and Contiguous Atlantic Area, OSPAR = Oslo and Paris Convention or Convention for the Protection of the Marine Environment of the North-East Atlantic, ASCOBANS = Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas, MSFD = Marine Strategy Framework Directives, EBV = Essential Biodiversity Variable, EOV = Essential Ocean Variables.

3.2. Examples of EBV workflows

The 70 EBV workflow templates revealed significant variability in their components and development levels (see completed templates in 'Data availability'). Despite this variability, certain patterns emerged within specific EBV classes and realms, indicating some commonalities in how these workflows are structured. Below we provide one example and visualisation for the marine, freshwater and terrestrial realms, respectively.

The first workflow visualisation is for the EBV 'Species distributions of marine mammals' (Fig. 3), representing an example of species populations EBVs. The primary data collection involves ship transect surveys, complemented with shore-based and aerial surveys. Advanced methods, such as marine drones, GPS tracking, and hydrophones, are being deployed to complement data collection. However, these data still have limited integration at a European scale. Each regional sea is managed by its respective Regional Sea Conventions, which operate with varying monitoring programs, investments, and protocols. In recent years, substantial efforts have been made to aggregate and harmonise different marine datasets through the European Marine Observation and Data Network (EMODnet). Species distribution models are produced for some mammal species (e.g. distribution of harbour porpoise *Phocoena phocoena* across the Baltic Sea), but those are limited to specific regions, and have a coarser resolution than that suggested for the EBV. Some initiatives and projects such as the MARine COastal BiOdiversity Long-term Observations (MARCO-BOLO, UKRI Horizon Europe), the Marine Biodiversity Observation Network (MBON) or the Intergovernmental Oceanographic Commission (IOC), are underway to coordinate the development and integration of EBVs with Essential Ocean Variables (EOVs) (Miloslavich et al., 2018). The data collection and integration components observed in the marine mammal species distribution EBV workflow, such as the diverse monitoring methods and region-specific integration bodies, reflect common characteristics across most marine species-focused EBVs.

A second workflow visualisation illustrates the EBV 'Harmful and non-harmful freshwater algal blooms' (Fig. 4), representing an example of freshwater ecosystem EBVs. Two parts can be distinguished, one based on in-situ lake water sampling and one based on satellite remote sensing data. The first is associated with the regulatory monitoring under the WFD, which is representative of most of the freshwater community composition EBVs. Water samples are collected in lakes and rivers using standardised protocols. In the case of algal blooms, the biovolume of cyanobacteria and their proportion of total phytoplankton biovolume are collected. A few countries report these data to the Water Information System for Europe (WISE). The second part of the workflow on algal blooms is linked to remote sensing data from the European Union's space programme Copernicus. The European Space Agency (ESA) operates satellites and is responsible for collecting satellite remote sensing data through its Earth Observation (EO) missions. The data are processed and further analysed by the Copernicus program, which ESA co-manages with the European Commission, providing a range of EO products. Information on algal blooms is included in the Lake Water Quality products of Copernicus, published every 10 days at 100 m resolution. This information, however, is currently not included in the WFD reporting because it only focuses on in-situ data. Moreover, many countries report the phytoplankton community EBV as Ecological Quality Ratio (EQR) values (rather than providing the biovolume raw data for cyanobacteria and phytoplankton), indicating the deviation from reference conditions. Since national EQR values are not always directly comparable, the European Environment Agency (EEA) or the data providers normalise them to a harmonised scale, ranging from 1 (best conditions) to 0 (worst conditions). The example of harmful and non-harmful algal blooms illustrates that community composition data from in-situ monitoring (derived from water samples) and satellite data from the Copernicus program are neither integrated nor used complementary for WFD reporting. A stronger European integration, including citizen science

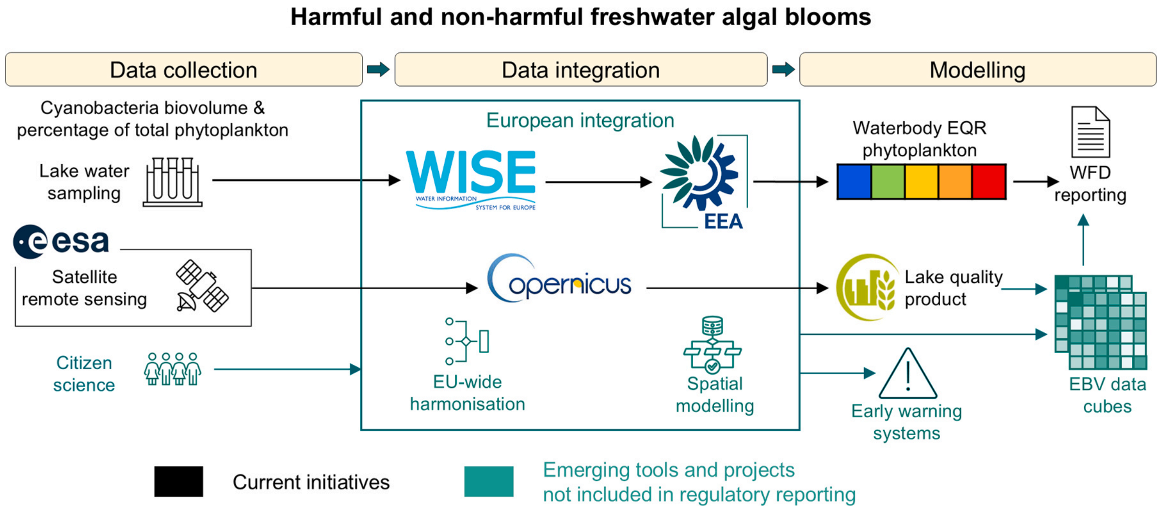

Fig. 4. EBV workflow for harmful and non-harmful freshwater algal blooms in Europe. Currently existing parts of the workflow are shown in black while emerging tools from new projects are shown in green. Additional details can be found in the EBV workflow template (Lumbierres et al., 2024). Abbreviations: ESA = European Space Agency, WISE = Water information system for Europe, EEA = European Environment Agency, EBV = Essential Biodiversity Variable, EQR = Ecological Quality Ratio, WFD = Water Framework Directive.

observations, could help to improve both early warning systems and regulatory monitoring under the WFD (Fig. 4).

The third workflow visualisation illustrates the EBV 'Community abundance and taxonomic diversity of pollinator insects' (Fig. 5), representing an example of a terrestrial community composition EBV. Current European-wide monitoring for pollinators is limited to butterflies and moths collected by the eBMS, which uses standardised protocols for transect sampling and a citizen science app to gather data on species counts. European data integration for the eBMS is coordinated by Butterfly Conservation Europe. The data are then used to estimate species trends, and in a European context, specifically the Grassland Butterfly Index. Since the approval of the EU Pollinators Initiative and the increased focus on pollinator monitoring within the Common Agricultural Policy (CAP), there has been growing interest in developing a comprehensive, systematic EU Pollinator Monitoring Scheme. This proposed scheme aims to expand the taxonomic scope of current monitoring efforts and multiple methods have been piloted by the SPRING project (Strengthening Pollinator Recovery through Indicators and Monitoring), which seeks to enhance taxonomic capacity for pollinating insects and prepare for the implementation of an EU Pollinator Monitoring Scheme. Similar to pollinators, other in-situ monitoring schemes, particularly for species-focused EBVs, could benefit from diversifying monitoring methods and incorporating advanced technologies, enabling an expanded geographic, temporal, and taxonomic scope. However, like pollinator monitoring, achieving this will require enhanced European integration to ensure standardised and harmonised data across initiatives.

3.3. *EBV implementation requirements and needs*

After harmonising the information from the 70 EBV workflow templates, a total of 483 requirements and needs and 257 emerging tools and projects were identified (see completed templates in 'Data availability'). These expert-based suggestions were well distributed across the three workflow components (Fig. 6a–c).

For data collection, the use of advanced data collection methods was identified as the highest need, closely followed by the expansion of geographical coverage, the increase or adjustment of taxonomic scope, the development of data collection protocols, and the increase of temporal coverage (Fig. 6a, dark green bars). Examples included the expansion of camera trapping networks across Europe, a wider coverage of marine biodiversity monitoring in the Mediterranean, Macaronesia and the Black Sea, and broadening the taxonomic scope of monitoring beyond the species listed in Annexes II and IV of the Habitats Directives (Council Directive 92/43/EEC). Among the emerging tools and projects identified by the experts, numerous initiatives were listed that focus on the use of advanced data collection methods and the development of data collection protocols. However, compared to the identified requirements and needs, there were fewer emerging tools and projects mentioned for targeting the expansion of geographical coverage, the increase or adjustment of taxonomic scope, and the increase of temporal coverage (Fig. 6a, compare light green with dark green bars).

