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Review

Towards a global terrestrial species monitoring program

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ABSTRACT

The Convention on Biological Diversity's strategic plan lays out five goals: "(A) address the underlying causes of biodiversity loss by mainstreaming biodiversity across government and society; (B) reduce the direct pressures on biodiversity and promote sustainable use; (C) improve the status of biodiversity by safeguarding ecosystems, species and genetic diversity; (D) enhance the benefits to all from biodiversity and ecosystem services; (E) enhance implementation through participatory planning, knowledge management and capacity building." To meet and inform on the progress towards these goals, a globally coordinated approach is needed for biodiversity monitoring that is linked to environmental data and covers all biogeographic regions. During a series of workshops and expert discussions, we identified nine requirements that we believe are necessary for developing and implementing such a global terrestrial species monitoring program. The program needs to design and implement an integrated

Abbreviations: BON, Biodiversity Observation Network; LTER, Long-term Ecological Research; GBIF, Global Biodiversity Information Facility; CBMP, Circumpolar Biodiversity Monitoring Program; BISE, Biodiversity Information System for Europe); PPBIO, Programa de Pesquisa em Biodiversidade; TEAM, Tropical Ecology & Assessment Monitoring network; NEON, National Ecological Observatory Network; IPBES, the Intergovernmental Panel for Biodiversity and Ecosystem Services; EPBRS, the European Platform for Biodiversity Research Strategy; IUCN, International Union for Conservation of Nature; GEOSS, Group of Earth Observation System of Systems; GEO BON, Group of Earth Observation Biodiversity Observation Network; EBV, Essential Biodiversity Variables; GEO, Group of Earth Observation; IPBES, Intergovernmental Panel for Biodiversity and Ecosystem Services; CBD, Convention on Biological Diversity; CMS, Convention on the Conservation of Migratory Species of wild animals; UNEP, United Nations Environment Programme.

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Modelling framework
Policy support

information chain from monitoring to policy reporting, to create and implement minimal data standards and common monitoring protocols to be able to inform Essential Biodiversity Variables (EBVs), and to develop and optimize semantics and ontologies for data interoperability and modelling. In order to achieve this, the program needs to coordinate diverse but complementary local nodes and partnerships. In addition, capacities need to be built for technical tasks, and new monitoring technologies need to be integrated. Finally, a global monitoring program needs to facilitate and secure funding for the collection of long-term data and to detect and fill gaps in under-observed regions and taxa. The accomplishment of these nine requirements is essential in order to ensure data is comprehensive, to develop robust models, and to monitor biodiversity trends over large scales. A global terrestrial species monitoring program will enable researchers and policymakers to better understand the status and trends of biodiversity.

Introduction

The Convention on Biological Diversity's (CBD's) Strategic Plan for Biodiversity 2011–2020 envisages that "by 2050, biodiversity is valued, conserved, restored and wisely used, maintaining ecosystem services, sustaining a healthy planet and delivering benefits essential for all people". Although 193 parties have adopted these goals, there is little infrastructure in place to collect the biodiversity information necessary to monitor progress towards the objectives of the Strategic Plan for Biodiversity (http://www.cbd.int/sp/targets/). Current international conservation policy requires biodiversity data to be current, reliable, comparable among sites, relevant, and understandable, as is becoming obvious from the work plan adopted by the Intergovernmental Panel for Biodiversity and Ecosystem Services (IPBES: http://www.ipbes.net/; http://tinyurl.com/ohdnknq) and from recent assessments of the international biodiversity targets (Butchart et al. 2010; Tittensor et al. 2014). Coordinated large-scale biodiversity monitoring linked to environmental data is needed for a comprehensive Global Observation Network that can meet the five strategic goals of the Strategic Plan for Biodiversity and its 20 accompanying Aichi Targets for 2020. This is the main motivation of the biodiversity axes of the Global Earth Observation System of Systems (GEOSS) (Christian 2005), which includes the Group of Earth Observation's Biodiversity Observation Network of the (GEO BON; Scholes et al. 2012).

