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Perspective

Unlocking biodiversity data: Prioritization and filling the gaps in biodiversity observation data in Europe

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A B S T R A C T

Large quantities of biodiversity data are required to assess the current status of species, to identify drivers of population and distributional change, and to predict changes to biodiversity under future scenarios. Nevertheless, currently-available data are often not well-suited to these purposes. To highlight existing gaps, we assess the availability of species observation data in Europe, their geographic and temporal range, and their quality. We do so by reviewing the most relevant sources for European biodiversity observation data, and identifying important barriers to filling gaps. We suggest strategies, tools and frameworks to continue to fill these gaps, in addition to producing data suitable for generating Essential Biodiversity Variables (EBVs). Our review of data sources shows that only around a third of data-providers provide unrestricted data access. Particularly large geographic gaps exist in Eastern European countries and many datasets are not suitable for generating EBVs due to the absence of long-term data. We highlight examples built on recent experiences from large data integrators, publishers and networks that help to efficiently improve data availability, adopt open science principles and close existing data gaps. Future strategies must urgently consider the needs of relevant data stakeholders, particularly science- and policy-related needs, and provide incentives for data-providers. Hence, sustainable, long-term infrastructures and a European biodiversity network are needed to provide such efficient workflows, incentives for data-provision and tools.

1. Introduction

Despite diverse and significant attempts to reduce biodiversity loss, global biological diversity is declining in the face of numerous pressures. At a regional level, the European Union has adopted ambitious political goals to address this ongoing challenge (European Union, 2011). If these goals are to be attained, it is crucial that biodiversity data are available for research and monitoring. The degree to which such data can be of use depends on their temporal, spatial and taxonomic completeness, and high quality biodiversity data can help to monitor the progress of conservation policy and management from local to global scales (Deinet et al., 2013; Sanderson et al., 2015; Wetzel

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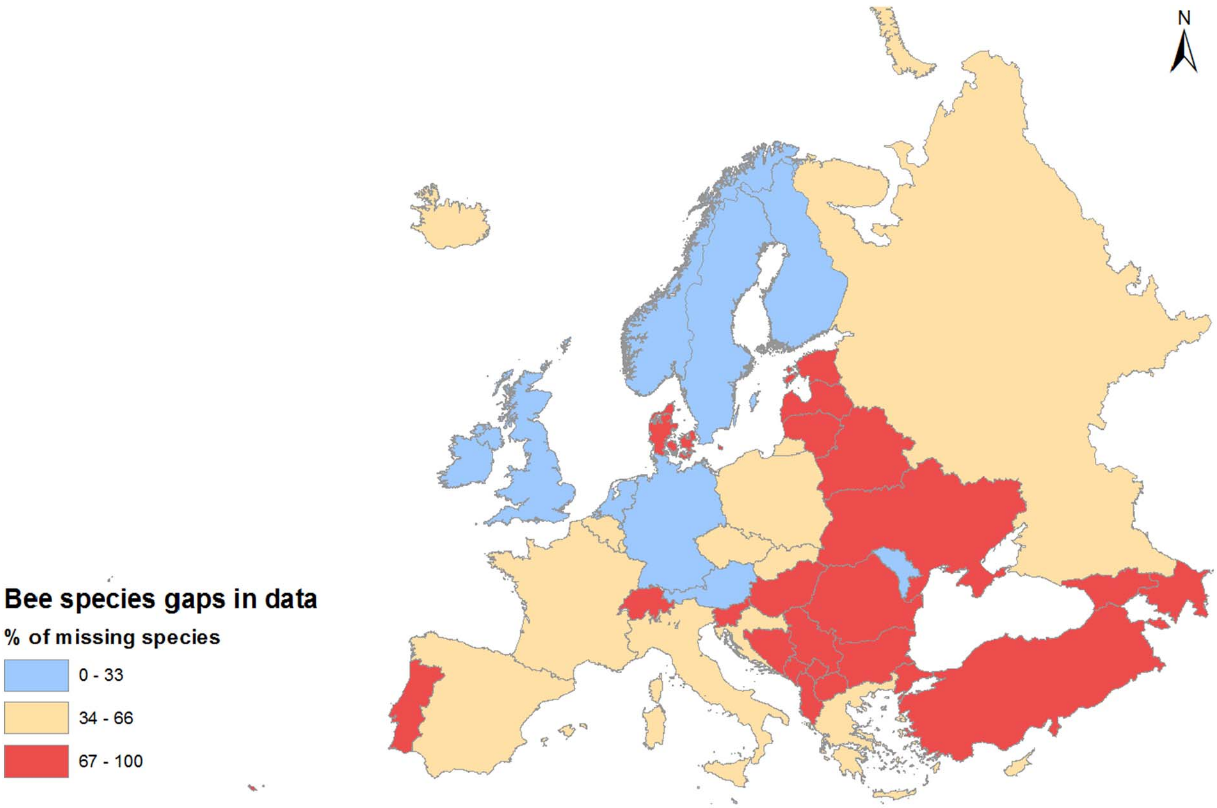

