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Perspective

Effective Biodiversity Monitoring Needs a Culture of Integration

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SUMMARY

Despite conservation commitments, most countries still lack large-scale biodiversity monitoring programs to track progress toward agreed targets. Monitoring program design is frequently approached from a top-down, data-centric perspective that ignores the socio-cultural context of data collection. A rich landscape of people and organizations, with a diversity of motivations and expertise, independently engages in biodiversity monitoring. This diversity often leads to complementarity in activities across places, time periods, and taxa. In this Perspective, we propose a framework for aligning different efforts to realize large-scale biodiversity monitoring through a networked design of stakeholders, data, and biodiversity schemes. We emphasize the value of integrating independent biodiversity observations in conjunction with a backbone of structured core monitoring, thereby fostering broad ownership and resilience due to a strong partnership of science, society, policy, and individuals. Furthermore, we identify stakeholder-specific barriers and incentives to foster joint collaboration toward effective large-scale biodiversity monitoring.

INTRODUCTION

Despite agreed national and international conservation targets, there is no evidence that the global loss of biodiversity is decelerating.[1] There have been repeated calls for large-scale biodiversity monitoring efforts,[2] but considerable taxonomic, spatial, and temporal gaps remain.[3,4] Understanding trends and drivers of biodiversity change is key for identifying appropriate conservation measures[5] and for measuring progress toward these targets.[6] For instance, many Aichi targets defined to measure progress toward the goals of the Convention of Biological Diversity (CBD) require information that should ultimately be derived from robust and comprehensive biodiversity monitoring programs.[7] This refers especially to strategic goal B "To reduce the direct pressures on biodiversity and promote sustainable use" and goal C "To improve the status of biodiversity by safeguarding ecosystems, species, and genetic diversity." Similarly, the 2030 Agenda for Sustainable Development Goals SDG 14 "Life below water" and SDG 15 "Life on land" require comprehensive monitoring to measure progress toward the sustainable use and conservation of biodiversity in water and on land. In addition, the post-2020 CBD targets are imminent. Hence, a more effective approach for large-scale biodiversity monitoring is urgently needed.

Most often, the design of large-scale monitoring schemes is approached from a data-centric perspective. This often leads to idealized top-down-driven sampling schemes that optimize data quality.[8] Practical implementation of such schemes on the national scale is, however, rare. When monitoring efforts are single sourced and single domained, they tend to be restricted in spatiotemporal and taxonomic coverage due to limited funding (usually from public budgets but also NGOs) and expertise.[3] The monitoring of Natura 2000 areas across EU member states is one attempt of joint monitoring as reporting duty to the EU Habitats Directive, with involvement of state and non-state actors, including NGOs (sometimes contracted) and citizen science data.[9] However, observations are restricted to protected areas and methodologies vary widely across EU member states. Moreover, biodiversity observation data often result from programs that initially had not been designed for monitoring, such as habitat mapping programs.[10] Few countries have managed to allocate the necessary resources and political support to implement fully standardized, unified monitoring programs at a national scale (for exceptions see, e.g., Switzerland[11] and New Zealand).[12] For instance, the Biodiversity Monitoring Switzerland scheme comprises systematic sampling of plants, mosses, molluscs, aquatic insects, butterflies, and birds within grid cells. Such programs are unlikely to represent a generic solution to be adopted by many countries, especially due to limited coordination, funding, and political support. In addition, establishing similar programs in other countries may ignore a large range of on-going grassroots biodiversity monitoring efforts. While a backbone of large-scale standardized monitoring is important for robust inferences on change,[13] a single top-down implemented monitoring program will often be insufficient to achieve sustainable biodiversity monitoring that will run over decades and address the broad range of questions that needs monitoring data.

In most countries, collective biodiversity monitoring has evolved through self-organization by different stakeholder groups, apart from government agencies, e.g., natural history societies, NGOs, and academic institutions. A considerable amount of biodiversity data is also produced by ecological research, which is frequently contributed to data sharing platforms and compiled in biodiversity observation databases, such as the Living Planet Index,[14] Predicts,[15] or BioTime.[16] With the cultural shift toward open science, such data are accumulating at an increasing rate. Furthermore, around 80%–90% of biodiversity observation data in Europe are estimated to be collected by dedicated volunteers.[17,18] Volunteers form a heterogeneous group, ranging from beginners and occasional participators to experts of their specialist taxa group. They have organized themselves into numerous scientific and natural history societies across the world (e.g., the East Africa Natural History Society: http://naturekenya.org; India: Bombay Natural History Society: https://www.bnhs.org; UK[19]). Volunteers also contribute to structured and coordinated recording schemes,[20] e.g., the European Butterfly Monitoring Scheme (eBMS).[21] Some of the best examples of rigorous, long-term, and large-scale monitoring schemes are based on citizen science, such as long running Breeding Bird Surveys (e.g., Pan-European Common Bird Monitoring Scheme [PECBMS], https://pecbms.info/) or butterfly monitoring schemes[22,23] and others across the globe.[17,24] These data have informed important international analyses, e.g., on changes in abundance of farmland species,[25,26] and reporting obligations.[23]

Most volunteer data collection are not coordinated at a national scale, rather volunteers collect opportunistic or semi-structured data that are aggregated through online platforms, such as eBird.[27] These data are rather fragmented geographically and taxonomically,[28] but see Kühn and colleagues,[22] and comprise a wide variety of species records across taxa, locations, time periods, and along a gradient of underlying drivers.[29] Despite not being collected as part of formal monitoring, these data can provide very useful information about species populations and communities, especially where there are gaps in standardized monitoring.[30]

Here, we design and propose an integrative framework to comprehensive biodiversity monitoring from national to regional scales. We highlight how integration at multiple levels (across data, schemes, and stakeholders) can lead to high-quality biodiversity data for policy and scientific research. While not negating the need for large-scale structured monitoring, an integrated approach explicitly recognizes that the biodiversity monitoring landscape comprises a network of stakeholders, each with different expertise and motivations, and contribute different types of relevant data and information as non-negligible buy-in.[31,32] However, since previous focus has been on large-scale structured biodiversity monitoring alone, we propose to integrate multiple efforts, including these large-scale structured programs. Smaller-scale independent efforts are more often overlooked for national monitoring and there is a need to particularly highlight these. In fact, the diversity of stakeholders—when aligned and integrated along a common cause—increases the diversity of funding routes (including volunteered data) as well as the resilience for biodiversity monitoring, if one of the stakeholder experiences capacity issues. The case for data integration and some of the practicalities involved has already been outlined a decade ago.[31] In addition, the Group on Earth Observations Biodiversity Observation Network (https://geobon.org) is an important effort, e.g., promoting biodiversity data integration through the concept of essential biodiversity variables.[33] Some countries have recently began working toward harmonization by establishing crosscutting activities and infrastructures, e.g., in Scotland (via the Scottish Biodiversity Information Forum) and in France (via the French Biodiversity Observation Network ECOSCOPE and French National Observatory for Biodiversity). More recent progress has been made on the statistical theory underpinning the integration of different datasets and the development of new tools, such as integrated population models.[34,35] Little progress, however, has been made on realizing integration across diverse stakeholders[36] and on establishing a culture of integration in biodiversity monitoring.

We believe the time is ripe for stakeholder integration—next to data integration. This approach needs to examine the costs and benefits of stakeholder integration for supporting organizations and society in the current biodiversity monitoring landscape. Then, a roadmap toward a culture of integration can be developed. Whereas a previous study[31] focused on statistical and data aspects of integration, we extend the concept by exploring the socio-political dimensions that are required for integrative

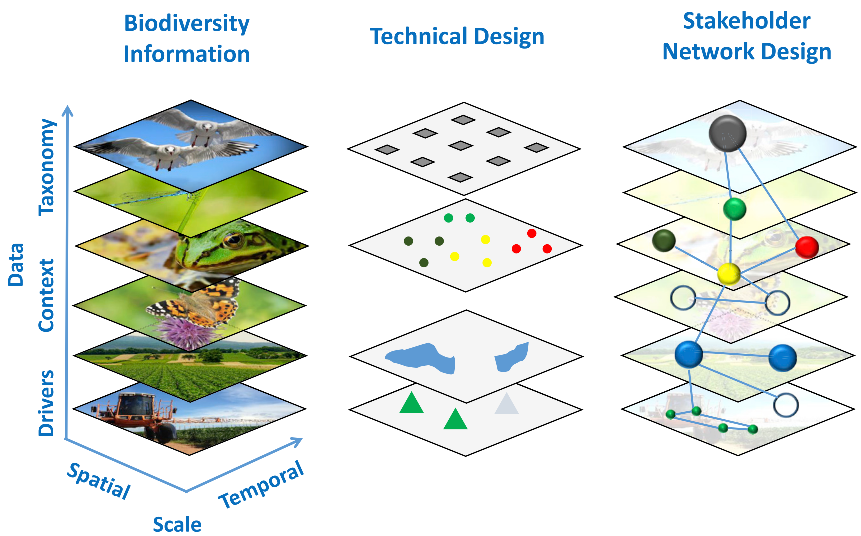

Figure 1. Schematic Representation of Integration in Biodiversity Monitoring

Aligning biodiversity and environmental information layers are shown with different technical designs and stakeholder networks. Comprehensive biodiversity information requires data on drivers and environmental contexts across taxonomic groups and spatiotemporal scales (left). To achieve this, the technical design (middle) integrates a standardized design (top layer), which may be limited in spatiotemporal extent and resolution due to costly data acquisition, with opportunistic and semi-structured observations (point layer), mapping (polygon layer), and long-term data collection at single sites (triangles, bottom layer) for increased spatiotemporal coverage. To enable and foster collaboration, and data and information sharing among stakeholders, a stakeholder network design (right) needs to take into account the different characteristics of the stakeholders (indicated by differing color and size of circles), and identify additional essential niches to be filled with stakeholders (large empty circles) or act as connectors in the network. Pictures downloaded from https://pixabay.com