The ultimate goal of a global biodiversity monitoring network is the timely delivery of adequate and defensible biodiversity data to inform conservation policy, using robust indicators to demonstrate the state of biodiversity, pressures on it, and responses to those pressures (Chiarucci et al. 2011). Biodiversity can be quantified at different levels of biological organization (i.e. from the molecular to the ecosystem level), but species diversity and abundance still represent the most intuitive and widely used measures of biodiversity (Butchart et al. 2010; Colwell & Coddington 1994; Tittensor et al. 2014). That is because these two measures are both ecological and evolutionary measures and strongly positively correlated with other levels of biodiversity organization, such as genetic diversity and ecosystem functioning (Pereira & Cooper 2006).

Any local monitoring program should acknowledge that monitoring data need to be collated at different scales, including the global scale, to be able to inform about trends, status and changes of biodiversity and to have a representative overview of environmental gradients in different areas of the world and for all taxonomic groups (Collen et al. 2011). For these purposes, monitoring standards would need to be followed and data harmonization is needed to allow easy data collation from different data sources. Aggregation is important because changes in individual species or sites are often only symptoms of regional or global changes, whilst a global monitoring scheme needs to consider the larger context (Collen et al. 2011). GEO BON has adopted these goals (Scholes et al. 2012) and has established an international group of experts to develop a global monitoring network. Within this initiative, one of the working groups of GEO BON aims to develop a global terrestrial species monitoring program (Pereira et al. 2010a).

Monitoring programs should be aware that data need to be condensed into summaries and indicators that are understandable by multiple user groups and useful for policy development (e.g. the Intergovernmental Panel for Biodiversity and Ecosystem Services (IPBES), the European Platform for Biodiversity Research Strategy (EPBRS), the Convention on Biological Diversity (CBD), the United Nations Environment Programme (UNEP), etc.), but also made available to research to address conservation questions across geographic and temporal scales (Henle et al. 2014; Magnusson et al. 2013).

GEO BON is closely cooperating with regional biodiversity observation networks (i.e. Arctic BON, EU BON, Asia-Pacific BON) to develop a framework to form a basis for global biodiversity monitoring focused on a set of ecologically relevant variables known as Essential Biodiversity Variables (EBVs) (Pereira et al. 2013). These EBVs act as an intermediate, integrative layer between indicators and raw biodiversity data. They allow for the averaging of trends of multiple species across multiple locations, and their measurement captures ongoing changes in the status of biodiversity. The EBVs can serve as a framework for biodiversity data integration by identifying how variables should be sampled and measured, by helping observation communities harmonize monitoring efforts, and by providing useful summary statistics of changes in biodiversity (Pereira et al. 2013).

One motivation for pursuing the EBV framework is to align disparate monitoring efforts with a community-derived set of priority measures. By identifying which variables should be monitored and providing the necessary guidelines for sampling and data recording, the EBVs are the first step in setting a framework for biodiversity data integration and modelling. This is of particular importance, as we currently lack a comprehensive understanding of biodiversity responses to change, especially at global scales (Lenoir et al. 2010; Pereira et al. 2012). Although it is possible to detect the response of some taxa to drivers of change at regional scales (e.g. birds and butterflies in Europe: Devictor et al. 2012; Thomas et al. 2004), most of the knowledge of response mechanisms or processes that is used to construct and parameterize more mechanistic process-based predictive models is from studies conducted at very local scales. Local measures of biodiversity responses are usually extrapolated to larger scales with the assumption that species will respond equally across their range (Henle et al. 2014). However, species response mechanisms can differ locally due to complex biotic and abiotic interactions (Gilman et al. 2010; Tylianakis et al. 2011) and therefore produce spatially heterogeneous patterns of a response to changes (e.g. along an elevation or latitudinal gradient: Chen et al. 2011; Devictor et al. 2012) as well as in community composition and turn-over (e.g. decline of 'cold' specialist species versus increase in 'warm' generalist species: Devictor et al. 2012; Julliard et al. 2006).