Fig. 1. Spatial gaps in occurrence records on policy-relevant pollinators in the Pan-European region, here exemplified with data on wild bee species (*Anthophila*) in Europe, comparing expert-validated country occurrences and available records in GBIF. This figure visualizes GBIF data gaps, for each country, expressed as the percentage of missing species in a country, ranging from large gaps (red colors, > 67% of species not covered in GBIF) to relatively minor gaps (blue colors < 33%). Despite highly active and skilled amateurs, bee species occurrence data are often not published digitally. A lack of resources for data mobilization at the national level is a likely cause, particularly for fields where the vast majority of experts are amateurs. In addition, such data may be an economically important resource for environmental assessment companies, creating a disincentive to sharing data. A similar situation applies to academic research projects, where data may be used to leverage grant funding. New models of mutual benefit, recognition and participation need to be developed to address these challenges.

et al., 2015; Geijzendorffer et al., 2016).

For conservation policy, biodiversity data are needed to evaluate progress towards conservation targets, to assess the effectiveness of management strategies and to determine conservation responsibilities (Schmeller et al., 2015). Data are also needed to build an understanding of the drivers of biodiversity loss (Proença et al., 2017) and to generate Essential Biodiversity Variables (EBVs) as an intermediate layer between primary observational data and derived indicators (Brummitt et al., 2017; Schmeller et al., 2017a). The resulting reliance on biodiversity data means that gaps and limitations in data can be highly problematic, and may lead to misleading baselines for evaluating the status of biodiversity and its trends (Mihoub et al., 2017). Data gaps may also introduce significant biases in assessments of progress in conservation, especially in biodiversity hotspots (Collen et al., 2008).

Therefore, policy-makers need to be aware of the limitations of the data on which they base decisions, to understand the uncertainties accompanying them, and to support measures to fill identified gaps (Pereira and Cooper, 2006). It is also important that data-collectors in the field are aware of the potential significance of their data at a national and continental scale. In this study, we evaluate European biodiversity data from key data-providers and mediators. We highlight key gaps in (1) spatial, (2) temporal and (3) taxonomic coverage of biodiversity observations, based on the needs of science and the requirements of policy. We further highlight barriers that prevent an efficient collection, analysis and open access to data. Based on our analysis, we propose ways of closing current biodiversity data gaps, and provide detailed recommendations to biodiversity data-providers and stakeholders.

2. Methods and approach

To evaluate data accessibility, we evaluated the level of access permitted by thirteen (Fig. 1) integrators of biodiversity occurrence data in Europe. We define data integrators as platforms or networks that offer data that has mostly been provided by external contributing organizations, institutions, initiatives or projects. Many of these host data from multiple data-providers or national biodiversity reporting systems (e.g. the Global Biodiversity Information Facility (GBIF)). We considered those data integrators meeting the following criteria: (a) the source provides occurrence information for freshwater, terrestrial or marine species in Europe with an adequate coverage of the European continent (meaning that there is no sub-European geographic focus); (b) the source provides at least basic metadata; (c) the source provides data on clearly specified taxonomic groups or species for scientific analyses. Therefore, we excluded data integrators that have a restricted (sub-European) geographical approach (e.g. national platforms).

Data integrators were ranked based on the accessibility of data using three categories: (i) Unrestricted data: characterized by data that can be accessed/downloaded under an open license or waiver. This also includes licenses under creative commons that require users to cite the authors of the source (cc-by), licenses that require modified content to be shared under the same terms (cc-by-sa), and licenses that give open access on the condition that the work is not used commercially (cc-by-nc). (ii) Unrestricted or restricted: data integrators deliver a variety of data, some open and others restricted. (iii) Restricted: data can be downloaded under a restrictive license, re-use must be requested, data can only be browsed online or cannot be accessed.

To assess the completeness of spatial biodiversity data for Europe,

Table 1
Selected data integrators of species occurrence data in Europe.

