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Important note:

Building the backbone for Europe’s biodiversity monitoring

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Abstract

Biodiversity is declining at an unprecedented pace, eroding the planet's natural heritage and destabilising the ecosystems that sustain societies and economies. Meeting global commitments — from the Kunming–Montreal Global Biodiversity Framework to the European Green Deal — demands precise and consistent tracking of biodiversity change from genes to ecosystems. Yet, current monitoring is fragmented, uneven, and rarely integrated across borders. Here, we present a Roadmap for a unified, transnational biodiversity observation system in Europe built around 84 Essential Biodiversity Variables (EBVs). The roadmap combines traditional field surveys, satellite and airborne remote sensing, DNA-based methods, citizen science, and emerging in-situ sensors within an optimised spatial design to close taxonomic and geographic gaps. Standardised data sharing, coordinated governance, and advanced modelling will fuse these streams into policy-ready insights. A proposed European Biodiversity Observation Coordination Centre (EBOCC) would oversee the network, ensuring interoperability, scalability, and alignment with policy needs. By delivering a scalable architecture for biodiversity monitoring, this framework will enable rapid detection of ecological change, strengthen conservation actions, and safeguard the natural systems that underpin human well-being — offering Europe a path to meet its biodiversity goals and a global template for coordinated, transnational, open, and technology-enabled observation.

Introduction

Global biodiversity has declined sharply over the last fivedecades[1-3], eroding the fabric of life itself and threatening ecosystem services and the people who rely on them[4]. Heightened political and societal awareness has spurred major policy responses such as the Kunming–Montreal Global Biodiversity Framework (GBF) under the Convention on Biological Diversity. Many policies and initiatives demand unbiased, integrated, and regularly updated biodiversity data to support decision making. Yet, biodiversity monitoring remains spatially and temporally patchy, taxonomically biased, and poorly integrated[5,6]. As a result, the resources required for successful outcomes are currently often lacking, creating a critical gap between policy needs and existing data and reporting systems.

Over more than four decades, the European Union (EU) has built a comprehensive biodiversity and ecosystem monitoring framework encompassing diverse goals, legally binding and voluntary targets, and commitments at both EU and global levels (for the evolution of biodiversity policy in Europe, see Supplementary Fig. S1). Key legislation includes the Birds Directive (BD), Habitats Directive (HD), Water Framework Directive (WFD), Marine Strategy Framework Directive (MSFD), EU Biodiversity Strategy for 2030 (BDS), and the Nature Restoration Regulation (NRR), which have binding targets and reporting obligations for EU member states. Additional policies such as the Common Agricultural Policy (CAP), Common Fisheries Policy (CFP), and the Pollinators Initiative (PI) safeguard ecosystem services, while other EU policies such as the Regulation on Invasive Alien Species (IAS) or the Directive on Soil Monitoring and Resilience (SML) set rules for sustainable management, monitoring, and conservation of aquatic and terrestrial biodiversity (for descriptions of each policy, see Supplementary Table S1). However, despite this extensive policy framework, tracking reliable biodiversity trends across Europe remains a major challenge[6].

Current EU-wide biodiversity assessments face major monitoring gaps. Spatial and temporal coverage of taxa and ecosystem types is insufficient for robust status and trend evaluations[6-9], and taxonomic coverage remains incomplete[6-8], including especially large data gaps for species included in EU legislation that require reporting by member states, particularly in Eastern and South-eastern Europe[6,7,10]. Many freshwater and terrestrial taxa — such as zooplankton, lichens, dragonflies, terrestrial arthropods, fungi, and crop pests — lack coordinated Europe-wide monitoring, while marine data remain fragmented and regionalised (for example, as in the Northeast Atlantic or the Baltic Sea) and sparse for Southern and Eastern European seas[8]. Despite thousands of EU monitoring schemes, raw data from diverse programmes, agencies, and infrastructures are rarely shared and integrated[8,11]. Addressing these gaps will require an improved EU-wide framework that includes advanced monitoring technologies, systematic gap-filling, and robust workflows for data integration, harmonization and modelling as the backbone of European biodiversity monitoring.

Here, we present a Roadmap for establishing a modern, integrated Biodiversity Observation Network (BON) in Europe designed to align and operationalize biodiversity monitoring across multiple EU policies. Developed under the European Commission–mandated EuropaBON project[12], which engaged over 1,600 stakeholders from nearly 1,000 organisations spanning diverse sectors (academia, government, NGOs, private sector, citizen science), broad environmental domains (terrestrial, freshwater, and marine realms), and various geographic regions (Northern, Western, Eastern, Southern Europe, and beyond)[13], this Roadmap translates diverse policy and user needs[9,14] into a coherent framework for action. Specifically, it (1) applies the Essential Biodiversity Variables (EBVs) framework[15] to define a core set of variables for monitoring biodiversity from genes to ecosystems across freshwater, marine, and terrestrial realms; (2) highlights emerging monitoring technologies that can enhance efficiency and scalability; (3) proposes spatially optimized sampling designs to expand coverage and co-locate activities; and (4) delineates data integration workflows that harmonize heterogeneous sources across space, time, taxa, and ecosystems. Looking forward, it (5) outlines strategic steps, partnerships, and governance structures to move from concept to implementation; and (6) situates Europe's BON within the global context as a contribution to monitoring and reporting progress under the Kunming–Montreal GBF. Together, these elements chart a clear and actionable pathway toward a next-generation European biodiversity observation system capable of meeting policy needs and supporting global biodiversity monitoring.

Essential Biodiversity Variables (EBVs)

The concept of essential biodiversity variables (EBVs) from the Group on Earth Observations Biodiversity Observation Network (GEO BON)[15] was adopted to define a complementary, minimum set of measurements for tracking biodiversity change in Europe. At the global scale, this concept includes 21 generic EBVs within six EBV classes: genetic composition, species populations, species traits, community composition, ecosystem functioning and ecosystem structure. The six EBV classes were used to capture major biodiversity dimensions (Fig. 1): species-focused EBVs (genetic composition, species populations and species traits) and ecosystem-focused EBVs (community composition, ecosystem functioning and ecosystem structure). EBVs in the context of European biodiversity monitoring were then specified within these EBV classes, separately for freshwater, marine, and terrestrial realms (Fig. 1). Selection of specific EBVs was tailored to Europe via extensive stakeholder engagement — workshops, surveys, semi-structured interviews, expert consultations, and meetings with EU Commission Services and Agencies[16]. Selection criteria included alignment with EU policies, feasible near-term monitoring operationalisation, coverage of diverse taxa and habitats, and balanced representation across realms and EBV classes.

The Roadmap prioritises 84 specific EBVs for European monitoring: 36 (43%) terrestrial, 26 (31%) freshwater, and 22 (26%) marine[16]. Of these, 43 are species-focused, tracking status and trends of individual species via genetic diversity (only for selected species prioritized based on conservation relevance), abundance, distribution, and phenology across multiple groups (Fig. 1). The remaining 41 are ecosystem-focused, assessing habitats and communities through biomass, composition, productivity, and distribution of European ecosystems (Fig. 1). Taxonomic coverage is extensive across multiple groups: species-focused EBVs include all taxa in major EU Directives (for example, conservation-relevant species of mammals, reptiles, amphibians, fish, arthropods, and plants), threatened species on the European Red List (marine reptiles, freshwater mammals, invertebrates, terrestrial reptiles and mammals), species of specific EU interest (commercial marine fish, invasive freshwater species, animal disease vectors, crop and forest pests), and species crucial to ecosystem functions or services (for example, lichens as air-pollution indicators, wild mushrooms of recreational value, pollinators in the EU monitoring initiative, and harmful algal blooms). Included habitats follow the standardized classifications used in Europe, such as the European Nature Information System (EUNIS) and the habitat lists in the EU Habitats Directive[16].

For each EBV, the Roadmap recommends a spatial resolution (for example, grid cell size, catchment units, river segments, lakes) and temporal reporting frequency (for example, 1, 6, or 10 years) to the EU[16]. Most EBVs (80%) have a recommended reporting resolution of 1 km or 10 km (Fig. 1), and the remainder (20%) have other grid resolutions (10–300 m), other spatial units — catchments, lakes, river segments (freshwater EBVs) — or specific sampling sites (for example, EBVs for genetic diversity of terrestrial, marine, or freshwater species for selected taxa). Nearly half of the EBVs (48%) are recommended to be reported every 3–6 years, consistent with existing reporting cycles in Europe, whereas more than one-third (37%) are proposed for annual reporting to capture interannual and spatial variability. Sampling underlying the EBVs might require finer spatial and temporal resolution than final reporting. Alignment with EU legislation shows that over half of the 84 EBVs are directly linked to major biodiversity and environmental policies (Supplementary Fig. S2), enabling their use in official reporting and ensuring that EBVs related to pollinators, deadwood, and terrestrial and marine habitats are embedded in Europe's core monitoring framework (see Supplementary Table S1). When indirect policy connections are considered, three-quarters of the EBVs demonstrate broader relevance, often by providing underlying or complementary information — for example, indicators of habitat condition or ecosystem health (Supplementary Fig. S2).

Monitoring methods

EBVs draw on diverse monitoring methods (Supplementary Figs. S3–S9). About 75% of the EBVs rely primarily on in-situ observations from structured monitoring programs, citizen science, and DNA-based methods (Fig. 2). Traditional in-situ sampling methods include point counts, area surveys, and transects (for birds, mammals, amphibians, reptiles, plants, marine turtles, butterflies, other pollinators); electrofishing (freshwater fish); boat sampling (phytoplankton, zooplankton and macrophytes); soil and water sampling (terrestrial and aquatic invertebrates); trawling (freshwater and marine fish); ship/aircraft surveys (marine mammals); trapping (wildlife, insects, crop and forest pests); and opportunistic citizen science records[17,18]. DNA metabarcoding can identify species of management and conservation interest (such as invasive or endangered species)[19] or characterize community composition[20-22], and genetic metrics (such as allelic richness, heterozygosity and differentiation) can monitor inter-and intra-specific diversity and population genetic parameters for selected taxa[19,23]. The remaining 25% of the EBVs rely mainly on remote sensing from satellites, aircraft, drones, and weather radar (Fig. 2). Copernicus Sentinels and Landsat provide EU-wide coverage at ≤10 m resolution and weekly frequency[17,24-26]. Additional remote sensing tools include weather and biological radars (tracking migratory birds, bats, insects)[27-29] and airborne laser scanning or low-cost drones for fine-scale habitat condition and vegetation structure[30,31].

Primary monitoring methods provide the most direct and reliable data for tracking EBVs, yet on their own cannot fully capture EBVs across Europe and therefore require complementing by automated and methodologically expanded approaches (Supplementary Fig. S9). Structured monitoring programs for some species-focused EBVs already rely heavily on volunteers (such as bird and butterfly distribution surveys). For many other EBVs, monitoring by professionals can be complemented by citizen science[32-34] — for example, volunteers tracking bird abundance and migration phenology[35,36], documenting plant distributions[37], recording freshwater fish migration[38], contributing to ecosystem-focused EBVs such as marine seagrass mapping[39] or freshwater ecological status assessments[40]. Digital recorders (such as microphones, cameras, and mobile/stationary sensors) with AI-driven pipelines can cost-effectively enhance species distribution and abundance monitoring[41-43]. High-throughput environmental DNA (eDNA) analyses from water, soil, air, or bulk samples is increasingly mature and affordable, enabling large-scale monitoring of endangered, invasive, and pest species, community composition, and diversity across realms[20-22,44-46]. DNA metabarcoding can therefore support fish community assessments, insect and invertebrate diversity surveys, and works on poorly studied taxa (such as Diptera and Hymenoptera), many of which remain taxonomically unresolved. In addition to eDNA, genetic monitoring typically relies on tissue samples collected from specimens, but can also be conducted through other non-invasive sources such as faeces[47]. Remote sensing requires targeted ground-truthing across terrestrial and aquatic environments[26], using field data such as soil and water samples, vegetation plots, and land surveys, complemented by selected physiological measurements (for example, leaf fluorescence, phenology, plant structure or colour) to calibrate and validate remotely sensed indicators rather than to monitor every species individually[17]. Building Europe's biodiversity monitoring will therefore require integrating traditional structured monitoring programs with technically mature, cost-effective tools — DNA analysis, digital sensors, remote sensing, and citizen science.

Spatial design

The Roadmap for a modern European BON outlines spatial design recommendations, drawing on expert workshops that evaluated grid-based and site-based designs; stratification by environmental, anthropogenic, and policy factors; opportunities for co-locating EBV monitoring; differences in sampling common versus rare species and habitats; optimal network sizes; and strategies to fill spatial, temporal, and taxonomic gaps.

EU-wide and local sampling designs

An EU-wide stratified random sampling framework (Fig. 3a) divides the region of interest (EU member states plus the Balkans, Iceland, Norway, and Switzerland) into geographic units. On land, these typically follow 2 × 2 km grid cells used in the Land Use/Cover Area frame Survey (LUCAS) and the European Monitoring of Biodiversity in Agricultural Landscapes (EMBAL)[48]. Marine realms might use coarser grids (for example, 10 × 10 km). Freshwater units can be defined as catchments, lakes, or river segments following the European catchments and rivers network system (ECRINS)[49] or functional elementary catchments[50], or as grids to ensure inclusion of small and temporary water bodies (such as intermittent rivers, ephemeral streams, pools and springs, small lakes, and ponds). Representativeness is ensured through three stratification types: environmental (for example, climate zones, biogeographic regions, geomorphology, soils, elevation, ocean depth, habitat types, or physical and/or chemical ocean parameters)[51-54]; anthropogenic (for example, land use, climate-change velocity, nitrogen deposition, nutrient pollution, and ecological status of water bodies)[55-57]; and policy-related (for example, protected areas, marine exclusive economic zones, administrative boundaries, spatial planning units, agri-environmental schemes, and river barriers)[58-62]. Site selection can be optimised using multivariate geographic clustering[63], generalised dissimilarity modelling[64], or conservation-planning optimisation[65]. Within selected units, local sampling designs (Fig. 3b) can be random, systematic, or stratified by habitat, land-use intensity, water quality, or management/restoration status, with co-location of monitoring methods whenever feasible.

Co-location — carrying out different EBV monitoring activities at the same site (Fig. 3b) — can improve efficiency and enable integrated multi-taxa biodiversity assessments[66,67]. However, taxa-specific needs, particularly for rare or threatened species, often limit full overlap and therefore require additional dedicated sites and specialized methods[68]. In freshwater systems, many EBVs can be sampled within the same water bodies[69], except for variables such as wetland bird migration phenology, freshwater EUNIS habitat distribution, and river connectivity. Sampling methods also create within-site separation: pelagic EBVs (for phytoplankton, zooplankton, and planktivorous fish) are monitored in the water column, while macrophytes, benthic invertebrates, benthic algae, and benthivorous fish are sampled in the benthic, sediment and littoral zones. Small, temporary, and ponded waters and their associated terrestrial or seasonal habitats must also be included. In terrestrial systems, co-location depends on the monitoring approach and EBV class: species distribution and/or abundance and some community composition EBVs can be broadly sampled via in-situ, sensor or DNA-based methods[18,41,66]; phenological EBVs require time-sensitive protocols aligned to species life cycles[67,70]; abundance of disease vectors and crop pests demands targeted spatiotemporal detection[17]; and remote sensing-enabled EBVs require distinct ground-truthing designs[67,71,72]. In marine systems, the high cost of boat surveys drives a grouping by method[73]. These include: boat-based surveys, covering genetic diversity of marine taxa, fish distributions, plankton, seagrasses, benthic invertebrates, as well as deep-sea surveys of corals, cold seeps, and sponges; shoreline, coastal station, or aerial surveys for marine birds, mammals, and turtles; satellite-based observations for macroalgal canopies, harmful algal blooms, and productivity; and in-situ sampling in transitional waters such as estuaries and tidal rivers for phytoplankton biomass, seagrass abundance, macroalgae, benthic invertebrates, and fish.

Number of monitoring sites across Europe

Detecting biodiversity trends requires large sample sizes, often thousands of sites across broad geographic areas[68,74,75]. Generic power analyses show that several thousand sites are needed to detect changes in local species richness over short intervals[74], and taxon-specific analyses for EU pollinators suggest at least 3,000 sites are required to detect a 1% annual change in major groups and a 3% annual change for individual species[68]. Such coverage is adequate for common taxa but insufficient for rare, range-restricted species, which need targeted sampling. For example, the European Butterfly Monitoring Scheme (eBMS) monitors butterflies at 5,800 transects yet lacks power for rare species due to site-selection biases and limited coverage. The required sample size depends on taxon, species rarity, effect size, site representativeness, and spatiotemporal variability, but <10,000 sites are likely to be insufficient for trend detection across diverse taxa at continental scales. Sampling and monitoring protocols for such sites should generally follow best-practice guidelines to minimize disturbance.

A European BON should therefore comprise at least 10,000 spatially well-spread sampling locations per terrestrial and freshwater realm, with up to 100,000 desirable (~1–10% of the LUCAS 2 × 2 km grid). Existing monitoring schemes for birds (Pan-European Common Bird Monitoring Scheme, PECBMS), vegetation (European Vegetation Archive, EVA) and land cover (LUCAS, EMBAL) already cover more than 10,000 sites (Supplementary Fig. S10). Only LUCAS and EMBAL exceed 100,000 sites, and these are used mainly for Earth Observation validation rather than for detecting biodiversity trends. In freshwater systems, monitoring of river biota such as aquatic flora, macrophytes, phytobenthos, fish and benthic invertebrates currently covers at least 8,300 sites (10–44% of the total of ca. 86,400 river water bodies, limited to catchments >10 km^2; Supplementary Fig. S11), whereas lake monitoring is much less extensive (typically >1,000 sites, or at least 5% of the total of ca. 19,000 lakes larger than 50 ha, Supplementary Fig. S11). Including smaller water bodies would require a substantial increase in sampling effort, as even 10,000 or 100,000 sites represent only ~0.7% and ~7%, respectively, of the 1,348,163 river and stream segments and 70,847 lakes larger than 25 ha. Transitional and coastal water bodies are currently sampled in <1,000 sites (Supplementary Fig. S11). For marine realms, our Roadmap recommends coverage of 550–5,500 10 km^2 grid cells (1–10% of the 5.5 million km^2 exclusive economic zones in European regional seas). Note that these numbers represent methodological requirements for statistically robust trend detection and are not intended as an assessment of investment needs, risks, or broader cost–benefit considerations.