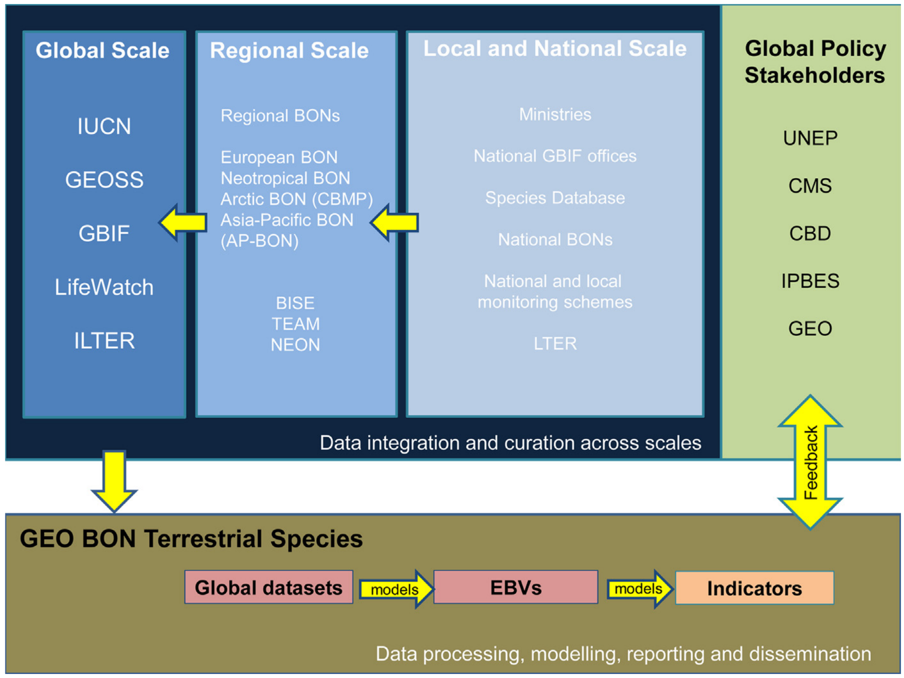

Fig. 1. The steps from 'local and national' to 'regional' to 'global' scale biodiversity monitoring. Data from the different scales need to be integrated and curated across scales. These global datasets will be processed by GEO BON Terrestrial Species, modelled, and used to inform EBVs and key indicators. The resulting reports will then be disseminated to important stakeholders on a global scale.

One goal of a global terrestrial species monitoring scheme under GEO BON is to foster effective coordination among existing monitoring programs. This is because biodiversity monitoring has historically lacked coordination and integration (Marsh & Trenham 2008; Schmeller 2008). There are many different initiatives that collectively could make a greater contribution to global biodiversity monitoring than can the sum of their individual parts, but currently do not. Each of the following types of programs could potentially contribute to this goal: (i) short-term monitoring programs targeted at impact assessment and mitigation (e.g. GLOBE: http://ecotope.org/projects/globe/), (ii) long-term study sites and networks that monitor a suite of organisms (e.g. Long-term Ecological Research (LTER), the National Ecological Observatory Network (NEON), the Tropical Ecology Assessment & Monitoring network (TEAM)), (iii) programs organized by taxa (e.g. North American and European breeding bird surveys, butterfly monitoring programs, species-specific monitoring programs), (iv) regional, state and national systematic inventory and monitoring programs (e.g. inventories of trees and vascular plants by national forest and park services, and the New Zealand Department of Conservation's Biodiversity Monitoring and Reporting System, http://tinyurl.com/k5en8ws), and (v) citizen science monitoring initiatives (e.g. Global Amphibian Bio-Blitz: http://www.inaturalist.org/projects/global-amphibian-bioblitz; a Ver Aves: http://averaves.org/; Great Backyard Bird Count: http://gbbc.birdcount.org/; see also Donnelly et al. 2013; Schmeller et al. 2009; Fig. 1).