efforts in biodiversity monitoring and considering additional benefits that go beyond improved data quality and information output. We focus especially on the integration of on-going or future monitoring activities rather than the compilation of historical data. In the following, we (1) consider the benefits of integration in monitoring for policy, society, and scientific research as well as for individual participants, (2) assess challenges to integration and identify stakeholder-specific incentives to overcome these, and (3) propose ways forward to develop technically and socio-politically coherent (i.e., considering relevant institution and networks at different scales) integrated biodiversity monitoring programs with a shared overall goal. We suggest that integration effort becomes a key priority for researchers, practitioners, and policy advisors for more effective large-scale biodiversity monitoring.

MEANING OF INTEGRATION FOR BIODIVERSITY MONITORING?

An integrated monitoring portfolio is a networked set of data types, sampling methods, designs, and stakeholders whose components and specifications complement each other. They can be brought together to address key questions so that the whole is greater than the sum of its parts. A culture of integration in the biodiversity monitoring landscape is characterized by a set of institutional rules and norms that are shared by all stakeholders and support the creation of common monitoring schemes. In general, integration will also entail open data access where possible. Since some of our key wording in this article may have different meaning in the diverse approaches and disciplines of the social and natural sciences,[37] we would like to refer to the following definitions and intended meaning to avoid confusion. We refer to "establishing a culture of integration in biodiversity monitoring" as the creation of an atmosphere and environment, in which the integration of biodiversity monitoring efforts by a stakeholder network is perceived as beneficial and is actively pursued given the various advantages we outline below. This includes a process (stakeholder integration) of aligning different motivations, agendas, and obligations in biodiversity monitoring with a subsequent close collaboration and cooperation of the different stakeholders.

Potential biodiversity information for integration comprises various taxonomic groups at different spatiotemporal scales and also data on drivers and environmental contexts (Figure 1, left). Data integration may be across temporal scales, e.g., the US Christmas bird count (https://www.audubon.org/) complementing the North American Breeding Bird Survey[38] or taxonomically specialized schemes (e.g., common and rare bird monitoring schemes). It may combine different data types (Figure 1, middle), such as standardized abundance schemes, opportunistic occurrence data collection, and long-term ecosystem research. Also, it may integrate spatially distributed data, e.g., the eBMS,[21] partly biased in space, with the Wider Countryside Butterfly Scheme.[39] These data types are supported by different stakeholders (Figure 1, right). Network integration out of independent schemes has the potential to form much larger functional biodiversity monitoring that goes beyond the capacity of any stand-alone program under real-world constraints (see also examples in Box 1).

BENEFITS OF INTEGRATION

Network integration will likely increase long-term continuity of biodiversity monitoring. In fact, monitoring activity in Europe over the last century was largely maintained by different NGOs and volunteer organizations, as monitoring was considered of minor importance to politics or research. Single-sourced programs may be vulnerable because they may be terminated when economic, political, or social situations become unfavorable. Hence, integrated monitoring may benefit monitoring directly by enhancing sustainability. Moreover, we also expect a range of further benefits for science, society, policy, and individuals.

Benefits for Science

Integration may allow robust analyses on a wide range of questions on the trends and causes of large-scale biodiversity

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Box 1. Case Studies of Integrated Monitoring Efforts

SCOTTISH BIODIVERSITY INFORMATION FORUM

Following calls for better integration of local and national biodiversity monitoring infrastructure in Scotland, the Scottish Biodiversity Information Forum (SBIF) was established in 2012 to bring together different monitoring stakeholders, address constraints on data mobilization and ensure that appropriate infrastructures are in place. The SBIF Advisory Group comprises various governmental bodies and NGOs and meets at least twice a year. Their first major review of the opportunities and challenges of monitoring infrastructure in Scotland, including a public questionnaire and cross-sectoral workshops, was published in 2018 and has made 24 recommendations to transform data flows, governance, and culture.[40] These recommendations include a central data warehouse, regional and national hubs, community funds and support, a governance model, and an implementation plan to reach the objectives by 2025.

LIVING ATLAS FAMILY

Initiated in 2007, the Atlas of Living of Australia (ALA) (www.ala.org.au) was established to share information about Australia's biodiversity. ALA has since its origin been closely associated with GBIF, and also serves as a national GBIF node. Currently, ALA provides the largest open repository of biological information for the Australian region. One of the more visible features of ALA is an advanced bio-environmental portal where data can be found, accessed, and integrated using a range of tools. For instance, the *spatial portal* targets users from management authorities and higher education, and provides tools to query the data and perform basic analysis on species distributions. ALA also has support tools, such as the crowdsourcing platform DigiVol, and the BioCollect tool, which can be used to organize and support data collection from citizen science programs as well as systematic data collection. Because all software is based on open source code, a global community has grown around the platform—known as the Global Atlas community. At the time of writing, 16 national atlas installations are now active, with 13 other countries currently working to establish national atlases (https://living-atlases.gbif.org/). As of 2019, the governance of the Living Atlas community is under development and will be more formalized.

UK BIOLOGICAL RECORDS CENTRE

The Biological Records Centre (BRC) was formed in 1964 to support biological recording in Great Britain. BRC facilitates the activities of 85 taxon-specific organizations that collectively cover the majority of macroscopic organisms.[41] The organizations, i.e., national schemes and societies, include some with professional staff (e.g., Butterfly Conservation, Botanical Society of Britain and Ireland), subscription-based societies (e.g., Bees, Wasps and Ants Recording Society), although schemes for some of the obscure taxonomic groups comprise small bands of dedicated amateur naturalists. For many years, key activities were to support data collation, data curation, and publication of atlases.[28] BRC then became an early promoter of online recording and verification, and has created numerous recording smartphone apps, e.g., for butterflies, ladybirds, and dragonflies. With iRecord (https://www.brc.ac.uk/irecord/home), citizen scientists can enter their observations online for many taxa. So far, it is only focused on opportunistic observations and does not store metadata on survey design. More recent emphasis has shifted to data interpretation, including the development of statistical methods,[42] data synthesis to estimate trends in species' status, documenting biological invasions,[41] and contributing to UK's State of Nature report. A key feature of BRC's long-term success has been the development of strong partnerships with stakeholders, including government agencies, NGOs, and the national schemes and societies. BRC has been involved in the development of new monitoring schemes complementing presence-only records, from the establishment of the UK Butterfly Monitoring scheme in 1976 to the National Plant Monitoring Scheme in 2015.[43] The most recent of these new schemes, the Pollinator Monitoring Scheme, was conceived specifically with integration of multiple data sources in mind.

MONITORING OF GREAT APES

African and Asian great apes are probably one of the best monitored taxonomic groups. Great apes receive a lot of public and research interest due to their anthropological relevance. They also serve as flagship species to raise awareness for tropical habitats and for implementation of conservation programs. Over the last decades, survey and monitoring efforts have been conducted independently in different countries by state authorities, NGOs, or individual researchers and supported by a number of funding bodies. These stakeholders share the common interest in assessing the state of apes, understanding drivers of decline, finding solutions for effective protection, and form a network of interacting partners. It is clear to everyone that this can only be achieved as a joint effort and not by a single institution alone and that taxon-level status information will provide additional leverage for advancing ape conservation than scattered site-level information alone.[44] Sharing of monitoring information has been institutionalized by the establishment of an IUCN database (http://apes.eva.mpg.de), hosting great ape field survey data. Data access and release is regulated by a strict policy that guarantees full control over contributed datasets by data providers and offers the additional benefit of receiving credit in reports and scientific studies.

