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Contribution of citizen science towards international biodiversity monitoring

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ABSTRACT

To meet collective obligations towards biodiversity conservation and monitoring, it is essential that the world's governments and non-governmental organisations as well as the research community tap all possible sources of data and information, including new, fast-growing sources such as citizen science (CS), in which volunteers participate in some or all aspects of environmental assessments. Through compilation of a database on CS and community-based monitoring (CBM, a subset of CS) programs, we assess where contributions from CS and CBM are significant and where opportunities for growth exist. We use the Essential Biodiversity Variable framework to describe the range of biodiversity data needed to track progress towards global biodiversity targets, and we assess strengths and gaps in geographical and taxonomic coverage. Our results show that existing CS and CBM data particularly provide large-scale data on species distribution and population abundance, species traits such as phenology, and ecosystem function variables such as primary and secondary productivity. Only birds, Lepidoptera and plants are monitored at scale. Most CS schemes are found in Europe, North America, South Africa, India, and Australia. We then explore what can be learned from successful CS/CBM programs that would facilitate the scaling up of current efforts, how existing strengths in data coverage can be better exploited, and the strategies that could maximise the synergies between CS/CBM and other approaches for monitoring biodiversity, in particular from remote sensing. More and better targeted funding will be needed, if CS/CBM programs are to contribute further to international biodiversity monitoring.

1. Introduction

International treaties such as the Convention on Biological Diversity, the Convention on International Trade in Endangered Species of Wild Fauna and Flora, and the Convention on the Conservation of Migratory Species recognise the need to assess change in the status and trends of global biodiversity. Moreover, one of the four main functions of the Intergovernmental Panel on Biodiversity and Ecosystem Services is to "perform regular and timely assessments of knowledge on biodiversity" (IPBES, 2013).

Current biodiversity informatics programs allow for inferences about the status and trends of global biodiversity, and gaps and priorities have already been identified (Ariño et al., 2016; Meyer et al., 2015; Peterson et al., 2015; Peters et al., 2014; Ruete, 2015; Wetzel et al., 2015). To help track global biodiversity change, the Group on Earth Observations Biodiversity Observation Network (GEO BON) proposed a candidate set of Essential Biodiversity Variables (EBVs; Pereira et al., 2013). EBVs represent the minimum set of measurements needed to capture major dimensions of biodiversity change, and are now being

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Table 1
Examples of the coverage of Essential Biodiversity Variables (EBVs) by citizen science (CS) and community-based monitoring (CBM) programs. Additional columns indicate the scale of the projects and the feasibility of data collection by citizens and community members. Green indicates EBVs with high adequacy in terms of remotely sensed products, yellow indicates medium adequacy while red is low adequacy or no remotely sensed products that can monitor these EBVs (O'Connor et al., 2015). References to CBM programs is available in Appendix 5.

EBV class	EBV	Scale of CS/CBM measurement	Feasibility	Examples from Global CS database	Examples from CBM database
Genetic composition	Co–ancestry	Local	Rare data, collected mostly by specialized projects and professional monitoring	–	–
	Allelic diversity				–
	Population genetic differentiation				–
	Breed and variety diversity				Suitability of different Mongolian pasture plants (Fernandez–Gimenez, 2000)
Species populations	Species distribution	Global, regional, local	Most abundant biodiversity–related citizen science observation	Christmas Bird Count, eBird, FeederWatch, India Biodiversity Portal, iNaturalist, iSpot, Reef Life Survey	Identification of multiple species in Madagascar and elsewhere (e.g. Andrianandrasana et al., 2005)
	Population abundance	Global, regional, local	Data collected as a part of many species distribution surveys and some local studies	Breeding Bird Survey, Butterfly Conservation (Europe), eBird, Extreme Citizen Science, International Waterbird Census	Monitoring of hornbills in India (Bachan et al., 2011) and mammals, birds and resource use in Philippines, Madagascar, Tanzania and Nicaragua (Danielsen et al. 2014d)
	Population structure by age/size class	Regional, local	Largely studied at local sites, but there are several regional programs for particular taxa	Monarch Larvae Monitoring Project, Monitoring Avian Productivity and Survivorship (MAPS), North American Butterfly Monitoring Network, several Earthwatch projects	Sea turtle nest counts (Granek and Brown, 2005); piscivorous and herbivorous reef fish (Uychiaoco et al., 2005); trophy size (Lyons, 1998)
Species traits	Phenology	Regional, local	Most abundant trait observation made by citizen science volunteers; many long–term datasets	Climatewatch (Australia), Nature's Calendar (UK), Phenoclim (France), USA National Phenology Network, Project Budburst	Monitoring of caribou migration timing in the Arctic (Huntington et al., 2004); migratory mammals in Tanzania (Topp–Jørgensen et al., 2005); grazing seasons in rangelands in Kenya (Roba and Oba, 2009)
	Body mass	Regional, local	Rare data, collected mostly by specialized projects	Some Earthwatch projects, MAPS, OpenTreeMap	Surveying of fish populations in Peru (Carvalho et al., 2009)
	Natal dispersal distance	Local	Only collected via professional monitoring	–	–
	Migratory behaviour	Global, regional, local	Abundant data for observing species across migratory ranges; much rarer data on migratory behaviours of individual organisms	eBird, Hawk Count, Journey North, Monarch Watch, Hawkwatch (Hawk Migration Association North America), documentation of amphibian migrations to breeding ponds	Monitoring of timing of large–mammal migrations (Huntington et al., 2004; Topp–Jørgensen et al., 2005).
	Demographic traits	Regional, local	Rare data, collected mostly by specialized projects	MAPS; Nest Record Scheme UK; Nestwatch; Projecte Orenetes "Swallow Project" and Projecte Nius "Nests Project"; Earthwatch projects	Assessment of the clutch size of turtles (Townsend et al., 2005).