Filling of gaps

The spatiotemporal sampling design of a European BON must integrate existing large-scale and pan-European monitoring networks (examples in Supplementary Table S2) to leverage historical data, reduce costs, and strengthen continuity. Current monitoring shows major spatial, temporal, and taxonomic gaps[6] and especially poor coverage of genetic diversity[6,76] — a priority for meeting global policy targets set by the Kunming–Montreal GBF[77,78]. Spatial gaps in terrestrial biodiversity monitoring are pronounced in Southern and Eastern Europe, where capacity is limited and access costly; even well-established monitoring schemes such as the eBMS have transects concentrated in central Europe (Fig. 4a). Minimum representative site networks across habitats and geographic units, as in the proposed EU pollinator monitoring scheme[68], are essential.

Freshwater monitoring is well established for large streams and rivers (> 10 km^2 catchment area) and large lakes (>50 ha), as well as for certain taxa (such as benthic invertebrates and phytoplankton), achieving over 90% coverage in smaller countries such as Belgium and Slovenia, but remaining sparse in Northern Europe and uneven in Southern and Eastern Europe (Fig. 4b, c). Freshwater monitoring needs to expand to fully represent all types of water bodies — including rivers, lakes, small and temporary waters, transitional and coastal systems, and their connected riparian habitats — as well as all ecological status classes (high, good, moderate, poor, and bad). Currently overlooked systems such as groundwater, intermittent rivers, permanent and temporary ponds, pools, springs, and small or ephemeral streams should also be urgently included in freshwater monitoring[40,79,80]. Europe's marine monitoring is patchy, and stark regional imbalances exist (Fig. 4d): the North and Baltic Seas are densely covered, whereas the Mediterranean and Black Seas remain data-poor[81]. High-resolution marine monitoring is also strongly coastal-biased, reflecting the concentration of land-based pressures such as nutrient runoff, pollution, ports and shipping, intensive fishing, and tourism. By contrast, deep-sea habitats remain largely unsampled[73], underscoring the need to expand offshore monitoring to detect less visible but substantial impacts, including climate change, ocean acidification, plastic pollution, industrial fishing, shipping noise, and potential future deep-sea mining.

Europe's biodiversity monitoring also suffers from temporal gaps[6], undermining the detection of trends in EBVs. Many schemes meet only minimal sampling frequencies —

sometimes 1–2 samples once every 6–18 years, which is far too sparse for EBVs that show large temporal variation such as those relating to phytoplankton, insects, and marine invertebrates, which require annual or seasonal sampling. Repeated, regularly spaced sampling using consistent or comparable methods is essential to discern long-term trends from interannual variability, preserve continuity with historical datasets, and future-proof monitoring in the face of rapidly evolving technologies such as DNA-based methods and digital sensors. Taxonomic gaps also remain stark[6,68]: key groups such as zooplankton, amphibians, fungi, marine invertebrates, and many plants are poorly covered. Many invertebrate, phytoplankton, and phytobenthos groups are monitored only at higher taxonomic levels (genus, family, or order) in most EU member states[82], rather than at the species level, underscoring the need for improved taxonomic harmonization and identification[17]. Rare, endemic, and habitat-specialist species remain largely unsampled by standardised schemes. Current schemes favour common, well-studied or economically important taxa (for example, forest trees, birds, butterflies, and commercially important fish), leaving much of Europe's biodiversity invisible to policy-relevant monitoring and necessitating targeted expansion and tailored methods to close these crucial gaps[68].

Data integration and modelling workflows

Raw observations from existing in-situ monitoring schemes and remote sensing, together with emerging tools such as digital sensors, citizen science apps, eDNA, and AI species identification, will feed the EBV workflows of a European BON (Fig. 5a). The Roadmap captures the first conceptual representation of each EBV workflow[17,83], based on an EU-wide stakeholder consultation that engaged hundreds of experts in science, policy, and practice[84]. Operationalising these workflows will require integrating multi-source data across space, time, taxa, ecosystems, and sampling methods into EBV cubes that capture spatiotemporal patterns, biological entities, and uncertainties[85-88]. Key steps include data harmonisation and integration, and subsequent modelling and analyses (Fig. 5a). These steps require harmonising sampling effort, spatial and temporal resolution, and measurement units through standardised protocols, automated data streams, quality control, and machine-readable metadata, supported by EU-wide integration initiatives[8] (Supplementary Table S2). Spatial interpolation and extrapolation via regression or machine learning can generate continuous datasets[85-87], while rigorous uncertainty estimation addresses biases from raw data to model outputs[86,87]. Advanced modelling will further enable trend detection and short-term ecological forecasting[2,88-93], translating diverse observations into policy-relevant biodiversity insights, while guiding adaptive sampling and monitoring to capture key spatiotemporal dynamics and improve data-collection efficiency.

Three simplified EBV workflows showcase current and emerging data integration and modelling in Europe (Fig. 5b). In terrestrial systems, butterfly monitoring engages over 100,000 volunteers and scientists in conducting standardised transect counts several times a year at roughly 5,800 sites in 30 EU countries, covering more than 312 butterfly and moth species, and is complemented by a new 15-min count app[7,8,17]. Butterfly Conservation Europe harmonises national datasets into a European database, and uses a combination of models and R-packages (such as, 'rtrim', 'rGAI', and 'rbms') to generate multi-species abundance trends[94], including the European Grassland Butterfly Indicator[95,96]. In marine systems, seagrass distribution is mapped by merging HD reporting, monitoring data, drone and satellite imagery, and in-situ validation with habitat classifications integrated via the European Marine Observation and Data Network (EMODnet), and modelled using geographic information systems and deep learning[17]. In freshwater systems, WFD-driven monitoring of phytoplankton, phytobenthos, macrophytes, benthic invertebrates, and fish — such as phytobenthos in over 13,000 rivers across 27 EU countries[7] — contributes to the Water Information System for Europe (WISE) database, in which indicator values quantify deviations from reference conditions[69] and enable trend analysis[97], although raw data are not reported at the EU level. Newly developed models fill spatial gaps using land-use and nutrient data, while DNA metabarcoding is increasingly applied for species identification, supported by improving reference libraries and new application programming interfaces (APIs) that link repositories such as the European Nucleotide Archive (ENA) to data aggregators such as the Global Biodiversity Information Facility (GBIF)[17].

Future directions

Advancing biodiversity monitoring and its policy relevance in Europe across sectors to effectively deliver on policy goals will require coordinated innovation across technologies, data infrastructures, and governance systems[9,98]. Progress depends on establishing robust, long-term funded monitoring systems[9,98], achieving transnational harmonisation of protocols and data standards[8,14,83,98], ensuring sufficient spatial and temporal resolution and extent to detect real biodiversity trends[74,75,99], harnessing joint expertise and enabling effective partnerships with a culture of integration of different stakeholders[9,98], and enabling the integration of heterogeneous data sources into interoperable systems[87,100]. To move from design to implementation, the proposed European BON must now translate these ambitions into concrete action. This section first outlines the key priorities for biodiversity monitoring that should guide implementation, then describes how to build the European monitoring system through effective partnerships, governance, and sustainable funding, before finally discussing how a fully operational network can connect Europe to global biodiversity monitoring.

Setting priorities for biodiversity monitoring

Establishing a modern, policy-relevant European BON requires addressing a set of interlinked technological, methodological, and organisational needs identified through the EuropaBON stakeholder process. This requires strengthening taxonomic expertise, expansion and harmonisation of monitoring through filling gaps with structured in-situ monitoring and application of new technologies and methods, better data integration, and finding smart organisational solutions. These needs span eight key thematic areas that together define the foundation for next-generation biodiversity monitoring in Europe (prioritized in Table 1 and presented as a complete list in Supplementary Table S3).

[H3] Strengthening taxonomic expertise

Securing Europe's taxonomic capacity is fundamental for reliable biodiversity monitoring. Priority actions are to expand and sustain the taxonomic workforce by investing in targeted training, mentorship, and permanent positions, and to develop modern, accessible educational programmes and training resources for both professional taxonomists and volunteers[9,17,98,101]. These efforts are urgently needed as many taxa — particularly invertebrates, aquatic plants, and algae — still depend on manual identification, and emerging technologies cannot yet substitute expert judgement. Strengthening human expertise will also help maintain enthusiasm and engagement across professional and volunteer communities, ensuring that monitoring remains both scientifically rigorous and socially rooted.

Harnessing digital sensors
Rapid advances in digital sensors — including camera traps for vertebrates, insect cameras, acoustic recorders, hydrophones, radar, sonar, and telemetry — are transforming biodiversity monitoring by enabling automated, AI-assisted identification of species and assessments of species distributions, abundance, phenology, and movement[41-43,102]. Priority actions include the development of standardised protocols, robust AI species recognition, consistent metadata, and interoperable repositories to ensure comparability and long-term data usability. Existing initiatives such as ENETWILD (wildlife density estimation via camera traps), the European Tracking Network (ETN, aquatic telemetry), and emerging insect-monitoring projects using acoustic and imaging devices[17,103-106], as well as centralised data platforms such as Movebank (animal tracking)[107], ETN[103], and Agouti[108] illustrate major advances—but also highlight the need for sustained investment in infrastructure, standardisation, and digital media management to achieve continental-scale integration.

Scaling DNA-based assessments
DNA-based methods have rapidly matured into reliable tools for biodiversity monitoring. (e)DNA and metabarcoding can provide harmonised data on species occurrence and community composition across broad taxonomic groups, while abundance-related or biomass-related EBVs require calibration with conventional surveys and experimental studies to account for marker-specific and taxon-specific detection biases and environmental transport. Several European countries have already developed national implementation Roadmaps[109], and standardised, automated metabarcoding workflows are increasingly available[20,110]. A European standard (EN 17805:2023) and complementary international drafts for standards developed under the ISO TC147/SC5/WG13, along with guidelines for publishing DNA-derived occurrence data in GBIF, provide an emerging operational framework[111,112]. Nevertheless, major barriers remain, including inconsistent quality assurance and quality control (QA/QC) and a lack of harmonised protocols and methods, which limit regulatory acceptance and cross-country comparability. Priority actions include establishing method standards under ISO and CEN, harmonising and intercalibrating different methods, and implementing QA/QC frameworks[113,114]. In addition, creating a network of accredited reference laboratories for compliance and intercalibration, developing central and curated FAIR-compliant (findable, accessible, interoperable, and reusable) reference databases[115], and implementing shared computational infrastructures with standardised bioinformatics pipelines is crucial. Linking DNA sequences to curated taxonomic backbones and phylogenetic trees will support phylogenetically informed indicators and consistent inclusion of unresolved lineages in EBVs. Coordinated investment in these areas will enhance the reliability, interoperability, and policy relevance of DNA-based monitoring, enabling its full integration into the European BON.

Integrating citizen science
Citizen science can greatly enhance biodiversity monitoring by complementing professional surveys and emerging technologies. Combined with in-situ schemes, AI-enabled apps, digital sensors, and eDNA tools enable volunteers to generate high-quality observations across wide spatial and temporal scales[34,41,106,116,117]. Priorities include promoting or developing well-designed apps with semi-structured recording schemes[118], providing training and incentives that emphasise data quality over quantity[119], and addressing sampling biases to enhance reliability[120-

[122]. When fully integrated into the European BON, citizen science will expand coverage, strengthen data quality, and deepen public understanding and engagement in biodiversity stewardship.

Advancing Earth observation
Earth Observation (EO) from satellites, aircraft, and drones is poised to become a cornerstone of a European BON[17,83] as EBV workflows can be supported by ongoing and anticipated EO developments (Supplementary Table S4). Realising this potential requires high-quality in-situ reference data for calibrating and validating EO products or training deep learning models[26]. Priority needs include standardized ground measurements and open access data of vegetation structure, flowering traits, soil properties (including wetness), phenology, and other habitat attributes, and their integration with satellite data[123,124] and airborne LiDAR or unmanned aerial vehicle (UAV) imagery[30]. Ensuring open access and harmonisation of continental-scale aerial datasets — such as weather radar data used to track migratory biomass flows[125] — is equally important. Coordinated investment in interoperable EO and in-situ data infrastructures will be essential to fully unlock the potential of remote sensing for biodiversity monitoring across Europe while preparing for new sensors that are scheduled in the near future to improve biodiversity monitoring from space.

Expanding data integration and modelling
Expanding Europe's capacity for transnational data integration and modelling is essential for generating robust EBVs[83]. Priority needs include achieving interoperability among national databases through machine-actionable data exchange based on human-readable and machine-readable standards[30,83,126], ensuring FAIR (meta)data[8,9,115], and securing open access to raw biodiversity data[8,17,83]. Developing EBV workflows further requires multi-source data integration across sampling methods and the adoption of open-source, spatially-explicit and community-level models to derive EBVs[17,83,127-129], supported by investments in indicator development (Supplementary Fig. S12). Establishing historical baselines and contemporary reference conditions will be critical to contextualise EBVs[69,130,131]. Together, these advances will underpin the interoperable, data-rich infrastructure needed to operationalise a European BON.

Connecting digital infrastructures
A coherent and interconnected digital infrastructure is essential for operationalising a European BON, yet Europe's biodiversity data landscape remains fragmented across scales — from global platforms (such as GBIF, the Ocean Biodiversity Information System (OBIS), and GEO BON's EBV data portal) to EU-level portals (for example, Biodiversity Information System for Europe (BISE), WISE) and major European research infrastructures (such as Copernicus, EOSC, LifeWatch, eLTER, and ELIXIR), as well as numerous national and regional systems (see examples and abbreviations in Supplementary Table S3). A key priority is to connect and align these infrastructures, improving links between national portals and EU-level systems, and strengthening interoperability among existing European services[98,126,132]. Achieving operational EBV workflows will require FAIR (meta)data, interoperable data pipelines, and enhanced data sharing across agencies and organisations[8,83,132]. Critical actions include mobilising raw biodiversity datasets currently inaccessible in EU reporting[11], supporting standardisation and metadata harmonization[8,83,132], and adopting evolving data models — such as GBIF's richer data structures for digital sensors (for example, Camtrap DP)[133] and species inventories (for example,

the Humboldt Extension)[134]. Together, these steps will create the scalable digital backbone needed to generate EBVs through transnational, cross-infrastructure biodiversity data workflows.

Securing stronger coordination and long-term resources.
Strengthening coordination and securing long-term resources are essential to overcome Europe's fragmented biodiversity monitoring landscape and to fill gaps in current monitoring systems[6,9]. Monitoring activities by NGOs, museums and universities often struggle with limited long-term funding — particularly in Eastern and Southern Europe — leading to high staff turnover and loss of vital expertise[135]. For policymakers, EU institutions, and member states, a core requirement is a stable financial and governance framework, including a permanent, centrally supported coordination mechanism with EU–member state co-funding and strengthened national capacity[98]. Implementing a fully operational European BON for all identified EBVs is estimated to cost €5.7 billion over 10 years, comprising ~€500 million in initial establishment costs, ~€460 million in annual operational costs, and ~€63 million in initial investment plus ~€54 million annually for central coordination activities[98,136]. Current resources, however, support only a small subset of EBVs and remain insufficient for sustained monitoring, expert training, and cross-country digital and institutional integration[9,98]. Long-term, structural investment in human expertise, monitoring capacity, and both physical and digital infrastructure — complemented by public–private partnerships, EU research and innovation programmes (for example, Horizon Europe), and joint funding from members states and the European Commission (for example, Biodiversa+) — will be crucial to build the coordination and operational capacity required. Importantly, these investments provide substantial returns: the societal benefits of a robust biodiversity evidence base — from ecosystem services assessments, enhanced regulatory compliance, and support for emerging biodiversity credit markets — are expected to far outweigh the associated costs[137].

Building the European monitoring system

A strategic framework for building a coherent European biodiversity monitoring system requires to combine strong central coordination with a phased, long-term implementation pathway. The Roadmap therefore proposes the establishment of a dedicated European coordination centre to harmonise data, standards, and governance across diverse actors, alongside a staged 10+ year roadmap to progressively scale from pilot activities to a fully operational, policy-relevant European Biodiversity Observation Network. Together, these elements aim to ensure interoperability, sustainability, and long-term responsiveness to EU and global biodiversity policy needs.

Establishing a European coordination centre for biodiversity monitoring
A dedicated EU-level body responsible for operational coordination, EBV workflow implementation, harmonisation, data governance, and alignment with policy needs is necessary for implementing a European BON, but has not yet been established. Our Roadmap proposes the creation of a European Biodiversity Observation Coordination Centre (EBOCC) to fulfil this role[98]. The EBOCC would coordinate data flows, promote standards and workflows, host shared solutions, and facilitate exchange among national coordinators, NGOs, research infrastructures, and private actors. In the proposed governance structure (Fig. 6a), the EBOCC acts as the central hub, supported by a small permanent secretariat with strong links to EU institutions and

agencies, and is responsible for coordinating a distributed network of national biodiversity monitoring hubs[98], pan-European monitoring networks (Supplementary Table S2), digital infrastructures (Supplementary Table S3), and thematic EBV or indicator-focused hubs. Seed funding from a European Parliament preparatory action will pilot core EBOCC functions for a subset of prioritised EBVs, marking an important first step toward a coherent, interoperable, and cost-effective European system for systematically collecting, integrating, and analysing high-quality biodiversity data to support EU, national, and global policy needs.

Pathway to a fully operational European Biodiversity Observation Network
To move toward a fully functioning European BON, a staged 10+ year implementation pathway is required in which core components mature progressively across five phases (Fig. 6b). During phase 1 (preparatory and testing), existing monitoring schemes and technological readiness are assessed, pilot EBV workflows initiated, early standards established, and initial funding secured. In phase 2 (foundation and development), sampling protocols are harmonised, the first set of EBV workflows is developed, national governance structures are aligned, and stable EU and national budget lines put in place. Phase 3 (infrastructure and scaling) focuses on expanding sampling networks, deploying technological innovations at scale, and connecting national and European data infrastructures through major investment. This enables phase 4 (full implementation), in which long-term sampling stabilises, EBV workflows become fully operational, EU-wide indicators are routinely produced, governance structures reach full capacity, and sustained operational funding is secured. Finally, phase 5 (continuous improvement) ensures the system remains robust and policy-relevant through periodic refinement of sampling designs, technology upgrades, enhanced data integration, and adaptive funding and governance mechanisms.