Table 1. Enhanced Features, Benefits, and Real-World Potential when Integrating Biodiversity Monitoring Schemes

Integration Axis	Types of Survey	Benefits	Real-World Potential
Across taxa	Surveys of taxa belonging to different orders or classes	Cross-taxa analysis, including species and multitrophic interactions	Insect and host plant,[51] multitrophic interaction across terrestrial[52] and aquatic realms
	Common species surveys plus targeted, specialist, or rare species surveys	Understanding of whole community change	Bird community dynamics[24] Competitor release or competitive exclusion through invasive species[53]
Seasonal/temporal	Winter and breeding bird surveys, plant phenology	Understanding of seasonal patterns	Tree phenology and bird migration;[54] diversity changes,[55] environmental change[56]
Data type	Structured surveys plus unstructured (opportunistic) observations	Increased sample size and spatiotemporal coverage	Local abundance surveys and widespread opportunistic data for large-scale trends[30] Combining systematic floristic grid mapping and habitat surveys[57] Citizen science data complement structured surveys to capture the full environmental niche breadth[58]
Space	Core survey area plus peripheral site surveys, combination of spatial surveys (e.g., across regions, countries)	Increased spatial extent for large-scale inferences	Detect spatially rare, pest-resistant plant individuals[59] Estimating national population sizes[60] Detection of large-scale species range shifts with climate change,[26] taxon-level abundance[44]
Time	Historic surveys plus re-surveys	Temporal extent and study of shifting base-line effects	Long-term changes in plant communities[61]

change.[1,31,45] Integrated distribution and population models (IMs) that simultaneously model different survey datasets naturally reflect how the information provided by a network of biodiversity monitoring activities can be overlaid and connected.[35] IMs have the potential to make better use of all information available (Table 1) which, at its simplest, can increase the precision of estimates of species occupancy, abundance, and trends by basing inferences on more data,[46,47] However, IMs can also help make better use of unstructured data, by combining these data with structured data to factor out potential biases.[48,49] IMs may be especially helpful for rare species that are often missed during the limited extent over which standardized surveys are conducted, but regularly captured by opportunistic surveys.[50]

Since monitoring schemes frequently focus on particular taxa, integrating data of different monitoring schemes may help answering new or long-standing questions that were previously difficult to answer, such as how ecological communities assemble or how species interact across taxonomic groups. Only relatively weak signals of species interactions have been detected in analyses of community datasets.[62] Strongest interactions may, however, occur among species sampled by different types of monitoring activities. Integrating data across monitoring schemes may help better understand these relationships, for instance, between insect and insectivorous bird dynamics,[63] butterflies and their host plants,[64] or multitrophic interactions.[65] Limited overlap due to incompleteness of collected data and compatibility of approaches taken may, however, restrict such attempts.[66]

Benefits for Society

Society can benefit from integrated monitoring, including citizen science approaches through the uptake of socially relevant questions, public empowerment and lifelong learning, community building, and development of long-term partnerships.[67] Integrated approaches have the potential to extend beyond traditional voluntary engagement in science.[68] For members of society, the co-creation of knowledge with scientists provides opportunities to raise novel questions and identify questions of societal relevance.[69] Wider understanding of the scientific process and its limitations is beneficial for debate within society about environmental problems.[70,71] Moreover, inclusion in these pathways may foster behavioral changes and engagement in political processes.[70] Involvement in monitoring schemes may create feelings of ownership and partnerships, providing the foundations for community building.[72] This can be fostered by infrastructures in volunteer coordination, such as central coordination, feedback, and face-to-face meetings, which enable social interactions among participants.[22] By embracing different survey types, integration also places value on data collected by people with varying degrees of expertise and spare time (e.g., schemes requiring regular commitment but also irregular BioBlitzs[73] or other monitoring events), allowing diverse people to contribute to monitoring.

Benefits for Policy

Policy benefits from integrated monitoring by a stronger evidence base to support official reporting duties on conservation targets, such as NATURA 2000, reports for EU member states and national reporting obligations on environmental policy regulations. Currently, most Red List data are based on a multitude of surveys and expert knowledge.[74] Monitoring data could also be used to support decision-making in environmental management, e.g., setting hunting quotas,[75] informing pest management,[59] or considering future biodiversity scenarios.[76] Since the preferred outcome of these decisions may differ among stakeholders, the incorporation of multiple stakeholders into the monitoring process may reduce conflict over results and improve the likelihood of finding a consensus.[75] Overall, while integrative monitoring will usually be formed around a backbone of structured biodiversity monitoring, e.g., the integrated European Long-Term Ecosystem, critical zone and socio-ecological systems Research Infrastructure (LTER)-Europe, the integration of diverse stakeholders and distributed responsibilities will ultimately increase socio-political relevance[77] and may enable smoother implementation of evidence-based policy actions. Integration of structured citizen science bird monitoring data across 22 European countries to produce the Farmland Bird Index has highlighted the negative impacts of agricultural intensification (https://pecbms.info) and is the only biodiversity context indicator for the EU's Common Agricultural Policy. Citizen science can be a powerful voice in policy.[78] In Germany, for example, the results of the Krefeld study[79] led by a natural history society, provided the political traction to establish an insect conservation program in the current German government coalition contract.[80]

Private Benefits

Individuals, no matter whether volunteer or professional scientist, may benefit from integrated monitoring through various ways. Such benefits include the opportunity to contribute to conservation science and to evidence for supporting conservation practice as well as a sense of self-efficacy by contributing to a greater cause.[81] In addition to an increased recognition of their efforts, they may receive opportunities to analyze their data in combination with other data, as, e.g., in the Living Atlas of Australia platform (Box 1), and this can provide a strong motivation to share own observation data. A good documentation of metadata and observer association can reduce the perceived risk of data misuse that is frequently a concern and a current limitation to sharing data more openly. More specifically, individuals may benefit from seeing their data used in larger-scale and often well-cited syntheses and thus receive a return value for their private efforts. Recent studies suggest that papers based on open data are more frequently cited than studies that are not.[82] Some compilation efforts have resulted in "data papers" that include all data contributors as co-authors,[16] although these data papers compile already existing data and do not directly help on-going or future data collection, but may still provide a motivation for further data collection efforts. Other return values may be acknowledgment of data sources, increased publication output, an extension of and inclusion in contact networks, or access to wider expertise. Overall, if data are well cited in subsequent analyses, observers may also benefit from better funding opportunities, once there is more evidence to support the value of their work.

CHALLENGES TO INTEGRATION

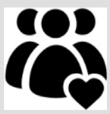
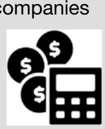
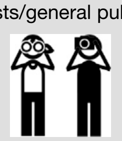
Integrated national to regional biodiversity monitoring faces several challenges. A lack of awareness of joint opportunities, required expertise, and possibly also lack of enough will among decision makers has so far prevented the emergence of integrated monitoring at national scales. Development of an integrated monitoring scheme requires a modern mode of thinking toward distributed responsibilities over a more traditional top-down approach and an openness to welcome different knowledge domains.[83] A change in mindset is needed to link with open science by allowing for internal (and external) data sharing and communication, as well as ideally moving toward open source solutions. Overall, national conservation authorities responsible for biodiversity monitoring should have a strong interest to invest resources in overcoming these impediments and building functional programs.

Social science research, most notably the social studies of science, have sensitized us to the need of considering issues of ownership, power, and values in the development of integrated biodiversity monitoring. Integrated biodiversity monitoring provides an extensive, ideally open-access database on the state of biodiversity to the public. As this database is a public good, all potential stakeholders face the challenge of cooperation in the provision of public goods.[84] The structure underlying the social dilemma of the provision of the public goods in the case of integrated national biodiversity monitoring identifies that some actors may openly share their data and efforts, while others may take advantage and be free riders, without contributing. In addition, historically, different monitoring systems and ownerships have emerged and evolved over time and, as with all knowledge structures, are associated with established societal power relations,[85] which may then be challenged. Also the motivation of data collectors differs (Table 2), and many data collectors, especially in citizen science projects or natural history societies, may not only be driven by the recording of biodiversity as data points, but also as a meaningful expression of their sense of place[86] or attachment to an organization, and this could disappear or become blurred in big biodiversity databases. It is important to recognize these values. Data providers therefore need to remain visible and possibly even attain more visibility in integrated biodiversity monitoring for creating joint ownership (as a key principle in all case studies, e.g., the IUCN Great Apes database, the UK Biological Record Scheme, the Living Atlas schemes or the Scottish Biodiversity Information Forum, Box 1). Also, individual collection efforts should be strengthened and empowered and alignment does not mean dissolving these. Aligning data streams was also considered to be associated with big transaction costs of giving up established routines or even data lines, or losing contextual information,[87] while now new scientific methods have become available to facilitate alignment[31,35] and acknowledging different data structures.