EBV class	EBV	Scale of CS/CBM measurement	Feasibility	Examples from Global CS database	Examples from CBM database
	Physiological traits	Local	R are, collected almost exclusively by specialized projects	Earthwatch projects; Public Lab projects	Cloud berry (*Rubus chamaemorus*) damage due to warm springs and summers (Huntington et al., 2004); fodder value of plant species categories for different livestock species in Kenya (Roba and Oba, 2009);
Community composition	Taxonomic diversity	Global, regional, local	Generally observed during specialized events (e.g. Bioblitz) or incidentally through checklist projects (e.g. iNaturalist)	BioBlitzes; Christmas Bird Count; eBird; iNaturalist; iSpot	Reef fish monitoring (Uychiaoco et al., 2005)
	Species interaction	Regional, local	Unusual data, collected mostly by specialized projects, but included in some larger–scale projects	Great Sunflower Project; iNaturalist; Nature's Notebook	Monitoring of insect harassment of caribou (Huntington et al., 2004); crop damage and livestock attack (Stuart–Hill et al., 2005); geese species interactions in the Arctic (Danielsen et al., 2014d).
Ecosystem function	Net primary productivity	Global, regional, local	Generally observed through remote sensing, but also measured by some citizen science projects	FreshWater Watch; GLOBE; many volunteer lake monitoring projects	Monitoring of quality and quantity of vegetation (Roba and Oba, 2009); aboveground forest biomass in REDD+ programs (Brofeldt et al., 2014)
	Secondary productivity	Local	Extremely rare for CS programs but very common for CBM programs	Some Earthwatch projects	Surveys of high–value species, meat, fish, shellfish and other non–timber forest and wetland products (e.g. Johannes, 1998; Uychiaoco et al., 2005)
	Nutrient retention	Regional, local	Nutrients frequently measured in lakes and streams, but rarely in terms of retention	FreshWater Watch; many volunteer lake monitoring projects	Environmental monitoring of watersheds in Ontario (Savan et al., 2003)
	Disturbance regime (e.g. pest outbreak)	Regional, local	Some CS programs dedicated to particular disturbances (e.g. earthquakes, invasives) and many incidental observations. Many CBM programs	Coral Watch; iMapInvasives; Phytoplankton Monitoring Network; GISIN; EDDMaPS and GLEDN for plants	Monitoring of bush fires (Lyons, 1998); poaching (Andrianandrasana et al., 2005; Stuart–Hill et al., 2005); cutting of trees to obtain Malva nuts and fishing in rivers using poison (Poulsen and Luanglath, 2005); trawling pressure and 'ghost' nets in the Arctic (Danielsen et al., 2014c)
Ecosystem structure	Habitat structure	Global, regional, local	Primarily collected through remote sensing and professional monitoring, but some CS and CBM programs	GLOBE, National Plant Monitoring Scheme (UK)	Bering Sea Sub–Network; Alaska Ocean Observing Systems; monitoring of percentage of hard coral/sand in reefs (Uychiaoco et al. 2005); observations of sea ice conditions in the Alaskan Arctic, fluctuating levels in subsistence hunting of specific species (Eicken et al., 2014 and www.aoos.org); historical records of snow properties by Sami reindeer herders to inform pasture availability, temperature profiles and herd ecology (Eira et al., 2013)