Connecting Europe to global monitoring

Europe's biodiversity monitoring efforts should be embedded within, and contribute to, a globally connected observation system. In this context, the specific EBVs for a European BON can provide a common, policy-relevant interface linking European monitoring to global biodiversity targets and reporting frameworks, while also being adapted and scaled to regions beyond Europe. Together, these perspectives position the European Roadmap as both a contributor to global biodiversity assessments and a transferable model for strengthening monitoring capacity worldwide.

Linking European EBVs to global biodiversity targets and reporting
Europe's Roadmap for a continental BON aligns closely with GEO BON's global effort to build an interconnected global biodiversity observing system (GBiOS) of national and regional BONs that strengthens monitoring, data harmonisation, and indicator development worldwide[77]. This alignment supports the Kunming–Montreal GBF and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), enabling improved trend detection, attribution, forecasting, and national reporting[77,138-141]. EBVs serve as the central link between monitoring data and indicators, providing consistent, policy-relevant metrics that track biodiversity change across freshwater, marine, and terrestrial realms. Mapping the 84 EBVs prioritised in the Roadmap to GBF targets (Supplementary Table S5) shows that they primarily

support biodiversity protection and restoration (Goal A), including associated targets focussed on reducing threats (targets 1-8) by detecting changes in species populations, community composition, habitat condition, and the impacts of invasive species and climate change. EBVs related to ecosystem structure, productivity, biomass, and disturbance contribute to sustainable use targets (Goal B), including sustainable agriculture, aquaculture, fisheries, and forestry (target 10), and nature's contributions to people (target 11). In this way, Europe's monitoring system feeds directly into national and global indicators, strengthens science–policy interfaces, and helps evaluate progress toward global biodiversity goals.

Scaling EBV-based monitoring frameworks beyond Europe

The European Roadmap provides a transferable framework for strengthening biodiversity monitoring in other regions, but implementation requires adaptation to local policies, capacities, and ecological realities. Whereas Europe benefits from dense infrastructure, long-standing datasets, and institutional integration, other regions — such as Africa, Southeast Asia, or South America — might need to phase in EBV approaches gradually by first establishing basic monitoring networks, stable data governance, interoperable digital infrastructures, and sustained investment in human and technical capacity. Core principles—co-locating observations, applying standardised workflows, integrating multiple data streams, and using modelling and remote sensing to fill gaps—remain broadly applicable but must be tailored to regional biodiversity, environmental conditions, and available resources. Incorporating indigenous and local knowledge, expanding coverage to taxa and ecosystems underrepresented in Europe, and adjusting monitoring density to regional needs are essential steps. Even in the absence of transnational coordination, this Roadmap can guide countries in building coherent national systems and connecting them over time to global biodiversity observation networks.

Conclusions

Our Roadmap presents an integrated framework for building a modern and efficient European BON, aligning policies, EBVs, realms, and monitoring methods into a coherent system. Its core principles — combining complementary sampling approaches, co-locating EBV measurements, using standardized and reproducible data workflows, enabling interoperable digital infrastructures, and applying advanced modelling for wall-to-wall EBV data products — are widely transferable, although regional adaptation will be essential. Incorporating indigenous knowledge, strengthening technical capacity, and fostering cross-border coordination can further support its uptake in data-poor regions. We encourage broad testing and contextual adaptation of this framework to accelerate the development of biodiversity observation networks that inform conservation from local to global scales.

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Competing interests

The authors declare no competing interests.

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Related links

Essential biodiversity variables: https://geobon.org/ebvs/what-are-ebvs/
Essential biodiversity variables for European monitoring: https://github.com/EuropaBON/EBV-Descriptions
European Nature Information System: https://eunis.eea.europa.eu/
Land Use/Cover Area frame Survey: https://ec.europa.eu/eurostat/web/lucas
European Monitoring of Biodiversity in Agricultural Landscapes: https://data.jrc.ec.europa.eu/dataset/723355a8-e549-4691-9c0d-83ab7fc7a0c4
European Butterfly Monitoring Scheme: https://butterfly-monitoring.net/
European Vegetation Archive: https://euroveg.org/eva-database/
Pan-European Common Bird Monitoring Scheme: https://pecbms.info/
European Marine Observation and Data Network : https://emodnet.ec.europa.eu/
Water Information System for Europe: https://water.europa.eu/
European Nucleotide Archive: https://www.ebi.ac.uk/ena
Global Biodiversity Information Facility: https://www.gbif.org/
ENETWILD: https://enetwild.com/
European Tracking Network: https://europeantrackingnetwork.org/
Movebank: https://www.movebank.org/cms/movebank-main
European eDNA standard: https://standards.cencenelec.eu/ords/f?p=CEN:110:::::FSP_PROJECT,FSP_ORG_ID:72999,6211&cs=1724A9E6CBB3F5C7D336BEE9B6C4B7769
Development of standards for eDNA from water (ISO TC147/SC5/WG13): https://www.iso.org/committee/52972.html
Ocean Biodiversity Information System: https://obis.org/
EBV Data Portal: https://portal.geobon.org/datasets
Biodiversity Information System for Europe: https://biodiversity.europa.eu/
Kunming-Montreal Global Biodiversity Framework Targets: https://www.cbd.int/gbf/targets

Tables

Table 1 | Prioritized needs for advancing a European Biodiversity Observation Network. Priority needs and expected outcomes for eight thematic areas. A complete list of needs together with potential lead actors and stakeholders, and examples of relevant digital infrastructures, is available in Supplementary Table S3.

Thematic area	Priority needs (most urgent next steps)	Expected outcome/impact
1. Strengthening taxonomic expertise	• Expand and secure taxonomic workforce through training, mentorship, and permanent positions. • Develop targeted educational programs and training resources for taxonomists and volunteers.	Skilled taxonomists ensure accurate species identification across European biodiversity monitoring.
2. Harnessing digital sensors	• Standardize protocols, AI pipelines, and metadata for automated networks with imaging, acoustic, and tracking devices. • Establish interoperable European repositories for digital sensor data with privacy and ethical safeguards.	Scalable, automated biodiversity monitoring using repeatable, high-resolution sensor data.
3. Scaling DNA-based assessments	• Implement harmonized protocols, EU-wide QA/QC frameworks, and accredited reference laboratories. • Develop shared bioinformatics infrastructures and FAIR-compliant reference databases for taxonomic assignments.	Reliable, comparable DNA-based biodiversity data usable for policy and regulation.
4. Integrating citizen science	• Integrate citizen observations with professional monitoring through harmonised platforms and mobile applications and portal software. • Strengthen training, incentives, and quality control to improve data reliability.	Expanded spatial and taxonomic coverage and greater public engagement in biodiversity monitoring.
5. Advancing Earth observation (EO)	• Standardize ground-truth data collection and harmonize metadata across Europe for calibration and validation. • Integrate hyperspectral, radar, and LiDAR data with in-situ measurements for habitat mapping.	Consistent, continental-scale EO-based EBVs and improved monitoring of habitat conditions and trends.
6. Expanding data integration and modelling	• Harmonize taxonomies, metadata, and data standards across national databases. • Develop interoperable modelling pipelines and open-source tools for EBV generation and indicator development.	Seamless workflows transforming raw observations into policy-ready indicators and forecasts.
7. Connecting digital infrastructures	• Mandate FAIR, open sharing of biodiversity data and metadata. • Interconnect existing European and national infrastructures through interoperable data pipelines.	Robust digital infrastructure enabling efficient data exchange, storage, and reporting.
8. Securing coordination and long-term resources	• Establish and sustainably fund a permanent, centrally supported coordination mechanism. • Secure stable multi-source financing through EU, national, and public–private partnerships.	Long-term, coordinated operation of Europe’s biodiversity monitoring system.

EBV, essential biodiversity variable; FAIR, findability, accessibility, interoperability, and reusability; QA, quality assurance; QC, quality control.

Figures

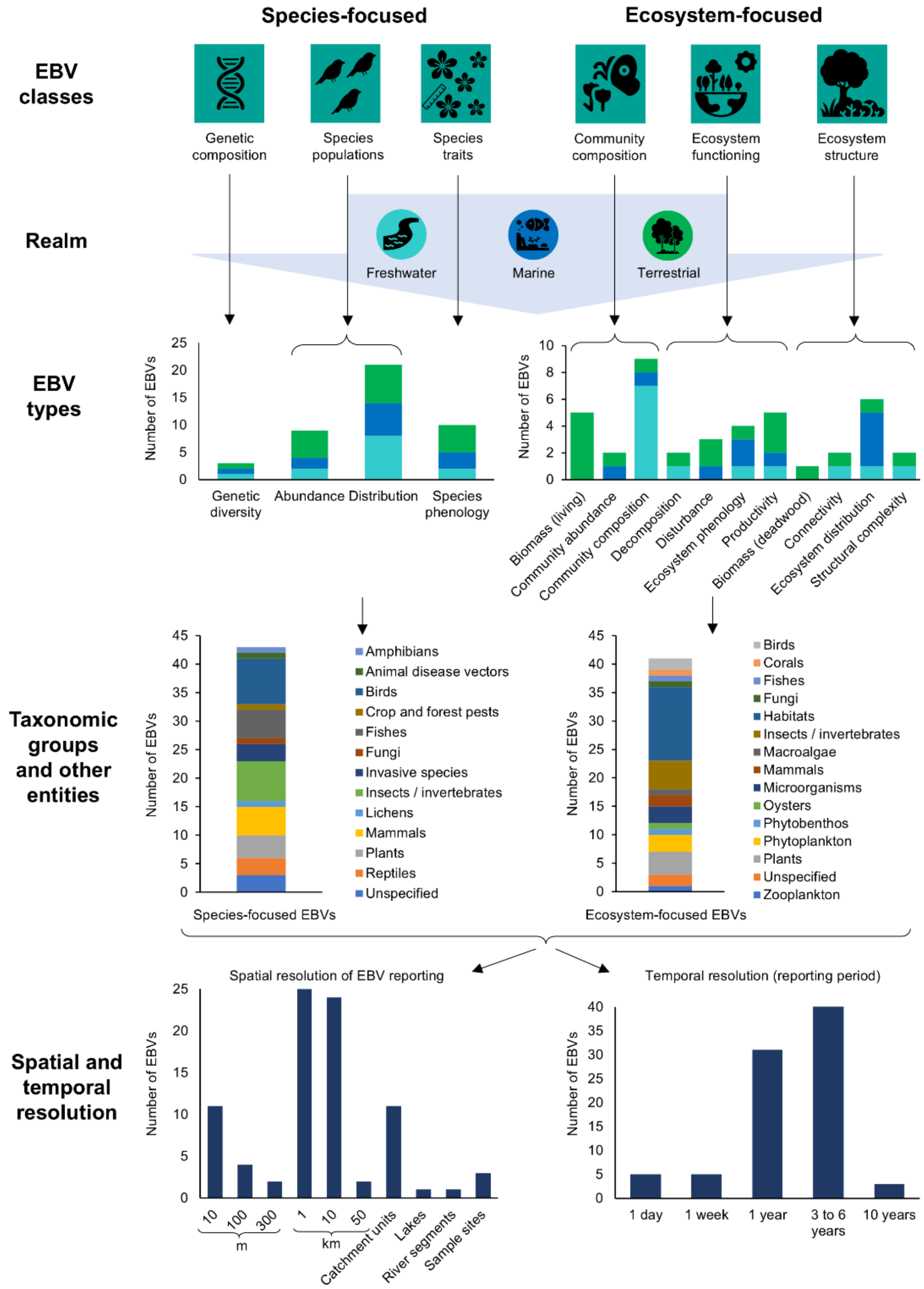

Fig. 1 | Prioritised biodiversity variables for Europe. Species-focussed and ecosystem-focused variables for each EBV class and realm cover a range of EBVs, taxonomic groups and recommended spatiotemporal resolutions. The full list with all EBV specifications is available from GitHub[142]. Data are available from Zenodo[143]. EBV, Essential Biodiversity Variable.

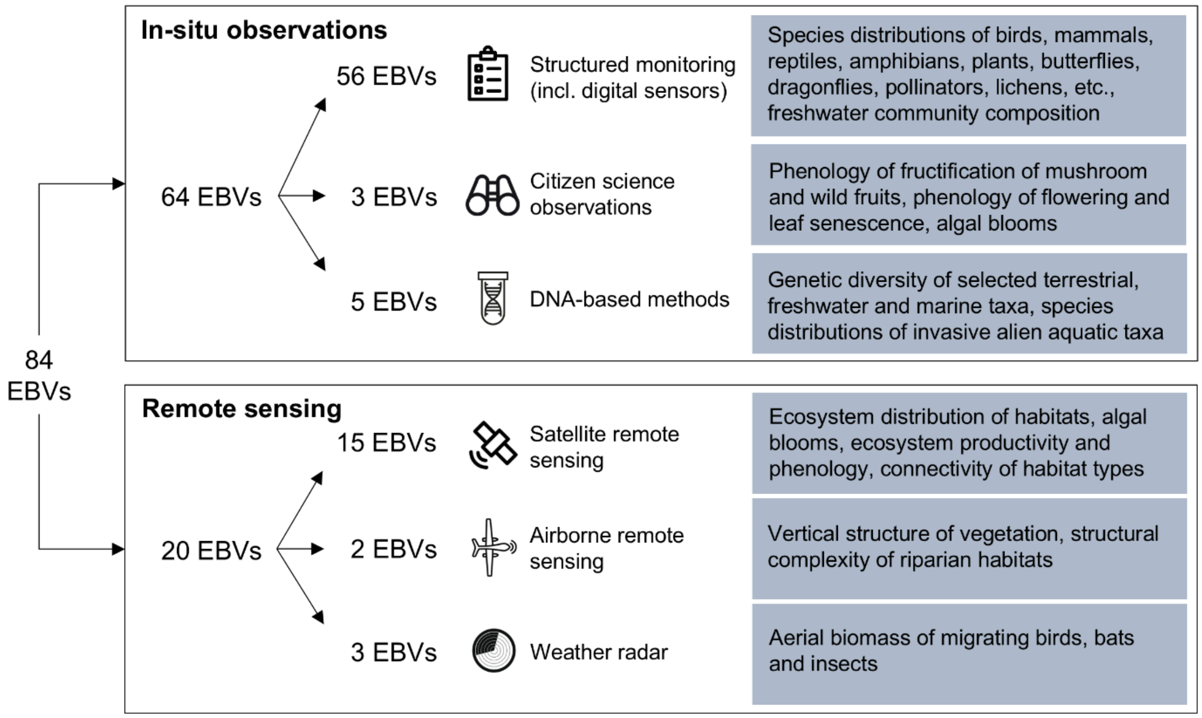

Fig. 2 | Primary monitoring techniques for biodiversity observations in Europe. For each of the 84 Essential Biodiversity Variables (EBVs), the most direct, reliable, and relevant monitoring technique was identified. In addition to these primary monitoring techniques, a diverse set of supplementary approaches is used for each EBV (see Supplementary Figs. S3–S9). Grey boxes provide illustrative, non-exhaustive examples of EBVs associated with each technique. Data are available from Zenodo[143].

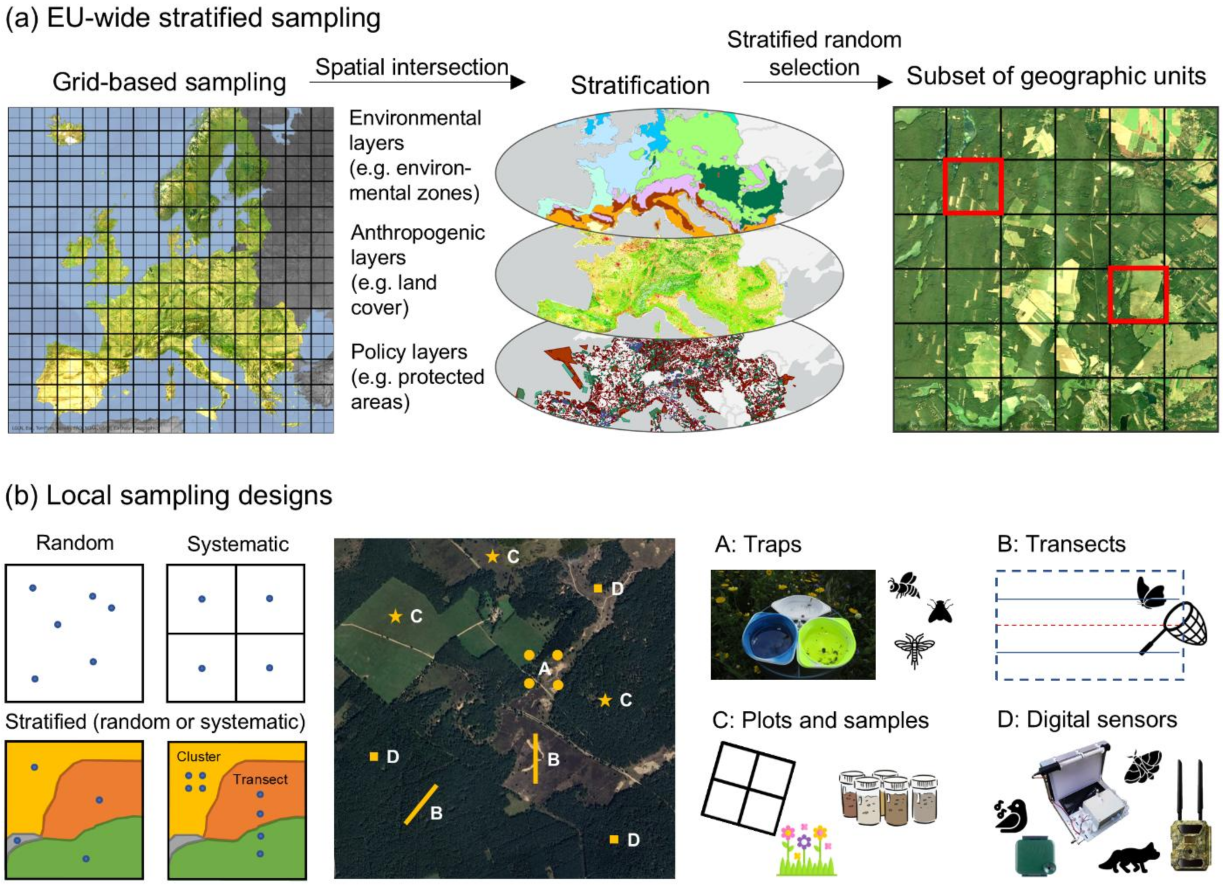

Fig. 3 | Example of EU-wide and local sampling designs. (a) An EU-wide stratified random selection of sites (for example, grid cells) across Europe with different stratification layers. (b) Local sampling designs that consider randomisation, replication and stratification and co-location of various field survey methods within a selected grid cell. Digital sensors depicted in panel D are a bird acoustic recorder, an automated moth light trap, and a wildlife camera.