Since 2009, the GEO BON working group on terrestrial species monitoring has conducted a range of workshops, teleconferences, and expert discussions to elaborate on the best ways to develop a global terrestrial species monitoring scheme. Here we present the outcome of these efforts and identify nine requirements that are important for the successful implementation of a global terrestrial species monitoring program.

Designing and implementing an integrated information chain from monitoring to policy reporting

A global terrestrial species monitoring program should coordinate and integrate global data and metadata collection, survey design (both sampling strategies and field protocols), data storage and access, computation and modelling of biodiversity indicators, and dissemination of policy-relevant reports in a comprehensive framework (Fig. 1). This integrated approach is required precisely because many previous attempts to coordinate biodiversity monitoring schemes have failed (for the European monitoring landscape, see Schmeller 2008). Moreover, many previous biodiversity monitoring schemes have been limited by poor survey design, lack of data interoperability, inadequate plans for data storage and quality assessment, and lack of alignment between data and policy information needs (e.g. Yoccoz et al. 2001).

Capacity-building to create a comprehensive spatial monitoring program

GEO BON Terrestrial Species will need to involve citizens, supported by professionals, to collect data, compute indicators, interpret trends, and implement policy. However, current monitoring efforts are very unevenly distributed geographically (Amano & Sutherland 2013; Martin et al. 2012) and are biased towards particular taxa (Schmeller et al. 2009). Capacity building and standardized infrastructure are most critical in regions that have difficult access (Magnusson et al. 2013:20). These information gaps in regard to geographic, temporal and especially taxonomic coverage, are well illustrated by the data used to report on the Wild Bird Index (e.g. Butchart et al. 2010), the Living Planet Index (Collen et al. 2008), the distribution of range-expanding species such as invasives (McGeoch et al. 2010), and the distribution of ecological field studies, including the network of LTER sites Martin et al. 2012; Metzger et al. 2010). The mismatch between where biodiversity is most abundant and diverse (the tropical regions) and where expertise and capacity is concentrated (the temperate zones) leaves research and policy largely uninformed about the status and trends of a large proportion of biodiversity. This includes targeting particular priority attributes or taxa, such as sites or species experiencing rapid species range contractions and expansions. There are tools that can aggregate and add value to local-scale monitoring programs by demonstrating broader-scale patterns (Arnquist & Wooster 1995; Karl et al. 2013). Monitoring efforts should encompass both range-expanding and range-contracting species (Gaston 2011). Capacity building in tropical regions is a major challenge, and GEO BON will facilitate this process by transferring expertise via training with lessons taken from existing research projects (e.g. BIOTA: Jürgens et al. 2012; PPBio (http://ppbio.inpa.gov.br/en/home): Magnusson et al. 2013) and fellowship programs (e.g. the Zoological Society of London's EDGE, or the Conservation Leadership program).

A further challenge for capacity building in large-scale and long-term biodiversity monitoring is the management of Big Data (Hampton et al. 2013; Lacher et al. 2012). Although the collection, storage, and curation of monitoring data might remain decentralized, data processing, indicator development and policy-relevant reports are scale-dependent with regard to administrative, geographic, taxonomic and temporal scales (Henle et al. 2010, 2014). A global terrestrial monitoring program has to provide part of the infrastructure, guidelines and technical standards needed for successful implementation of biodiversity observation networks and monitoring programs.