Ecosystem extent and fragmentation	Global, regional, local	Primarily collected through remote sensing and professional monitoring, but some citizen science collection, especially community–based	GLOBE and community based projects, such as Hampshire Landscape Watch and some Earthwatch projects	Annual extent of marshland burned seen from viewpoints (Andrianandrasana et al., 2005); fixed point photography of forested hillsides (Danielsen et al., 2005); extent of burning of trees when extracting yang oil in Laos (Poulsen and Luanglath, 2005); and reef health (Granek and Brown, 2005)
Ecosystem composition by functional type	Global, regional, local	Primarily collected through remote sensing and professional monitoring, but some citizen science collection, especially community–based	Earthwatch and Freshwater Watch at some locations	Landscape grazing suitability (Roba and Oba, 2009)

used to set up frameworks for global monitoring of biodiversity (e.g. Kissling et al., 2015; O'Connor et al., 2015; Schmeller et al., 2015). A list of EBVs is provided in Table 1. EBVs are intended to be general enough for use across major taxa groups, across terrestrial, freshwater and marine realms and across ecosystem types within each of these realms (GEO BON, 2015). A list of widely agreed upon EBVs is unlikely to be finalised for some years (Pettorelli et al., 2016). However, the EBV concept represents a useful way to organise biodiversity indicators and meet top-down global treaty obligations.

Many EBVs such as ecosystem composition by functional type, nutrient retention, and ecosystem extent and fragmentation can be monitored by large-scale sensors or Earth Observation systems. Earth Observation refers to satellite remote sensing (e.g. Landsat, Sentinel) and aerial imagery as well as land-based observation platforms (e.g. National Ecological Observatory Network, camera trap arrays; O'Connor et al., 2015; Skidmore et al., 2015). These systems can greatly improve efficiency, standardisation, and the value of monitoring data for many uses. Yet Earth Observation systems cannot monitor all EBVs and still require human-assisted data collection (O'Connor et al., 2015; Proença et al., 2016). In other cases, human observations can supplement remotely sensed data and derived models and assessments (e.g. species distribution models, species habitat association models, seasonal productivity models such as the Spring Index) by providing much needed calibration and validation data (Evangelista et al., 2012). There are not enough professionals (or funding to support them), however, to monitor EBVs at large scale and adequate resolution. Citizen science (CS) offers an additional way to monitor EBVs, and also offers other benefits to conservation through public engagement (McKinley et al., 2016).

In this paper we use CS to refer to scientific projects that include the participation of volunteers (novices or experts) in some aspect of the projects (sensu Bonney et al., 2009; Miller-Rushing et al., 2012). We also refer to community-based monitoring (CBM)—i.e. a subset of CS in which local stakeholders use their own resources to monitor natural resources to achieve goals that make sense to them (Danielsen et al., 2014c). CBM is often contrasted with large-scale, top-down CS monitoring projects, such as eBird, although the two approaches are not mutually exclusive and can be blended. For the purpose of this paper, however, we consider CS and CBM as distinct approaches.

The aim of this paper is to examine how and to what degree CS and CBM might contribute to regional and global assessments in the trends and status of biodiversity by undertaking: (1) a general assessment of current strengths and gaps in using CS and CBM to monitor biodiversity at large-scale; (2) an assessment of CS and CBM data that have contributed to global biodiversity databases to date, using the Global Biodiversity Information Facility (GBIF) as a case study; and (3) a discussion of the challenges, solutions and limitations of using CS and CBM for monitoring global biodiversity.

2. Methods and approach

For our analysis, we make a distinction between CS projects, portals and programs. We define a CS project as a distinct, biodiversity recording scheme or volunteer survey, often with a specific management team and discrete goals and taxonomic or geographical focus. Sometimes multiple CS projects are aggregated together in an online portal, which provides a single access point for citizen scientists. For example, iNaturalist functions as a portal, with many related projects that collect species presence data, but have different goals, and have different taxonomic and geographic foci. The portal uses one online interface for all the projects. We use the term CS program as a generic term that covers both CS stand-alone projects and portals. For compiling our database, we used the largest appropriate unit, i.e. portals when possible, and projects when they were not a part of any portal, to avoid double counting.

We considered programs to be CS when >50% of the data were collected by volunteers.

2.1. Assessment of strengths and gaps in CS and CBM

We compiled two distinct databases—one on CBM and one on CS—for our assessment of current strengths and gaps in using CS and CBM to monitor global biodiversity. We coded each project for taxonomic focus, geographic scope, and other factors that help to link these projects to specific EBVs.

2.1.1. Community-based monitoring programs

CBM programs are distinct from other CS programs in that citizens and community members not only participate in data collection but also in program design, data interpretation, or implementation of management interventions emanating from the monitoring (Danielsen et al., 2009, 2014c; Kennett et al., 2015). The CBM programs were found by searching for publications in the databases BIOSIS PreViews (2004–2012), Biological Abstracts (1990–2000) and Biological Abstracts Reports, Reviews and Meetings (1989–2003). The primary search terms were 'monitoring' and 'conservation', searched with the use of 'and' between the words. Schemes on environmental monitoring are often hidden in publications on traditional ecological knowledge (Huntington, 2000). Few examples of decentralised local approaches to monitoring are found in the literature (Brook and McLachlan, 2008). Therefore the search term 'traditional ecological knowledge' was also used. Most publications were in English but a few were in German. Each CBM program was coded by two of the authors (FD and AB) by taxonomic focus, geographic scope, and EBV. FD coded 65% of the CBM programs and reviewed all the data coded by AS for consistency.