ACHIEVING INTEGRATION

Overcoming the social dilemma underlying the provision of public goods is the main challenge facing integrated national biodiversity monitoring,[88] which will vary with the national context. First, the potential barriers and relevant benefits need to be understood, as values with regard to monitoring may differ between stakeholders (Table 2). Then, the right incentives need to be established. This involves, among others, increasing the awareness of joint opportunities, providing expertise, and lobbying with decision makers. In the European context, the General Data Protection Regulation,[89] the widespread use of open-access licences[90] and freewares, as well as the institutionalization of data sharing within the scientific community,[91] provide an institutional framework that already favors internal (and

Table 2. Stakeholder Characteristics, Motivations, and Benefits for Participating in Integrated Biodiversity Monitoring as Identified by the Group of Authors

Stakeholders	Motivations	Benefits	Impediment to Participation	Incentives for Participation
State authorities 	Statutory obligation and reporting duties	Access to additional information otherwise not available	Limited resources, understaffed, limiting communication; political conflicts; concern of losing sovereignty	Increased participation and involvement of stakeholders; added value by closing existing spatial, temporal, and taxonomic gaps; increased visibility
Non-governmental organizations 	Filling gaps in knowledge, integration of members	Access to reliable, quantitative information for highlighting threats	Specific agendas; perceived loss of own visibility; reluctance to share unique output of frequently privately funded initiatives	Increased evidence base for influencing policy and legislation; increased visibility
Natural history societies  	Intrinsic motivation	Exchange with like-minded people; impact at science-policy interface	Reluctance to share unique output of frequently privately funded initiatives	Access to analytical and statistical expertise; increased valuation through collaboration and gaining broad-picture insights
Research institutions, federated research infrastructures 	Scientific interest	Access to quality controlled, high-resolution, and large extent data; increase of publication output	Reluctance to participate or share data due to pressure of publishing first; biodiversity monitoring not considered as attractive research topic or innovative;	Access to new funding sources and large-scale, high-quality data gaining from taxonomic expertise in natural history societies and citizen scientists provides new opportunities for scientific work; increased visibility and recognition for work when supporting large networks
Biological field stations/academies/museums 	Scientific interest	Access to analytical and statistical expertise; public recognition	Lack of recognition, funding, and staff	Increased visibility; recognition and valuing of museum work; access to new funding sources; influence on policy
Private sector companies 	Monetary benefit; gain of reputation; reporting duties and certification	Access to data, analytical expertise; monetary/marketing benefit when sharing data	No financial benefit by participating in biodiversity monitoring programs or by sharing data	Access to available data previously collected by others for reducing cost; expanding contact network to more monitoring experts for potential collaboration in future commissions; increased visibility
Citizen scientists/general public 	Intrinsic motivation; enjoying nature	Being part of a monitoring program and science; acknowledgment; opportunities for exchange with experts	Lack of guidance and infrastructure to contribute to monitoring schemes or to access results	Increasing usability of collected information in integrated program; influencing policy; community building

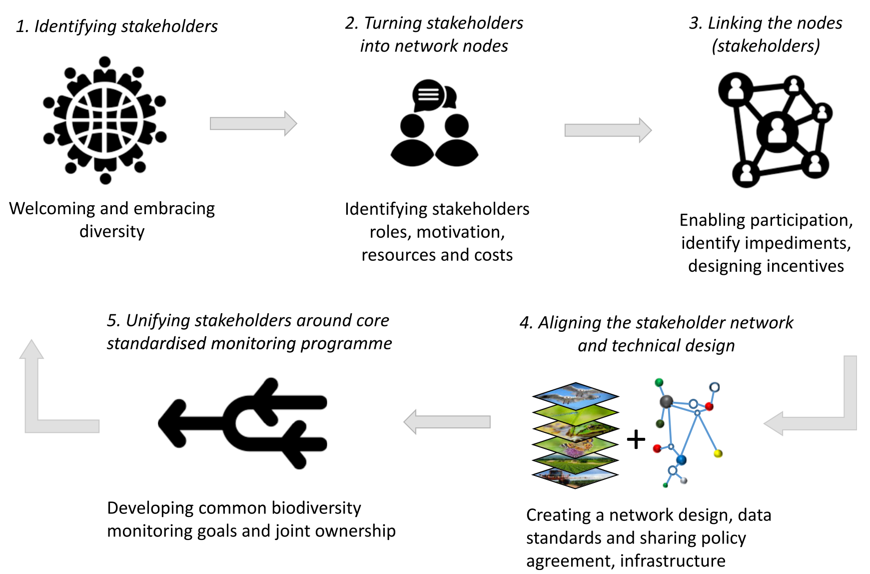


Figure 2. The Five Important Steps for Achieving Integration
Since integration is an iterative process, step 5 is not an endpoint, and the system remains open to new stakeholders (e.g., collecting new data types or using emerging technologies).

external) data sharing and communication. Moreover, national conservation authorities responsible for biodiversity monitoring should have a strong interest to invest resources in building functional programs, and integrated national biodiversity monitoring becomes a possibility, at least in the European context to help meet legal obligations on monitoring and conservation.

From a social point of view, developing an integrated monitoring scheme depends crucially on building trust and developing a co-production approach, in which stakeholders work together to reach a collective outcome.[92] It is essential to find the right incentives for stakeholders to cooperate in the provision of the public good. This means participating in the network to provide the biomonitoring data. From a technical point of view, it can be approached as an optimization problem: the integration of on-going data collection efforts by different monitoring stakeholders and the quality of data/information on the state of biodiversity both need to be maximized. Over the long-term, integration is a dynamic process, and we propose five key steps to achieving integration provided in Figure 2.

Identifying Stakeholders

Organizations and individuals relevant to biodiversity monitoring are very diverse with regard to legitimacy, mission, scope, and organizational structure.[93] They include state authorities, non-governmental organizations, research institutions, natural history societies, foundations, and private sector companies, being active on the local, national, or international scale. Stakeholders differ substantially in their prime motivation, core expertise and focal output, day-to-day activities, responsibilities and duties, performance standards, data sharing philosophies, and treatment of intellectual property rights. Here, we use the term stakeholders to group them all together (Figure 3, Table 2).

Welcoming a diversity of stakeholders requires effective communication, collaboration, and cooperation to avoid competition over spheres of responsibilities or resources.[94] In practical terms, a series of roundtable meetings, workshops, and symposia are needed to identify stakeholder interests and possible contributions to the monitoring network and to clarify motivations and potential constraints[95] (see Box 1). Discussions should consider the costs and benefits of having diverse monitoring approaches, evaluate how they might be combined, and where the gaps are with regard to taxonomy, spatiotemporal coverage, or methodology.

Turning Stakeholders into Network Nodes

A key requirement for enabling integration of stakeholders within the network is that stakeholders participate within their own capacities, with clear benefits and clearly defined roles and responsibilities according to the stakeholder's mission and scope (Table 2). Good examples are the PECBMS (https://pecbms.info), and the eBMS,[21] which have achieved this by integrating national bird and butterfly monitoring schemes across 27 (birds) or 16 (butterflies) countries to date. The UK Biological Records Center (Box 1) unites 85 recording schemes, while fostering sovereignty with them. This strengthens the unique profile of participating stakeholders, as well as their intrinsic motivation toward the network, and also minimizes overlap in responsibilities, thereby reducing the potential for conflict. A social network analysis of existing monitoring stakeholders can help assess network structure, nodes, linkages, and centrality of actors and identify unique capabilities as well as potential vulnerabilities or missing links.[72]

Linking the Nodes (Stakeholders)

Since stakeholders differ in their mission, values, and scope, incentives for integration need to be tailored and aligned to the stakeholder profiles (Table 2). Research institutions may be inclined to participate in a biodiversity monitoring program if it increases publication output. State authorities, motivated by statutory obligations, may be most interested in increasing the overall performance of a biodiversity monitoring program, leading to an increased efficacy in statutory reporting.[36] NGOs, in contrast, are primarily motivated by mission and membership and may therefore be enthused by educational benefits. In practical terms, integration can be fostered by capacity building for biodiversity monitoring, by facilitating exchange among them, and by jointly developing a vision and framework for the monitoring program.

Creating a path toward integration of stakeholders also requires a realistic acknowledgment of existing constraints and traditions that may represent significant barriers to integration (Table 2). For example, there has usually been little tradition of data sharing due to differing institutional constraints and value systems.[36] As these barriers likely vary with national context, incentives need to be well designed to overcome these constraints

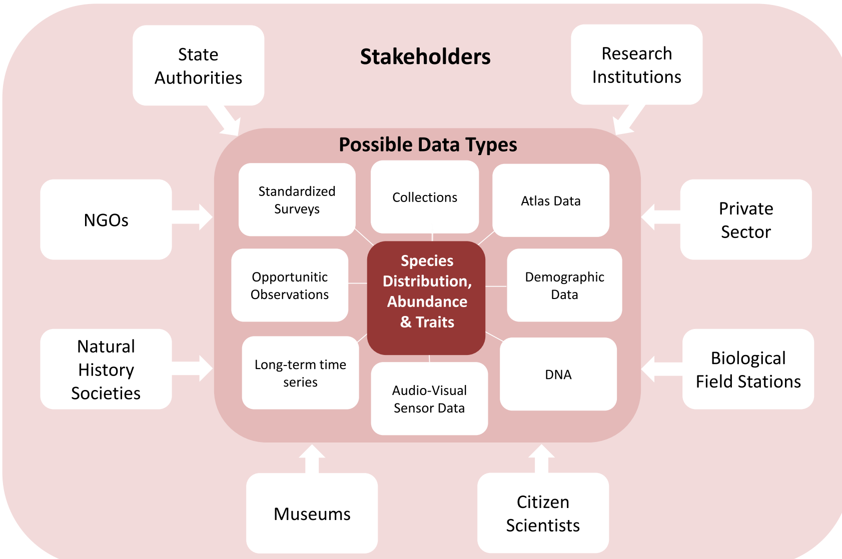


Figure 3. The Diversity of Biodiversity Monitoring Data and Information Collected
A diversity of stakeholders collect, use, work on, or archive a diversity of data sources across varying spatiotemporal scales. These different data types contain information on the distribution, abundance, and traits of species and hence can be used for biodiversity monitoring.

and to encourage data sharing, including joint analyses across monitoring schemes, gaining analytical help, and publishing findings, fostered by the wider push toward open data and reproducible research (see Box 1). However, additional barriers may arise, when the provision of own data, e.g., impact assessments, generates a (rare) source of income for NGOs, and as such the notion of open-access data sharing may therefore receive little support.