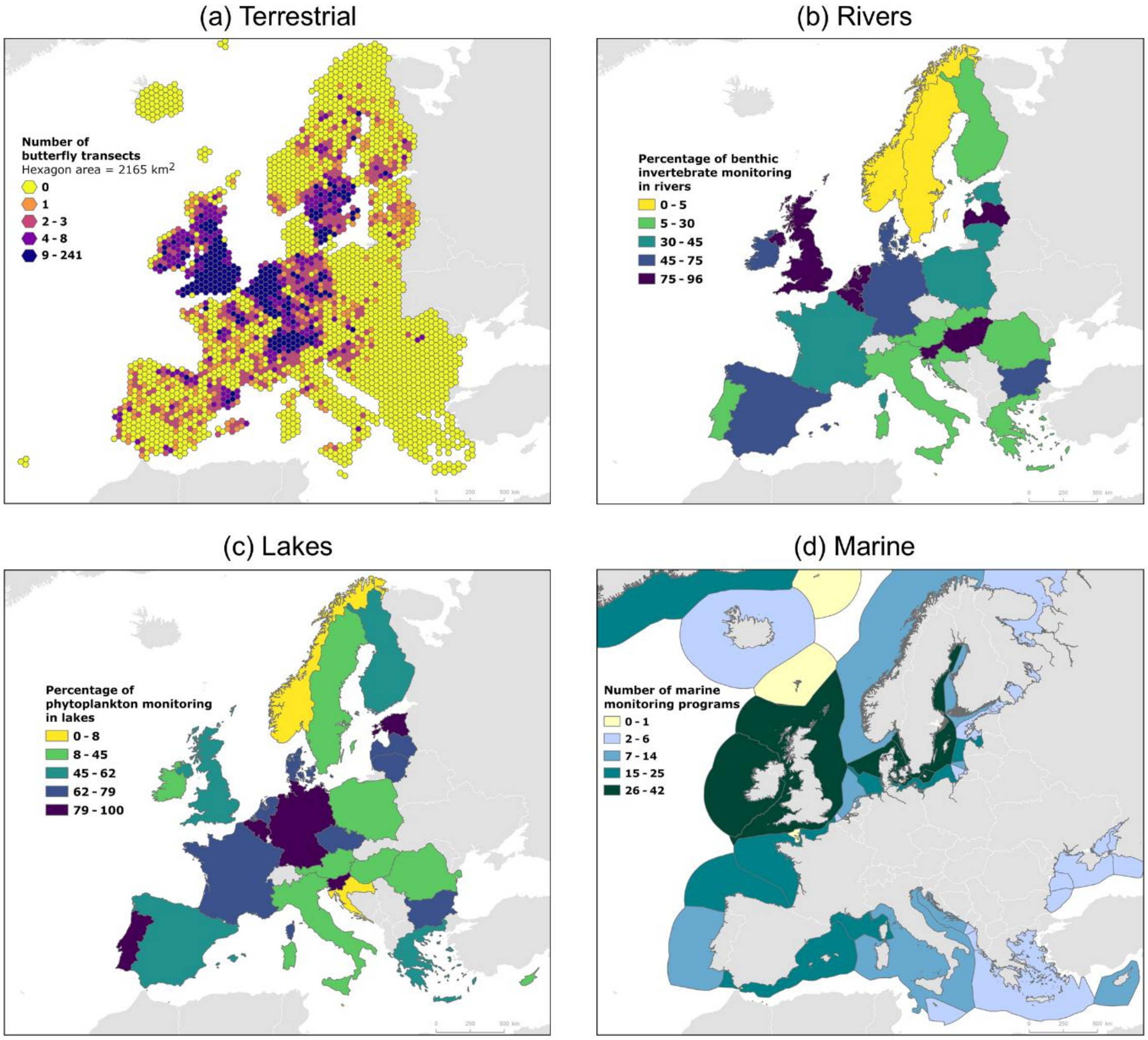

Fig. 4 | Examples of existing spatial gaps in European biodiversity monitoring. (a) Number of fixed transect routes in which butterflies are recorded every year. (b) Percentage of rivers (> 10 km^2 catchment area) within countries that have regulatory benthic invertebrate monitoring. (c) Percentage of lakes (>25 ha) within countries that have regulatory phytoplankton monitoring. (d) Number of marine monitoring programmes in European regional seas for which country-level spatial data around Europe are available. Colours are shown using a quantile classification. Data for part a are from the European Butterfly Monitoring Scheme (eBMS), for parts b and c are reported in the 2nd River Basin Management Plan (RBMP) of the Water Information System for Europe (WISE) Water Framework Directive (WFD) reference spatial datasets (covering EU member states plus Norway and the UK), and for part d are from ref [81]. Data are available from Zenodo[143].

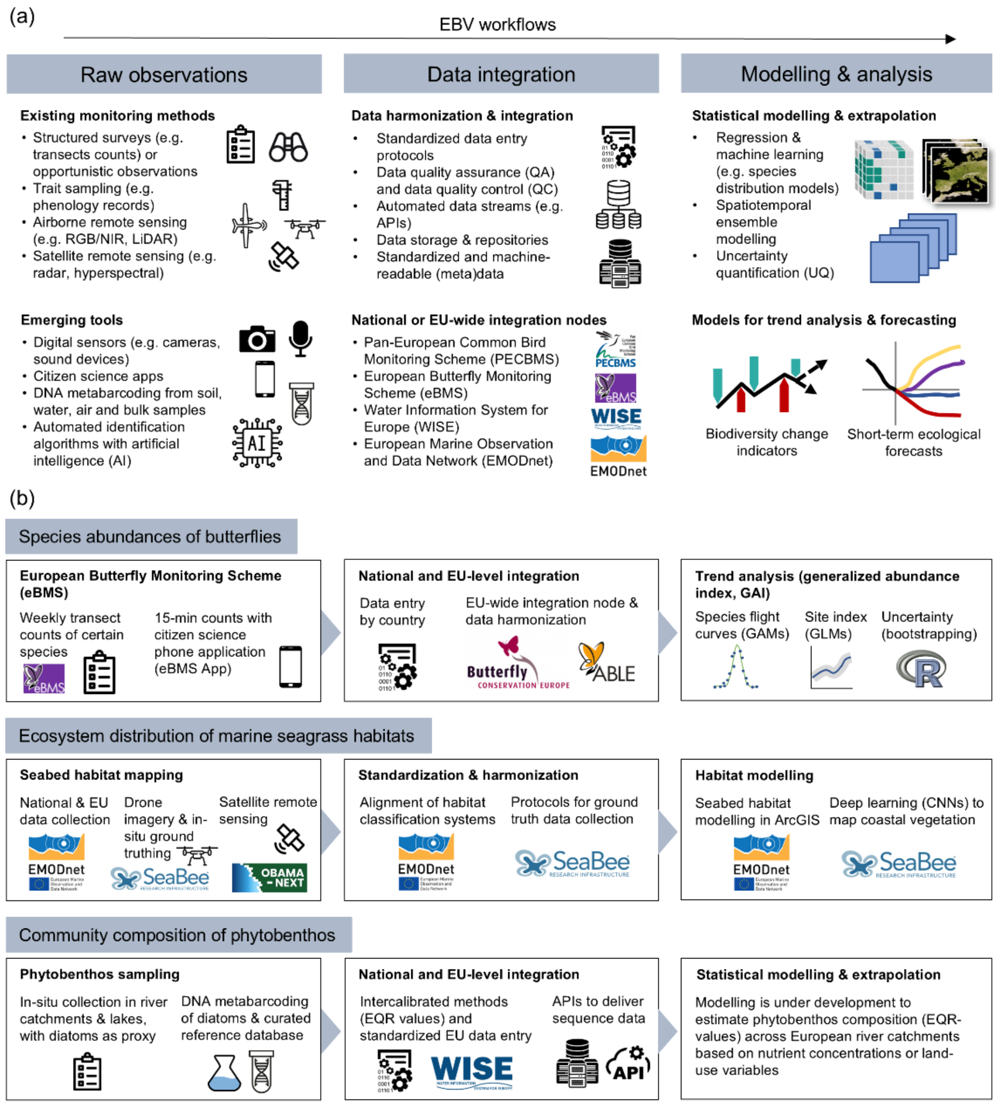

Fig. 5 | EBV workflow examples from generic pipelines to European case studies. (a) Generalised EBV workflow structure showing how raw biodiversity observations — from field surveys, citizen science, digital sensors, and remote-sensing platforms — are standardised, integrated, and modelled to produce EBV-based indicators and forecasts. Key steps include data ingestion (QA/QC, metadata standards, automated data streams), harmonisation across monitoring systems, and modelling approaches such as regression, machine learning, and spatiotemporal forecasting. (b) Three applied EBV workflow examples in Europe illustrating different realms and EBV classes: species populations (terrestrial butterflies), ecosystem structure (marine seagrass habitats), and community composition (freshwater phytobenthos). Each example highlights typical data sources, national and EU-level integration nodes, modelling methods, and resulting EBV-derived metrics. See ref. [17] for EBV workflows details. EBV, Essential Biodiversity Variable; RGB, red, green, and blue imagery; NIR, near infrared spectroscopy; LiDAR, light detection and ranging; API, application programming interface; GAM, generalised additive model; GLM, generalised linear model; CNN, convolutional neural network; EQR, ecological quality ratio; QA, quality assurance; QC, quality control.

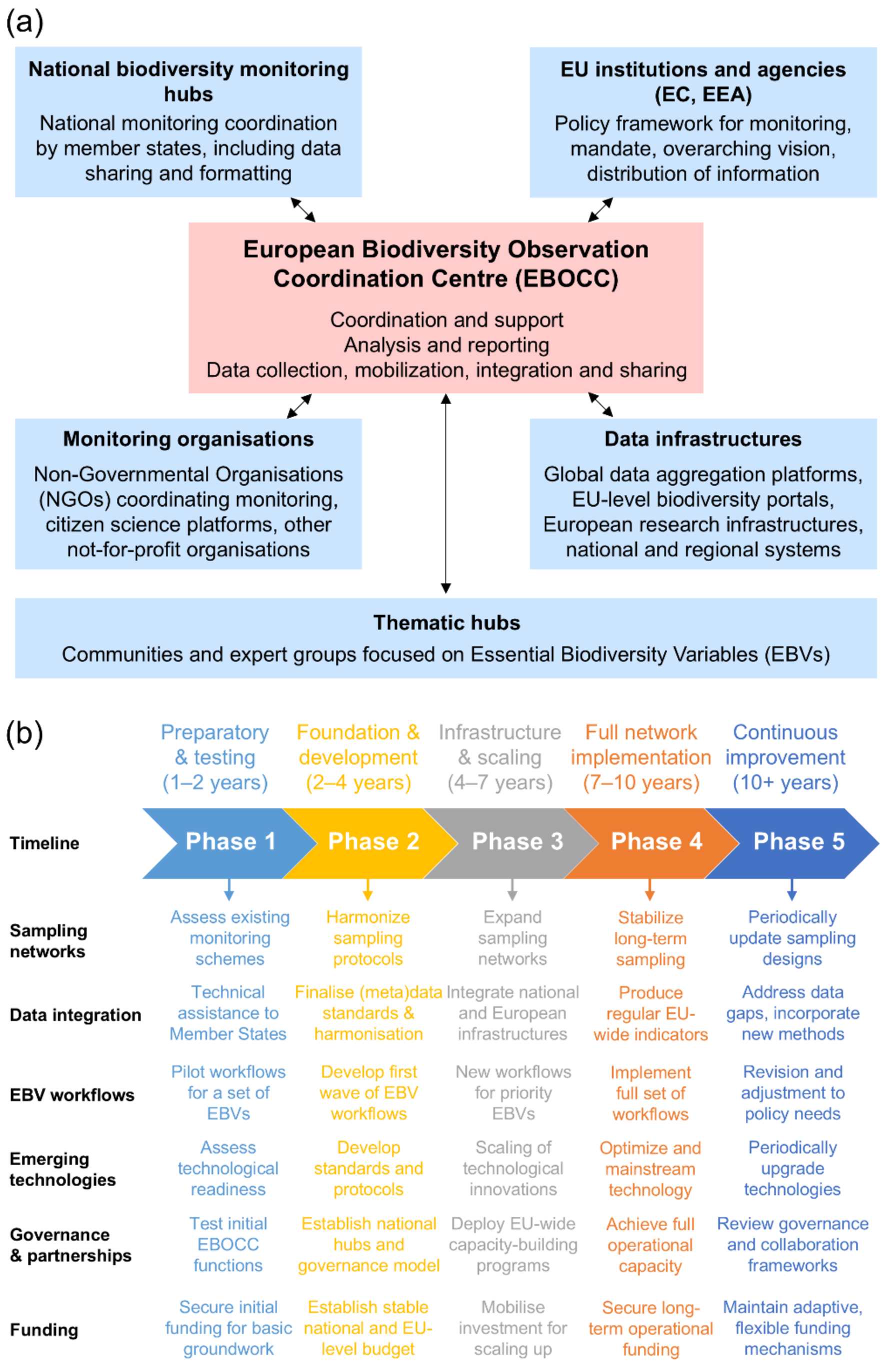

Fig. 6 | Core elements of establishing a European Biodiversity Observation Network. (a) Proposed governance architecture, in which the EBOCC acts as the central hub and has close links to EU institutions and agencies, coordinating national hubs, thematic expert groups and major data infrastructures and monitoring organisations (for details, see ref.[98]). (b) Conceptual development timeline outlining key milestones and capacity needs across five phases, from preparatory actions to long-term consolidation.

Supplementary information

Table S1 | Biodiversity policy framework of the European Union (EU). The listed legislation drives the development of biodiversity and ecosystem monitoring and assessments in the EU and fosters management measures for the conservation and sustainable use of EU ecosystems. The policies are ordered by publication year.

EU policy	Abbreviation	Year	Description	Weblink
Birds Directive	BD	1979	Requires the EU member states to monitor and report on the conservation status of all wild bird species natural occurring within and outside protected areas. It includes the assessment of population size, trends and species distributions.	https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:31979L0409
Habitats Directive	HD	1992	Requires the EU member states to monitor and report on the conservation status of habitats. This includes the assessment of the extent and condition of 200 habitat types and over 1000 animals and plant species within and outside of the Natura 2000 protected areas.	https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:31992L0043
Water Framework Directive	WFD	2000	Requires EU member states to monitor and report on the ecological and chemical status of water bodies, including a wide range of biological quality elements in rivers, lakes, transitional and coastal waters.	https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32000L0060
National Emission Ceilings Directive	NECD	2001	Establishes the emission reduction commitments for the EU member states anthropogenic atmospheric emissions. EU countries need to measure in-situ the impact of air pollution on terrestrial and freshwater ecosystems.	https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32001L0081
Marine Strategy Framework Directive	MSFD	2008	Requires EU member states to monitor and report on the environmental status of all marine EU waters, including environmental status and biodiversity criteria covering all species groups and broad habitat types.	https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32008L0056
Common Fisheries Policy (reform)	CFP	2013	Establishes rules for sustainably managing European fishing fleets and conserving fish, including a monitoring framework targeting population sizes of various marine fish stocks.	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32013R1380&qid=1686913584860
Regulation on Invasive Alien Species	IAS	2014	Requires EU member states to set up a surveillance system which collects and records data on the occurrence of invasive alien species of EU concern.	https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32014R1143#d1e1376-35-1
Land Use, Land Use Cover and Forestry Regulation	LULUCF	2018	Requires the monitoring of change in carbon stocks in managed forests, croplands, grasslands, and wetlands. The 2023 consolidated version aims to remove annually 310 million tonnes CO_2 equivalents from the atmosphere by 2030.	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32018R0841
EU Biodiversity Strategy for 2030	BDS	2020	Provides high-level ambitions of the EU to halt biodiversity decline and to put biodiversity on the path towards recovery by 2030. Includes more than 100 actions with headline indicators linked to 16 targets. Those indicators have different sources and do not necessarily depend on official reporting obligations of EU member states.	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52020DC0380

Common Agricultural Policy (reform)	CAP	2021	Aims to help tackling climate change and the sustainable management of natural resources in rural areas and landscapes across the EU. This requires a monitoring framework targeting selected species in agricultural areas. Farmland birds are reported as indicator under this monitoring and evaluation framework.	https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32021R2115
Proposed Forest Monitoring Regulation	FMR	2023	Sets out a common monitoring framework for the consistent collection and sharing of accurate and comparable forest data to ensure a coherent high-quality monitoring of EU forests and other wooded land.	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52023PC0728
Pollinators Initiative	PI	2023	Develops and tests an EU-wide pollinator monitoring sampling scheme that includes bees, butterflies and hoverflies while also increasing taxonomic capacity and expertise in countries.	https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52023DC0035
Regulation on New Environmental Economic Accounts	EEA-EA	2024	Sets out a common framework for collecting, compiling, transmitting, and evaluating European environmental economic accounts. Includes accounts on forests and other ecosystems.	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32024R3024&qid=1755612929160
Nature Restoration Regulation	NRR	2024	Multiple binding restoration targets and obligations to achieve the continuous, long-term, and sustained recovery of biodiverse and resilient nature across the EU's land and sea areas. Aim is to restore ecosystems and to contribute to achieving Union climate mitigation and climate adaptation objectives and meet its international commitments.	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32024R1991&qid=1728024382866
Directive on Soil Monitoring and Resilience	SML	2025	Sets out a soil monitoring framework for all soils across the EU and aims to achieve and maintain healthy soils by 2050, so that they can supply multiple ecosystem services.	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52023PC0416&amp%3Bqid=1706624227744

Table S2 | Examples of large-scale or pan-European monitoring networks or integration nodes in Europe. The list is not exhaustive but exemplifies some of the major monitoring data integration efforts for land cover and biodiversity in the EU.