2.1.2. Citizen science programs

To build the 'Global CS Database', we considered a breadth of CS typologies (Shirk et al., 2012; Haklay, 2015), which range from larger crowdsourced CS projects in more extensive monitoring schemes (Couvet et al., 2011) to smaller, more intensive monitoring efforts (e.g. field expeditions, Chandler et al., 2016a). Because the primary objective for compiling this Global CS Database was to assess CS contributions to monitoring EBVs, we only considered CS programs that fulfilled two minimum requirements. First the program is already (or likely to be) contributing biodiversity data for monitoring purposes, and the second is that these data contributions are substantial. We searched for programs where the data are quality controlled and shared—e.g. verification is made of the data collected; the metadata are made publicly available; and there is evidence that the data are used in practice for management actions or for scientific publications. Regarding the second requirement, programs were considered to make 'substantial data contributions' if >100 observations were collected per year. We included inactive projects if they collected data for the intention of sharing them with existing monitoring programs.

To compile the database, we started by pulling together programs from existing network portals, which house data from CS programs not managed by the hosting organisation, and which usually provide an assortment of sorting tools to help readers find the right CS program (e.g. the Atlas of Living Australia (ALA), SciStarter, CitizenScience.org) or serve as research infrastructures for managing and publishing the aggregated data (e.g. GBIF, the UK National Biodiversity Network, the National Defense Research Committee). We also extracted programs from similar previous publications on the same topic (Danielsen et al., 2014c; Theobald et al., 2015; Kullenberg and Kasperowski, 2016; Valland, 2016; Chandler et al., 2016b; Groom et al., 2016); see Table A1 for the guide used to code the data.

To this list we added CS programs whose publishers share CS data with GBIF. We then supplemented the inventory through directed web searches to discover programs that were not captured through other sources. We used search terms that included synonyms to citizen science, related words, and regions and taxonomic groups underrepresented in our database—e.g. 'volunteer monitoring', 'data sharing', 'open data', 'Africa', 'South America' and 'Asia'. Finally, we asked experts in the field to identify programs that might fill gaps in the geography, taxonomy, or EBVs that were poorly represented in our database.

Each program (i.e. project or portal) was scored using criteria and associated metadata modified from Theobald et al. (2015). If the program was a portal, then the number of projects that were both developed and hosted by the portal was added to the database. Coding of all initiatives apart from the ones taken from the Theobald et al. (2015) data set was performed by four of the authors (MC, KC, BC, and AMR) using material available from associated websites. MC entered 90% of the criteria and reviewed >25% of the data coded by the others for consistency.

To our knowledge, the Global CS Database that we developed for this study represents the largest and most comprehensive database of CS programs, yet it is not complete. For example, we only included programs that made substantial data contributions for biodiversity monitoring purposes. It is also likely that we have missed programs published in languages other than English, programs without an online presence, and programs that describe themselves using terms other than those used in our search (Kullenberg and Kasperowski, 2016).

2.2. Assessment of citizen science data in a global biodiversity database

To assess the contributions of CS data that make it into global databases, we analyzed CS contributions to the world's largest species occurrence database, GBIF.org. This open data research infrastructure gathers hundreds of millions of records from >800 institutions worldwide and covers >1.6 million species. Researchers have applied these data in >1700 peer-reviewed journal articles since 2008. Several studies have reviewed the gaps and limitations in GBIF-mediated data (Beck et al., 2013, 2014; Samy et al., 2013; García-Roselló et al., 2015; Meyer et al., 2015; Troia and McManamay, 2016); which may be representative of other international databases on biodiversity (Amano and Sutherland, 2013; Troia and McManamay, 2016).

We conducted full-text searches of metadata to extract datasets available through GBIF.org, as of March 1, 2016, whose records included significant CS contributions. We reviewed and refined the list by consulting contributors to the GBIF network. In the case of publishers who are themselves networks that include many individual projects, like the UK National Biodiversity Network, datasets with CS contributions were disaggregated from those known or unlikely to contain few if any CS-derived records, which are therefore not included in the results.

We analyzed the contributions from CS projects by calculating the total number of occurrences in these datasets according to taxonomy, source country of data provider, and continent of species occurrence. As a disproportionate amount of CS contributions to GBIF come from a single source (eBird), we analyzed all GBIF-mediated data with and without the eBird data. Although our study was limited to assessing datasets that individually and collectively blend records gathered by professionals and amateurs, we consider the magnitude of our estimates and their relative proportions acceptable for the purposes of this paper, although the individual figures on CS contributions to GBIF-mediated data are subject to uncertainty.