For data integration, the integration and harmonisation of multi-source data was identified as the most important need, closely followed by the improvement of data availability and accessibility, the implementation of metadata and data standards, and the creation, support or improvement of coordination and integration nodes (Fig. 6b, dark green bars). Additionally, the establishment of databases and automatization of data streams was considered important. Several emerging tools and projects were highlighted as addressing these needs, albeit with strong differences when compared to the needs (Fig. 6b, compare light green with dark green bars). For instance, few emerging tools and projects were identified relative to the need for improving data availability and accessibility and creating, supporting, or improving coordination and integration nodes (Fig. 6b). In contrast, the integration and harmonisation of multi-source data, the implementation of metadata and data standards, and the establishment and improvement of databases showed a

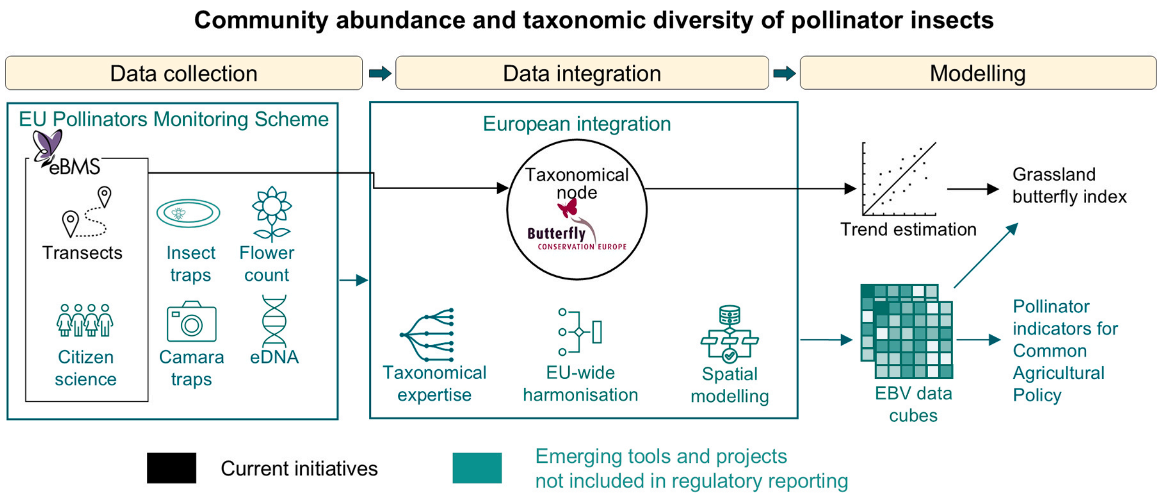

Fig. 5. EBV workflow for community abundance and taxonomic diversity of pollinator insects in Europe. Currently existing parts of the workflow are shown in black while emerging tools from new projects are shown in green. Additional details can be found in the EBV workflow template (Lumbierres et al., 2024). Abbreviations: eBMS = European Butterfly Monitoring Scheme, EBV = Essential Biodiversity Variable.

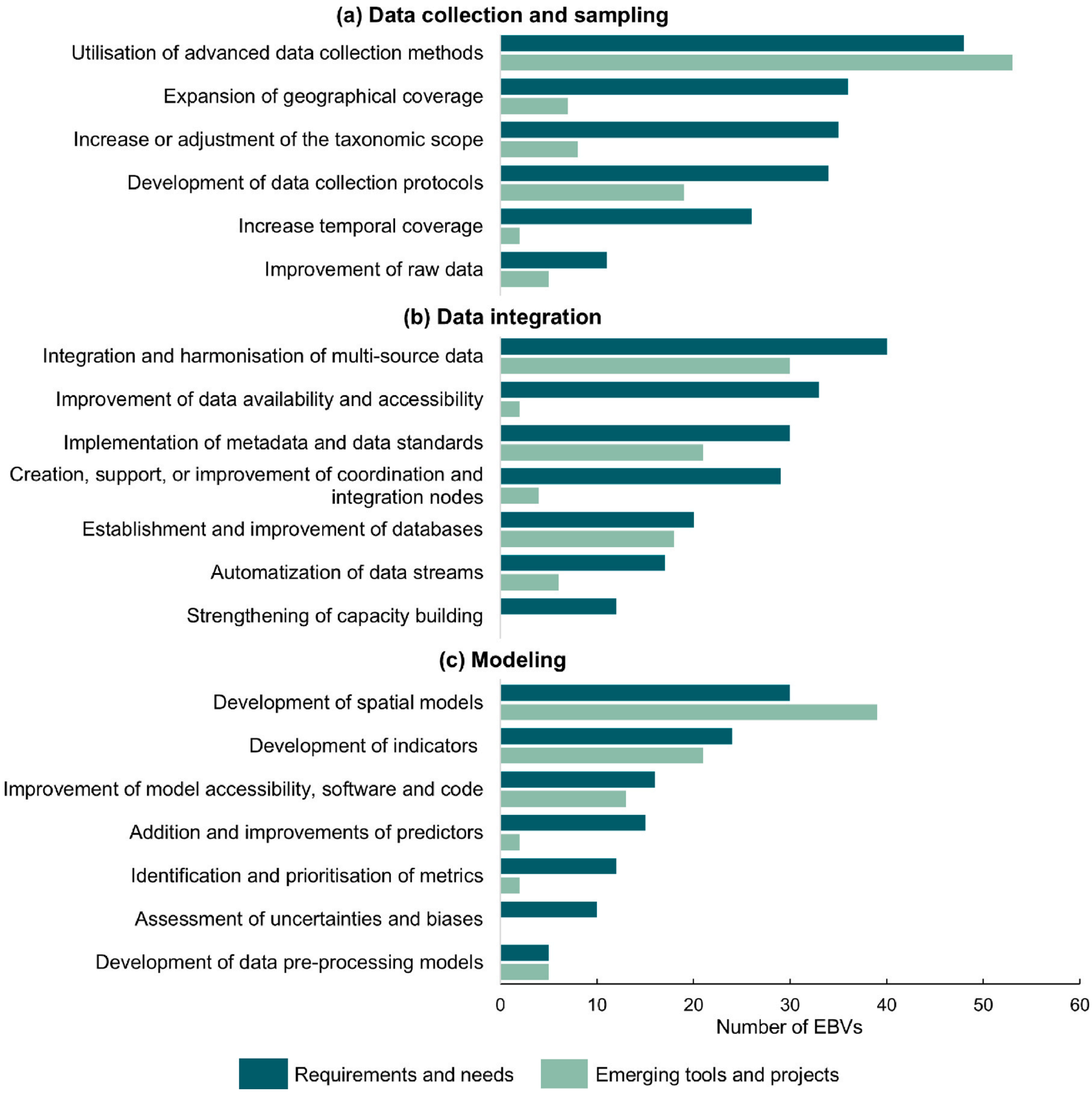

Fig. 6. Expert-based assessment of the requirements and needs for EBV workflow implementation relative to emerging tools and projects that address them. Shown is the number of EBVs for which needs and requirements have been identified (dark green bars) vs. the number of EBVs for which emerging tools and projects address these needs (light green bars). Three components of EBV workflows are differentiated, namely (a) data collection, (b) data integration, and (c) modelling. See Table 1 for the definition of categories.

comparable number of EBVs for the needs and requirements vs. the emerging tools and projects (Fig. 6b). Examples included the work of the B-Cubed project for standardising access to biodiversity data and the development of novel databases for marine genetics, species traits of freshwater organisms, or terrestrial camera trap data.

For modelling, the development of spatial models and indicators was identified as the most important need (Fig. 6c, top dark green bar). For example, EBVs on the distribution and abundance of species require the use of species distribution models to derive continuous wall-to-wall estimates and spatially-explicit indicators across Europe. Several emerging tools and projects were highlighted which partly address this, e.g. through the development of Bayesian dynamic abundance models for amphibians, or mapping tools. Additional needs identified by experts were the improvement of model accessibility, software, and code, the addition and improvement of predictors, and the identification and prioritisation of metrics for EBVs (Fig. 6c, dark green bars). While the emerging tools and projects matched well with the identified needs for the development of models and indicators and for the improvement of model accessibility software and code (Fig. 6c, compare light green with dark green bars), fewer emerging tools and projects were identified for the addition and improvement of predictors, the identification and prioritisation of metrics, and the assessment of uncertainties and biases. This could indicate a lack of emerging tools and projects for those categories.

4. Discussion

In this paper, we provide the first comprehensive overview of the information required to develop EBV workflows at a European scale, based on stakeholder engagement across 70 species-focused and ecosystem-focused EBVs spanning freshwater, marine, and terrestrial realms. Our results show the potential contributions of diverse monitoring techniques, suggesting that a wider range of monitoring methods need to be incorporated into current and future workflows. Selected workflows illustrate how biodiversity data are currently collected, integrated, and modelled, how current monitoring can be improved and expanded with advanced monitoring technologies and incorporated into the regulatory reporting to EU policies, and how European integration can be strengthened while building on existing national and regional integration nodes. An expert-based assessment of the requirements and needs for EBV workflow implementation further revealed that many emerging tools and projects are already addressing the identified requirements and needs, but also highlighted substantial remaining gaps. Below, we discuss a synthesis of EBV workflows (Fig. 7) for both species-focused and ecosystem-focused EBVs. Our discussion is structured into the three main workflow components: data collection, data integration, and modelling.