Implementing minimal data standards to capture EBVs

Primary (raw) occurrence records, such as those stored in the Global Biodiversity Information Facility (GBIF), are currently insufficient for the development of EBVs, as only two EBVs (species distributions and community composition) can be informed by GBIF data. Observation or locality data on its own is not informative enough, as it does not give a timeframe over which a species has been sighted (e.g. five individuals of a species during one monitoring event). By adding an observation time (e.g. the maximum number seen simultaneously at one location), the information becomes much more valuable, as it can now be compared across sites and years (if the monitoring protocol is consistent and spatially explicit). Additional information is needed to link biodiversity data to habitat management practices, such as a measure of species assemblage, a standardized habitat description, a geo-referenced location, and other data on processes associated with biodiversity decline. In addition, occurrence or abundance records need to be used in the context of the relevant sampling framework and sampling design or else there is a risk that they are misused.

A biodiversity observation network (BON) needs to develop data collection and metadata standards for the different EBVs in order to promote the collection of data beyond the triplet species, location and date (Lindenmayer et al. 2012; Pereira et al. 2013). Such data and databases must then be maintained as both functional and accessible, which is currently not always the case (Magnusson et al. 2013). Critical to creating value-added indicators from species-presence data is the addition of complementary information on species absences and places where a species was searched for, but not found. Checklist data aggregators, such as eBird are beginning to fill this gap for selected taxa. This is less of a problem for remote-sensing surrogates, but validation of the relationship between these surrogates and species and habitats they are meant to represent has only recently been started (Bunce et al. 2013; Nagendra et al. 2013, see also Caro 2010). Without information on the amount of search effort that is required for registering a species' presence, it is usually impossible to robustly evaluate trends in abundance or geographical occupation (but see Syfert et al. 2013; Van Strien et al. 2013).

Implementing common monitoring protocols

The adoption of common observation and monitoring protocols for new programs, together with assimilating existing ones (Allen et al. 2003; Henry et al. 2008; Lengyel et al. 2008; Schmeller et al. 2009, 2012b), would foster data integration, data interoperability and indicator extraction. A shortlist of protocols needs to be developed by examining the feasibility and complementarity of what is currently implemented (Magnusson et al. 2013). From the outset, plans should be made for systems that will enable the estimation of frequencies of false absences and the probability of detection so that data can be integrated across observers and technologies (e.g. Buckland et al. 2010; MacKenzie et al. 2002). A minimum requirement would be the delivery of certain data types, such as the relative numbers of a species in a certain site at a particular date that can inform different EBVs and is compliant with data standards. Further, at least part of the sampling should cover the area of interest in a way that is as close to random sampling, including also stratified random sampling, to account for regional differences, and targeted sampling to consider rare species (Ortega et al. 2013). The sampling strategy employed must be feasible and not concentrated only where the species is expected to be (Gitzen & Millspaugh 2012; Gregory et al. 2004; Magnusson et al. 2013).

Developing and optimizing semantics and ontologies for data interoperability

Whilst adoption of common protocols would greatly increase the usability of biodiversity data, it is not practical for existing long-term monitoring programs to change methodologies, as long time-series using common methodologies are invaluable for detecting accurate trends in biodiversity status. Techniques for harmonizing data collected with disparate methodologies exist (e.g. Henry et al. 2008), but sufficiently structured, machine-readable metadata are critical to this integration (Lin et al. 2015). For example, bird densities over much of boreal Canada have been estimated from multiple disparate data sources by explicitly modelling detection probabilities as functions of distance, duration, vegetation, and singing-rates (Sólymos et al. 2013). Critical to this type of integration is the capacity to discover and filter data and metadata from primary sources (Walls et al. 2014). Whilst there are methodological advances (e.g. Aizpurua et al. 2015; Bird et al. 2014; Pagel et al. 2014), biodiversity scientists capture and assemble data as well as the semantics of the data in so many ways that it is still necessary to either improve existing approaches or develop new ones (Walls et al. 2014). Newer techniques, such as Natural Language Processing to extract names of species and places from text messages in a citizen science project, might make opportunistically collected data accessible to scientific analyses in the future (Lin et al. 2015).