3. Results

3.1. The database

We developed a database with 420 distinct CS programs, including 114 (27%) that are CS portals serving multiple, distinct CS projects (Table A2). Some portals serve dozens of projects, others hundreds or more, resulting in 3603 CS projects represented by our dataset. Half of this number are found within the iNaturalist portfolio of projects (N = 1850). The vast majority (88%) of the CS programs in the database are projects that are currently known to be active (N = 374). Most are run by civil society organisations and only few by government agencies or the private sector (N = 269; 64%). Most CS programs monitored terrestrial ecosystems (N = 347, 82% of total CS programs), with substantial numbers monitoring freshwater (N = 139; 33%) and marine biomes (N = 128; 30%). The CBM database consisted of 40 programs (Table A3), which were drawn from reviews of environmental monitoring programs extracted from 3500 monitoring publications since 1987 (described in Danielsen et al., 2010, 2014c), all of which are distinct projects. Most CBM programs also monitored all three biomes (N = 40; terrestrial 45%, freshwater 40%, marine 20%).

3.1.1. Status and gaps in essential biodiversity variables

Fig. 1, which summarizes the data found in Tables A2 and A3, displays the proportion of each EBV covered by CS programs (portals and projects) and CBM programs, and shows that almost every EBV is covered by at least some CS or CBM programs. Natal Dispersal Distance and most EBVs in the Genetic Composition Class are the only ones collected by neither CS nor CBM programs across our two databases. One EBV (Species Distribution) is monitored by 80% of CS programs and 68% of CBM programs. Of the remaining programs in the CS Database, five other EBVs (Population Abundance, Phenology, Demographic Traits, Migratory Behaviour, and Disturbance Regime) are collected in >20 CS programs each (Fig. 1; examples in Table 1). Fig. 1 also shows that CBM programs monitor EBVs in different proportions than CS programs. CBM projects contributed relatively more to Population Abundance (90%) and Secondary Productivity (65%). Moreover, the majority of CS programs (70%) focused on only one EBV while most CBM programs collected data on more than one EBV (95%; Tables A2 and A3).

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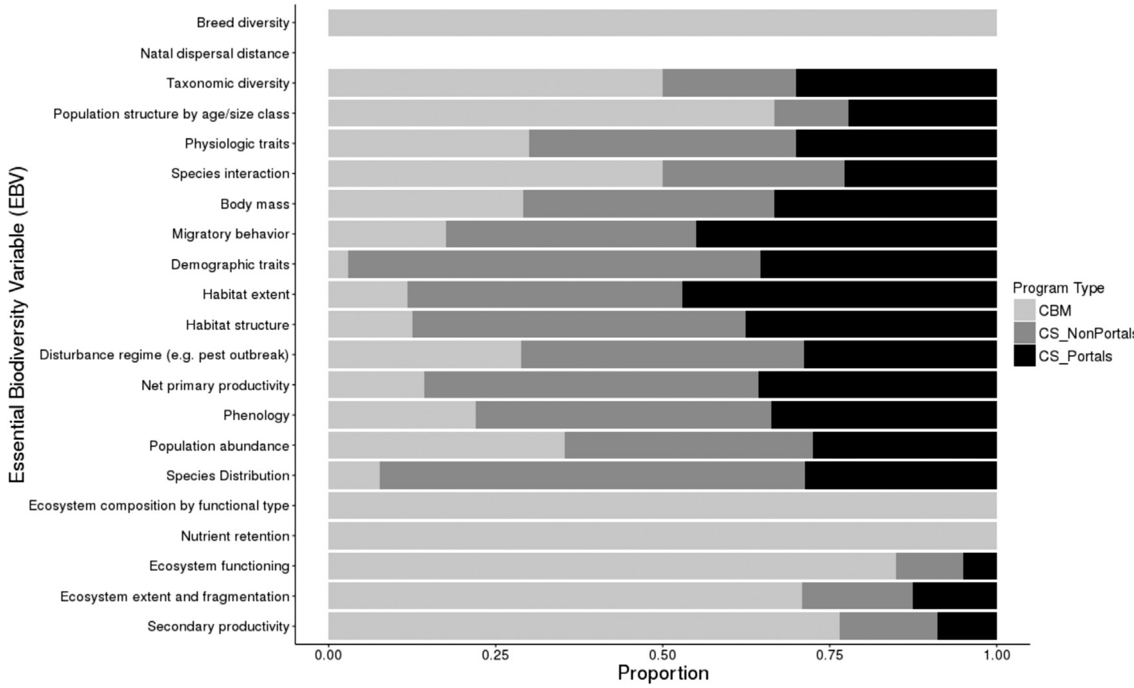

Fig. 1. Distribution of citizen science (CS) and community-based monitoring (CBM) programs by Essential Biodiversity Variable. CS programs could either be online "portals" supporting multiple CS projects, or single CS projects ("non-portals"). A full description can be found in Tables A2 and A3 respectively. Note that some projects contribute to more than one EBV.