Data provider	Acronym	Taxon Focus	Time-series	Occurrence data	Taxonomic coverage/number of records	URL
Atlas Florae Europaeae	AFE	Plants		x	European occurrence data for 4473 species and subspecies	http://www.luomus.fi/en/atlas-florae-europaeae-afe-distribution-vascular-plants-europe
Atlas of European Breeding Birds		Birds		x	339,386 European species records from 497 European bird species	http://www.ebcc.info/
Atlas Hymenoptera		Hymenoptera		x	Hymenoptera distribution records, e.g. 988,187 records for 69 European bumblebees collected (STEP project).	http://www.atlashymenoptera.net/
Checklist of Western Palaearctic Bees		Bees		x	3351 bee species in total and 2546 species with occurrence records	http://westpalbees.myspecies.info/
Euro + Med PlantBase	Euro + Med	Plants		x	Data on 187 plant families ~ 92% of the European flora of vascular plants	http://www.emplantbase.org/home.html
EU data: Habitats Directive Article 17 and Bird Directive Article 12		Birds, others	x	x	450 species bird directive and 1200 species of other taxonomic groups	http://www.eea.europa.eu/data-and-maps
European Vegetation Archive of European Vegetation Survey	EVS	Plants	x	x	65 databases with > 1.2 million vegetation plots	http://euroveg.org/eva-database
Fauna Europaea	FaEu	Animals		x	About 145,000 metazoan terrestrial and freshwater species	http://www.faunaeur.org/
Global Biodiversity Information Facility	GBIF	No focus	x	x	796 Mio occurrence records	http://www.gbif.org/
Long-term Ecosystem research network	LTER	No focus	x	x	446 registered datasets	https://data.lter-europe.net/deims/
Ocean Biogeographic Information System	OBIS	Marine	x	x	Over 45 million observations of nearly 120,000 marine species	http://www.iobis.org/
The National Center for Biotechnology Information	GenBank	No focus		x	197,390,691 nucleotide sequences (October 15, 2016) from environment, lab experiments … Only a (unknown) part are taxon occurrences with Darwin Core.	http://www.ncbi.nlm.nih.gov/genbank/
European Register of Marine Species	ERMS	Marine		x	Data on 33,000 accepted species	http://www.marinespecies.org/

Number of records: From evaluation 2014–2016 or latest online available information, actual numbers might differ due to ongoing updates.

occurrence data from GBIF, including observation and specimen-based data, were compared with expert-validated species country occurrences from the Checklist of Western Palaearctic Bees (hereafter called Checklist) from the Natural History Museum in London (http://westpalbees.myspecies.info/). This is an expert-driven database of country-specific occurrence records (i.e. it gives information on species presence/absence for a country). Thus the Checklist allows checking for data gaps in GBIF occurrence records for a country. The checklist contains 3351 bee species in total and 2546 species with occurrence records relevant to the region in question (extended Pan-European region, including Turkey and countries of the Caucasus. For more information see Suppl. 1).

Temporal data from the Long-Term Ecosystem Research Network (LTER; Suppl. 1) were used to identify the history of data collection at individual sites, based on the year of first data collection. To analyse biases and limitations in research networks, we used metadata from LTER–Europe (Long-Term Ecosystem Research). The LTER-Europe network is the European branch of the International LTER network (ILTER), a global network of research sites located in a wide array of ecosystems. Currently the LTER-Europe network consists of 24 national LTER networks comprising 438 LTER and long-term socio-economic and ecological research (LTSER) sites, including a suite of long-term observations of a diversity of environmental variables, such as genetic data, species occurrence data, climate, habitat condition, ecological function and services, as well as socio-economic data.

Included in the analysis of the LTER data was an assessment of the research focus at the respective LTER site, including both the taxonomic focus and the research topic. Research topics were grouped into research focused on particular species groups, functional ecology, ecosystem ecology, and anthropogenic effects on biodiversity. Information on the LTER sites and their data is available via Drupal Ecological Information Management System (DEIMS, cf. https://data.lter-europe.net/deims/).

Taxonomic gaps were identified using data from EuMon (http://eumon.ckff.si/) a European project that has established a database of biodiversity monitoring practices across Europe. The number of species monitored and recorded in the EuMon database was compared to the estimated number of European species for eight different taxonomic groups (based on data from Fauna Europaea, Euro + Med PlantBase and IUCN records). In addition, the number of species monitored and recorded in EuMon per country was compared to the estimated number of species present in the country. The example of birds is presented in the results.

3. Results

3.1. Accessibility of data

There were clear differences in terms of data accessibility of the 13 data integrators (Table 1), with only four data integrators providing data with no restrictions. This means that metadata and data are accessible and licensing information is provided (e.g. Creative Common licenses in GBIF and OBIS) for less than one third of the data integrators. Three integrators varied their restrictions based on the particular data being accessed. This means that parts of the data were inaccessible, or accessible with other restrictions, and often clear licensing information was not provided. Nearly half of the integrators (i.e. six out of thirteen) provide data with access or use restrictions (e.g. permission for use must be requested, data can only be used with a restrictive license or only be browsed online, or data are not accessible at all).