4.1. Data collection

For EBV data collection, the surveys of monitoring techniques showed that new methods are available to complement current monitoring methods. For species-focused EBVs, data collection through citizen science, digital sensors and DNA-based methods were

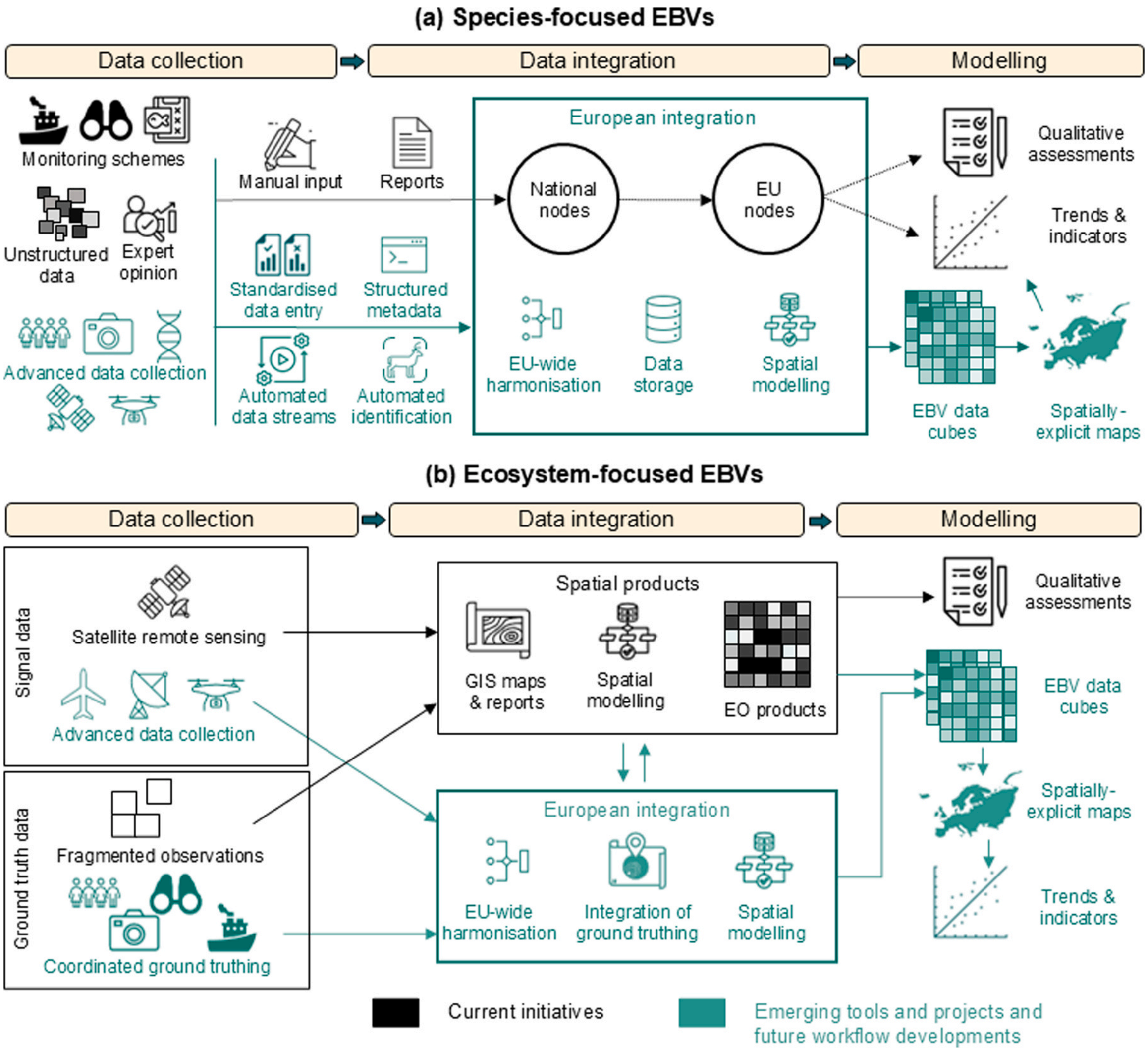

Fig. 7. Synthesis of EBV workflows for (a) species-focused EBVs, and (b) ecosystem-focused EBVs. Main aspects of current workflows are shown in black whereas emerging tools and future needs are shown in green. The figure summarizes and generalizes information from 70 individual EBV workflow templates (Lumbierres et al., 2024). Abbreviations: EBV = Essential Biodiversity Variable, EO = Earth Observation.

repeatedly identified as crucial for complementing existing data streams (Fig. 7a). For instance, a citizen science app has now been developed by the eBMS to conduct 15-minute counts of butterflies (European Commission, et al., 2024a), whole genome sequencing and de novo genome sample analysis are implemented for monitoring genetic diversity (O'Brien et al., 2022), and wildlife camera networks with automated data streams and machine learning are used to monitor mammal distributions (Kissling et al., 2024b; Tuia et al., 2022). Moreover, across the 70 workflow templates the workshop participants identified the utilisation of advanced data collection methods as the highest needs for advancing EBV workflow implementation (Fig. 6a). Although our results support the promise that recent technological advances offer great potential to enhance species monitoring by expanding geographic, taxonomic, and temporal coverage (Besson et al., 2022; Dornelas et al., 2023; van Klink et al., 2022; Morán-Ordóñez et al., 2023a), they also present technical challenges and raise concerns about data quality. Citizen science data can suffer spatial and taxonomic biases, as well as issues related to data quality, such as inconsistent sampling effort, observer error, and uneven geographic coverage (Kosmala et al., 2016; Bowler et a., 2022; Prenda et al., 2024). DNA-based monitoring methods face rapid DNA degradation, short environmental persistence, are prone to contamination, and can yield false positives or negatives (Rishan et al., 2023). Digital sensor technologies have detection biases linked to equipment placement and species or habitat sensitivity and frequently produce false triggers (Burton et al., 2015; Gibb et al., 2019). These limitations can be mitigated through sampling designs that are extensive and representative, standardised protocols, clear training, replication in sampling and across observers, and statistical modelling to account for systematic biases (Bowler et al., 2022; Burton et al., 2015; Gibb et al., 2019; Kelling et al., 2019; Prenda et al., 2024; Rishan et al., 2023; Valdez et al., 2023). Moreover, the use of novel and advanced monitoring techniques also creates new challenges for coordination, data integration and modelling, including the integration of multi-source species data (Isaac et al., 2020), the development of new metadata (e.g. Bubnicki et al., 2023), and the use of artificial intelligence for species identification from images, sound and DNA (Borowiec et al., 2022; Tuia et al., 2022; van Klinck et al., 2022). Finally, some managers may hesitate to adopt new methods due to concerns about disrupting time series and compromising data comparability for legal assessments and policy trend analyses.

For ecosystem-focused EBVs, satellite remote sensing is currently providing the best source for spatially contiguous data with a synoptic (regional to near-global) coverage and pre-defined temporal lags (Fig. 7b). However, in the context of EBVs, ground truth data that are needed to validate the satellite products are often repurposed from projects that were originally not designed for validation. For instance, vegetation surveys from the European Vegetation Archive (EVA) are combined with satellite imagery to train and validate models for mapping terrestrial EUNIS habitats (Bruelheide et al., 2024; Mücher et al., 2015). Promising examples of in-situ data collection specifically designed for EO product validation exist, such as the in-situ Land Use/Cover Area Frame Survey (LUCAS) Copernicus module from the EU space programme with > 130,000 ground truth points for validating land cover and land use products across Europe (d'Andrimont et al., 2024). However, the ground truth data for land cover validation do not necessarily provide the appropriate data for mapping ecosystem distributions of terrestrial habitats. Nevertheless, some other existing EO products from Copernicus can be directly used as an EBV, such as the High Resolution Vegetation Phenology and Productivity (HR-VPP) data for monitoring terrestrial ecosystem phenology or the Burnt Area product for monitoring fire disturbance (Lumbierres et al., 2024). However, many other ecosystem-focused EBVs are currently lacking equivalent EO products. Moreover, a recurrent suggestion from workshop participants is that satellite data should be complemented with aircraft surveys, drones, and weather radar (Fig. 7b), e.g. to obtain high resolution data on vegetation structure and habitat condition (Dronova et al., 2021; Kissling et al., 2023) or to monitor aerial biomass flows of migrating birds, bats and insects (Shamoun-Baranes et al., 2021). However, these monitoring techniques face some challenges for continental-scale monitoring, including the standardisation of metadata on sensor characteristics and survey designs protocols, integration of heterogeneous data, and development of robust metrics and transferable models (Kissling et al., 2024c).

4.2. Data integration

Our results highlight the critical need for improved harmonisation and standardisation of data, along with the creation and strengthening of national, regional and EU-wide integration nodes to coordinate a consistent integration and aggregation of biodiversity monitoring data at the national and EU level. For species-focused EBVs, data from ongoing monitoring schemes (e.g. marine trawling and ship surveys, terrestrial point counts or transect surveys, and electrofishing or sampling from boats in freshwater) together with unstructured data (e.g. citizen science observations) and expert opinion are often used to fulfil the requirements for EU policy reporting (Fig. 7a). However, the different data sources are typically not combined and integrated, but insted entered locally or nationally into various spreadsheets and databases that are not necessarily interoperable. The information is subsequently used to make national-level assessments that are provided by EU member states via reporting forms to the EEA (European Environment Agency, 2020). In most cases, national and sub-national data are summarised into qualitative indicators (descriptive or categorical measures that capture non-numerical information) which may be combined at the EU level into supra-national indicators to describe the status and trends of species (Rigal et al., 2023). Consequently, data access at the EU level is often restricted to the derived and aggregated data (e.g. qualitative indicators and trends). Nevertheless, many data flows from national or regional nodes to European integration nodes have already been established but are usually dependent on loose governance structures (Morán-Ordóñez et al., 2023a), e.g. through the European Bird Census Council (EBCC), Butterfly Conservation Europe, the WISE-2 platform for the WFD, or EMODnet and WISE Marine for the MSFD. Access to raw data remains difficult, which limits the transparency, accessibility, and reproducibility of biodiversity information at the national and EU level. Some initiatives are addressing these challenges by developing harmonised data models to aggregate biodiversity data from multiple sources across Europe. For example, Enetwild has developed a model to integrate different types of wildlife data—including hunting statistics, occurrence records, and abundance estimates—for the wild boar across Europe (ENETWILD-consortium et al., 2024).