Monitoring network	Abbreviation	Description	Source or weblink
Terrestrial			
Pan-European Common Bird Monitoring Scheme	PECBMS	Joint initiative of the European Bird Census Council (EBCC) and BirdLife International with a large European network of collaborators to provide information on bird numbers, distribution, and their changes in Europe	https://pecbms.info/
European Butterfly Monitoring Scheme	eBMS	Collects data from national and sub-national butterfly monitoring schemes to analyse and produce the population trends of European butterfly species	https://butterfly-monitoring.net/
Integrated European Long-Term Ecosystem, critical zone and socio-ecological Research	eLTER	A pan-European, in-situ research infrastructure with central facilities and distributed well-instrumented sites to study integrated human-nature systems (includes also freshwater and transitional water ecosystems)	https://elter-ri.eu/
European Vegetation Archive	EVA	An initiative of the European Vegetation Survey Working Group aimed at establishing and maintenance of a single data repository of vegetation-plot observations from Europe	https://euroveg.org/eva-database/
EU Pollinator Monitoring Scheme	EU PoMS	Development of a field-based monitoring scheme for assessing the status and trends of pollinator populations in EU countries	https://joint-research-centre.ec.europa.eu/jrc-news-and-updates/proposal-eu-pollinator-monitoring-scheme-eu-poms-2021-01-18_en
Land Use / Cover Area frame Survey	LUCAS	An in-situ survey to provide detailed information on harmonised and comparable land use and land cover information for the EU	https://ec.europa.eu/eurostat/web/lucas
European Monitoring of Biodiversity in Agricultural Landscapes	EMBAL	Development of a monitoring scheme to collect information on the state of biodiversity in agricultural landscapes in EU member states	https://data.jrc.ec.europa.eu/dataset/723355a8-e549-4691-9c0d-83ab7fc7a0c4
Freshwater			
Freshwater Information System for Europe	WISE FRESHWATER	Integration node that collects biological data from national monitoring programs for rivers, lakes, transitional and coastal waters in the context of the Water Framework Directive	https://water.europa.eu/freshwater
Marine			
Marine Information System for Europe	WISE MARINE	Integration node that collects biological data from marine monitoring programs Europe's seas in the context of the Marine Strategy Framework Directive	https://water.europa.eu/marine

European Marine Observation and Data Network	EMODnet	Network of organisations supported by the EU to provide access to European marine data (including distribution, abundance and biomass data from several taxa)	https://emodnet.ec.europa.eu/en

Table S3 | Comprehensive overview of identified needs and actions for a European Biodiversity Observation Network. The list provides specific needs and actions for eight thematic areas, together with potential lead actors and stakeholders, a time horizon for implementation, and examples of relevant digital infrastructures.

Abbreviations (in alphabetical order): AI = Artificial Intelligence; API = Application Programming Interface; BMD = Biodiversity Meets Data; BioDT = Biodiversity Digital Twin prototypes; BISE = Biodiversity Information System for Europe; Camtrap DP = Camera Trap Data Package; CEN = European Committee for Standardization; CETAF = Consortium of European Taxonomic Facilities; CoL = Catalogue of Life; DG ENV = Directorate-General for Environment (European Commission); DG RTD = DG RTD = Directorate-General for Research and Innovation (European Commission); DiSSCo = Distributed System of Scientific Collections; eBird = global citizen-science platform for bird observations; EBOCC = European Biodiversity Observation Coordination Centre; EBV = Essential Biodiversity Variable; eDNA = Environmental DNA; EEA = European Environment Agency; EIONET = European Environment Information and Observation Network; ELIXIR = European Life-Science Infrastructure for Biological Information; eLTER = Long-Term Ecosystem, critical zone and socio-ecological Research infrastructure; EMBAL = European Monitoring of Biodiversity in Agricultural Landscapes; ENA = European Nucleotide Archive; EO = Earth Observation; EOSC = European Open Science Cloud; ETN = European Tracking Network; EU = European Union; EU PoMS = EU Pollinator Monitoring Scheme; FAIR = Findable, Accessible, Interoperable, Reusable; GBIF = Global Biodiversity Information Facility; GEO BON = Group on Earth Observations Biodiversity Observation Network; HELCOM = Helsinki Commission, also known as Baltic Marine Environment Protection Commission; HPC = High-Performance Computing; iESTF = International eDNA Standardization Task Force; iNaturalist = international citizen-science platform where users record and share biodiversity observations; ISO = International Organization for Standardization; IT = Information Technology; JRC = Joint Research Centre (European Commission); LiDAR = Light Detection and Ranging; LifeWatch = e-Science and Biodiversity Research Infrastructure; MARCO BOLO = MARine COastal BiOdiversity Long-term Observations; NGO = Non-Governmental Organization; OBIS = Ocean Biodiversity Information System; Plazi = non-profit organisation to promote the free accessibility of taxonomic treatments and images; PESI = Pan-European Species directories Infrastructure; QA/QC = Quality Assurance / Quality Control; TDWG = Biodiversity Information Standards (formerly Taxonomic Databases Working Group); TNRS = Taxonomic Name Resolution Service; UAV = Unmanned Aerial Vehicle (drone); WISE = Water Information System for Europe.

Thematic area	Specific needs and actions	Lead actors / stakeholders	Implementation horizon	Examples of relevant digital infrastructures
1. Strengthening taxonomic expertise	• Develop taxonomic curricula at all levels, offer targeted courses and field training, and implement proficiency testing for both professionals and volunteers. • Increase the number of trained taxonomists, secure permanent positions, and create clear career pathways in academia, research, government, NGOs, and private sector. • Combine manual identification with DNA-based and imaging techniques and use experts to quality check automated methods. • Standardize taxonomic nomenclature, link morpho-taxonomic and genetic databases, and ensure interoperable, high-quality data reporting across Europe.	EBOCC; DG ENV; DG RTD; EEA; Biodiversa+; research infrastructures; universities; research institutions; natural history museums; botanical gardens;	Short → medium → long term	GBIF; national biodiversity databases; CoL; BISE; DiSSCo; TDWG; CETAF; Fauna Europaea; PESI; BOLD; ENA; ELIXIR; Europeana Collections; iNaturalist / Observation.org (EU nodes); TNRS; Plazi; digital portals of natural history museums

	• Maintain and expand physical and digital collections, and develop centralized platforms for protocols, reference materials, and training tools. • Strengthen partnerships among universities, museums, natural history societies, and international taxonomic communities. • Embed taxonomy in environmental policy, conservation planning, and decision-making; raise awareness of its societal and scientific importance. • Ensure sustainable financial support for training, capacity building, monitoring, and maintenance of taxonomic infrastructure.	CETAF; TDWG; citizen science & volunteer networks		
2. Harnessing digital sensors	• Develop standardised operating procedures, calibration, and metadata for digital sensors (e.g. camera traps, acoustic recorders, radar, sonar, and telemetry devices). • Establish AI-based species recognition libraries covering multiple taxa. • Create interoperable repositories for digital sensor platforms at national and EU-level. • Adopt common data formats and privacy/ethical guidelines for digital imagery and recordings. • Promote co-location of digital sensors with traditional monitoring sites.	EBOCC; Biodiversa+; research infrastructures; AI developers; national agencies; MARCO BOLO; NGOs; private sector.	Short → medium term	Movebank; ETN; Agouti; EOSC; LifeWatch; eLTER.
3. Scaling DNA-based assessments	• Define and implement minimum QA/QC standards across Europe. • Establish accredited national and regional reference laboratories for (e)DNA analyses. • Align sampling and analytical protocols with recognised best-practice guidelines and, where available, formal standards such as CEN and ISO. • Develop computational infrastructures for standardised bioinformatics pipelines. • Maintain and expand curated DNA reference libraries and metadata in line with FAIR principles. • Coordinate national DNA workflows through EBOCC to ensure comparability and long-term consistency. • Agree on and accept the use of (e)DNA in national monitoring programmes and in official reporting. • Agree on and adopt criteria for validated taxonomic assignment. • Promote the use of tools such as the GBIF Metabarcoding Data Toolkit for efficient sharing of standardised (e)DNA sampling data.	CEN; ISO; GBIF; ENA; ELIXIR; iESTF; TDWG; MARCO BOLO; national environment agencies.	Medium term	ELIXIR; GBIF; EBOCC; national genomics centres.

4. Integrating citizen science	• Develop harmonised platforms for biodiversity reporting, using existing mobile applications and portal software where possible. • Integrate structured (schemes) and opportunistic (apps) data using advanced modelling approaches. • Provide training, accreditation, and community support to volunteers. • Implement incentive structures rewarding data quality rather than volume. • Address spatial and taxonomic biases through adaptive sampling and feedback mechanisms. • Promote inclusion and long-term engagement through targeted outreach and education.	NGOs; citizen-science networks; research institutions; EBOCC; EU agencies; private sector.	Ongoing → short term	EU PoMS; eBird; iNaturalist; GBIF; national or regional citizen science portals.
5. Advancing Earth observation	• Standardise and democratise ground-truth data collection and metadata (e.g. vegetation structure, flowering traits, soil properties, phenology) to fit for EO processing (e.g. overpass time, number of samples, geospatial and temporal coverage). • Ensure geolocation accuracies compatible with EO sensor resolution. • Integrate hyperspectral, radar, and LiDAR data with in-situ observations for ecosystem structure and function EBVs. • Enable open access to aerial datasets (UAV, aircraft) and weather-radar data for biodiversity uses. • Create EU-wide EO data standards and open-source pre-processing pipelines. • Combine EO with national mapping for habitat condition and restoration monitoring.	EEA; Copernicus programme; national mapping and space agencies; research infrastructures; MARCO BOLO.	Short → Medium term	Copernicus; ESA; EEA; EMBAL; GEO BON EBV portal; EOSC; EBOCC.
6. Expanding data integration and modelling	• Implement interoperable data and metadata standards (machine-readable formats). • Expand European data integration nodes connecting national databases (including the integration of legacy data). • Harmonise taxonomic references and classification systems. • Provide open access to raw biodiversity data currently restricted to reports. • Develop spatially explicit modelling pipelines for abundance, community composition, and ecosystem EBVs. • Create open-source modelling tools and APIs for indicator generation. • Establish historical baselines and reference conditions to	EBOCC; data scientists; DG ENV, DG RTD; GBIF; OBIS; MARCO BOLO; national biodiversity centres.	Short → medium term	GBIF; OBIS; EOSC; LifeWatch; eLTER; BMD.

	contextualise EBV trends. • Provide training and support for national data modellers.			
7. Connecting digital infrastructures	• Interconnect existing global, European and national infrastructures. • Mandate sharing of original source data under FAIR and Open principles. • Support automated ingestion pipelines and cloud/HPC computing for EBV workflows. • Enhance data standardisation, metadata harmonisation, and persistent identifiers. • Ensure long-term technical maintenance, IT staffing, and version control. • Leverage evolving GBIF data model to capture richer contextual information (e.g. Camtrap DP, Humboldt Extension).	EBOCC; EU Commission (DG ENV, DG RTD, JRC); GBIF (secretariat and EU nodes); OBIS; EOSC; HELCOM; national data providers.	Medium term	GBIF (global and national platforms); OBIS; EOSC; Copernicus; GEO BON EBV portal; BISE; WISE; LifeWatch; eLTER; ELIXIR; BMD; BioDT.
8. Securing coordination and long-term resources	• Operationalise EBOCC as a permanent coordination hub. • Develop a stable financial framework integrating EU and national budgets. • Secure multiyear funding for monitoring programmes, data integration, and IT infrastructure. • Promote public–private partnerships and biodiversity-credit mechanisms. • Invest in long-term human capacity (training, data stewardship, modelling expertise). • Embed biodiversity monitoring needs in Horizon Europe and Biodiversa+ calls.	EU Commission; EEA; national ministries; national biodiversity programmes; EBOCC; Biodiversa+; NGOs; HELCOM; private sector.	Medium → long term	GBIF; OBIS; EOSC; Copernicus; BISE; WISE; LifeWatch; eLTER; ELIXIR; DiSSCo; CETAF; EIONET

Table S4 | Examples of current and future expected developments for the use of Earth Observation (EO) for biodiversity monitoring with Essential Biodiversity Variables (EBVs) workflows. The overview was obtained during the EuropaBON workshop on EBV workflows (online, February 2023) through involvement of experts in the domain of EO and biodiversity monitoring.

Topic	Current	Future
EO input signals	Satellite multi-spectral Airborne LiDAR (local) Satellite LiDAR (continental)	Satellite hyperspectral Satellite or airborne very-high resolution (<1 m) Continental LiDAR (regular collection) Night-time
Data collection and sampling	Vegetation plots Chlorophyll a (Chl-a)	Harmonized vegetation plots, including standardized taxonomic information and better geospatial accuracy Landscape features (e.g. hedgerows, stonewalls, etc.) Biophysical properties (e.g. leaf chemistry, eDNA) Harmonized data collection with UAV flights
Data integration	Samples in space and time	Automated workflows Long consistent time-series Change detection and attribution
Modelling	Band indices Statistical models Machine learning (e.g. Random Forest)	Deep learning Ensemble models Spatiotemporal modelling Handling of uncertainties
Infrastructure & interoperability	Cloud optimized data	FAIR principles Semantic technologies Public cloud with free credits Central code repository
Knowledge	Few examples	Online tutorials, e-learnings Capacity building, COST actions Sustained funds Support, helpdesk

Table S5 | Alignment of Essential Biodiversity Variables (EBVs) with the goals and targets of the Kunming–Montreal Global Biodiversity Framework (GBF). The rationale outlines how each EBV contributes to, or informs progress toward, specific GBF goals and targets.

Realm	EBV class	EBV name	GBF relevance	Rationale
Freshwater	Community composition	Community composition of phytoplankton	Goal A, Goal B, T11	Monitors ecosystem integrity, ecosystem services (water quality)
Freshwater	Community composition	Community composition of macrophytes	Goal A, Goal B, T11	Monitors ecosystem integrity, ecosystem services (water quality)
Freshwater	Community composition	Community composition of phytobenthos	Goal A, Goal B, T11	Monitors ecosystem integrity, ecosystem services (water quality)
Freshwater	Community composition	Community composition of benthic invertebrates	Goal A, Goal B, T11	Monitors ecosystem integrity, ecosystem services (water quality)
Freshwater	Community composition	Community composition of fishes	Goal A, T4, T5	Monitors ecosystem integrity, species conservation, sustainable exploitation
Freshwater	Community composition	Community composition of zooplankton	Goal A, Goal B, T11	Monitors ecosystem integrity, ecosystem services (water quality)
Freshwater	Community composition	Community composition of aquatic fungi	Goal A, Goal B, T11	Monitors ecosystem integrity, ecosystem services (water quality)
Freshwater	Ecosystem function	Harmful and non-harmful freshwater algal blooms	Goal B, T7, T10, T11	Monitors pollution, sustainable agriculture, ecosystem services (water quality)
Freshwater	Ecosystem function	Freshwater ecosystem productivity	Goal A, Goal B, T5, T11	Monitors ecosystem integrity, sustainable exploitation, ecosystem services
Freshwater	Ecosystem function	Rate of decomposition	Goal A	Monitors ecosystem integrity and resilience
Freshwater	Ecosystem structure	River Connectivity/Free river flow	T1, T3	Monitors biodiversity-inclusive spatial planning, protection (connectivity)
Freshwater	Ecosystem structure	Ecosystem distribution of freshwater EUNIS Habitats	T3	Monitors protection (representativeness)
Freshwater	Ecosystem structure	Structural complexity of riparian habitats	Goal A, T2	Monitors ecosystem integrity, restoration
Freshwater	Genetic composition	Genetic diversity of selected freshwater taxa	Goal A, T4	Monitors conservation of genetic diversity

Freshwater	Species populations	Species abundances of selected wetland bird species	Goal A, T4	Monitors species abundance
Freshwater	Species populations	Species distributions of freshwater fishes	Goal A, T4	Monitors species conservation
Freshwater	Species populations	Species distributions of amphibians	Goal A, T4	Monitors species conservation
Freshwater	Species populations	Species distributions of freshwater mammals	Goal A, T4	Monitors species conservation
Freshwater	Species populations	Species distributions of freshwater invertebrates	Goal A, Goal B, T4, T11	Monitors species conservation, ecosystem services (water quality)
Freshwater	Species populations	Species abundances of dragonflies	Goal A, T4	Monitors species abundance
Freshwater	Species populations	Species distributions of dragonflies	Goal A, T4	Monitors species abundance
Freshwater	Species populations	Species distributions of freshwater macrophytes	Goal A, Goal B, T4, T11	Monitors species conservation, ecosystem services (water quality)
Freshwater	Species populations	Species distributions of invasive alien freshwater taxa of European concern	T6	Monitors invasive alien species
Freshwater	Species populations	Species distributions of freshwater reptiles	Goal A, T4	Monitors species conservation
Freshwater	Species traits	Phenology of migration of wetland birds	T8	Monitors impacts of climate change
Freshwater	Species traits	Phenology of migration of freshwater fishes	T8	Monitors impacts of climate change
Marine	Community composition	Functional composition of marine plankton (based on traits)	Goal A	Monitors ecosystem integrity
Marine	Community composition	Community abundance of functional groups of soft-bottom benthic macroinvertebrate communities	Goal A, T7	Monitors ecosystem integrity, pollution
Marine	Ecosystem function	Degree of seabed disturbance	Goal A, T1, T3	Monitors ecosystem integrity, biodiversity-inclusive spatial planning, protection
Marine	Ecosystem function	Harmful marine algal blooms	T7, T10, T11	Monitors pollution, sustainable agriculture, ecosystem services
Marine	Ecosystem function	Phenology of marine spring phytoplankton bloom	T8	Monitors impacts of climate change
Marine	Ecosystem function	Marine ecosystem productivity	Goal A, Goal B, T5, T11	Monitors ecosystem integrity, sustainable exploitation, ecosystem services
Marine	Ecosystem structure	Ecosystem distribution of hard corals habitats	Goal A, T8	Monitors ecosystem integrity, impacts of climate change
Marine	Ecosystem structure	Ecosystem distribution of marine macroalgae canopy cover	Goal A, T5, T7	Monitors ecosystem integrity, sustainable exploitation, pollution