3.2. Spatial data

A comparison of GBIF occurrence data with expert-validated species' ranges identified notable gaps outside the European Union,

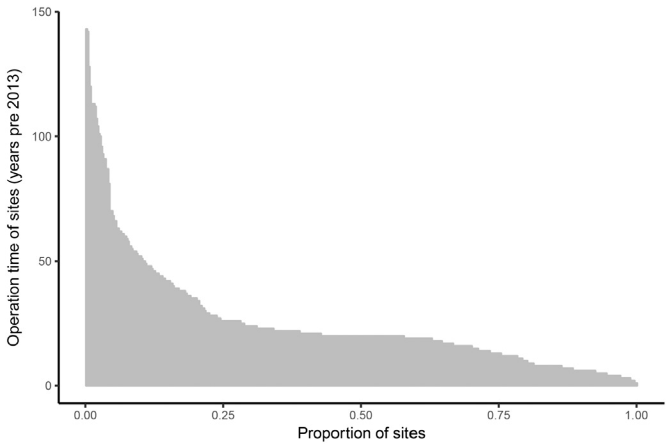

Fig. 2. Duration of the longest time series that is recorded at each of the 438 LTER sites that were registered in the Drupal Ecological Information Management System (DEIMS) in January 2013.

including in the Russian Federation and in the Carpathian and Caucasus regions of Eastern Europe. The analysis of the GBIF wild bee species data identified gaps in Eastern European countries such as the Baltic States, Belarus, the Ukraine and the Caucasus region (Fig. 1). However, there are also gaps in Denmark, and in Southern European countries, such as the Balkan States and Portugal.

3.3. Temporal data

Of the 438 European LTER sites analysed, 45 sites (10.3%) had data spanning > 50 years and 11 sites spanned > 100 years. Data spanning 20 years or more were available for 187 sites (42.7%), and data exceeding ten years existed for 79% of sites (Fig. 2). The mean length of time series was 25.4 years with a standard error of 1.07. In addition to their temporal limitations, these datasets are not always comprehensive across species' ranges. Close examination of the data revealed that many species, including well-known butterflies, have long-term data only for a few particular locations.