For ecosystem-focused EBVs, data integration for satellite remote sensing products is conducted through centralised EO programs at the EU level (Fig. 7b), especially through the ESA and the Copernicus program. Other types of remote sensing data often lack such European integration and EU-wide harmonisation because the raw data are collected at the local or national scale. For instance, airborne laser scanning (ALS) surveys from which high-resolution metrics of vegetation structure can be calculated are usually conducted at a national scale (Kissling et al., 2023). Without European coordination, the data are heterogeneous and difficult to access, complicating the consistent calculation of habitat condition metrics. Similarly, weather radar networks have great potential for the continuous and long-term monitoring of aerial biomass of birds, bats, and insects, but sharing and standardising weather radar for biodiversity data across European countries encounters many challenges often derived from standardisation that is targeting other purposes (Shamoun-Baranes et al., 2022). The monitoring of habitats with drones is typically done at single sites or within protected areas (Díaz-Delgado and Mücher, 2019), and the lack of standards and best practices for sensor use procedures and metadata generation constrain possibilities for data integration (Barbieri et al., 2023). Hence, remote sensing data that are not obtained by satellites require improved standardisation and harmonisation across Europe because the data are usually collected locally or nationally without European or transnational coordination. This also applies to new technology to collect ground truth data, e.g. citizen science apps for algal blooms (Mishra et al., 2020) and phenocams for plant phenology EBVs (Brown et al., 2016). In this context, the proposed European Biodiversity Observation Coordination Centre (EBOCC) could play an important role in achieving a better standardisation and harmonisation for both signal and ground truth data across Europe (Liquete et al., 2024).

4.3. Modelling

Our results show that the most identified requirement for modelling is the development of spatial models to allow generating continuous spatio-temporal data cubes by integrating diverse data types and filling gaps in coverage (Fernández et al., 2020; Kissling et al., 2018a). However, few EU monitoring initiatives produce spatially-explicit products and those that do not often align with the EBV requirements identified by EuropaBON (Fig. 7a, Morán-Ordóñez et al., 2023a). For species-focused EBVs, many emerging tools and projects are developing and refining models, particularly species distribution models (SDMs) (Fig. 7, Jetz et al., 2019). SDM developments can be seen across realms, e.g., for freshwater invertebrates (da Silva et al., 2023), marine turtles (Almpanidou et al., 2021) and terrestrial birds (Herrando et al., 2024). Spatially-explicit products for species abundance remain limited due to scarce data (Jetz et al., 2019). However, some examples exist where various data sources are combined to produce high-resolution abundance maps at the European scale, such as for wild boar (ENETWILD-consortium et al., 2024). Similarly, data scarcity limits the production of spatially-explicit models for species traits (Kissling et al., 2018b), but operationalising monitoring methods like citizen science offers the potential to complement existing data and create large-scale trait products at the species level (Capinha et al., 2024). Our results show that few tools are currently available to assess bias and uncertainty in spatial models, which may limit their applicability for policy and decision-making. One example addressing this gap is ROBITT, a tool designed to assess the risk of bias in studies of temporal trends (Boyd et al., 2022).

For ecosystem-focused EBVs, some current EO products from the Copernicus program are very similar to the EBVs (Fig. 7b). For example, the EBV fire disturbance regimes closely resembles the Burnt Area product from Copernicus, which uses deep learning on Sentinel-3 imagery to map fire-induced spectral changes globally at a 300 m resolution (European Commission et al., 2024b). Similarly, the EBV on terrestrial ecosystem phenology aligns with the Vegetation Phenology products from the 300 m Land Surface Phenology collection from Copernicus, derived from smooth seasonal trajectories of the Plant Phenology Index (PPI) based on reflectance data from the Sentinel-3 imagery. In the marine realm, EMODnet offers several spatial products analogous to marine EBVs. For example, EMODnet Seabed Habitat, with iterations from 2011 to 2023, utilises spatial distribution models based on logistic regression of different habitats (Populus et al., 2017). These models could help derive EBVs such as hard coral cover, seagrass cover, and macroalgal canopy cover. Many other new modelling frameworks are being developed to integrate remote sensing data with various types of ground truth data, e.g. random forest models of barrier density in European rivers (Belletti et al., 2020), convolutional neural networks (CNNs) to map seagrass and macroalgae in the coastal zone (Liu et al., 2022) and Gaussian process regression to interpolate bird densities measured by weather radars at high temporal resolution (Nussbaumer et al., 2019). The development of these new models could also address several other needs highlighted by workshop participants, including the identification and prioritisation of metrics, the assessment of uncertainties and biases, and the improvement of predictors. Some tools for harmonising predictor variables at the European scale are already available, e.g., Ecodatacube (Witjes et al., 2023). Additionally, initiatives that produce ready-to-use R packages such as 'Wallace' for producing SDMs (Kass et al., 2018) or mapping tools such as 'AquaMaps' for marine species distributions (Scarponi et al., 2018) can further streamline the modelling process. Finally, a crucial requirement identified is the development of indicators for policy, which necessitates further processing of EBV data cubes to meet specific targets (Fernández et al., 2024). Therefore, improving the EBVs will refine the quality of indicators, allow for better integration of data sources, and enhance the tracking of biodiversity change across Europe.

5. Conclusions

Our results provide a forward-looking perspective on the development of EBV workflows in Europe, building on a comprehensive stakeholder engagement and considering novel technologies, emerging tools and ongoing projects. Most of the described EBV workflows still need to be technically developed, but our work offers a first conceptual representation of workflow elements that can guide future implementation. The development stages of the analysed EBVs vary widely, from EBVs that have established monitoring networks and protocols, to EBVs that are monitored only at small spatial extents or in pilot phases, or those that currently lack any systematic data collection and thus require the development of new monitoring schemes. The development stage of a technology and the upscaling capacity of tools and monitoring methods also vary substantially, constraining the feasibility of already implementing them in ongoing biodiversity monitoring schemes. Operationalising EBVs therefore requires to develop solutions across all workflow components, including data collection (e.g., harmonising taxonomy and assessing data quality and bias), data integration (e.g., standardising and harmonising data), and modelling (e.g., ensuring adequate computing infrastructure and regular updates). Advancing these EBV workflows will be crucial for effective biodiversity monitoring across Europe. At the same time, it is essential to build on existing networks and workflows that are already in place, despite their current limitations, while progressively improving data accuracy, expanding monitoring coverage, and integrating advanced technologies and emerging tools to meet the requirements and needs identified for each workflow. Successful implementation of EBV workflows and gradual expansion will require enhanced coordination ensuring strong collaboration between monitoring institutions, policymakers, and researchers. The EU Biodiversity Observation Coordination Centre proposed by EuropaBON could play an essential role in coordinating these efforts and ensuring their success.

Funding

This work was funded by the European Union (grant agreement 101003553). The content does not necessarily reflect the official opinions of the European Commission or other institutions of the European Union.

CRediT authorship contribution statement

Maria Lumbierres: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marija Milanovic:** Writing – review & editing, Data curation. **Pedro Beja:** Writing – review & editing, Funding acquisition. **Aletta Bonn:** Writing – review & editing, Funding acquisition. **Tom D. Breeze:** Writing – review & editing, Funding acquisition. **Lluís Brotons:** Writing – review & editing, Funding acquisition. **Néstor Fernández:** Writing – review & editing, Funding acquisition. **Jessica Junker:** Writing – review & editing, Project administration, Funding acquisition. **Camino Liquete:** Writing – review & editing. **Anne Lyche Solheim:** Writing – review & editing, Funding acquisition. **Alejandra Morán Ordóñez:** Writing – review & editing, Data curation. **Francisco Moreira:** Writing – review & editing. **Joana Santana:** Writing – review & editing, Data curation. **Stacy Shinneman:** Writing – review & editing, Data curation. **Bruno Smets:** Writing – review & editing. **Henrique M. Pereira:** Writing – review & editing, Project administration, Funding acquisition. **Jose W. Valdez:** Writing – review & editing. **Roy H. A. van Grunsvenu:** Writing – review & editing. **W. Daniel Kissling:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

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.

Acknowledgements

We thank all participants of the EuropaBON stakeholder workshop and the wider EuropaBON network for their valuable insights and willingness to share information. We are also grateful to our colleagues who helped with the organisation and realisation of the stakeholder workshop, namely Ian McCallum, Ivelina Georgieva, Laurence Carvalho, Pier Luigi Buttigieg, Maria Azeredo de Dornelas, Yifang Shi and Bart Kranstauber.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gecco.2025.e03699.

Data availability

The data is publicly available and can be accessed at Zenodo using the following DOI: 10.5281/zenodo.10680435 and DOI: 10.5281/zenodo.14444148.

EuropaBON EBV workflow templates and Dataset supporting the implementation of workflows for Essential Biodiversity Variables (EBVs) at a European scale (Zenodo)

References

Almpanidou, V., Chatzimentor, A., Tsapalou, V., Mazaris, A.D., 2021. Investigating the distribution of foraging habitat for loggerhead sea turtles, *Caretta caretta*, in the Mediterranean Sea. Biol. Life Sci. Forum 2, 27.

Barbieri, L., Wyngaard, J., Swanz, S., Thomer, A.K., 2023. Making drone data FAIR through a community-developed information framework. Data Sci. J. 22, 1–9.