Integrating emerging technologies (monitoring, data management and analysis)

Technologies, such as remote sensing, camera trap networks (Rowcliffe et al. 2008, 2011), soundscaping (Pijanowski & Farina 2011), drones (Anderson & Gaston 2013; Koh & Wich 2012), copter-based transects, phenocams, and radio tracking can help automate standard observations, decrease long-term monitoring costs, increase the frequency of assessments, and extend coverage to remote places, although each comes at a cost and has its own strengths and weaknesses. Especially remote sensing is developing rapidly (Nagendra et al. 2013) and has the potential to rapidly increase the coverage of biodiversity monitoring in all realms and difficult to access ecosystems, e.g. using the L-band in mangrove monitoring (Lucas et al. 2007, 2014; Ortega et al. 2013). Metagenomics offers the possibility of non-invasive monitoring of whole assemblages, and data repositories are available for data collected that may be of use in the future. Adoption of new technologies is imperative to fill the huge monitoring gaps and to overcome current biases in monitoring coverage (Balmford et al. 2005; Collen et al. 2008). However, if not properly integrated into a comprehensive biodiversity observation network, the increasing amount of biodiversity data collected with high-tech tools may not benefit local and regional BONs. Developments in this sector are rapid (Ortega et al. 2013), and it is important to consider data comparability as many of the new techniques may soon be outdated, whilst the data collected with them is of high value. Employed effectively, high-tech biodiversity monitoring tools could boost biodiversity monitoring, both by complementing field-based surveys with desk-based analyses and by targeting different users and audiences. However, high-tech tools also generate large datasets that present challenges for storage and analysis (see above, capacity building needs).

Coordinating diverse but complementary local nodes

A global species monitoring network needs to offer a platform for dialogue between existing monitoring programs through fostering the coordination of efforts by regional and national biodiversity observation networks (e.g. Arctic BON, Asia-Pacific BON, BIOTA; national BONs: ECOSCOPE (France), Countryside survey (Great Britain), NEM (Netherlands), NILS (Sweden), PPBio (Brazil)). It is important that these networks explore interoperability and identify opportunities for integration that will allow a global analysis of the state and trends of biodiversity and to detect globally relevant patterns. Such integration is challenging because monitoring programs and networks differ in spatial coverage (number of sites monitored), intensity of information (quantity of data collected per site), and frequency of coverage (number of times a site is visited in a survey period or per year, or between years). The various programs contribute differently to the description of patterns and processes of biodiversity, and are thus highly complementary, but harmonization might be achieved by global stratification to account for regional differences (Metzger et al. 2013). To track biodiversity trends at the global scale, it will be important to identify all under-studied regions and taxa. It would be further important to prioritize future capacity building efforts in those places using e.g. an approach of national responsibilities and global stratification (Metzger et al. 2013; Schmeller et al. 2008a, 2008b, 2012a, 2014) or topical priorities (Henle et al. 2013). Protocols used for intensive studies usually differ from those used in wide-scale surveys. If a minimum set of common methods were used in both situations, it would greatly increase the possibilities for integrated analyses (Costa & Magnusson 2010; Magnusson et al. 2013). A global monitoring program will need to facilitate this process via workshops and coordination on a global scale.