Aligning the Social and Technical Network

Technology facilitates the flow of information through the stakeholder network and thereby increases transparency to build trust and long-term collaboration. Online communication can facilitate the sharing of expertise among taxonomists, ecologists, statisticians, and decision makers during the whole workflow from monitoring objectives, sampling design, data collection, analysis, presentation of results, and interpretation. Sharing of data standards and best practice guidelines can help uniformly improve data quality. To realize the alignment between the social and technical network, experts from both fields need to closely collaborate.[96]

Similarly, there is growing technology for networked online data sharing and archiving,[97,98] e.g., the Dutch National Database Flora and Fauna (https://www.ndff.nl) or the Atlas of Living Australia family (Box 1). The provision of central, yet customized, adaptable IT solution for stakeholders is a key issue. Centralized IT solutions to national data infrastructures, e.g., provision of taxonomic backbones, data management, and archiving tools, as well as rapid data validation among participants, interoperalization, analyses, and visualization can provide powerful support for people and organizations. France, for example, is now investing several million euros into such a system that operates to support a range of monitoring schemes, centered by the Muséum National d'Histoire Naturelle in Paris, providing important institutional and policy support for integration. Data portals can maintain the intellectual property rights of data collectors and owners, both of institutions and individuals,[99] and can provide persistent identifiers for datasets (e.g., DOIs) making them citable. The recently suggested FAIR (findable, accessible, interoperable, and reusable data) guidelines for the management of data may represent a good framework.[100] Documentation of metadata information about sampling protocols and sampling effort also needs to be shared to ensure effective re-use. Joint data papers with all data contributors provide opportunities to give full credit to all those involved in data collection and are becoming common in ecology, with dedicated journals (e.g., Scientific Data, Biodiversity Data Journal).

While there are scientific foundations to the statistical theory of data integration,[34] there is still a need for more theory and guidance on the relative importance of different survey types and sample sizes, especially the necessary amount of standardized data[49] as well as more user-friendly statistical tools for integration.

Unifying Stakeholders for National-Level Monitoring

Integration of stakeholders and their activities within a national-level monitoring program requires long-term effort that continuously works toward improving and standardized sampling methods and data quality (Figure 4). The same integration principles apply to nations with federal state structures, where the states can be viewed as stakeholders that need to be part of integration. The long-term vision of the program can be molded by the perspectives of different stakeholders. However, it should ensure that a sufficiently large amount of the data being collected follows the statistical principles for large-scale monitoring.[13] Within these principles, different scenarios of monitoring design, techniques, and metrics and their alignment with the jointly defined vision and goals can be assessed.

Fostering collaboration between different stakeholders, especially citizen scientists and professional scientists, should lead to improvements in data collection methodologies in nodes with less robust data collection activities. For example, in eBird,[101] citizen scientists can submit their records under different types of sampling protocols, beyond incidental, which vastly enhances their value for subsequent analyses.[29] More recently, it has been shown how citizen scientists may be guided to collect data at times and places that have the highest marginal value with respect to the other data available.[102] Despite a mosaic of contributors, alignment of the available efforts between structured monitoring and more heterogeneous data collection has the potential to provide the required output regarding the status and trends of biodiversity (Figure 4, right, Box 1).

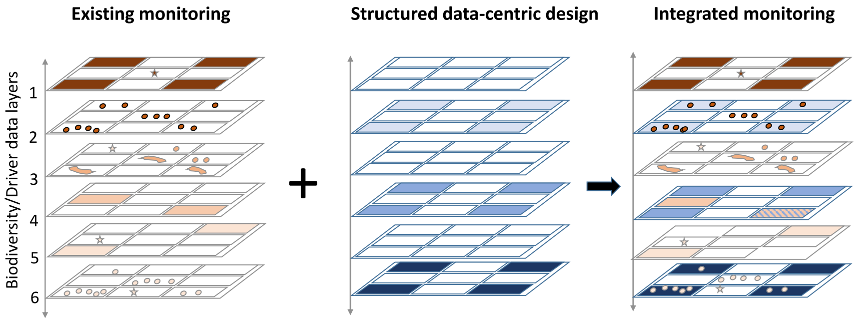


Figure 4. Unifying Stakeholders around a National-Level Monitoring Program

Layers represent the extent of the survey landscape. Left: existing monitoring efforts are frequently diverse in approaches, across taxonomic and spatiotemporal scales with differing levels of standardization. Middle: a standardized design optimizing data quality is usually limited in taxonomic and spatiotemporal coverage due to limited funding when single-sourced (only few squares are monitored). Right: an integrative design approach optimizes data quality (left) in combination with stakeholder involvement (middle) and thus could achieve increased taxonomic and spatiotemporal coverage and analytical power, and—importantly—also participation and thereby joined ownership and social licence. Filled squares indicate standardized protocols, circles and polygons represent other types of observational information, and stars indicate standardized time-series data. Existing monitoring efforts may already be highly standardized (as in level 1, top layer) or show varying degrees of standardization (e.g., level 5). A standardized design (middle) as a backbone may focus on specific taxa, with the gaps covered in an integrative design (right, level 2, 6). Consequently, an integrative design (right) represents a mosaic and reflects the stakeholder network activities, but achieves both standardization and increased taxonomic depth. Limited funding or methodological constraints may also restrict standardization (level 3, right), at least temporarily. Once integration is achieved, standardization can be improved over time.

Overall, we expect an integrative approach to be more effective compared with a single stand-alone program, largely because of the considerable buy-in by the different stakeholders. By taking part in an integrative biomonitoring scheme, stakeholders provide very substantial resources in terms of time, staff, expertise, or financial means. Furthermore, as multiple stakeholders are inherently better connected to society, we expect an integrative approach also to be more effective in the communication, education, and opinion formation. Eventually, all of this will increase long-term stability of an integrated biodiversity monitoring approach compared with a stand-alone program.

NETWORK GOVERNANCE

The integration of stakeholders through a network means that someone needs to establish and take care of the network itself. In a centralized, top-down-driven monitoring scheme, a governing institution has all responsibilities and *defines the biodiversity monitoring standards in all its facets*. Although an integrated scheme also requires a governing institution, the responsibilities are very different.[103] The responsibility of the governing institution is to *foster and facilitate the functionality of the networked approach by enabling processes of integration of stakeholders, self-organization, and transfer of knowledge*. While this is a general principle, there is unlikely to be a single best solution on how to govern a stakeholder monitoring network, given different contexts, value systems, and history. Instead, each situation will require its own approach and already existing monitoring networks (e.g., State of Nature;[104] the Scottish Biodiversity Information Forum [SBIF];[105] see also Box 1) may give helpful insights. For example, the IUCN Great Apes network (Box 1) is governed by the IUCN Section on Great Apes, while the SBIF Advisory Group comprises various governmental bodies and NGOs and meet at least twice a year (Box 1). The most obvious form for network governance is through a governmental entity. Another possibility is governance of a network through a university associated center or a neutral not-for-profit organization or charity (see the SBIF) that has an Advisory Group composed of the main sectors involved in biodiversity data in Scotland, Box 1). eLTER will likely be governed by a legal entity at the European level. The main challenge is to ensure the continual flow of resources needed to keep the network running. At its minimum, this may involve a very lean coordination to foster effective collaboration and provide administrative, statistical, and technological support of the network.[106]

Good governance is centered around true partners engagement to ensure that the network is fit-for-purpose. A well-balanced advisory board with experts from the different stakeholder groups can facilitate, for example, the integration of overarching aims and questions and develop a networked approach to data mobilization and interoperability. Importantly, the governance body should develop support mechanisms to enhance the visibility and capacity of all participants. Importantly, self-organizing principles should be encouraged, such as taxonomic and regional specialization across stakeholders, as well as self-assessment of established processes and structures to evaluate success or failure of the different facets of integrated monitoring schemes. All these measures aim at continually building trust among participating stakeholders to foster cooperation and ensure the quality and continuity of the collective monitoring efforts.

FUTURE PROOFING

Any monitoring scheme requires flexibility and adaptive capacity to adjust to the challenges arising from changes in the state of biodiversity (e.g., invasive species, emergent threats), political (change in funding or environmental policy), or societal context (in- or decreasing interest for participation, resource demands). Integrative monitoring programs may be advantageous to this challenge compared with standardized single data collection schemes, as the participating stakeholders have a larger capacity than stand-alone programs to pick up new developments in biodiversity trends or political and societal demands. Metabarcoding and eDNA is currently emerging as an important monitoring tool and may provide crucial information, especially for cryptic species, not only in current data collection schemes,[107] but also for assessment of historic biodiversity, such as in soil.[108] In addition, cheap sensor technology together with artificial intelligence approaches are rapidly progressing to provide new opportunities for automated species identification in audiovisual recordings from passive acoustic monitoring, remote camera traps (e.g., Zamba [https://zamba.drivendata.org/], Wildlife Insights [https://wildlifeinsights.org/]) or mobile data collection platforms (https://floraincognita.com/).