Belletti, B., Garcia de Leaniz, C., Jones, J., Bizzi, S., Börger, L., Segura, G., Castelletti, A., van de Bund, W., Aarestrup, K., Barry, J., Belka, K., Berkhuysen, A., Birnie-Gauvin, K., Bussettini, M., Carolli, M., Consuegra, S., Dopico, E., Feierfeil, T., Fernández, S., Fernandez Garrido, P., Garcia-Vazquez, E., Garrido, S., Giannico, G., Gough, P., Jepsen, N., Jones, P.E., Kemp, P., Kerr, J., King, J., Łapińska, M., Lázaro, G., Lucas, M.C., Marcello, L., Martin, P., McGinnity, P., O'Hanley, J., Olivo del Amo, R., Parasiewicz, P., Pusch, M., Rincon, G., Rodriguez, C., Royte, J., Schneider, C.T., Tummers, J.S., Vallesi, S., Vowles, A., Verspoor, E., Wanningen, H., Wantzen, K.M., Wildman, L., Zalewski, M., 2020. More than one million barriers fragment Europe's rivers. Nature 588, 436–441.

Besson, M., Alison, J., Bjerge, K., Gorochowski, T.E., Høye, T.T., Jucker, T., Mann, H.M.R., Clements, C.F., 2022. Towards the fully automated monitoring of ecological communities. Ecol. Lett. 25, 2753–2775.

Borowiec, M.L., Dikow, R.B., Frandsen, P.B., McKeeken, A., Valentini, G., White, A.E., 2022. Deep learning as a tool for ecology and evolution. Methods Ecol. Evol. 13, 1640–1660.

Bowler, D.E., Callaghan, C.T., Bhandari, N., Henle, K., Benjamin Barth, M., Koppitz, C., Klenke, R., Winter, M., Jansen, F., Bruelheide, H., Bonn, A., 2022. Temporal trends in the spatial bias of species occurrence records. Ecography 2022, e06219.

Boyd, R.J., Powney, G.D., Burns, F., Danet, A., Duchenne, F., Grainger, M.J., Jarvis, S.G., Martin, G., Nilsen, E.B., Porcher, E., Stewart, G.B., Wilson, O.J., Pescott, O.L., 2022. ROBITT: A tool for assessing the risk-of-bias in studies of temporal trends in ecology. Methods Ecol. Evol. 13, 1497–1507.

Boyd, R.J., August, T.A., Cooke, R., Logie, M., Mancini, F., Powney, G.D., Roy, D.B., Turvey, K., Isaac, N.J.B., 2023. An operational workflow for producing periodic estimates of species occupancy at national scales. Biol. Rev. 98, 1492–1508.

Brown, T.B., Hultine, K.R., Steltzer, H., Denny, E.G., Denslow, M.W., Granados, J., Henderson, S., Moore, D., Nagai, S., SanClements, M., Sánchez-Azofeifa, A., Sonnentag, O., Tazik, D., Richardson, A.D., 2016. Using phenocams to monitor our changing Earth: toward a global phenocam network. Front. Ecol. Environ. 14, 84–93.

Bruelheide, H., Jandt, U., Fernández, N., Marmol-Guijarro, A., Smets, B., Buchhorn, M., Giagnacovo, L., Milli, G., Jimenez-Alfaro, B., Álvarez-Martínez, J.M., 2024. D5.2 Past-to-present EBV modelled datasets and status indicator for selected terrestrial habitats in the Habitats Directive. ARPHA Prepr. 5, e128158.

Bubnicki, J.W., Norton, B., Baskauf, S.J., Bruce, T., Cagnacci, F., Casaer, J., Churski, M., Cromsigt, J.P.G.M., Farra, S.D., Fiderer, C., Forrester, T.D., Hendry, H., Heurich, M., Hofmeester, T.R., Jansen, P.A., Kays, R., Kuijper, D.P.J., Liefting, Y., Linnell, J.D.C., Luskin, M.S., Mann, C., Milotic, T., Newman, P., Niedballa, J., Oldoni, D., Ossi, F., Robertson, T., Rovero, F., Rowcliffe, M., Seidenari, L., Stachowicz, I., Stowell, D., Tobler, M.W., Wieczorek, J., Zimmermann, F., Desmet, P., 2023. Camtrap DP: an open standard for the FAIR exchange and archiving of camera trap data. Remote Sens. Ecol. Conserv 47, 283–295.

Burton, A.C., Neilson, E., Moreira, D., Ladle, A., Steenweg, R., Fisher, J.T., Bayne, E., Boutin, S., 2015. REVIEW: Wildlife camera trapping: a review and recommendations for linking surveys to ecological processes. J. Appl. Ecol. 52, 675–685.

Capinha, C., Ceia-Hasse, A., de-Miguel, S., Vila-Viçosa, C., Porto, M., Jarić, I., Tiago, P., Fernández, N., Valdez, J., McCallum, I., Pereira, H.M., 2024. Using citizen science data for predicting the timing of ecological phenomena across regions. BioScience 74, 383–392.

d'Andrimont, R., Yordanov, M., Sedano, F., Verhegghen, A., Strobl, P., Zachariadis, S., Camilleri, F., Palmieri, A., Eiselt, B., Rubio Iglesias, J.M., van der Velde, M., 2024. Advances in LUCAS Copernicus 2022: enhancing Earth observations with comprehensive in situ data on EU land cover and use. Earth Syst. Sci. Data 16, 5723–5735.

Díaz, S., Settele, J., Brondízio, E.S., Ngo, H.T., Guèze, M., Agard, J., Arneth, A., Balvanera, P., Brauman, K.A., Butchart, S.H.M., Chan, K.M.A., Garibaldi, L.A., Ichii, K., J.L, Subramanian, S.M., Midgley, G.F., Miloslavich, P., Molnár, Z., Obura, D., Pfaff, A., Polasky, S., Purvis, A., Razzaque, J., Reyers, B., Chowdhury, R.R., Shin, Y. J., Visseren-Hamakers, I.J., Willis, K.J., Zayas, C.N., 2019. IPBES (2019) Summary policymakers global assessment report biodiversity ecosystem services Intergovernmental SciencePolicy Platform Biodiversity Ecosystem Services. Bonn Germany.

Díaz-Delgado, R., Mücher, S., 2019. Editorial of Special Issue "Drones for Biodiversity Conservation and Ecological Monitoring. Drones 3, 47.

Dornelas, M., Chow, C., Patchett, R., Breeze, T., Brotons, L., Beja, P., Carvalho, L., Jandt, U., Junker, J., Kissling, W.D., Kühn, I., Lumbierres, M., Solheim, A.L., Mjelde, M., Moreira, F., Musche, M., Pereira, H., Sandin, L., Grunsven, R.V., 2023. Deliverable 4.2 Novel technologies for biodiversity monitoring - Final Report. ARPHA Prepr. 4, e105600.

Dronova, I., Kislik, C., Dinh, Z., Kelly, M., 2021. A review of unoccupied aerial vehicle use in wetland applications: emerging opportunities in approach, technology, and data. Drones 5, 45.

ENETWILD-consortium, Croft, S., Blanco-Aguiar, J.A., Acevedo, P., Illanas, S., Vicente, J., Warren, D.A., Smith, G.C., 2024. Modelling wild boar abundance at high resolution. EFSA Support. Publ. 21, 8965E.

European Commission, Joint Research Centre (JRC), 2024b. Burnt Area 2023–present (raster 300 m), global, daily – version 3.1. Copernicus Land Monitoring Service. ⟨https://land.copernicus.eu/en/products/vegetation/burnt-area-v3-1-daily-300m⟩ (Available at:).

European Commission, Joint Research Centre (JRC), Potts, S.G., Bartomeus, I., Biesmeijer, K., Breeze, T., Casino, A., Dauber, J., Dieker, P., Hochkirch, A., Høye, T., Isaac, N., Kleijn, D., Laikre, L., Mandelik, Y., Montagna, M., Montero Castaño, A., Öckinger, E., Oteman, B., Pardo Valle, A., Polce, C., Povellato, A., Quaranta, M., Roy, D., Schweiger, O., Settele, J., Ståhls-Mäkelä, G., Tamborra, M., Troost, G., van der Wal, R., Vujić, A., Zhang, J., 2024a. Refined proposal for an EU Pollinator Monitoring Scheme (EUR 40089 EN). Publications Office of the European Union, Luxembourg.

European Environment Agency, 2020. State of nature in the EU: results from reporting under the nature directives *2013–2018* (EEA Report No 10/2020. Publications Office of the European Union, Luxembourg.

Fernández, N., Ferrier, S., Navarro, L.M., Pereira, H.M., 2020. Essential Biodiversity Variables: Integrating In-Situ Observations and Remote Sensing Through Modelling. In: Cavender-Bares, J., Gamon, J.A., Townsend, P.A. (Eds.), Remote Sensing of Plant Biodiversity. Springer International Publishing, Cham, pp. 485–501.

Gibb, R., Browning, E., Glover-Kapfer, P., Jones, K.E., 2019. Emerging opportunities and challenges for passive acoustics in ecological assessment and monitoring. Methods Ecol. Evol. 10, 169–185.