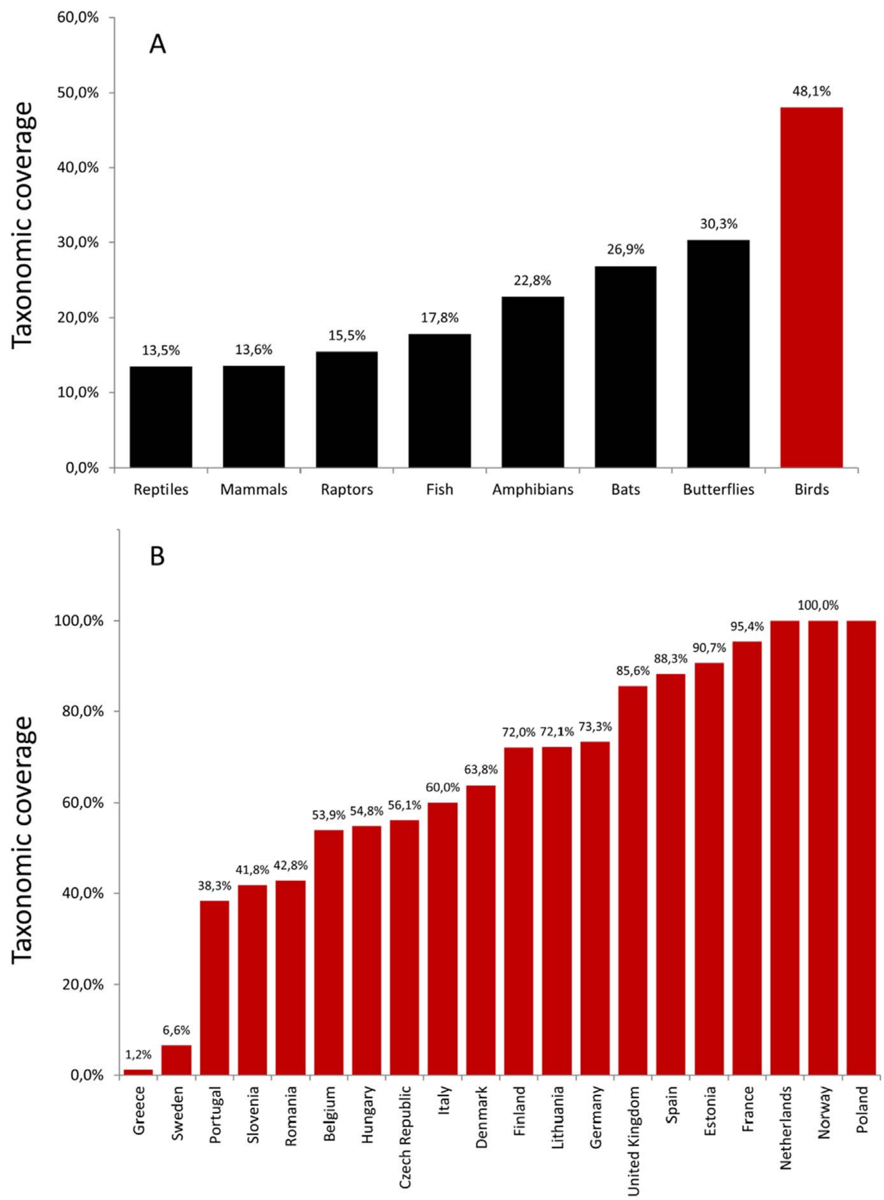

Fig. 3. Estimated percentage of vertebrate species monitored by taxonomic group (A) and percentage of birds monitored per country (B). The analysis is based on the estimated species numbers per country compared with the number of species monitored in the monitoring programs recorded in the EuMon database.

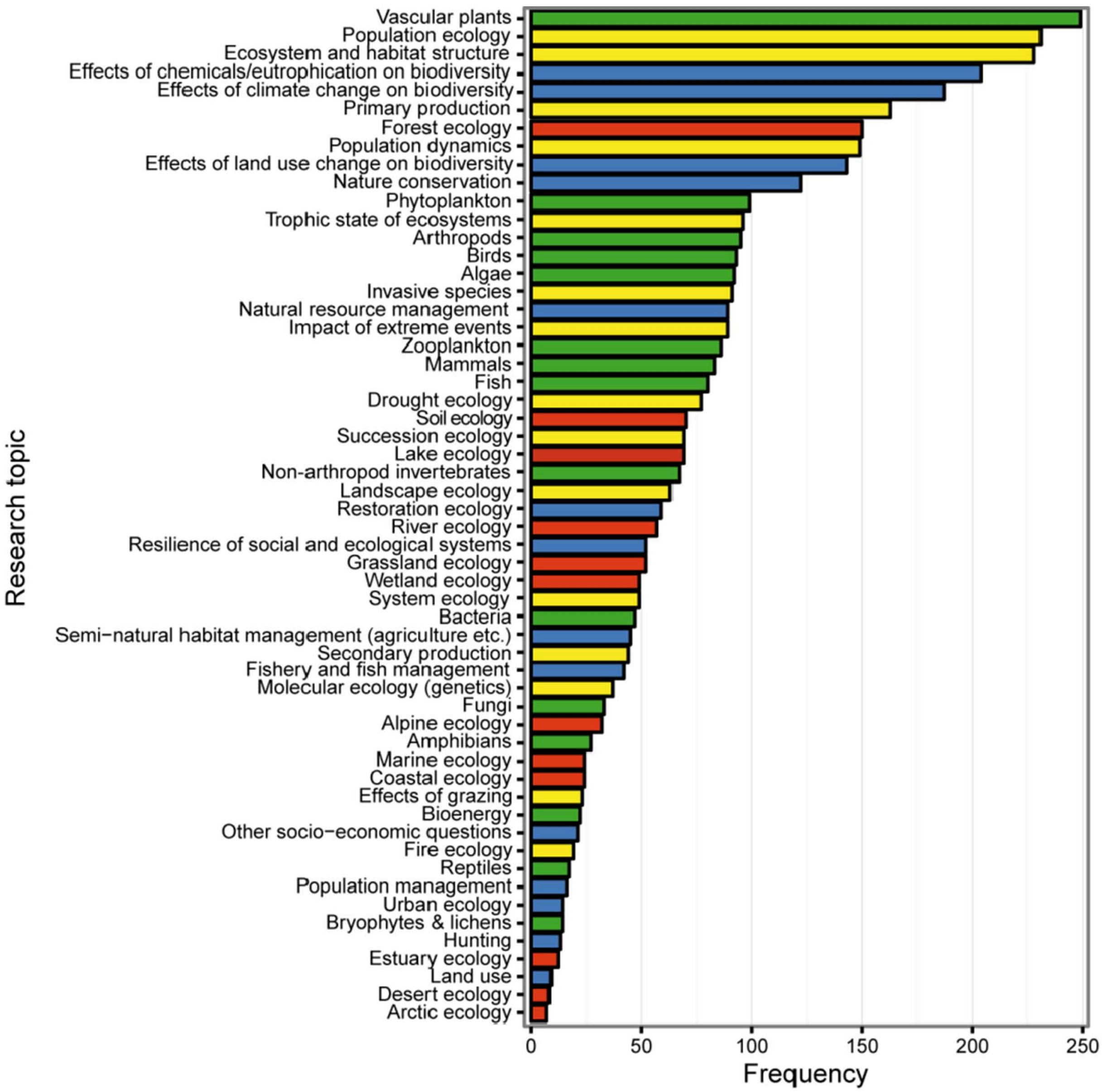

Fig. 4. Absolute frequency of biodiversity-related research topics at the 438 LTER sites that were registered in the Drupal Ecological Information Management System (DEIMS) in January 2013 based on the keywords that were entered to characterize the research at each site. The number of keywords per site was not limited. Research topics are grouped to species groups (green), anthropogenic effects on biodiversity (blue), functional ecology (yellow), and ecosystem ecology (red).