With changes in methodology, and turn-over in participating individuals, it is key to establish and maintain a reliable, integrated data, and stakeholder network platform. Here, a network approach of central storage of selected data and a portal to access stakeholder-based platforms may provide a viable solution. These platforms not only serve as archives on biodiversity data over time but will also become essential tools for allocating future monitoring effort and knowledge exchange. They thus need to be sustainable, use accepted (community) standards for data and metadata, implement agreed upon protocols, and provide standardized application interfaces for programmatic access, e.g., via web services. Ideally, these repositories should be certified (e.g., https://www.coretrustseal.org/). At a minimum they should implement measures to avoid data loss, including replication, backup, and a contingency plan to move data in case a platform can no longer be maintained. However, the sustainable operation of these distributed stakeholder platforms also requires sustainable funding, which remains a challenge for many stakeholders. Important to future proofing will be the continued co-design of a sustainable governance and adaptive management of the integrated monitoring that shares responsibilities and benefits, and thereby builds on strong joint ownership across the diversity of biodiversity experts and stakeholders.

CONCLUSIONS

Overall, we suggest that data integration needs to build on stakeholder integration within a unified network for the creation of a shared, ideally fully or partly open-access database that allows for robust analyses on a wide range of questions on the causes and trends of large-scale biodiversity change. Such a unified monitoring network will only be successful by valuing the diversity of motivations, responsibilities, expertise, and knowledge pathways and the variety of existing biodiversity recording schemes. Acknowledging the different pathways and aligning these in an interoperable format, together with a strong backbone of structured core monitoring, will work toward a truly integrated monitoring scheme with broad ownership and resilience due to a strong partnership. This will, however, only be achieved if a culture of integration with a shared set of institutional values, rules, and norms can be implemented among stakeholders. We hope the outlined steps of integration and demonstrated case studies can inspire discussion and actions toward integrated biodiversity monitoring networks that allow for enhanced evidence-based decision-making and for joined working of science, society, and policy.

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REFERENCES

1. IPBES (2019). In Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, E.S. Brondizio, J. Settele, S. Díaz, and H.T. Ngo, eds. (IPBES Secretariat) https://www.ipbes.net/news/ipbes-global-assessment-summary-policymakers-pdf.
2. Navarro, L.M., Fernández, N., Guerra, C., Guralnick, R., Kissling, W.D., Londoño, M.C., Muller-Karger, F., Turak, E., Balvanera, P., Costello, M.J., et al. (2017). Monitoring biodiversity change through effective global coordination. Curr. Opin. Environ. Sustain. *29*, 158–169.
3. Mihoub, J.B., Henle, K., Titeux, N., Brotons, L., Brummitt, N.A., and Schmeller, D.S. (2017). Setting temporal baselines for biodiversity: the limits of available monitoring data for capturing the full impact of anthropogenic pressures. Sci. Rep. *7*, 41591.
4. Eisenhauer, N., Bonn, A., and Guerra, C.A. (2019). Recognizing the quiet extinction of invertebrates. Nat. Commun. *10*, 50.
5. Lindenmayer, D.B., and Likens, G.E. (2009). Adaptive monitoring: a new paradigm for long-term research and monitoring. Trends Ecol. Evol. *24*, 482–486.
6. CBD (2010). Decision CBD/COP/X/2. Strategic Plan for Biodiversity 2011–2020 (Convention on Biological Diversity). https://www.cbd.int/sp/targets/default.shtml.
7. Tittensor, D.P., Walpole, M., Hill, S.L., Boyce, D.G., Britten, G.L., Burgess, N.D., Butchart, S.H.M., Leadley, P.W., Regan, E.C., Alkemade, R., et al. (2014). A mid-term analysis of progress toward international biodiversity targets. Science *346*, 241–244.
8. Yoccoz, N.G., Nichols, J.D., and Boulinier, T. (2001). Monitoring of biological diversity in space and time. Trends Ecol. Evol. *16*, 446–453.
9. Waylen, K.A., Blackstock, K.L., van Hulst, F.J., Damian, C., Horváth, F., Johnson, R.K., Kanka, R., Külvik, M., Macleod, C.J.A., Meissner, K., et al. (2019). Policy-driven monitoring and evaluation: does it support adaptive management of socio-ecological systems? Sci. Total Environ. *662*, 373–384.
10. Bruelheide, H., Jansen, F., Jandt, U., Bernhardt-Römermann, M., Bonn, A., Bowler, D., Dengler, J., Eichenberg, D., Grescho, V., Harter, D., et al. (2020). Using incomplete floristic monitoring data from habitat mapping programmes to detect species trends. Divers. Distrib. https://doi.org/10.1111/DDI.13058.
11. .http://www.biodiversitymonitoring.ch/en/home.html.
12. Lee, W., McGlone, M., and Wright, E. (2005). Biodiversity Inventory and Monitoring: A Review of National and International Systems and a Proposed Framework for Future Biodiversity Monitoring by the Department of Conservation. Landcare Research contract report LC0405/122.
13. Buckland, S.T., and Johnston, A. (2017). Monitoring the biodiversity of regions: key principles and possible pitfalls. Biol. Conserv. *214*, 23–34.
14. WWF (2018). In Living Planet Report 2018: Aiming Higher, N. Grooten and R.E.A. Almond, eds. (WWF).
15. Hudson, L.N., Newbold, T., Contu, S., Hill, S.L., Lysenko, I., De Palma, A., Phillips, H.R., Senior, R.A., Bennett, D.J., Booth, H., et al. (2014). The PREDICTS database: a global database of how local terrestrial biodiversity responds to human impacts. Ecol. Evol. *4*, 4701–4735.
16. Dornelas, M., Antão, L.H., Moyes, F., Bates, A.E., Magurran, A.E., Adam, D., Akhmetzhanova, A.A., Appeltans, W., Arcos, J.M., Arnold, H., et al. (2018). BioTIME: a database of biodiversity time series for the Anthropocene. Glob. Ecol. Biogeogr. *27*, 760–786.
17. Schmeller, D.S., Henry, P.Y., Julliard, R., Gruber, B., Clobert, J., Dziock, F., Lengyel, S., Nowicki, P., Déri, E., and Budrys, E. (2009). Advantages of volunteer-based biodiversity monitoring in Europe. Conserv. Biol. *23*, 307–316.
18. Henle, K., Bauch, B., Auliya, M., Külvik, M., Pe'er, G., Schmeller, D.S., and Framstad, E. (2013). Priorities for biodiversity monitoring in Europe: a review of supranational policies and a novel scheme for integrative prioritization. Ecol. Indic. *33*, 5–18.
19. .https://www.bnhc.org.uk.

20. Pocock, M.J., Chandler, M., Bonney, R., Thornhill, I., Albin, A., August, T., Bachman, S., Brown, P.M., Cunha, D.G.F., and Grez, A. (2018). A vision for global biodiversity monitoring with citizen science. Adv. Ecol. Res. *59*, 169–223.

21. .https://butterfly-monitoring.net/ebms.

22. Kühn, E., Feldmann, R., Harpke, A., Hirneisen, N., Musche, M., Leopold, P., and Settele, J. (2008). Getting the public involved in butterfly conservation: lessons learned from a new monitoring scheme in Germany. Isr. J. Ecol. Evol. *54*, 89–103.

23. Van Swaay, C.A.M., Dennis, E.B., Schmucki, R., Sevilleja, C.G., Balalaikins, M., Botham, M., Bourn, N., Brereton, T., Cancela, J.P., Carlisle, B., et al. (2019). The EU butterfly indicator for grassland species: 1990-2017: technical report. Butterfly conservation Europe & ABLE/eBMS. https://butterfly-monitoring.net/sites/default/files/Publications/Technical%20report%20EU%20Grassland%20indicator%201990-2017%20June%202019%20v4%20(3).pdf.

24. Schmeller, D.S., Arvanitidis, C., Böhm, M., Brummitt, N., Chatzinikolaou, E., Costello, M.J., Ding, H., Gill, M.J., Haase, P., and Julliard, R. (2017). Case studies of capacity building for biodiversity monitoring. In The GEO Handbook on Biodiversity Observation Networks, M. Walters and R. Scholes, eds. (Springer), pp. 309–326.

25. Rada, S., Schweiger, O., Harpke, A., Kühn, E., Kuras, T., Settele, J., and Musche, M. (2019). Protected areas do not mitigate biodiversity declines: a case study on butterflies. Divers. Distrib. *25*, 217–224.

26. Devictor, V., van Swaay, C., Brereton, T., Brotons, L., Chamberlain, D., Heliola, J., Herrando, S., Julliard, R., Kuussaari, M., Lindstrom, A., et al. (2012). Differences in the climatic debts of birds and butterflies at a continental scale. Nat. Clim. Change *2*, 121–124.

27. Sullivan, B.L., Aycrigg, J.L., Barry, J.H., Bonney, R.E., Bruns, N., Cooper, C.B., Damoulas, T., Dhondt, A.A., Dietterich, T., Farnsworth, A., et al. (2014). The eBird enterprise: an integrated approach to development and application of citizen science. Biol. Conserv. *169*, 31–40.

28. Pocock, M.J., Roy, H.E., Preston, C.D., and Roy, D.B. (2015). The Biological Records Centre: a pioneer of citizen science. Biol. J. Linn. Soc. *115*, 475–493.