Gonzalez, A., Vihervaara, P., Balvanera, P., Bates, A.E., Bayraktarov, E., Bellingham, P.J., Bruder, A., Campbell, J., Catchen, M.D., Cavender-Bares, J., Chase, J., Coops, N., Costello, M.J., Czúcz, B., Delavaud, A., Dornelas, M., Dubois, G., Duffy, E.J., Eggermont, H., Fernandez, M., Fernandez, N., Ferrier, S., Geller, G.N., Gill, M., Gravel, D., Guerra, C.A., Guralnick, R., Harfoot, M., Hirsch, T., Hoban, S., Hughes, A.C., Hugo, W., Hunter, M.E., Isbell, F., Jetz, W., Juergens, N., Kissling, W.D., Krug, C.B., Kullberg, P., Le Bras, Y., Leung, B., Londoño-Murcia, M.C., Lord, J.-M., Loreau, M., Luers, A., Ma, K., MacDonald, A.J., Maes, J., McGeoch, M., Mihoub, J.B., Millette, K.L., Molnar, Z., Montes, E., Mori, A.S., Muller-Karger, F.E., Muraoka, H., Nakaoka, M., Navarro, L., Newbold, T., Niamir, A., Obura, D., O'Connor, M., Paganini, M., Pelletier, D., Pereira, H., Poisot, T., Pollock, L.J., Purvis, A., Radulovici, A., Rocchini, D., Roeoesli, C., Schaepman, M., Schaepman-Strub, G., Schmeller, D.S., Schmiedel, U., Schneider, F.D., Shakya, M.M., Skidmore, A., Skowno, A.L., Takeuchi, Y., Tuanmu, M.-N., Turak, E., Turner, W., Urban, M.C., Urbina-Cardona, N., Valbuena, R., Van de Putte, A., van Havre, B., Wingate, V.R., Wright, E., Torrelio, C.Z., 2023. A global biodiversity observing system to unite monitoring and guide action. Nat. Ecol. Evol. 7, 1947–1952.

Hardisty, A.R., Michener, W.K., Agosti, D., Alonso García, E., Bastin, L., Belbin, L., Bowser, A., Buttigieg, P.L., Canhos, D.A.L., Egloff, W., De Giovanni, R., Figueira, R., Groom, Q., Guralnick, R.P., Hobern, D., Hugo, W., Koureas, D., Ji, L., Los, W., Manuel, J., Manset, D., Poelen, J., Saarenmaa, H., Schigel, D., Uhlir, P.F., Kissling, W.D., 2019. The Bari Manifesto: An interoperability framework for essential biodiversity variables. Ecol. Inf. 49, 22–31.

Hermoso, V., Clavero, M., Villero, D., Brotons, L., 2017. EU's conservation efforts need more strategic investment to meet continental commitments. Conserv. Lett. 10, 231–237.

Herrando, S., Fraixedas, S., Pocull, G., Villero, D., Gamero, A., Martí, D., Keller, V., Voříšek, P., Klvaňová, A., Gargallo, G., Brotons, L., 2024. D5.1 Past-to-present EBV modelled datasets and status indicator for selected species in the Birds Directive. ARPHA Prepr. 5, e126021.

Hoban, S., Archer, F.I., Bertola, L.D., Bragg, J.G., Breed, M.F., Bruford, M.W., Coleman, M.A., Ekblom, R., Funk, W.C., Grueber, C.E., Hand, B.K., Jaffé, R., Jensen, E., Johnson, J.S., Kershaw, F., Liggins, L., MacDonald, A.J., Mergeay, J., Miller, J.M., Muller-Karger, F., O'Brien, D., Paz-Vinas, I., Potter, K.M., Razgour, O., Vernesi, C., Hunter, M.E., 2022. Global genetic diversity status and trends: towards a suite of Essential Biodiversity Variables (EBVs) for genetic composition. Biol. Rev. 97, 1511–1538.

Isaac, N.J.B., Jarzyna, M.A., Keil, P., Dambly, L.I., Boersch-Supan, P.H., Browning, E., Freeman, S.N., Golding, N., Guillera-Arroita, G., Henrys, P.A., Jarvis, S., Lahoz-Monfort, J., Pagel, J., Pescott, O.L., Schmucki, R., Simmonds, E.G., O'Hara, R.B., 2020. Data integration for large-scale models of species distributions. Trends Ecol. Evol. 35, 56–67.

Jetz, W., McGeoch, M.A., Guralnick, R., Ferrier, S., Beck, J., Costello, M.J., Fernandez, M., Geller, G.N., Keil, P., Merow, C., Meyer, C., Muller-Karger, F.E., Pereira, H.M., Regan, E.C., Schmeller, D.S., Turak, E., 2019. Essential biodiversity variables for mapping and monitoring species populations. Nat. Ecol. Evol. 3, 539–551.

Junker, J., Beja, P., Brotons, L., Fernandez, M., Fernández, N., Kissling, W.D., Lumbierres, M., Solheim, A.L., Maes, J., Morán-Ordóñez, A., Moreira, F., Musche, M., Santana, J., Valdez, J., Pereira, H., 2023. D4.1. List and specifications of EBVs and EESVs for a European wide biodiversity observation network. ARPHA Prepr. 4, e102530.

Kass, J.M., Vilela, B., Aiello-Lammens, M.E., Muscarella, R., Merow, C., Anderson, R.P., 2018. Wallace: A flexible platform for reproducible modelling of species niches and distributions built for community expansion. Methods Ecol. Evol. 9, 1151–1156.

Kelling, S., Johnston, A., Bonn, A., Fink, D., Ruiz-Gutierrez, V., Bonney, R., Fernandez, M., Hochachka, W.M., Julliard, R., Kraemer, R., Guralnick, R., 2019. Using Semistructured surveys to improve citizen science data for monitoring biodiversity. BioScience 69, 170–179.

Kissling, W.D., Lumbierres, M., 2023. Essential Biodiversity Variable workflows: designing the freshwater, marine and terrestrial EBV workflows from data collection to modelling. ARPHA Prepr. 4, e101949.

Kissling, W.D., Ahumada, J.A., Bowser, A., Fernandez, M., Fernández, N., García, E.A., Guralnick, R.P., Isaac, N.J.B., Kelling, S., Los, W., McRae, L., Mihoub, J.B., Obst, M., Santamaria, M., Skidmore, A.K., Williams, K.J., Agosti, D., Amariles, D., Arvanitidis, C., Bastin, L., De Leo, F., Egloff, W., Elith, J., Hobern, D., Martin, D., Pereira, H.M., Pesole, G., Peterseil, J., Saarenmaa, H., Schigel, D., Schmeller, D.S., Segata, N., Turak, E., Uhlir, P.F., Wee, B., Hardisty, A.R., 2018a. Building essential biodiversity variables (EBVs) of species distribution and abundance at a global scale. Biol. Rev. 93, 600–625.

Kissling, W.D., Walls, R., Bowser, A., Jones, M.O., Kattge, J., Agosti, D., Amengual, J., Basset, A., van Bodegom, P.M., Cornelissen, J.H.C., Denny, E.G., Deudero, S., Egloff, W., Elmendorf, S.C., Alonso García, E., Jones, K.D., Jones, O.R., Lavorel, S., Lear, D., Navarro, L.M., Pawar, S., Pirzl, R., Rüger, N., Sal, S., Salguero-Gómez, R., Schigel, D., Schulz, K.S., Skidmore, A., Guralnick, R.P., 2018b. Towards global data products of Essential Biodiversity Variables on species traits. Nat. Ecol. Evol. 2, 1531–1540.

Kissling, W.D., Shi, Y., Koma, Z., Meijer, C., Ku, O., Nattino, F., Seijmonsbergen, A.C., Grootes, M.W., 2023. Country-wide data of ecosystem structure from the third Dutch airborne laser scanning survey. Data Brief. 46, 108798.

Kissling, W.D., Breeze, T.D., Liquete, C., Solheim, A.L., McCallum, I., Maes, J., Hirsch, T., Lumbierres, M., Grunsven, R.H.A., van, Beja, P., Smets, B., Capinha, C., Ceia-Hasse, A., Fernández, N., Moreira, F., Junker, J., Leese, F., Hammond, E., Brotons, L., Ordóñez, A.M., Potts, S.G., Santana, J., Valdez, J.W., Kühn, I., Milanović, M., Schmidt-Kloiber, A., Bormpoudakis, D., Villero, D., Haase, P., Meissner, K., Bruelheide, H., Buchhorn, M., Calderon-Sanou, I., Fernandez, M., Gamero, A., Gobin, A., Guerrero, I., Jandt, U., Klvaňová, A., Viti, M.M., Moe, S.J., Bonn, A., Pereira, H.M., 2024a. Towards a modern and efficient European biodiversity observation network fit for multiple policies. EcoEvoRxiv Prepr. https://doi.org/10.32942/X2K34F.

Kissling, W.D., Shi, Y., Wang, J., Walicka, A., George, C., Moeslund, J.E., Gerard, F., 2024c. Towards consistently measuring and monitoring habitat condition with airborne laser scanning and unmanned aerial vehicles. Ecol. Indic. 169, 112970.

Kissling, W.D., Evans, J.C., Zilber, R., Breeze, T.D., Shinneman, S., Schneider, L.C., Chalmers, C., Fergus, P., Wich, S., Geelen, L.H.W.T., 2024b. Development of a cost-efficient automated wildlife camera network in a European Natura 2000 site. Basic Appl. Ecol. 79, 141–152.

van Klink, R., August, T., Bas, Y., Bodesheim, P., Bonn, A., Fossøy, F., Høye, T.T., Jongejans, E., Menz, M.H.M., Miraldo, A., Roslin, T., Roy, H.E., Ruczyński, I., Schigel, D., Schäffler, L., Sheard, J.K., Svenningsen, C., Tschan, G.F., Wäldchen, J., Zizka, V.M.A., Åström, J., Bowler, D.E., 2022. Emerging technologies revolutionise insect ecology and monitoring. Trends Ecol. Evol. 37, 872–885.

Kosmala, M., Wiggins, A., Swanson, A., Simmons, B., 2016. Assessing data quality in citizen science. Front. Ecol. Environ. 14, 551–560.