3.4. Taxonomic data

Based on the EuMon analyses, birds are the taxonomic group best covered by monitoring schemes, followed by butterflies and bats (Fig. 3). Reptiles are the most poorly represented, followed closely by mammals. In the case of birds, the proportion of species monitored differs considerably by country (Fig. 3). The Netherlands, Norway and Poland have comprehensive monitoring, but major gaps exist in Greece and Sweden.

A limitation of the LTER data is a bias towards particular focal organisms and research topics. For instance, three of the five most frequently covered taxonomic groups are plants (vascular plants, phytoplankton, algae: Fig. 4), while plants are not among the species that are intensively monitored according to the EuMon database (Fig. 3A). Questions around functional ecology were found to be the primary motivation for long-term monitoring in the LTER community, followed by anthropogenic effects on biodiversity, and ecosystem ecology (Fig. 4).

4. Discussion

This study demonstrates the existence of significant gaps in European biodiversity data. There are geographic gaps, such as those in several Eastern European countries, the Caucasus, and the Russian Federation, as confirmed by other studies (e.g. Boakes et al., 2010; Amano et al., 2016). This is despite the fact that Europe is relatively data-rich compared to other regions of the world (Meyer et al., 2015). There are also temporal and taxonomic gaps (Schmeller et al., 2012; Pimm et al., 2014) as well as barriers to data availability. To improve data usefulness, broaden access and reduce gaps, biodiversity data must meet the needs of several groups: scientists, policy-makers, and data-providers (Fig. 5). For scientific studies on transfrontier, plurinational and global phenomena, long-term data series (> 10 years) with full European coverage are needed (Schmeller et al., 2015). Policy-driven requirements state that data need to be suitable to monitor policy implementation, including with regards to regulations and international processes (e.g. Sustainable Development Goals and Aichi Biodiversity

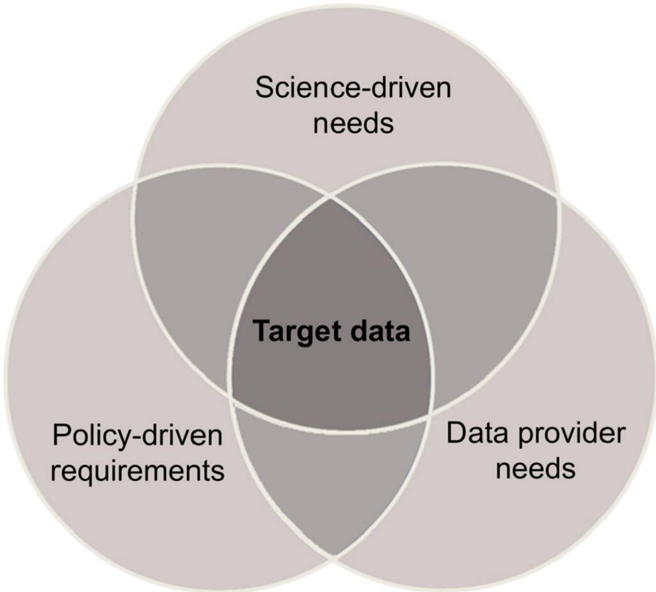

Fig. 5. Biodiversity observation data has to fulfil specific requirements and needs imposed by science, policy and data-providers in order to minimize gaps and to become useful for research and policy reporting (i.e. to become high-quality 'target data').

Targets, cf. Wetzel et al., 2015). Lastly, data workflows need to provide incentives for data-providers, and reward-mechanisms for sharing data. As our gap analysis showed, many of these requirements are not met, resulting in the significant gaps in European biodiversity data.

Here, we discuss possible solutions for generating data that are of optimum use in research and Europe's implementation of its biodiversity targets (Wetzel et al., 2015).