A number of EBVs are not well covered by CS or CBM programs—i.e. Nutrient Retention, Ecosystem Composition by Functional Type, Net Primary Productivity (NPP), Physiological Traits, Natal Dispersal Distance and all of the EBVs in the Genetic Composition Class (Co-ancestry, Allelic Diversity, Population Genetic Differentiation and Breed and Variety Diversity). Although some of these EBVs can be monitored by remote sensing systems, Natal Dispersal Distance, Population Structure, Physiological Traits and the four EBVs in the Genetic Composition Class, cannot be measured well using existing remote sensing technology and so require ground-based measurements from either professional or CS/CBM monitoring (Table 1).

3.1.2. Status and gaps in geographical coverage

Most of the CS programs that we found focus their monitoring activities in North America (184 programs or 43% of the total) or Europe (136 programs or 32% of the total; Table 2). Relatively few CS programs were found in Africa, Asia, and Central and South America. Around 10% of the CS programs incorporate observations of biodiversity from everywhere. These programs included species observation programs (iNaturalist, eBird, Naturgucker) as well as coordinated global networked schemes (International Waterbird Count, BirdLife programs, and the Global Coral Reef Monitoring Network of WorldFishcenter at http://www.gcrmn.org).

A total of 64% of the CS programs in Europe make their data available to GBIF while only 9% of those in North America submit their data to GBIF (Table 2). The similar figures for CS programs in Asia and South/Central America are 55% and 100% (N = 10 and 3, respectively). Of the two programs in Africa, no data are made available to GBIF while 17% of the 42 programs in Oceania submit their data to GBIF. In contrast to CS as a whole, a relatively high proportion of CBM programs operate in Africa (34%) and Asia (24%), often in low-income countries (65% in countries with a Gross National Income per capita <2570 USD at the time of the assessment; World Bank, 2012). South and Central America had the lowest coverage by either CS or CBM programs.

3.1.3. Taxonomic coverage of citizen science and community based monitoring programs

CS programs cover a wide taxonomic breadth of global biodiversity (Table 3). The great majority of projects focus on animals (83%) while 20% of CS programs collect data on multiple taxonomic groups. For those CS programs with a taxonomic focus, most collect data on non-lepidopteran insects (24%), birds (19%), plants (17%), Lepidoptera (12%), or mammals (9%). In terms of the Population Abundance EBV, birds are commonly counted as part of regular censuses (e.g. Christmas bird counts, breeding bird surveys). One global model to assess population trends is exemplified in the International Waterbird Census (IWC) (see Box 1). The taxa most commonly surveyed by CBM are plants (24%) and within the animal kingdom, mammals (37%), fish (32%) and birds (32%).

Table 2
Geographical distribution of citizen science programs (by location of headquarters and activities) and community-based monitoring programs (see also Tables A2 & A3).

Continent	Citizen science program headquarters			Citizen science program activities		Community-based monitoring programs	
	Number	% of total	% who make data available to GBIF	Number	% of total	Number	% of total
Africa	2	0%	0%	2	1%	13	33%
Asia	10	3%	55%	13	3%	9	23%
Europe	136	35%	65%	136	33%	5	13%
North America	211	50%	9%	184	42%	8	20%
Central & South America	3	1%	100%	4	1%	2	5%
Oceania	41	10%	17%	37	9%	3	8%
Global	6	1%	52%	44	10%	0	0%

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Table 3
Distribution of observations from citizen science (CS) and community-based monitoring (CBM) initiatives and CS-contributed occurrence records in the Global Biodiversity Information Facility (GBIF) by taxonomy (as of March 1, 2016). A full description of the CS and CBM initiatives can be found in Tables A2 & A3 respectively.