Marine	Ecosystem structure	Ecosystem distribution of marine seagrass habitats	T1, T3	Monitors biodiversity-inclusive spatial planning, protection
Marine	Ecosystem structure	Ecosystem distribution of oyster reef habitats	Goal A, Goal B, T1, T2, T3, T11	Monitors ecosystem integrity, ecosystem services, biodiversity-inclusive spatial planning, restoration, protection
Marine	Genetic composition	Genetic diversity of selected marine taxa	Goal A, T4	Monitors conservation of genetic diversity
Marine	Species populations	Species abundances of selected marine bird species	Goal A, T4	Monitors species abundance
Marine	Species populations	Species distributions of marine fishes	Goal A, T4, T5, T8	Monitors species conservation, sustainable exploitation, impacts of climate change
Marine	Species populations	Species abundances of marine commercial fish species and long-distance migratory fishes	T1, T3, T5	Monitors biodiversity-inclusive spatial planning, protection, sustainable exploitation
Marine	Species populations	Species distributions of marine birds	Goal A, T4, T5	Monitors species conservation, sustainable exploitation (avoiding negative impacts of fisheries)
Marine	Species populations	Species distributions of marine mammals	Goal A, T4, T5	Monitors species conservation, sustainable exploitation (avoiding negative impacts of fisheries)
Marine	Species populations	Species distribution of marine turtles	Goal A, T4, T5	Monitors species conservation, sustainable exploitation (avoiding negative impacts of fisheries)
Marine	Species populations	Species distributions of benthic marine invertebrates	Goal A, T7	Monitors ecosystem integrity, pollution
Marine	Species populations	Species distributions of invasive alien marine taxa of European concern	T6	Monitors invasive alien species
Marine	Species traits	Phenology of migration of marine birds	T8	Monitors impacts of climate change
Marine	Species traits	Phenology of migration of highly migratory marine mammals	T8	Monitors impacts of climate change
Marine	Species traits	Phenology of migration of highly migratory marine fish	T8	Monitors impacts of climate change
Terrestrial	Community composition	Community biomass of selected functional groups of terrestrial arthropods (e.g. predator, decomposer)	Goal A	Monitors ecosystem integrity

Terrestrial	Community composition	Community biomass of soil microbes	Goal A, Goal B, T10, T11	Monitors ecosystem integrity, sustainable agriculture, ecosystem services (soil quality)
Terrestrial	Community composition	Community abundance and taxonomic diversity of pollinator insects	Goal A, Goal B, T11	Monitors ecosystem integrity, ecosystem services (pollination)
Terrestrial	Community composition	Aerial biomass of migrating birds	Goal A, T4	Monitors species abundance, species conservation
Terrestrial	Community composition	Aerial biomass of migrating bats	Goal A, T4	Monitors species abundance, species conservation
Terrestrial	Community composition	Aerial biomass of migrating insects	Goal A, T4	Monitors species abundance, species conservation
Terrestrial	Community composition	Functional composition of soil biota	Goal A, Goal B, T10, T11	Monitors ecosystem integrity, sustainable agriculture, ecosystem services (soil quality)
Terrestrial	Ecosystem function	Terrestrial ecosystem productivity	Goal A, Goal B, T5, T11	Monitors ecosystem integrity, sustainable exploitation, ecosystem services
Terrestrial	Ecosystem function	Total bird herbivory	Goal A	Monitors ecosystem integrity
Terrestrial	Ecosystem function	Total mammal herbivory	Goal A	Monitors ecosystem integrity
Terrestrial	Ecosystem function	Rate of decomposition	Goal A	Monitors ecosystem integrity and resilience
Terrestrial	Ecosystem function	Fire disturbance regime	Goal A, T8	Monitors ecosystem integrity, impacts of climate change
Terrestrial	Ecosystem function	Ecosystem disturbance as measured by HANPP	T16	Monitors sustainable consumption
Terrestrial	Ecosystem function	Terrestrial ecosystem phenology	T8	Monitors impacts of climate change
Terrestrial	Ecosystem structure	Vertical structure of vegetation	Goal A	Monitors ecosystem integrity
Terrestrial	Ecosystem structure	Ecosystem distribution of terrestrial EUNIS Habitats	T3	Monitors protection (representativeness)
Terrestrial	Ecosystem structure	Connectivity of terrestrial ecosystem habitat types	T1, T3	Monitors biodiversity-inclusive spatial planning, protection (connectivity)
Terrestrial	Ecosystem structure	Standing and lying deadwood	Goal A, T10	Monitors ecosystem integrity and resilience, sustainable forestry
Terrestrial	Genetic composition	Genetic diversity of selected terrestrial taxa	Goal A, T4	Monitors conservation of genetic diversity

Terrestrial	Species populations	Species abundances of selected terrestrial bird species	Goal A, T4	Monitors species abundance
Terrestrial	Species populations	Species distributions of terrestrial birds	Goal A, T4	Monitors species conservation
Terrestrial	Species populations	Species abundances of selected terrestrial mammals	Goal A, T4	Monitors species abundance
Terrestrial	Species populations	Species distributions of all terrestrial mammals	Goal A, T4	Monitors species conservation
Terrestrial	Species populations	Species distributions of terrestrial reptiles	Goal A, T4	Monitors species conservation
Terrestrial	Species populations	Species abundances of butterflies	Goal A, T4	Monitors species abundance
Terrestrial	Species populations	Species distributions of terrestrial priority invertebrates and key pollinators	Goal A, Goal B, T10, T11	Monitors ecosystem integrity, sustainable agriculture, ecosystem services (pollination)
Terrestrial	Species populations	Species distributions of selected terrestrial plants	Goal A, T4	Monitors ecosystem integrity, species conservation
Terrestrial	Species populations	Species distributions of lichens (as indicators of pollution)	T7	Monitors pollution
Terrestrial	Species populations	Species distributions of invasive alien terrestrial taxa of European concern	T6	Monitors invasive alien species
Terrestrial	Species populations	Species abundances of selected terrestrial animal disease vectors	T6	Monitors disease vectors
Terrestrial	Species populations	Species abundances of selected terrestrial crop and forest pests	T6	Monitors invasive alien species
Terrestrial	Species traits	Phenology of fructification of mushrooms	T8, T11	Monitors impacts of climate change, ecosystem services
Terrestrial	Species traits	Phenology of fructification of wild fruits	T8, T11	Monitors impacts of climate change, ecosystem services
Terrestrial	Species traits	Phenology of flowering and leaf senescence	T8	Monitors impacts of climate change
Terrestrial	Species traits	Phenology of migration of terrestrial birds	T8	Monitors impacts of climate change
Terrestrial	Species traits	Phenology of the emergence of butterflies and time of arrival of migratory butterflies	T8	Monitors impacts of climate change

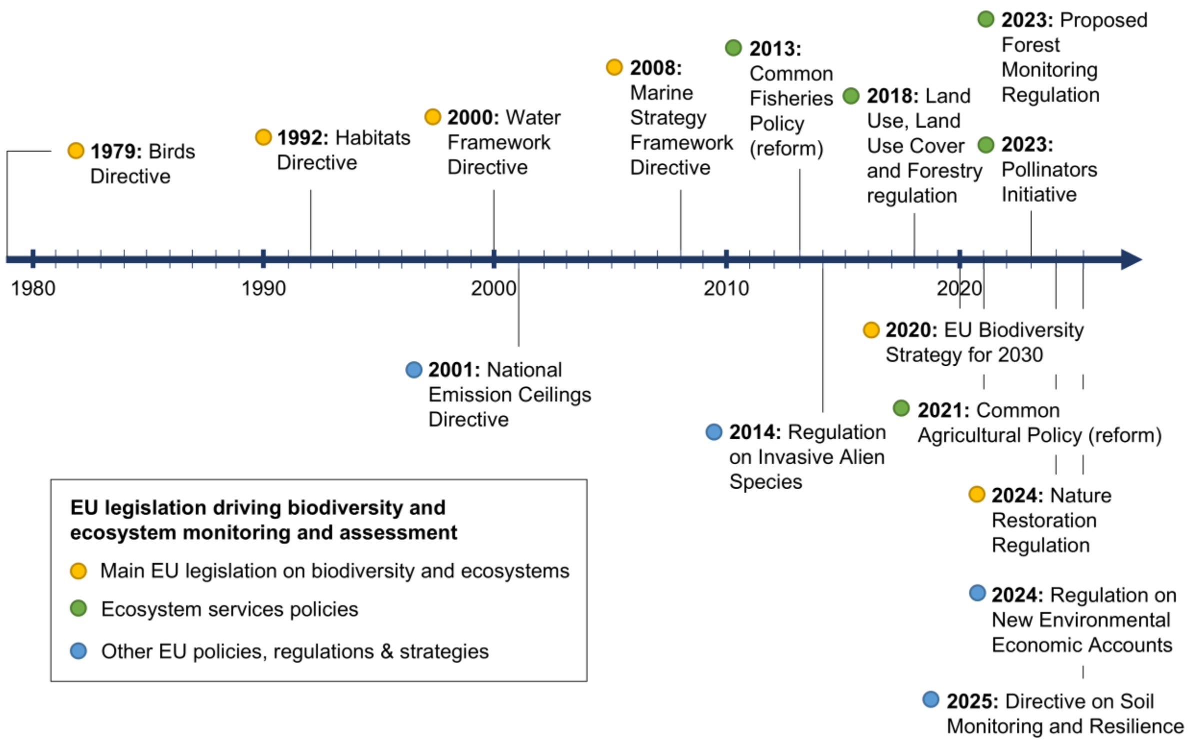

Fig. S1 | Evolution of biodiversity policy in Europe. The illustrated milestones are not exhaustive, but include specific EU policies, laws and initiatives that are most relevant for biodiversity and ecosystem monitoring and assessment (grouped into main EU legislation on biodiversity and ecosystems, ecosystem service polices, or other legislation). EU, European Union. For descriptions of each policy, see Supplementary Table S1.

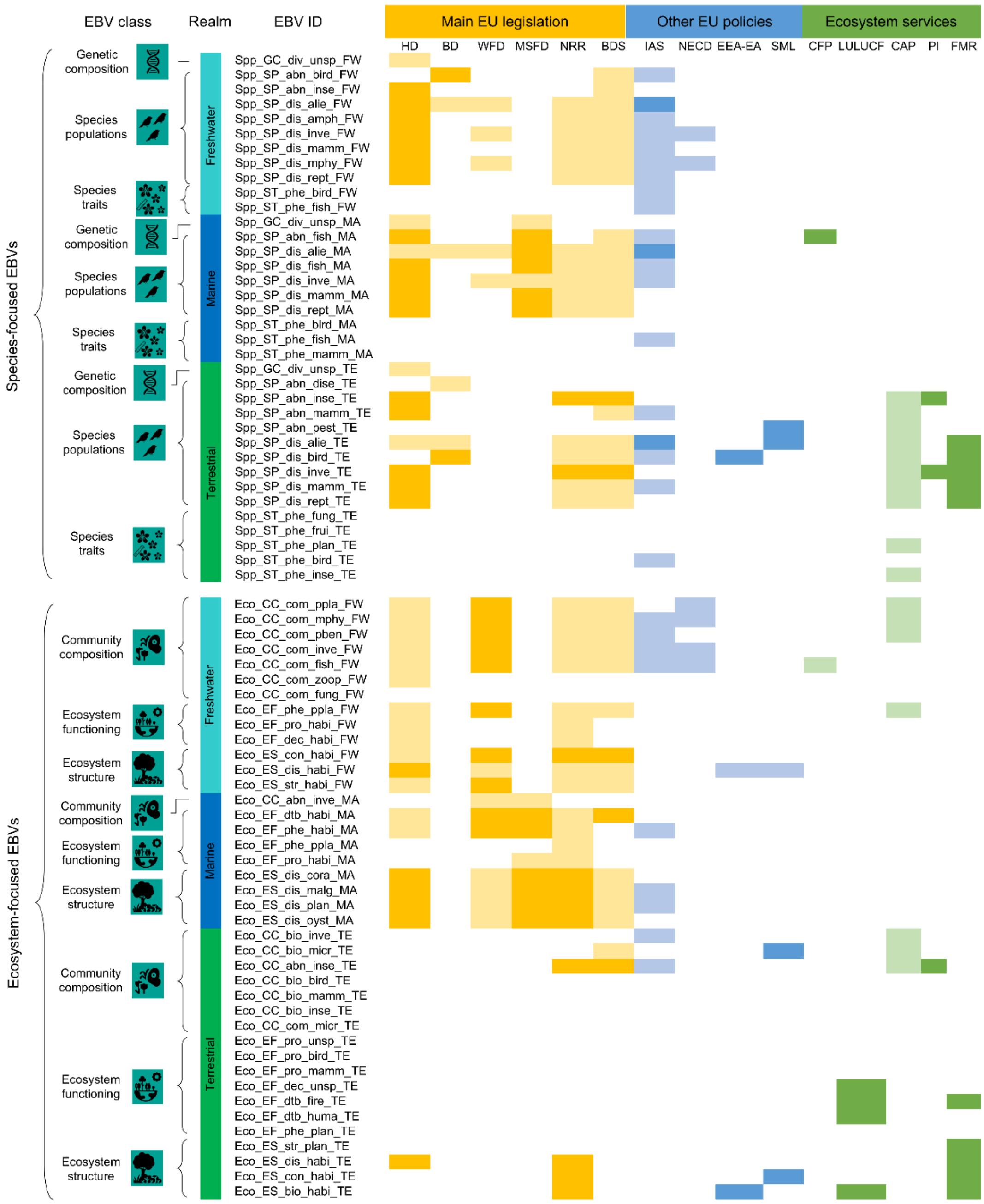

Fig. S2 | Direct and indirect links between EBVs and EU legislation. Main EU legislation on biodiversity in yellow, ecosystem service policies in green, and other EU policies, regulations and strategies in blue (see Table S1 for abbreviations). Dark (yellow, blue and green) colours indicate direct links (EBVs can be used to respond to a reporting requirement) whereas light (yellow, blue and green) colours indirect links (EBVs can provide underlying, complementary or voluntary information for reporting requirements. Species-focused EBVs (top) and ecosystem-focused EBVs (bottom) are ordered separately for each EBV class and the freshwater, marine and terrestrial realm, respectively. IDs for each EBV follow a coding system available on GitHub (https://github.com/EuropaBON/EBV-Descriptions/wiki). Data are available from Zenodo[1]. EBVs, Essential Biodiversity Variables.

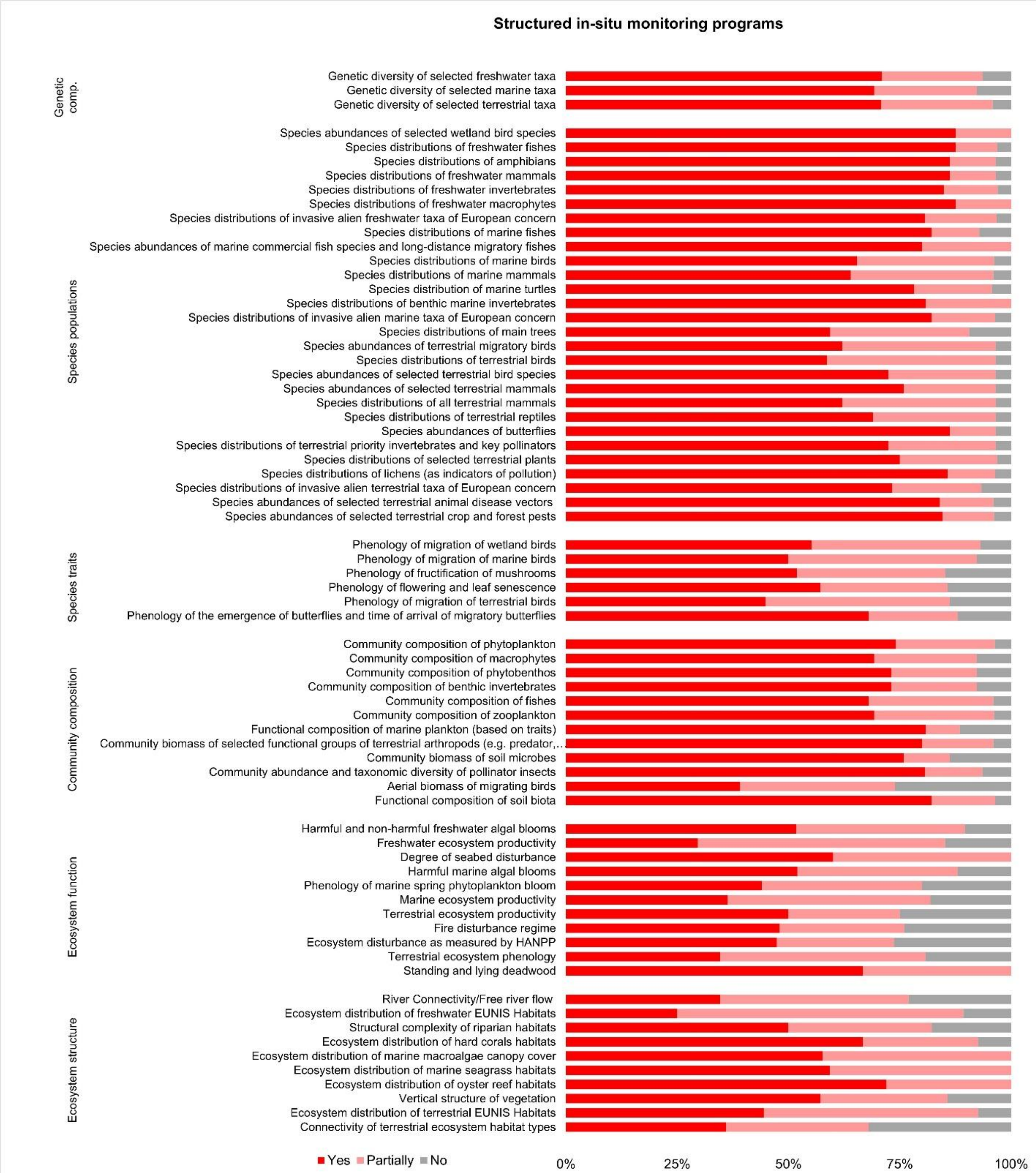

Fig. S3 | Structured in-situ monitoring programs and their importance for EBVs. The relative importance of this monitoring method for each of 70 EBVs was obtained from an online survey during the EuropaBON workshop on EBV workflows[2]. Workshop participants were asked to assess whether this monitoring technique is of central importance for each EBV at a European scale. Relative importance is indicated with % answers (yes, partially, and no). The list of 70 EBVs was further developed with experts and stakeholders and was the basis of the final roadmap proposal of 84 EBVs[3]. Data are available from Zenodo[1].