4.1. Making data accessible

The results presented here indicate that open access to data is not the norm in Europe, and that inaccessibility of existing data is causing gaps that are as severe as missing data. Data need to be made available via data integrators such as GBIF to inform the EBV framework. This is particularly true of those EBVs deemed to be the most urgent to document biodiversity change (Schmeller et al., 2017b). Unclear and restrictive data licensing limits the use of data for research (Groom et al., 2017), and researchers often provide their data with different degrees of restriction. However, some recent developments have helped to improve access to occurrence data. One example is GBIF, which, as the largest integrator of occurrence data (providing access to over 796 million records, GBIF, 2017), is now fully open access for academic research following recent changes to its data policy.

To build on such positive trends, we propose the following solutions. First, data that are already open access should be clearly labelled as such with standard licenses. There is also a need to make more data accessible via major data platforms. One solution could be to provide tools and training on uploading and curating biodiversity data, as exemplified in the EU BON project (Smirnova et al., 2016, e.g. via the PlutoF workbench). This could be particularly important to citizen science organizations that may not have the technical knowledge, capacity or infrastructure to mobilize their data. Citizen science and community-based monitoring provide large-scale data on species occurrence (Chandler et al., 2016), and most people involved in European species-monitoring schemes are non-professionals (e.g. 86.7% of people in an evaluation of European monitoring schemes, Schmeller et al., 2009). A notable initiative is eBird, which has contributed over 275 million records to GBIF (2017). However, there remains further potential for citizen science contributions elsewhere (Theobald et al., 2015). For example, only 9% of North American and 35% of European citizen science projects evaluated in a study by Chandler et al. (2016) make their data available to GBIF.

Second, open access to data should be incentivised, such as through the option of publication in peer-reviewed data journals. An example is the Biodiversity Data Journal (Chavan and Penev, 2011). Many researchers have expressed serious concerns about sharing their data openly. For example, one study identified such concerns among 63% of principal investigators working on long-term ecological and evolutionary studies (Mills et al., 2015). Initiatives to tackle this could include the provision of specific incentives. Successful examples exist that demonstrate the importance of such incentives (e.g., de Jong et al., 2014). Options include the promotion of accurate citation and data-provider attribution in scientific papers (Haase et al., 2016). A further method of raising the visibility of data-providers (Table 2) is to allow institutional branding on publishers' pages and dataset metadata pages. This could include integrating maps and analytics, thereby giving publishers a ready-made 'homepage' for the data they share. Another incentive is to enable and promote Digital Object Identifiers (DOIs) for citation of both datasets and downloads, a practice already well-established in many scientific communities. This also supports open science principles, as the underlying data used in scientific research can be traced (Wilkinson et al., 2016).

Third, innovative, sustainable funding mechanisms should be explored. These funding mechanisms could support sustainable storage of data, and long-term initiatives that collect data for specific purposes, such as generating EBVs, or addressing research- and policy-relevant questions. Such funding mechanisms need to be implemented on a continental scale – for example, a European wide (meta)data repository for the data of all biodiversity research that is funded by EU projects (Horizon 2020, LIFE projects and others) and the support of long-term monitoring schemes that would be essential parts of a European Biodiversity Observation Network. Also, European and national funding require improved efforts from both existing and future projects in terms of allocating components of funding to the actions explained above (data collection and storage). Furthermore, legal and financial mechanisms need to be provided whereby beneficiaries of the open access to biodiversity data contribute to the valorisation of these data. Such beneficiaries include industries that are required to conduct environmental impact assessments and those that exploit natural resources.

Finally, measures should be introduced to generate more data and

Table 2
Examples of incentives that help to motivate data-providers to supply data for open access.

Infrastructure, tools and training	Offer tools and provide training for uploading and curating biodiversity data, core infrastructure for data storage and curation.
Peer-reviewed data papers	Promote peer-reviewed data papers, encourage robust descriptions of e.g. methodology in metadata.
Institutional branding	Enable institutional branding on publishers' pages and dataset metadata pages, including maps and analytics and a ready-made 'homepage' for the data they share.
DOIs	Enable and promote Digital Object Identifiers (DOIs) for citation both for datasets and downloads – give clear citation recommendations to use DOIs.
Regional approaches	Support regional approaches, e.g. the GBIF Node system, allow national partners to engage their own data holding community and apply arguments for their own country to encourage institutions to share.
Innovative funding mechanisms	Create innovative funding mechanisms that promote sustainability, open access and adoption of open science principles as well as management of high quality data.

to fill important information gaps. At the national and European level, this could entail the provision of a common core infrastructure, such as data storage and curation platforms to support existing and future biodiversity monitoring schemes (Schmeller et al., 2015). Technological innovations could provide additional assistance in mobilizing data by enhancing data–collection methods. These could include advanced audio and image-recognition software and recording devices, drones, and complementary satellite-based remote sensing techniques (Stephenson et al., 2017). Another important target is the digitization of data from museum collections and legacy literature, as these provide the most comprehensive historical coverage (c.f. Boakes et al., 2010, Groom, 2015, Mihoub et al., 2017).