Providing a common predictive modelling framework

To develop global-scale models with greater predictive power, GEO BON Terrestrial Species advocates a common modelling framework. Traditional modelling approaches are insufficient for modelling changes in ecological systems reliably (Sutherland 2006). Non-linear, 'tipping point', or complex feedback loops are currently the biggest limitations for most modelling approaches for extrapolating conditions in time and space beyond the boundaries of current knowledge (Evans 2012; Evans et al. 2013; Pereira et al. 2010b; Polasky et al. 2011). A variety of methods have been developed for optimizing biodiversity monitoring practices in terms of survey design (e.g. of sampling methods and frequency) by identifying the most strategic alternatives that allow for accurately detecting and tracking changes whilst minimizing efforts and resources (e.g. Lindenmayer & Possingham 1996). Also, the more recently developed predictive mechanistic process-based models, relating different variables and/or different spatial and temporal scales (e.g. Harfoot et al. 2014), rely on comprehensive biodiversity information. Extending the use of such predictive modelling approaches to larger spatial, temporal and taxonomic scales would be an essential element in defining the best practices for integrative biodiversity monitoring at the regional or global scale. However, we currently lack regional-to-global-scale datasets to calibrate and validate predictive models of change for each of the EBVs. An improved modelling framework, adoption of a suitable monitoring design, and optimized spatial coverage based on the parameter and data needs, would lead to reliable predictions and would help to prioritize conservation planning strategies (Gillson et al. 2013; Henle et al. 2013; Wilson et al. 2006).

Facilitating and securing funding

A solid and long-term financial base is critical for maintaining the structures and institutions that generate, curate and interpret biodiversity data so that they are functional and effective over time. Policymakers and stakeholders must recognize that biodiversity data collection, storage and processing require funding. With strategic organization and coordination, global biodiversity monitoring can be cost-effective (Targetti et al. 2014). Establishment of national, regional and global offices to coordinate biodiversity on the respective scales often necessitates startup funds for building informatics infrastructures and capacity where needed. Therefore, one of the goals of GEO BON Terrestrial Species is to engage policymakers in finding ways to fund biodiversity monitoring that can serve decision-making in the long-term.

Discussion

Here, we have outlined nine requirements for the successful development of a global terrestrial species monitoring program. A global program is urgently needed, as currently most biodiversity data allow the measurement of a few aspects of biodiversity change only and we only partially understand the relation of biodiversity change to environmental change, especially at global scales. Whilst there are a number of programs monitoring biodiversity, for very disparate purposes and using a large variety of methods and approaches, integrating data from monitoring programs operating on local, regional, national and continental scales has generally not been achieved. A notable exception is the work on birds and butterflies in North America and in Europe (Butchart et al. 2010; Gregory & van Strien 2010; Tittensor et al. 2014; van Swaay et al. 2008). More integrative biodiversity monitoring targets at global scales addressing multiple variables across e.g. the EBV framework, by prioritizing efforts using e.g. stratifications and matching complementary monitoring schemes are urgently needed. Critical thought needs to be given to design future biodiversity monitoring strategies in order to make sure that data collection can fill existing gaps in the comprehensiveness of biodiversity measurements (e.g. individual traits and functional interactions). For that, we also need systematic monitoring of biophysical parameters at biodiversity monitoring sites, which rarely occurs (but see e.g. NEON, PPBio). This disconnection undermines our ability to determine the causes and consequences of biodiversity loss, as models cannot be correctly parameterized (Magnusson et al. 2013). Hence, the nine requirements outlined here aim to lead to the integration of monitoring programs and would help to fill existing data gaps, to develop robust predictive models of future change scenarios, and to monitor biodiversity trends on large spatial scales. Such a comprehensive network might enable scientists and policymakers to better understand the status and trends of biodiversity and act accordingly with the interests of both nature and people in mind. Such a global effort is also important for assessing international progress in biodiversity conservation and progress towards agreed conservation targets, such as the Aichi targets of the CBD. Whilst national, regional, and thematic BONs might serve their respective geographic scales best, GEO BON Terrestrial Species will need to focus on global and supraregional patterns and policies. The nine requirements identified here represent a pathway for achieving effective species monitoring on the global scale: our past experience has contributed to identify the main pitfalls targeted by each of these requirements. We believe that international organization and political willingness will be necessary to make the best of the already large but un-coordinated monitoring effort. Rather than simply a call for more funding, GEO BON Terrestrial Species calls for the improved coordination and policy support at all scales necessary to improve efficiency of current spending on biodiversity monitoring.

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