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

30. Pagel, J., Anderson, B.J., O'Hara, R.B., Cramer, W., Fox, R., Jeltsch, F., Roy, D.B., Thomas, C.D., and Schurr, F.M. (2014). Quantifying range--wide variation in population trends from local abundance surveys and widespread opportunistic occurrence records. Methods Ecol. Evol. *5*, 751–760.

31. Henry, P.Y., Lengyel, S., Nowicki, P., Julliard, R., Clobert, J., Čelik, T., Gruber, B., Schmeller, D.S., Babij, V., and Henle, K. (2008). Integrating ongoing biodiversity monitoring: potential benefits and methods. Biodivers. Conserv. *17*, 3357–3382.

32. Pereira, H.M., Belnap, J., Brummitt, N., Collen, B., Ding, H., Gonzalez-Espinosa, M., Gregory, R.D., Honrado, J., Jongman, R.H.G., Romain, J., et al. (2010). Global biodiversity monitoring. Front. Ecol. Environ. *8*, 459–460.

33. Pereira, H.M., Ferrier, S., Walters, M., Geller, G.N., Jongman, R.H.G., Scholes, R.J., Bruford, M.W., Brummitt, N., Butchart, S.H.M., Cardoso, A.C., et al. (2013). Essential biodiversity variables. Science *339*, 277–278.

34. Miller, D.A., Pacifici, K., Sanderlin, J.S., and Reich, B.J. (2019). The recent past and promising future for data integration methods to estimate species' distributions. Methods Ecol. Evol. *10*, 22–37.

35. Isaac, N.J., Jarzyna, M.A., Keil, P., Dambly, L.I., Boersch-Supan, P.H., Browning, E., Freeman, S.N., Golding, N., Guillera-Arroita, G., and Henrys, P.A. (2020). Data integration for large-scale models of species distributions. Trends Ecol. Evol. *35*, 56–67.

36. Bell, S., Marzano, M., Cent, J., Kobierska, H., Podjed, D., Vandzinskaite, D., Reinert, H., Armaitiene, A., Grodzińska-Jurczak, M., and Mursič, R. (2008). What counts? Volunteers and their organisations in the recording and monitoring of biodiversity. Biodivers. Conserv. *17*, 3443–3454.

37. Vadrot, A.B., Akhtar-Schuster, M., and Watson, R.T. (2018). The Social Sciences and the Humanities in the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). . Innov. Eur. J. Soc. Sci. Res., *31*, pp. S1–S9.

38. .https://www.pwrc.usgs.gov/bbs/.

39. Brereton, T.M., Cruickshanks, K.L., Risely, K., Noble, D.G., and Roy, D.B. (2011). Developing and launching a wider countryside butterfly survey across the United Kingdom. J. Insect Conserv. *15*, 279–290.

40. Wilson, E., Edwards, L., Judge, J., Johnston, C., Stroud, R., McLeod, C., and Bamforth, L. (2018) A review of the biological recording infrastructure in Scotland by the Scottish Biodiversity Information Forum: enabling Scotland to be a global leader for biodiversity. Scottish Biodiversity Information Forum Commissioned Report No. 1

41. Roy, H.E., Preston, C.D., and Roy, D.B. (2015). Fifty years of the biological records centre. Biol. J. Linn. Soc. *115*, 469–474.

42. Isaac, N.J., Strien, A.J., August, T.A., Zeeuw, M.P., and Roy, D.B. (2014). Statistics for citizen science: extracting signals of change from noisy ecological data. Methods Ecol. Evol. *5*, 1052–1060.

43. Pescott, O.L., Walker, K.J., Harris, F., New, H., Cheffings, C.M., Newton, N., Jitlal, M., Redhead, J., Smart, S.M., and Roy, D.B. (2019). The design, launch and assessment of a new volunteer-based plant monitoring scheme for the United Kingdom. PLoS One *14*, e0215891.

44. Heinicke, S., Mundry, R., Boesch, C., Amarasekaran, B., Barrie, A., Brncic, T., Brugière, D., Campbell, G., Carvalho, J., Danquah, E., et al. (2019). Advancing conservation planning for western chimpanzees using IUCN SSC APES—the case of a taxon-specific database. Environ. Res. Lett. *14*, 064001.

45. Honrado, J.P., Pereira, H.M., and Guisan, A. (2016). Fostering integration between biodiversity monitoring and modelling. J. Appl. Ecol. *53*, 1299–1304.

46. Zipkin, E.F., Rossman, S., Yackulic, C.B., Wiens, J.D., Thorson, J.T., Davis, R.J., and Grant, E.H.C. (2017). Integrating count and detection–nondetection data to model population dynamics. Ecology *98*, 1640–1650.

47. Bowler, D.E., Nilsen, E.B., Bischof, R., O'Hara, R.B., Yu, T.T., Oo, T., Aung, M., and Linnell, J.D. (2019). Integrating data from different survey types for population monitoring of an endangered species: the case of the Eld's deer. Sci. Rep. *9*, 7766.

48. Fithian, W., Elith, J., Hastie, T., and Keith, D.A. (2015). Bias correction in species distribution models: pooling survey and collection data for multiple species. Methods Ecol. Evol. *6*, 424–438.

49. Dorazio, R.M. (2014). Accounting for imperfect detection and survey bias in statistical analysis of presence-only data. Glob. Ecol. Biogeogr. *23*, 1472–1484.

50. Snäll, T., Kindvall, O., Nilsson, J., and Pärt, T. (2011). Evaluating citizen-based presence data for bird monitoring. Biol. Conserv. *144*, 804–810.

51. Schleuning, M., Fründ, J., Schweiger, O., Welk, E., Albrecht, J., Albrecht, M., Beil, M., Benadi, G., Blüthgen, N., Bruelheide, H., et al. (2016). Ecological networks are more sensitive to plant than to animal extinction under climate change. Nat. Commun. *7*, 13965.

52. Trogisch, S., Schuldt, A., Bauhus, J., Blum, J.A., Both, S., Buscot, F., Castro-Izaguirre, N., Chesters, D., Durka, W., Eichenberg, D., et al. (2017). Towards a methodical framework for comprehensively assessing forest multifunctionality. Ecol. Evol. *7*, 10652–10674.

53. Roy, H.E., Adriaens, T., Isaac, N.J.B., Kenis, M., Onkelinx, T., Martin, G.S., Brown, P.M.J., Hautier, L., Poland, R., Roy, D.B., et al. (2012). Invasive alien predator causes rapid declines of native European ladybirds. Divers. Distrib. *18*, 717–725.

54. McGrath, L.J., Van Riper, C., III, and Fontaine, J.J. (2009). Flower power: tree flowering phenology as a settlement cue for migrating birds. J. Anim. Ecol. *78*, 22–30.

55. Root, T.L., Price, J.T., Hall, K.R., Schneider, S.H., Rosenzweig, C., and Pounds, J.A. (2003). Fingerprints of global warming on wild animals and plants. Nature *421*, 57–60.

56. Schmitt, C.J., Cook, J.A., Zamudio, K.R., and Edwards, S.V. (2018). Museum specimens of terrestrial vertebrates are sensitive indicators of environmental change in the Anthropocene. Philos. Trans. R. Soc. B *374*, 20170387.

57. Jansen, F., Bonn, A., Bowler, D.E., Bruelheide, H., and Eichenberg, D. (2019). Moderately common plants show highest relative losses. Conserv. Lett. *13*, e12674.

58. Tiago, P., Pereira, H.M., and Capinha, C. (2017). Using citizen science data to estimate climatic niches and species distributions. Basic Appl. Ecol. *20*, 75–85.

59. Ingwell, L.L., and Preisser, E.L. (2011). Using citizen science programs to identify host resistance in pest-invaded forests. Conserv. Biol. *25*, 182–188.

60. Hewson, C.M., Miller, M., Johnston, A., Conway, G.J., Saunders, R., Marchant, J.H., and Fuller, R.J. (2018). Estimating national population sizes: methodological challenges and applications illustrated in the common nightingale, a declining songbird in the UK. J. Appl. Ecol. *55*, 2008–2018.

61. Finderup Nielsen, T., Sand-Jensen, K., Dornelas, M., and Bruun, H.H. (2019). More is less: net gain in species richness, but biotic homogenization over 140 years. Ecol. Lett. *22*, 1650–1657.

62. Mutshinda, C.M., O'Hara, R.B., and Woiwod, I.P. (2009). What drives community dynamics? Proc. R. Soc. B Biol. Sci. *276*, 2923–2929.

63. Bowler, D.E., Heldbjerg, H., Fox, A.D., de Jong, M., and Böhning-Gaese, K. (2019). Long-term declines of European insectivorous bird populations and potential causes. Conserv. Biol. *33*, 1120–1130.

64. Schweiger, O., Heikkinen, R., Harpke, A., Hickler, T., Klotz, S., Kudrna, O., Kühn, I., Pöyry, J., and Settele, J. (2012). Increasing range mismatching of interacting species under global change is related to their ecological characteristics. Glob. Ecol. Biogeogr. *21*, 88–99.

65. Grimm-Seyfarth, A., Mihoub, J.-B., and Henle, K. (2018). Importance of prey, predators and climatic extremes to a desert reptile community with different functional traits. Ecosphere *10*, e02865.