Kühl, H.S., Bowler, D.E., Bösch, L., Bruelheide, H., Dauber, J., Eichenberg, D., Eisenhauer, N., Fernández, N., Guerra, C.A., Henle, K., Herbinger, I., Isaac, N.J.B., Jansen, F., König-Ries, B., Kühn, I., Nilsen, E.B., Pe'er, G., Richter, A., Schulte, R., Settele, J., Dam, N.M. van, Voigt, M., Wägele, W.J., Wirth, C., Bonn, A., 2020. Effective biodiversity monitoring needs a culture of integration. One Earth 3, 462–474.

Liquete, C., Bormpoudakis, D., Maes, J., McCallum, I., Kissling, W.D., Brotons, L., Breeze, T., Moran, A., Lumbierres, M., Friedrich, L., Herrando, S., Solheim, A.L., Fernandez, M., Fernández, N., Hirsch, T., Carvalho, L., Vihervaara, P., Junker, J., Georgieva, I., Kühn, I., Grunsven, R.V., Lipsanen, A., Body, G., Goodson, H., Valdez, J., Bonn, A., Pereira, H.M., 2024. D2.3 EuropaBON Proposal for an EU Biodiversity Observation Coordination Centre (EBOCC). ARPHA Prepr. 5, e128042.

Liu, Y., Liu, Q., Sample, J.E., Hancke, K., Salberg, A.-B., 2022. Coastal habitat mapping with UAV multi-sensor data: an experiment among dcnn-based approaches. ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci. V. 32022 439–445.

Lumbierres, M., Kissling, W.D., 2023. Important first steps towards designing the freshwater, marine and terrestrial Essential Biodiversity Variable (EBV) workflows for the European Biodiversity Observation Network. Res. Ideas Outcomes 9, e109120.

Lumbierres, M., Abecasis, D., Alcaraz-Segura, D., Alison, J., Álvarez-Presas, M., Anderle, M., Avci, F., Bajocco, S., Baldo, M., Beja, P., Bergamini, A., Bergami, C., Blanco-Aguiar, J.A., Boada, J., Bonn, A., Borges, P., Borgwardt, F., Borja, A., Breeze, T., Brotons, L., Brucet, S., Bruelheide, H., Buttigieg, P.L., Buzan, E., Calderón-Sanou, I., Camacho, A., Camacho-Santamans, A., Campanaro, A., Cani, A., Cariñanos, P., Carvalho, L., Castellan, G., Castro, A., Ceia-Hasse, A., Chianucci, F., Chowdhury, S., C. Lima, A., Costa, V., Crespo, D., Crepaz, H., Dahlkamp, A., De Knijf, G., De Koning, K., Demars, B.O.L., De Stefano, M., Desmet, P., Diem, A., Díaz-Delgado, R., Díaz Martín, B., Drakare, S., Eljasik, P., Falaschi, M., Fernandes, I., Fernández Bejarano, S.J., Fernandez, N., Fernández-López, J., Ferrara, C., Ferré Codina, A., Fiegenbaum, H., Floccia, F., Galbusera, P., Galdies, J., Gañán, M., Garcia-Gonzalez, F., Garzoli, L., Gundersen, H., Haysom, K.A., Hedenås, H., Heremans, S., Hilpold, A., Hinojo, B., Holmgren, K., Hunger, S., Huybrechts, P., Hvilsom, C., Ilarri, M., Illa-Bachs, E., Isaac, N., Jandt, U., Jankauskaite, G., Junker, J., Kahlert, M., Kamilaris, A., Kasmi, Y., Kiran, H., Koma, Z., Kranstauber, B., Kopatz, A., Lanzén, A., Lecegui Carnero, V., Lever, J.J., Liquete, C., Luque, S., Madon, B., Majaneva, M., Manea, E., March, D., Marco, M., Martínez-López, J., Martinez-Vicente, V., McCallum, I., Méndez, M., Milanovic, M., Moe, S.J., Morant, D., Muir, M.A.K., Müllerová, J., Múrria, C., Musche, M., Nascimbene, J., Nestola, E., Oggioni, A., Oikonomou, A., Oldoni, D., Ott, D., Pace, G., Padubidri, C., Palomino Gaviria, Á.P., Paniccia, C., Pereira, H.M., Pérez-Girón, J.C., Pérez-Haase, A., Petriccione, B., Philipson, P., Pit, I.R., Pladevall-Izard, E., Pop, D.A., Puerta-Piñero, C., Quaranta, M., Radoux, J., Rasmussen, J.J., Renan, I., Reubens, J., Roeoesli, C., Rolph, S., Rūsiņa, S., Samoila, C., Santana, J., Schakel, J.K., Schepers, L., Schletterer, M., Schmidt-Kloiber, A., Seeber, J., Shi, Y., Shinneman, S., Smets, B., Soares, J., Soccodato, A., Solé-Medina, A., Sorvari, J., Sousa, R., Souza, A.T., Souza Dias, A., Spinosa, A., Strasser, T., Thulin, S.M., Trottet, A., Turicchia, E., Uriarte, A., Vagenas, G., Valdez, J., Vallefuoco, F., Van de Putte, A.P., Van Grunsven, R.H.A., Vicente, J., Villegas-Rios, D., Villero, D., Viti, M.M., Vriend, S.J.G., Walentowitz, A., Ward, R.J., Wijesingha, J., Zhang, J., Ziemba, A., Zimmermann, J., Kissling, W.D., 2024. EuropaBON EBV workflow templates. Zenodo: https://doi.org/10.5281/zenodo.10971094.

Miloslavich, P., Bax, N.J., Simmons, S.E., Klein, E., Appeltans, W., Aburto-Oropeza, O., Andersen, M., Batten, S.D., Benedetti-Cecchi, L., Jr, D.M.C., Chiba, S., Duffy, J.E., Dunn, D.C., Fischer, A., Gunn, J., Kudela, R., Marsac, F., Muller-Karger, F.E., Obura, D., Shin, Y.-J., 2018. Essential ocean variables for global sustained observations of biodiversity and ecosystem changes. Glob. Change Biol. 24, 2416–2433.

Mishra, D.R., Kumar, A., Ramaswamy, L., Boddula, V.K., Das, M.C., Page, B.P., Weber, S.J., 2020. CyanoTRACKER: A cloud-based integrated multi-platform architecture for global observation of cyanobacterial harmful algal blooms. Harmful Algae 96, 101828.

Moersberger, H., Valdez, J., Martin, J.G.C., Junker, J., Georgieva, I., Bauer, S., Beja, P., Breeze, T.D., Fernandez, M., Fernández, N., Brotons, L., Jandt, U., Bruelheide, H., Kissling, W.D., Langer, C., Liquete, C., Lumbierres, M., Solheim, A.L., Maes, J., Morán-Ordóñez, A., Moreira, F., Pe'er, G., Santana, J., Shamoun-Baranes, J., Smets, B., Capinha, C., McCallum, I., Pereira, H.M., Bonn, A., 2024. Biodiversity monitoring in Europe: User and policy needs. Conserv. Lett. 17 (5), e13038.

Morán-Ordóñez, A., Beja, P., Fraixedas, S., Herrando, S., Junker, J., Kissling, W.D., Lumbierres, M., Solheim, A.L., Miret, G., Moe, J., Moreira, F., Pereira, H., Santana, J., Villero, D., Brotons, L., 2023a. D3.3 Identification of current monitoring workflows and bottlenecks. ARPHA Prepr. 4, e103765.

Morán-Ordóñez, A., Pino, D.M., Brotons, L., 2023b. D3.1 Inventory of current European network for monitoring. Web-based database. ARPHA Prepr. 4, e109168.

Mücher, C., Hennekens, S., Schaminée, J., Halada, L., Halabuk, A., 2015. Modelling the spatial distribution of EUNIS forest habitats based on vegetation relevés and Copernicus HRL. European Topic Centre Biological Diversity, Paris.

Navarro, L.M., Fernández, N., Guerra, C., Guralnick, R., Kissling, W.D., Londoño, M.C., Muller-Karger, F., Turak, E., Balvanera, P., Costello, M.J., Delavaud, A., El Serafy, G., Ferrier, S., Geijzendorffer, I., Geller, G.N., Jetz, W., Kim, E.-S., Kim, H., Martin, C.S., McGeoch, M.A., Mwampamba, T.H., Nel, J.L., Nicholson, E., Pettorelli, N., Schaepman, M.E., Skidmore, A., Sousa Pinto, I., Vergara, S., Vihervaara, P., Xu, H., Yahara, T., Gill, M., Pereira, H.M., 2017. Monitoring biodiversity change through effective global coordination. Curr. Opin. Environ. Sustain 29, 158–169.

Nussbaumer, R., Benoit, L., Mariethoz, G., Liechti, F., Bauer, S., Schmid, B., 2019. A Geostatistical Approach to Estimate High Resolution Nocturnal Bird Migration Densities from a Weather Radar Network. Remote Sens 11, 2233.

O'Brien, D., Laikre, L., Hoban, S., Bruford, M.W., Ekblom, R., Fischer, M.C., Hall, J., Hvilsom, C., Hollingsworth, P.M., Kershaw, F., Mittan, C.S., Mukassabi, T.A., Ogden, R., Segelbacher, G., Shaw, R.E., Vernesi, C., MacDonald, A.J., 2022. Bringing together approaches to reporting on within species genetic diversity. J. Appl. Ecol. 59, 2227–2233.

Pereira, H.M., Ferrier, S., Walters, M., Geller, G.N., Jongman, R.H.G., Scholes, R.J., Bruford, M.W., Brummitt, N., Butchart, S.H.M., Cardoso, A.C., Coops, N.C., Dulloo, E., Faith, D.P., Freyhof, J., Gregory, R.D., Heip, C., Höft, R., Hurtt, G., Jetz, W., Karp, D.S., McGeoch, M.A., Obura, D., Onoda, Y., Pettorelli, N., Reyers, B., Sayre, R., Scharlemann, J.P.W., Stuart, S.N., Turak, E., Walpole, M., Wegmann, M., 2013. Essential Biodiversity Variables. Science 339, 277–278.