	CS project survey		CBM project survey		GBIF.org species records			
	(N = 420)		(N = 40 projects)					
Taxa	Number	Proportion	Number	Proportion	Total GBIF records per taxon	% contribution of taxon to total records	# records from CS projects	CS as a % of total records
All taxa	–	–	–	–	640,465,555		349,404,699	55%
Multi-taxa surveys	82	19.5%	5	13%	–	–	–	–
Animalia			–	–	449,595,895	70%	316,557,034	70%
Animals (multi-taxa surveys)	12	2.8%%	–	–	–	–	–	–
Arachnida	5	1.1%	–	–	2140,148	0%	440,973	21%
Insecta	101	23.7%	4	10%	46,552,525	7%	12,624,550	27%
Lepidoptera	49	11.5%	–	–	18,072,050	3%	7,785,904	43%
Mollusca	9	2.1%	–	–	8,762,130	1%	390,772	4%
Crustacea	12	2.8%	–	–				
Gastropoda	4	4.0%	–	–				
Amphibia	15	3.5%	–	–	3,864,189	1%	147,192	4%
Aves	80	19.0%	12	30%	345,498,795	54%	301,679,747	87%
Elasmobranchs	8	2.2%	–					
Mammalia	39	9.3%	15	38%	10,766,217	2%	598,206	6%
Osteichthyes	12	2.8%	13	33%	13,786,592	2%	126,597	1%
Reptilia	7	1.6%	3	8%	4,900,221	1%	93,380	2%
Plantae	70	16.7%	8	20%	170,391,526	27%	26,746,904	16%
Magnoliophyta	–	–	–	–	151,349,644	24%	24,581,185	16%
Gymnospermae	–	–	–	–	1,650,640	0%	247,506	15%
Pteridophyta	–	–	–	–	5,109,597	1%	715,772	14%
Bryophyta	1	0.20%	–	–	6,419,902	1%	666,085	10%
Vegetation (all)	–	–	2	5%	–	–	–	–
Trees (all)	–	–	1	3%	–	–	–	–
Forest types	–	–	1	3%	–	–	–	–
Fungi	4	0.9%	1	3%	10,497,206	2%	4,942,493	47%
Ascomycota					6,446,739	1%	2,502,232	39%
Basidiomycota	–	–	–	–	3,968,737	1%	2,439,452	62%
Other/unknown kingdoms	–	–	–	–	9,980,928	2%	381,350	4%
Archaea/bacteria/protists	5	1.1%	1	3%	–	–	–	–
Algae/chromista	10	2.2%	–	–		–	–	–

3.2. Case study analysis: CS contribution via GBIF to species distribution EBV

More than half (349 M) of the >640 M species occurrence data available through GBIF.org come from sources that include >50% of the contributions from CS (Table 3; Table A4).

3.2.1. Taxonomic coverage of GBIF-mediated data

Overall, the contributions of CS programs to GBIF-mediated data are uneven across taxa—some taxa are well represented by CS data, while others are not (Table 3). CS programs account for 70% of animal records and 87% of bird records in GBIF. Birds are the most frequently recorded taxon with close to 300 M records in GBIF. CS programs account for over 1 M plant, insect, and Fungi records and over 500,000 mammal records. CS contributions represent a significant proportion of total GBIF records for Fungi (47%) and insects (27%).

3.2.2. Geographic coverage of GBIF-mediated data

Geographic patterns of CS data shared through GBIF are similar to those found in our survey of CS programs generally (Table 4 and Fig. 2). >90% of CS records in GBIF are published by programs located in North America and Europe, most likely due to a language bias. However, the provenance of programs currently sharing their data through GBIF does not necessarily reflect the geographic distribution of GBIF-mediated data. Data reported to a CS program headquartered in one country could have been collected in another country. For example, data from global CS programs such as eBird (USA) or Atlas of European Breeding Birds (NL) are collected from all over the world, but the provenance of the program is listed as one country.

Using country-level information available through GBIF, we examined the variation in data coverage for taxa across northern European countries, since each has national-level recording platforms for observations of most taxa, and most make their data available to GBIF. We chose to examine records for four taxa which are well-represented globally by CS programs: Lepidoptera, non-lepidopteran insects, mammals, and birds. Fig. 3 shows large disparities between these countries despite access to similarly robust observation recording platforms and CS programs.

3.2.3. Contributions of portals to GBIF

The great majority of CS data available through GBIF comes from programs with either narrow taxonomic focus but broad geographic scope (e.g. eBird, antweb, Birdlife programs) or national network portals that aggregate observations across multiple CS projects and multiple taxa (e.g. UK National Biodiversity Network, ArtDatabanken; Fig. 3 and Table A4). The single largest contributor of occurrence records is the eBird Observation Dataset with 219 M observations. Contributions from the 100+ different CS programs sharing with GBIF is strongly skewed, as the top 10 CS programs contribute over 94% of the data. When the CS programs in the Global CS database were compared to the CS programs that contribute data to GBIF, less then <10% were found to be in common, indicating that there is a large gap in data sharing. We could not identify any CBM programs that contribute data directly to GBIF.

CS programs associated with portals tended to contribute more frequently to GBIF than CS programs that were not portals. Whereas 45% (N = 52 of CS 115 programs) of portals contribute to GBIF, only 31% (N = 95 of 310 CS programs) of stand-alone projects (i.e. non-portals) were found to contribute (Fig. 4). Geographically, this effect was most

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Table 4
Distribution of species records from citizen science (CS) projects by taxa and continent using GBIF-mediated data (as of March 31, 2016).