66. Peterson, A.T., Soberón, J., Ramsey, J., and Osorio-Olvera, L. (2020). Co-occurrence networks do not support identification of biotic interactions. Biodivers. Inform. *15*, 1–10.

67. Turrini, T., Dörler, D., Richter, A., Heigl, F., and Bonn, A. (2018). The threefold potential of environmental citizen science—generating knowledge, creating learning opportunities and enabling civic participation. Biol. Conserv. *225*, 176–186.

68. Couvet, D., and Prevot, A.C. (2015). Citizen-science programs: towards transformative biodiversity governance. Environ. Dev. *13*, 39–45.

69. Couvet, D., Jiguet, F., Julliard, R., Levrel, H., and Teyssedre, A. (2008). Enhancing citizen contributions to biodiversity science and public policy. Interdiscip. Sci. Rev. *33*, 95–103.

70. Bela, G., Peltola, T., Young, J.C., Balázs, B., Arpin, I., Pataki, G., Hauck, J., Kelemen, E., Kopperoinen, L., Van Herzele, A., et al. (2016). Learning and the transformative potential of citizen science. Conserv. Biol. *30*, 990–999.

71. Fernandez-Gimenez, M., Ballard, H., and Sturtevant, V. (2008). Adaptive management and social learning in collaborative and community-based monitoring: a study of five community-based forestry organizations in the western USA. Ecol. Soc. *13*, 4.

72. Richter, A., Hauck, J., Feldmann, R., Kühn, E., Harpke, A., Hirneisen, N., Mahla, A., Settele, J., and Bonn, A. (2018). The social fabric of citizen science—drivers for long-term engagement in the German butterfly monitoring scheme. J. Insect Conserv. *22*, 731–743.

73. Lundmark, C. (2003). BioBlitz: getting into backyard biodiversity. BioScience *53*, 329.

74. Maes, D., Isaac, N.J., Harrower, C.A., Collen, B., Van Strien, A.J., and Roy, D.B. (2015). The use of opportunistic data for IUCN Red List assessments. Biol. J. Linn. Soc. *115*, 690–706.

75. Nilsen, E.B., Brøseth, H., Odden, J., and Linnell, J.D. (2012). Quota hunting of Eurasian lynx in Norway: patterns of hunter selection, hunter efficiency and monitoring accuracy. Eur. J. Wildl. Res. *58*, 325–333.

76. Titeux, N., Henle, K., Mihoub, J.B., Regos, A., Geijzendorfer, I.R., Cramer, W., Verburg, P.H., and Brotons, L. (2016). Biodiversity scenarios neglect future land-use changes. Glob. Change Biol. *22*, 2505–2515.

77. Levrel, H., Fontaine, B., Henry, P.Y., Jiguet, F., Julliard, R., Kerbiriou, C., and Couvet, D. (2010). Balancing state and volunteer investment in biodiversity monitoring for the implementation of CBD indicators: a French example. Ecol. Econ. *69*, 1580–1586.

78. Hecker, S., Wicke, N., Haklay, M., and Bonn, A. (2019). How does policy conceptualise citizen science? A qualitative content analysis of international policy documents. Citizen Sci. Theor. Pract. *4*, 32.

79. Hallmann, C.A., Sorg, M., Jongejans, E., Siepel, H., Hofland, N., Schwan, H., Stenmans, W., Müller, A., Sumser, H., and Hörren, T. (2017). More than 75 percent decline over 27 years in total flying insect biomass in protected areas. PLoS One *12*, e0185809.

80. Bundesministerium für Umwelt; Naturschutz und nukleare Sicherheit (BMU) (2019). Aktionsprogramm Insektenschutz, Gemeinsam wirksam gegen das Insektensterben, p. 67. https://www.bmu.de/fileadmin/Daten_BMU/Pools/Broschueren/aktionsprogramm_insektenschutz_kabinettversion_bf.pdf.

81. Rotman, D., Preece, J., Hammock, J., Procita, K., Hansen, D., Parr, C., Lewis, D., and Jacobs, D. (2012). Dynamic changes in motivation in collaborative citizen-science projects. In Proceedings of the ACM 2012 Conference on Computer Supported Cooperative Work, pp. 217–226.

82. Piwowar, H.A., and Vision, T.J. (2013). Data reuse and the open data citation advantage. PeerJ *1*, e175.

83. Kühn, E., Musche, M., Harpke, A., Wiemers, M., Feldmann, R., and Settele, J. (2018). Tagfalter-monitoring Deutschland: Jahresauswertung 2017. Oedippus *35*, 6–37.

84. Olson, M. (1971). The Logic of Collective Action (Harvard University Press).

85. Jasanoff, S. (2004). Ordering knowledge, ordering society. In States of Knowledge: The Co-production of Science and Social Order, S. Jasanoff, ed. (Routledge), pp. 13–45.

86. Lawrence, A. (2006). 'No personal motive?' Volunteers, biodiversity, and the false dichotomies of participation. Ethics Place Environ. *9*, 279–298.

87. Devictor, V., and Bensaude-Vincent, B. (2016). From ecological records to big data: the invention of global biodiversity. Hist. Philos. Life Sci. *38*, 13.

88. Escribano, N., Galicia, D., and Ariño, A.H. (2018). The tragedy of the biodiversity data commons: a data impediment creeping nigher? Database (Oxford) *2018*, bay033.

89. European Commission (2018). EU data protection rules. https://ec.europa.eu/info/priorities/justice-and-fundamental-rights/data-protection/2018-reform-eu-data-protection-rules/eu-data-protection-rules_en.

90. Morrison, H., and Desautels, L. (2016). Open access, copyright and licensing: basics for open access publishers. J. Orthopaedic Case Rep. *6*, 1–2.

91. Nature. (2020). Recommended data repositories. https://www.nature.com/sdata/policies/repositories.

92. Heubach, K., and Lambini, C.K. (2018). Distribution and selection of experts in the intergovernmental science-policy platform on biodiversity and ecosystem services (IPBES): the case of the regional assessment for Africa. Innovation *31* (sup1), S61–S77.

93. Ganzevoort, W., and van den Born, R. (2019). The thrill of discovery: significant nature experiences among biodiversity citizen scientists. Ecopsychology *11*, 22–32.

94. Boiral, O., and Heras-Saizarbitoria, I. (2017). Managing biodiversity through stakeholder involvement: why, who, and for what initiatives? J. Bus. Ethics *140*, 403–421.

95. Sterling, E.J., Betley, E., Sigouin, A., Gomez, A., Toomey, A., Cullman, G., Malone, C., Pekor, A., Arengo, F., Blair, M., et al. (2017). Assessing the evidence for stakeholder engagement in biodiversity conservation. Biol. Conserv *209*, 159–171.

96. Bowker, G., Star, S.L., Gasser, L., and Turner, W. (2014). Social Science, Technical Systems, and Cooperative Work: Beyond the Great Divide (Psychology Press).

97. Waterton, C. (2010). Experimenting with the archive: STS-ers as analysts and Co-constructors of databases and other archival forms. Sci. Technol. Hum. Values *35*, 645–676.

98. Brenton, P., von Gavel, S., Vogel, E., and Lecoq, M.E. (2018). Technology infrastructure for citizen science. In Citizen Science—Innovation in Open Science, Society and Policy, S. Hecker, M. Haklay, A. Bowser, Z. Makuch, J. Vogel, and A. Bonn, eds. (UCL Press), pp. 63–80.

99. Jansen, F., Ewald, J., and Jandt, U. (2015). Vegetweb 2.0—remaking the national vegetation dataportal for Germany. Tuexenia *35*, 309–319.

100. Wilkinson, M.D., Dumontier, M., Aalbersberg, I.J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J.-W., da Silva Santos, L.B., Bourne, P.E., et al. (2016). The FAIR guiding principles for scientific data management and stewardship. Sci. Data *3*, 160018.

101. Wood, C., Sullivan, B., Iliff, M., Fink, D., and Kelling, S. (2011). eBird: engaging birders in science and conservation. PLoS Biol. *9*, e1001220.

102. Callaghan, C.T., Poore, A.G., Major, R.E., Rowley, J.J., and Cornwell, W.K. (2019). Optimizing future biodiversity sampling by citizen scientists. Proc. R. Soc. B *286*, 20191487.

103. Gibbons, M. (1994). Transfer sciences: management of distributed knowledge production. Empirica *21*, 259–270.

104. Hayhow, D.B., Burns, F., Eaton, M.A., Al Fulaij, N., August, T.A., Babey, L., Bacon, L., Bingham, C., Boswell, J., Boughey, K.L., et al. (2016). State of Nature 2016.

105. .https://nbn.org.uk/about-us/where-we-are/in-scotland/.

106. Reed, M.S. (2008). Stakeholder participation for environmental management: a literature review. Biol. Conserv. *141*, 2417–2431.

107. Astrin, J.J., Fonseca, V.G., Geiger, M.F., Grobe, P., Rulik, B., and Wägele, J.W. (2015). Lessons from the first phase of the German Barcode of Life initiative (2012–2015). Genome *58*, 190.

108. Bálint, M., Márton, O., Schatz, M., Düring, R.A., and Grossart, H.P. (2018). Proper experimental design requires randomization/balancing of molecular ecology experiments. Ecol. Evol. *8*, 1786–1793.