Pereira, H.M., Junker, J., Fernández, N., Maes, J., Beja, P., Bonn, A., Breeze, T., Brotons, L., Bruehlheide, H., Buchhorn, M., Capinha, C., Chow, C., Dietrich, K., Dornelas, M., Dubois, G., Fernandez, M., Frenzel, M., Friberg, N., Fritz, S., Georgieva, I., Gobin, A., Guerra, C., Haande, S., Herrando, S., Jandt, U., Kissling, W.D., Kühn, I., Langer, C., Liquete, C., Solheim, A.L., Martí, D., Martin, J.G.C., Masur, A., McCallum, I., Mjelde, M., Moe, J., Moersberger, H., Morán-Ordóñez, A., Moreira, F., Musche, M., Navarro, L.M., Orgiazzi, A., Patchett, R., Penev, L., Pino, J., Popova, G., Potts, S., Ramon, A., Sandin, L., Santana, J., Sapundzhieva, A., See, L., Shamoun-Baranes, J., Smets, B., Stoev, P., Tedersoo, L., Tiimann, L., Valdez, J., Vallecillo, S., Grunsven, R.H.A.V., Kerchove, R.V.D., Villero, D., Visconti, P., Weinhold, C., Zuleger, A.M., 2022. Europa Biodiversity Observation Network: integrating data streams to support policy. ARPHA Prepr. 3, e81207.

Pocock, M.J.O., Chandler, M., Bonney, R., Thornhill, I., Albin, A., August, T., Bachman, S., Brown, P.M.J., Cunha, D.G.F., Grez, A., Jackson, C., Peters, M., Rabarijaon, N.R., Roy, H.E., Zaviezo, T., Danielsen, F., 2018. A Vision for Global Biodiversity Monitoring With Citizen Science. Adv. Ecol. Res., Next Generation Biomonitoring: Part 2 (59), 169–223.

Populus, J., Vasquez, M., Albrecht, J., Manca, E., Agnesi, S., Al Hamdani, Z., Andersen, J., Annunziatellis, A., Bekkby, T., Bruschi, A., Doncheva, V., Drakopoulou, V., Duncan, G., Inghilesi, R., Kyriakidou, C., Lalli, F., Lillis, H., Mo, G., Muresan, M., Salomidi, M., Sakellariou, D., Simboura, M., Teaca, A., Tezcan, D., Todorova, V., Tunesi, L., Albrecht, J., Manca, E., Agnesi, S., Al Hamdani, Z., Andersen, J., Annunziatellis, A., Bekkby, T., Bruschi, A., Doncheva, V., Drakopoulou, V., Duncan, G., Inghilesi, R., Kyriakidou, C., Lalli, F., Lillis, H., Mo, G., Muresan, M., Salomidi, M., Sakellariou, D., Simboura, M., Teaca, A., Tezcan, D., Todorova, V., Tunesi, L., 2017. EUSeaMap: a European broad-scale seabed habitat map. Final Report. IFREMER. https://doi.org/10.13155/49975.

Prenda, J., Domínguez-Olmedo, J.L., López-Lozano, E., Fernández de Villarán, R., Negro, J.J., 2024. Assessing citizen science data quality for bird monitoring in the Iberian Peninsula. Sci. Rep. 14, 20307.

Proença, V., Martin, L.J., Pereira, H.M., Fernandez, M., McRae, L., Belnap, J., Böhm, M., Brummitt, N., García-Moreno, J., Gregory, R.D., Honrado, J.P., Jürgens, N., Opige, M., Schmeller, D.S., Tiago, P., van Swaay, C.A.M., 2017. Global biodiversity monitoring: From data sources to Essential Biodiversity Variables. Biol. Conserv 213, 256–263.

Rigal, S., Dakos, V., Alonso, H., Auniņš, A., Benkő, Z., Brotons, L., Chodkiewicz, T., Chylarecki, P., de Carli, E., del Moral, J.C., Domşa, C., Escandell, V., Fontaine, B., Foppen, R., Gregory, R., Harris, S., Herrando, S., Husby, M., Ieronymidou, C., Jiguet, F., Kennedy, J., Klvaňová, A., Kmecl, P., Kuczyński, L., Kurlavičius, P., Kålås, J.A., Lehikoinen, A., Lindström, Å., Lorrillière, R., Moshøj, C., Nellis, R., Noble, D., Eskildsen, D.P., Paquet, J.-Y., Pélissié, M., Pladevall, C., Portolou, D., Reif, J., Schmid, H., Seaman, B., Szabo, Z.D., Szép, T., Florenzano, G.T., Teufelbauer, N., Trautmann, S., van Turnhout, C., Vermouzek, Z., Vikstrøm, T., Voříšek, P., Weiserbs, A., Devictor, V., 2023. Farmland practices are driving bird population decline across Europe. Proc. Natl. Acad. Sci. 120, e2216573120.

Rishan, S.T., Kline, R.J., Rahman, M.S., 2023. Applications of environmental DNA (eDNA) to detect subterranean and aquatic invasive species: A critical review on the challenges and limitations of eDNA metabarcoding. Environ. Adv. 12, 100370.

Santana, J., Porto, M., Brotons, L., Junker, J., Kissling, W.D., Lumbierres, M., Moe, J., Morán-Ordóñez, A., Pereira, H., Solheim, A.L., Villero, D., Moreira, F., Beja, P., 2023. D3.2 Report on gaps and important new areas for monitoring in Europe. ARPHA Prepr. 4, e103657.

Scarponi, P., Coro, G., Pagano, P., 2018. A collection of Aquamaps native layers in NetCDF format. Data Brief. 17, 292–296.

Shamoun-Baranes, J., Bauer, S., Chapman, J.W., Desmet, P., Dokter, A.M., Farnsworth, A., Haest, B., Koistinen, J., Kranstauber, B., Liechti, F., Mason, T.H.E., Nilsson, C., Nussbaumer, R., Schmid, B., Weisshaupt, N., Leijnse, H., 2021. Weather radars' role in biodiversity monitoring. Science 372, 248.

Shamoun-Baranes, J., Bauer, S., Chapman, J.W., Desmet, P., Dokter, A.M., Farnsworth, A., Gasteren, H. van, Haest, B., Koistinen, J., Kranstauber, B., Liechti, F., Mason, T.H.E., Nilsson, C., Nussbaumer, R., Schmid, B., Weisshaupt, N., Leijnse, H., 2022. Meteorological data policies needed to support biodiversity monitoring with weather radar. Bull. Am. Meteorol. Soc. 103, E1234–E1242.

da Silva, J.P., Gonçalves, D.V., Garcia-Raventós, A., Lopes-Lima, M., Varandas, S., Froufe, E., Teixeira, A., Hui, F.K.C., Filipe, A.F., Sousa, R., 2023. Joint species distribution models unveil co-occurrences between freshwater mussels and their fish hosts. J. Biogeogr. 50, 730–742.

Steenweg, R., Hebblewhite, M., Kays, R., Ahumada, J., Fisher, J.T., Burton, C., Townsend, S.E., Carbone, C., Rowcliffe, J.M., Whittington, J., Brodie, J., Royle, J.A., Switalski, A., Clevenger, A.P., Heim, N., Rich, L.N., 2017. Scaling-up camera traps: monitoring the planet's biodiversity with networks of remote sensors. Front. Ecol. Environ. 15, 26–34.

Tuia, D., Kellenberger, B., Beery, S., Costelloe, B.R., Zuffi, S., Risse, B., Mathis, A., Mathis, M.W., van Langevelde, F., Burghardt, T., Kays, R., Klinck, H., Wikelski, M., Couzin, I.D., van Horn, G., Crofoot, M.C., Stewart, C.V., Berger-Wolf, T., 2022. Perspectives in machine learning for wildlife conservation. Nat. Commun. 13, 792.

Valdez, J.W., Callaghan, C.T., Junker, J., Purvis, A., Hill, S.L.L., Pereira, H.M., 2023. The undetectability of global biodiversity trends using local species richness. Ecography 2023, e06604.

Wilkinson, M.D., Dumontier, M., Aalbersberg, Ij.J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J.-W., da Silva Santos, L.B., Bourne, P.E., Bouwman, J., Brookes, A.J., Clark, T., Crosas, M., Dillo, I., Dumon, O., Edmunds, S., Evelo, C.T., Finkers, R., Gonzalez-Beltran, A., Gray, A.J.G., Groth, P., Goble, C., Grethe, J.S., Heringa, J., 't Hoen, P.A.C., Hooft, R., Kuhn, T., Kok, R., Kok, J., Lusher, S.J., Martone, M.E., Mons, A., Packer, A.L., Persson, B., Rocca-Serra, P., Roos, M., van Schaik, R., Sansone, S.-A., Schultes, E., Sengstag, T., Slater, T., Strawn, G., Swertz, M.A., Thompson, M., van der Lei, J., van Mulligen, E., Velterop, J., Waagmeester, A., Wittenburg, P., Wolstencroft, K., Zhao, J., Mons, B., 2016. The FAIR Guiding Principles for scientific data management and stewardship. Sci. Data 3, 160018.

Witjes, M., Parente, L., Križan, J., Hengl, T., Antonić, L., 2023. Ecodatacube.eu: analysis-ready open environmental data cube for Europe. PeerJ 11, e15478.