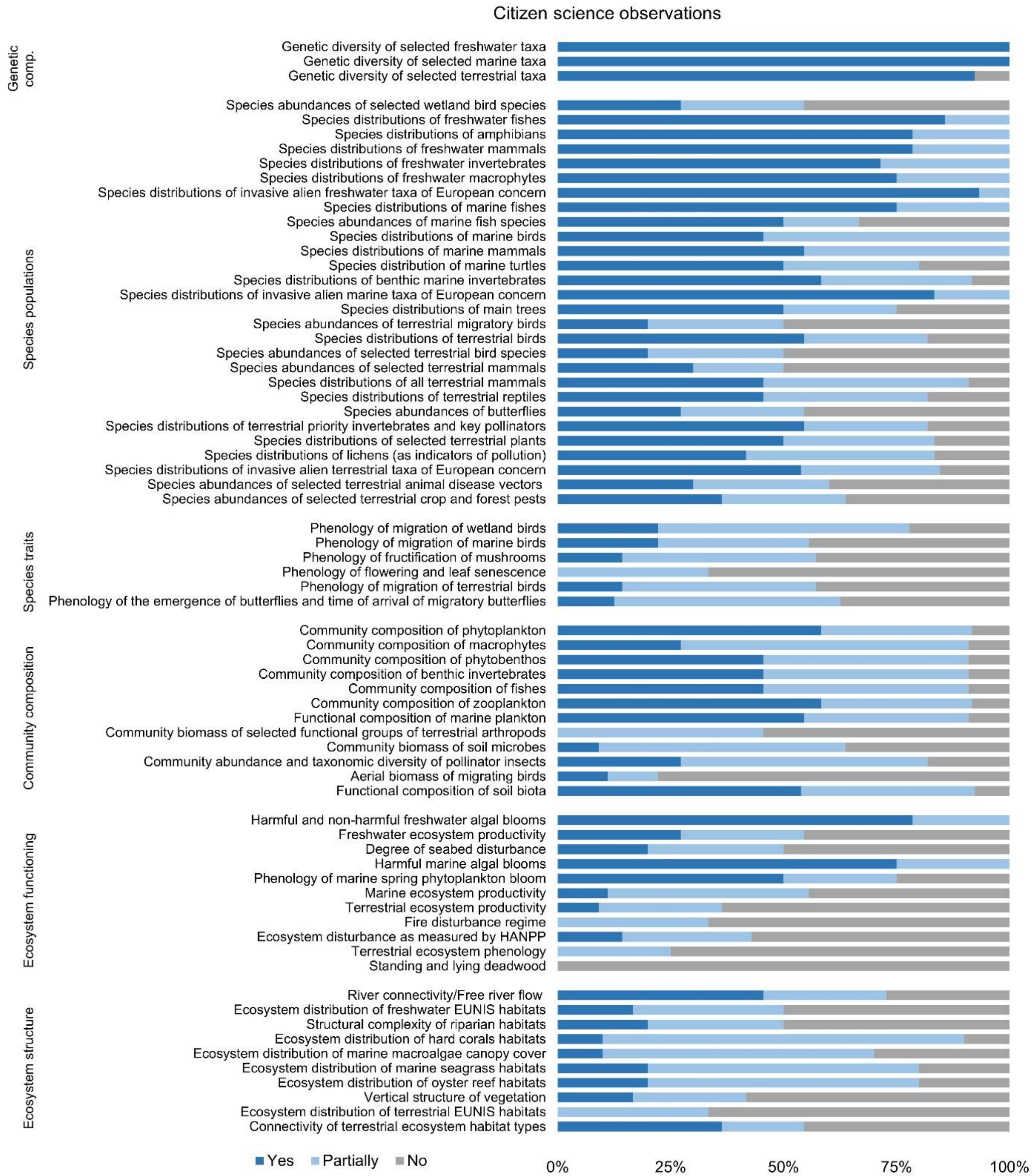

Fig. S4 | Citizen science observations and their importance for EBVs. The relative importance of this monitoring method for each of 70 EBVs was obtained from an online survey during the EuropaBON workshop on EBV workflows[2]. Workshop participants were asked to assess whether this monitoring technique is of central importance for each EBV at a European scale. Relative importance is indicated with % answers (yes, partially, and no). The list of 70 EBVs was further developed with experts and stakeholders and was the basis of the final roadmap proposal of 84 EBVs[3]. Data are available from Zenodo[1].

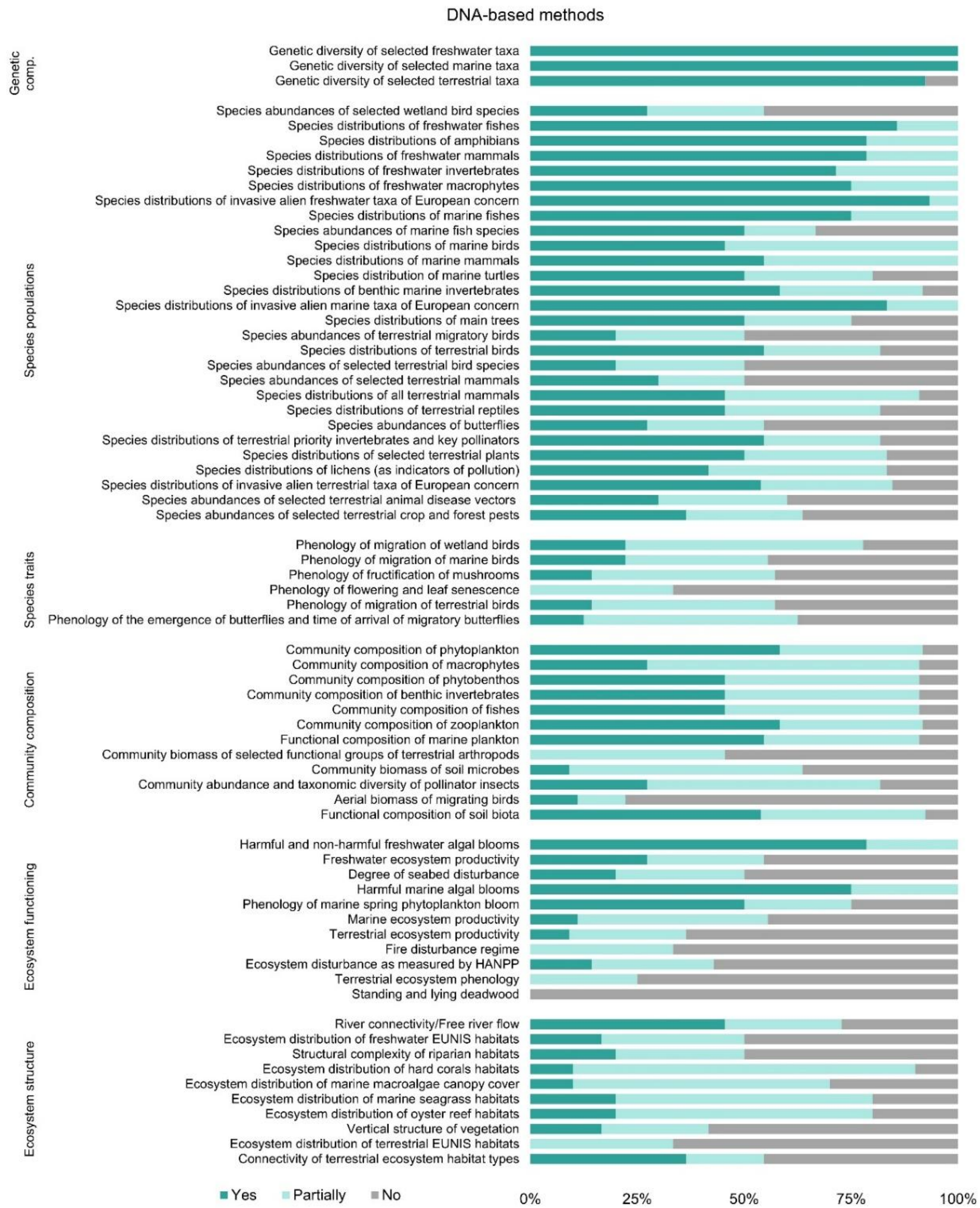

Fig. S5 | DNA-based methods and their importance for EBVs. The relative importance of DNA methods (e.g. AFLP/microsatellite, SNPs, and metabarcoding eDNA) for each of 70 EBVs was obtained from an online survey during the EuropaBON workshop on EBV workflows[2]. Workshop participants were asked to assess whether this monitoring technique is of central importance for each EBV at a European scale. Relative importance is indicated with % answers (yes, partially, and no). The list of 70 EBVs was further developed with experts and stakeholders and was the basis of the final roadmap proposal of 84 EBVs[3]. Data are available from Zenodo[1].

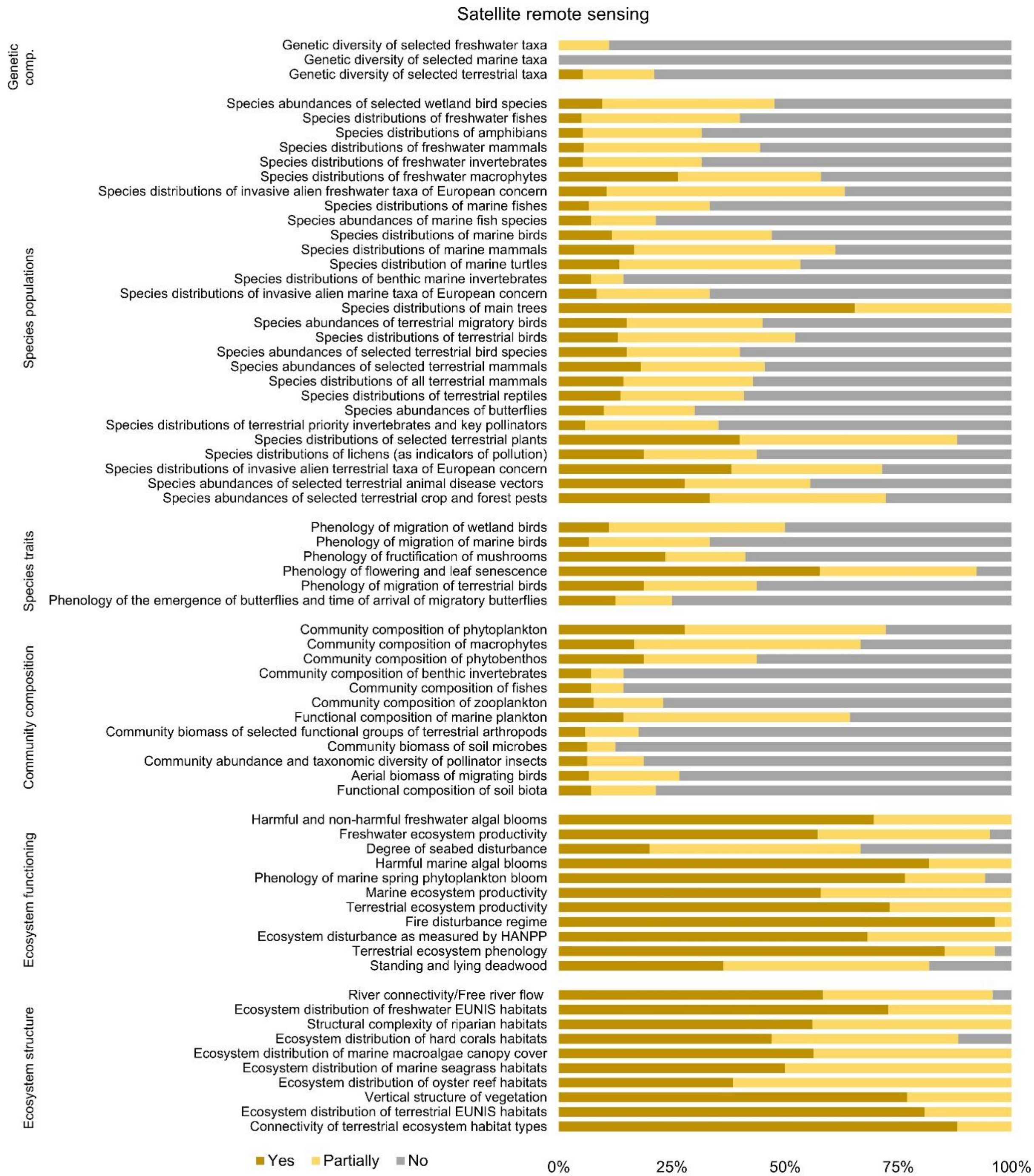

Fig. S6 | Satellite remote sensing and its importance for EBVs. The relative importance of this monitoring method for each of 70 EBVs was obtained from an online survey during the EuropaBON workshop on EBV workflows[2]. Workshop participants were asked to assess whether this monitoring technique is of central importance for each EBV at a European scale. Relative importance is indicated with % answers (yes, partially, and no). The list of 70 EBVs was further developed with experts and stakeholders and was the basis of the final roadmap proposal of 84 EBVs[3]. Data are available from Zenodo[1].

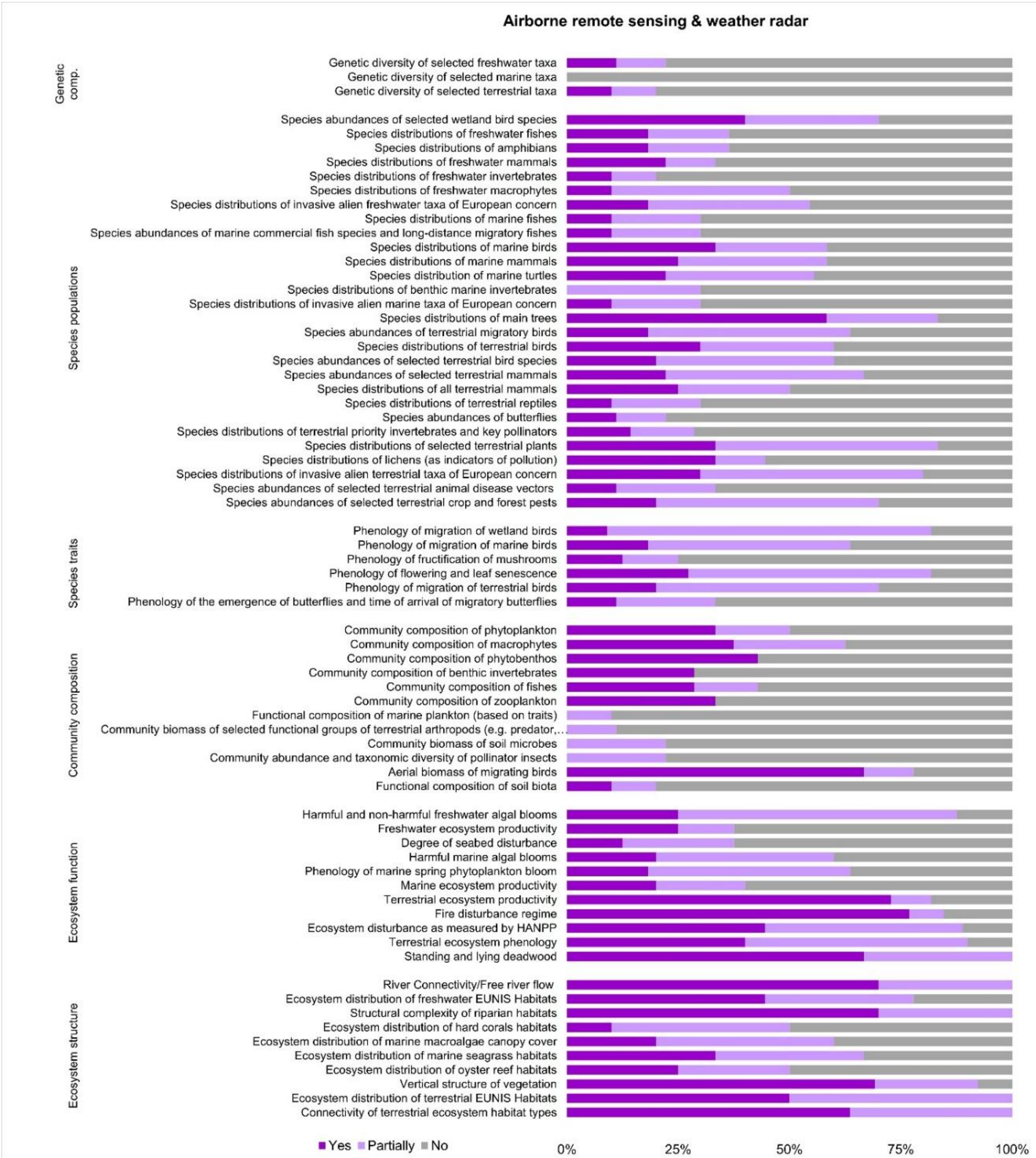

Fig. S7 | Aerial remote sensing and its importance for EBVs. The relative importance of aerial remote sensing methods (e.g. drones, airplane surveys and weather radar) for each of 70 EBVs was obtained from an online survey during the EuropaBON workshop on EBV workflows[2]. Workshop participants were asked to assess whether this monitoring technique is of central importance for each EBV at a European scale. Relative importance is indicated with % answers (yes, partially, and no). The list of 70 EBVs was further developed with experts and stakeholders and was the basis of the final roadmap proposal of 84 EBVs[3]. Data are available from Zenodo[1].