4.2. Making data discoverable

Gaps arise not only because the data do not exist or are not accessible, but because they are not discoverable. This is of particular relevance in the case of temporal data, which is fundamental to understanding biodiversity trends, and where the only way to fill gaps is to make historical data discoverable (Mihoub et al., 2017). Making standardized and complete metadata available by providing information on the basic features of the data, including spatio-temporal taxonomic information as well as methodology is of equal importance. Such metadata enable rapid evaluation of data quality and fitness for use. The improvement of metadata can also act as an interim solution in cases where there are challenges preventing full access to data. Discoverability of existing data could also be enhanced through the proliferation of visualization tools. These tools enable users to obtain a rapid understanding of a dataset. Data can often be efficiently searched and evaluated via such tools, such as interactive web-based maps, examples of which are Protected Planet (UNEP-WCMC and IUCN, 2017), interdisciplinary data portals (e.g., GEOSS portal) and visualization tools for species trends in Europe (e.g. in the EU BON Biodiversity Portal).

4.3. Evaluating what we need

It is clear that we cannot monitor European biodiversity reliably with the currently available data. In order to make progress we need to identify the types and volumes of data that are needed. Without clear targets it will be impossible to persuade volunteers, NGOs and politicians to make the necessary changes. This requires research on the methods and monitoring costs in Europe (Targetti et al., 2014). At the same time, we need data workflows on a European scale with integrated feedback loops and constant gap analyses to determine where efforts are sufficient or need to be adjusted (Kissling et al., 2017). In a next step, there is the need for efforts to improve national inventories with regards to their taxonomic, spatial and temporal coverage. However, a key success factor is in turn to make such national inventories freely available for research and conservation policy. Hence, in addition to continental analyses, specific national analyses are needed to evaluate the quantity and quality of national repositories, determine the reasons for insufficient coverage, and provide specific recommendations on how to close the gaps.

Closing the gaps must take into account science-driven needs and policy-driven requirements, and provide incentives for data-providers. We also propose further studies on open access and open science with regards to biological and environmental data. We have discussed a set of key data-providers on a European scale, however, there are many initiatives that were not specifically addressed in our study and could be evaluated as a next step.

4.4. Importance of biodiversity data for conservation outcomes and outputs

In order to develop successful conservation actions and strategies, and to enable evidence-based decision-making, high quality data are needed. These data must have a sufficient geographical, taxonomic and temporal resolution (Westgate et al., 2013). Without such data, inappropriate actions in conservation management become more likely. For example, until recently the distribution of the European wildcat (*Felis s. silvestris*) in Central Europe was considered to be restricted to two isolated areas in western and central Germany (Birlenbach and Klar, 2009). Based on advanced genetic monitoring methods, Steyer et al. (2013) showed that the European wildcat is much more broadly distributed across Central Europe than previously assumed, and that the allegedly isolated areas are well-connected. Accordingly, previously planned conservation actions (building corridors between the two isolated areas) were revised, illustrating the importance of obtaining data with adequate geographical coverage to appropriately inform conservation managers. Similarly, discoverable and accessible data is needed to evaluate the success of river restoration projects. River restoration was regarded as a prime conservation measure to improve the ecological status of freshwater habitats, a measure that usually found high support by the local community. However, a study analysing monitoring data for fish, macrophytes and benthic invertebrates found no projects that actually reached a good ecological status after restoration (Haase et al., 2013; Leps et al., 2016), showing that conservation impacts must be continually tested against observed data, which must be available, discoverable and accessible.

5. Conclusion

Embracing the solutions identified here depends on Europe-wide cooperation between the key stakeholders from research (data collection and analysis), citizen science and policy. There is currently neither a unified European terrestrial biodiversity network, nor European funding in sight that could provide a substantial contribution for such an infrastructure, neither in the short nor in the long-term. An important political and scientific effort is needed to streamline and integrate the various approaches that already exist in Europe. This could be achieved with the help of a permanent European regional biodiversity observation network (Hoffmann et al., 2014) that links current research with citizen science initiatives and projects (http://biodiversity.eubon.eu/home). Such a network could also promote biodiversity data mobilization and integration, as well as the adoption of open science principles. In addition, it could help to report and provide data to global networks (e.g. Group on Earth Observations Biodiversity Observation Network) and data integrators such as GBIF. Ultimately, it could secure the transformation of data into information and knowledge to support evidence-based decision making. This, in combination with incentives for data-providers, would avoid further fragmentation of the biodiversity data landscape, which would be detrimental to large scale ecological analyses. These solutions would build and strengthen links between web-based data portals, platforms, data integrators and networks, while facilitating a much-needed revolution in data accessibility and discoverability.

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