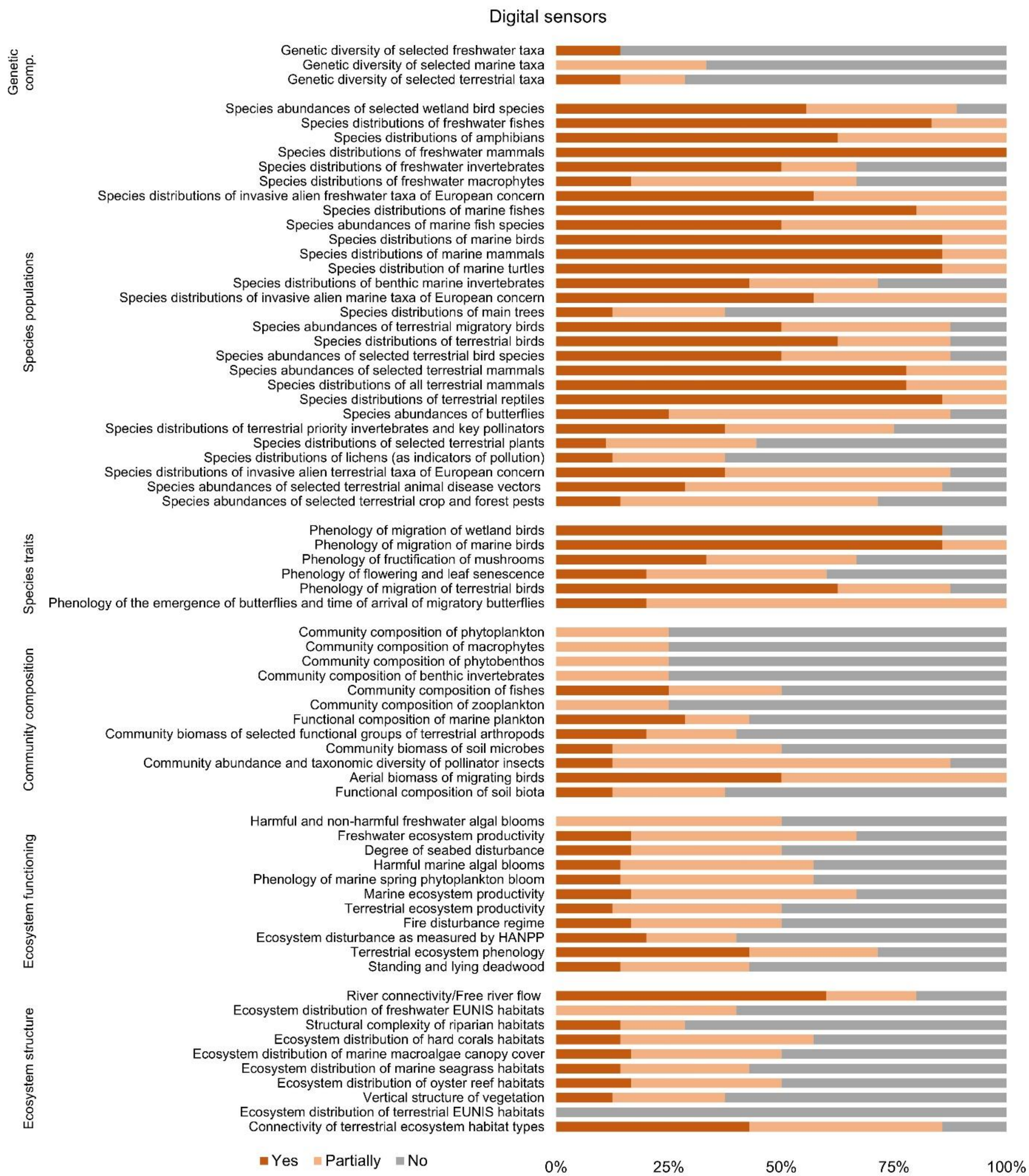

Fig. S8 | Digital sensors and their importance for EBVs. The relative importance of digital sensors (e.g. e.g. cameras, acoustic devices, GPS tags) for each of 70 EBVs was obtained from an online survey during the EuropaBON workshop on EBV workflows[2]. Workshop participants were asked to assess whether this monitoring technique is of central importance for each EBV at a European scale. Relative importance is indicated with % answers (yes, partially, and no). The list of 70 EBVs was further developed with experts and stakeholders and was the basis of the final roadmap proposal of 84 EBVs[3]. Data are available from Zenodo[1].

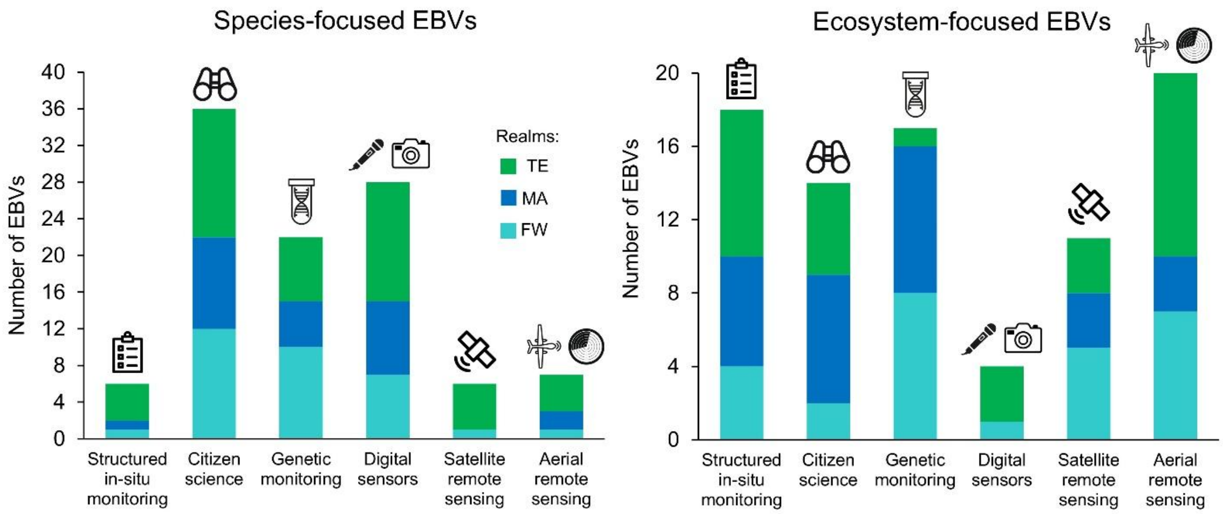

Fig. S9 | Supplementary approaches for monitoring EBVs. The importance (number of EBVs) of each monitoring technique for complementing primary monitoring techniques is shown for species-focused EBVs (left) and ecosystem-focused EBVs (right). The complementary role of a monitoring technique was obtained from results of an online survey during the EuropaBON workshop on EBV workflows[2]. Data are available from Zenodo[1]. EBV, Essential Biodiversity Variable; TE, terrestrial; MA, marine; FW, freshwater.

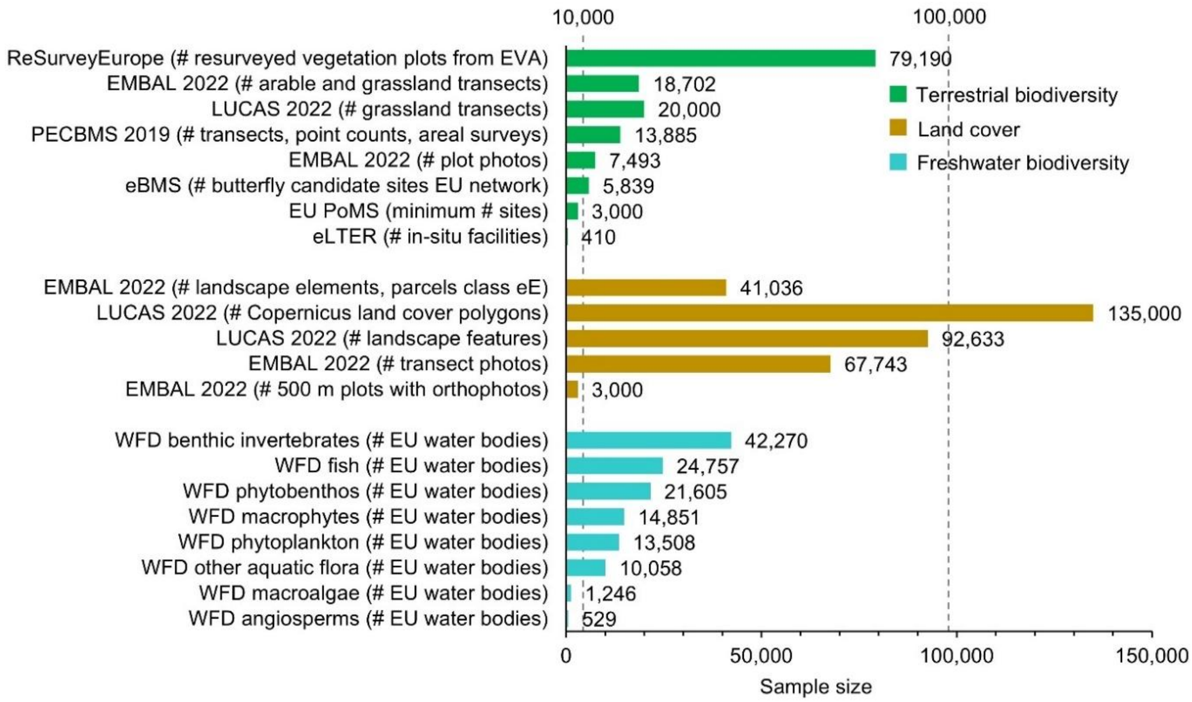

Fig. S10 | Monitoring sample sizes. Examples show the number of sites, transects, photos, landscape elements, polygons, or water bodies (incl. lakes, river segments, transitional and coastal water bodies) from existing EU-wide monitoring schemes. For freshwater biodiversity, a detailed separation for different water bodies (river segments, large lakes, coastal and transitional water bodies) is provided in Supplementary Fig. S11. EU, European Union; ReSurveyEurope, a subset of vegetation plots with time series from the European Vegetation Archive (EVA); PECBMS, Pan-European Common Bird Monitoring Scheme; EMBAL, European Monitoring of Biodiversity in Agricultural Landscapes; LUCAS, Land Use/Cover Area frame Survey; eBMS, European Butterfly Monitoring Scheme; EU PoMS, EU Pollinator Monitoring Scheme; eLTER, Integrated European Long-Term Ecosystem, critical zone and socio-ecological Research (note that sites can sites cover up to ~100 km^2); WFD, Water Framework Directive. Data are available from Zenodo[1].

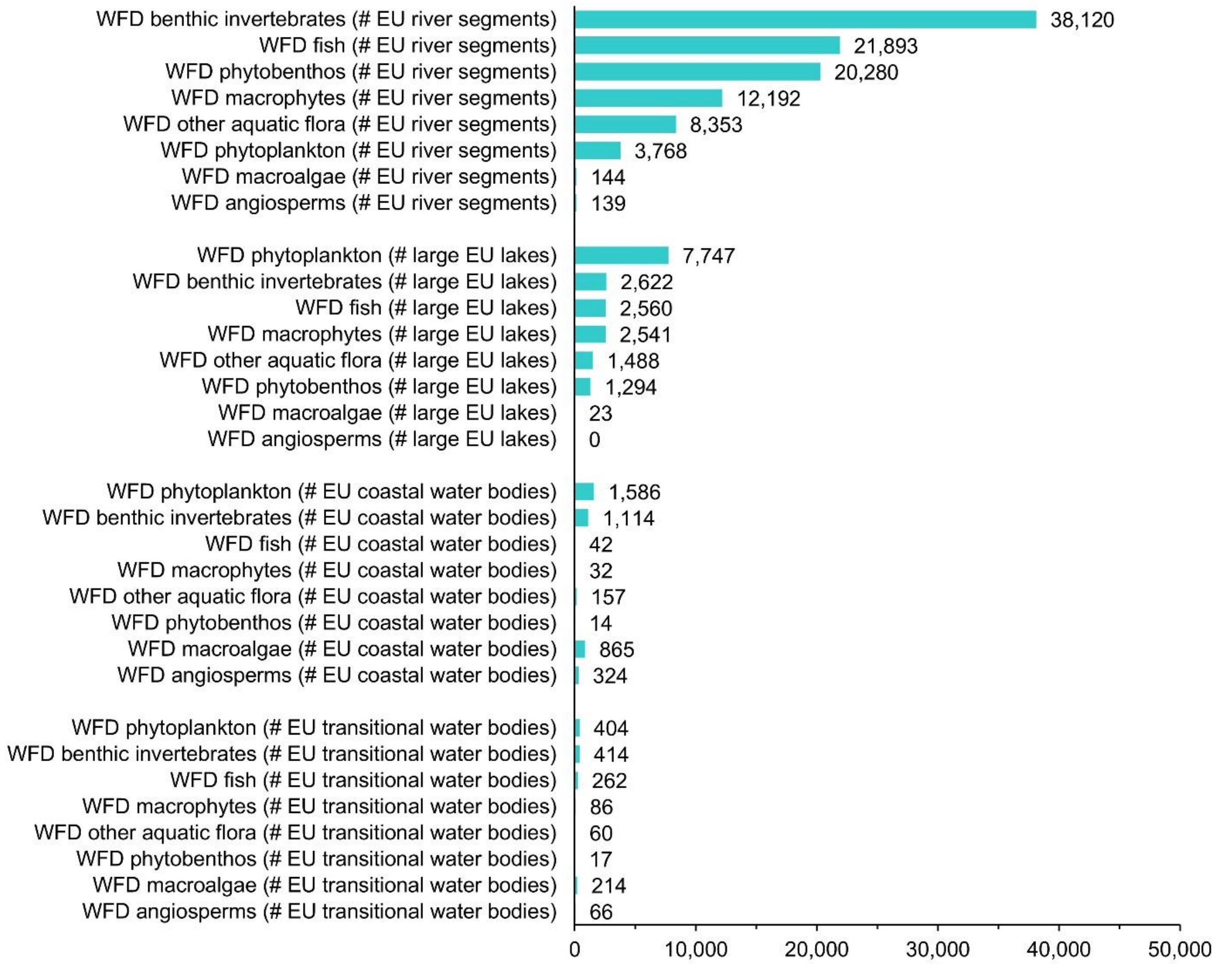

Fig. S11 | Number of monitoring sites in EU freshwaters. The examples show the number of different water bodies (river segments, lakes, coastal and transitional waters) that are sampled for various biological quality elements in the context of the Water Framework Directive (WFD). Data are available from Zenodo[1]. Source: https://tableau-public.discomap.eea.europa.eu/views/WISE_SOW_SWB_QualityElement_qeMonitoringResults/SWB_QualityElement_qeMonitoringResults?%3Aembed=y&%3AisGuestRedirectFromVizportal=y

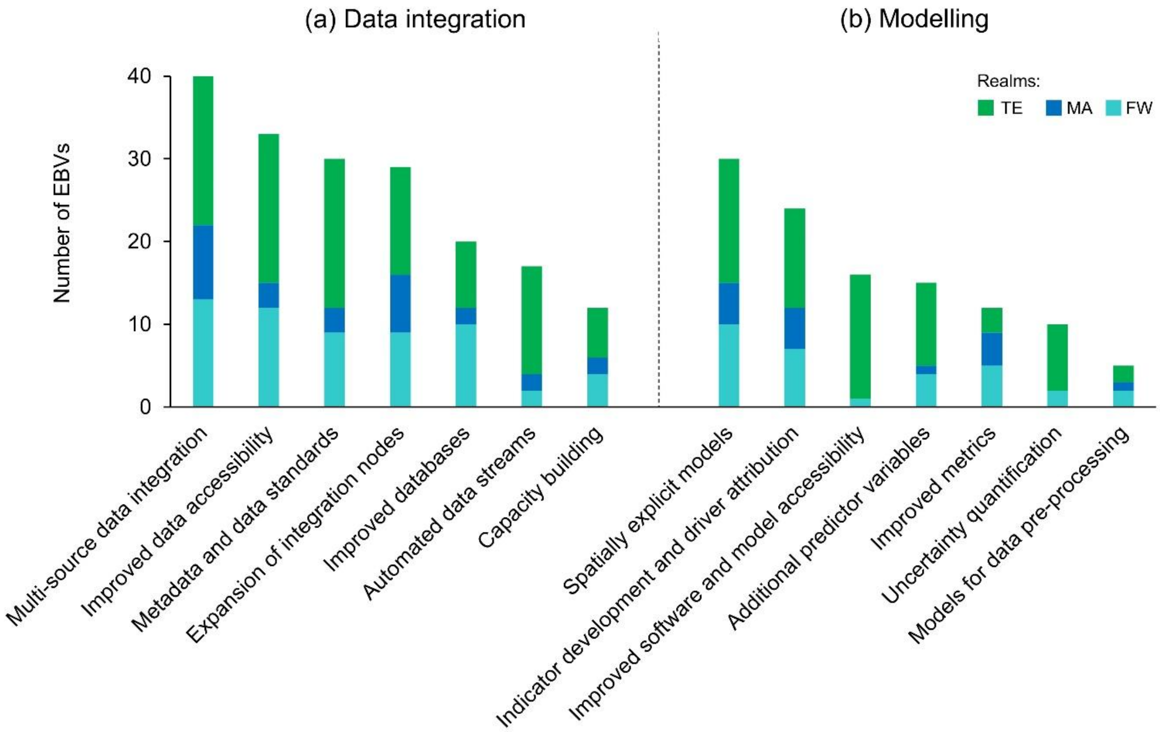

Fig. S12 | Priorities for developing workflows of Essential Biodiversity Variables (EBVs) in the context of a European Biodiversity Observation Network. Priorities are separately shown for (a) data integration and (b) modelling. They were specified for each EBV by experts during the EuropaBON workshop on EBV workflows[2] and subsequently grouped into the different categories as shown on the x-axis. Data are available from Zenodo[1]. TE, terrestrial; MA, marine; FW, freshwater.

References

1 Kissling, W. D. *et al.* Data underpinning the EuropaBON roadmap for a unified, transnational biodiversity observation system in Europe. *Zenodo*, doi:10.5281/zenodo.16940232 (2025).

2 Lumbierres, M. & Kissling, W. D. Important first steps towards designing the freshwater, marine and terrestrial Essential Biodiversity Variable (EBV) workflows for the European Biodiversity Observation Network. *Research Ideas and Outcomes* **9**, e109120, doi:10.3897/rio.9.e109120 (2023).

3 Junker, J. *et al.* D4.1. Revised list and specifications of EBVs and EESVs for a European wide biodiversity observation network. *ARPHA Preprints* **4**, e102530, doi:10.3897/arphapreprints.e102530 (2023).