Continent	Total # records	Plantae	Fungi	Animalia	Arachnida	Insecta	Lepidoptera	Bony fish	Amphibia	Reptilia	Mammalia	Aves	Aves w/o eBird	Other/unknown
Africa	3,574,723	4415	16	1,784,757	61	401,706	2337	3953	395	1964	8809	1,366,286	49,890	24
Antarctica	22,114	7	0	11,054	0	0	0	0	0	0	93	10,960	335	0
Asia	5,674,341	7795	49	2,820,712	124	73,125	29,763	11,731	734	2140	1633	2,726,423	103,523	112
Europe	213,153,276	26,444,138	4,434,380	87,162,132	430,287	11,062,393	7,645,507	90,701	94,717	43,804	576,126	74,075,023	70,116,937	1,094,068
North America	390,294,031	206,755	10,397	195,011,240	7187	224,867	79,167	8909	50,186	39,834	32,518	194,620,460	7,620,397	2511
Oceania	35,879,731	68,847	8021	17,887,441	1629	186,406	4373	5694	448	1841	2846	17,683,589	11,759,269	28,596
Central & South America	23,432,769	15,367	456	11,704,854	1694	578,435	11,235	5068	2205	6390	6169	11,100,832	80,389	64
No location	44,994	62	0	22,591	0	20	9	1022	2	72	2	21,211	11	3

pronounced in Oceania, where CS programs were twice as likely to be published if they were portals (76% vs 36%; Fig. 4).

The likelihood of publishing data to GBIF from CS programs operating as portals also increased when looking across several of the taxa with data collected by substantial numbers of programs (>14 programs; Fig. 5). This ranged from large increases in proportions publishing mammals (from 26% for non-portals publishing to GBIF to 65% for portals) and plants (from 23% for non-portals publishing to GBIF to 60% for portals). More modest increases were seen for birds, insects and Lepidoptera. Little or no increase in publishing to GBIF by CS portals was seen for amphibians or multi-taxa surveys (Fig. 6).

4. Discussion: challenges, solutions and limitations

Our review suggests that existing CS and CBM programs collect data on nearly all EBVs and cover a very broad range of taxa and geographic locations, but nevertheless CS and CBM programs have strengths and weaknesses in terms of contributions to biodiversity monitoring at an international scale (Fig. 1; Table 1; Pimm et al., 2014; Geijzendorffer et al., 2015; Amano et al., 2016).

The majority of CS programs (70%) are focused on a single EBV, i.e. species occurrence, which is one of the main sources of data for biodiversity monitoring (Geijzendorffer et al., 2015). CS programs also have a bias towards monitoring species distributions, particularly for birds (86% of data from CS programs in GBIF are for birds; Amano et al., 2016), and in North America and Europe. Yet data requirements for international biodiversity monitoring may be met by CS and CBM for many more taxa, regions and EBVs. For example, CS programs account for a significant proportion of GBIF-mediated data for several taxa, including non-lepidopteran insects, Lepidoptera, arachnids and Fungi. Determining key global bio-indicators (see e.g. McGeoch et al., 2010) and identifying data sufficiency thresholds will identify data requirements and help investigate where CS/CBM can play a key role.

Below we explore four questions in relation to meeting international biodiversity monitoring obligations using CS/CBM: What can be learned from successful CS/CBM programs that could facilitate the scaling up of CS and CBM contributions from local to international biodiversity monitoring? How do we make more from our existing strengths in data coverage? What strategies maximise synergies between CS/CBM and other approaches for monitoring biodiversity? What limitations exist in expanding the coverage of CS and CBM programs?

First, the CS programs that contribute most to GBIF tend to serve existing and vibrant communities of expert amateurs and hobbyists (Lawrence, 2006; Bell et al., 2008; Lewandowski and Specht, 2015), perhaps best exemplified by the preponderance of data and CS programs from birding communities and natural history societies (e.g. Botanical Society of the British Isles). These programs tend to be large, linked to well-funded institutions, have academic scientists associated with the programs, and are mainly found in Europe and North America where English is a common language. However, two other types of CS/CBM programs of note also compile large volumes of biodiversity data: (1) programs that allow volunteers with little or no expertise to make observations of a variety of species, but which include expert verification of data (e.g. iNaturalist, iSpot, iMapInvasives, antweb, Earthwatch field expeditions); and (2) CBM programs (e.g. Conrad and Hilchey, 2011; Danielsen et al., 2014a, 2014c; Johnson et al., 2016) that can cover many less well-represented EBVs (e.g. Species Interaction, Secondary Production, Population Structure; Table 1).

The accomplishments of CS/CBM programs have been attributed by behavioural psychologists to participants who appreciate the opportunity to build on their existing interests, try something new with little effort, and participate in projects associated with place and community (Lawrence, 2006; Bell et al., 2008). Successful programs leverage these interests by supporting and building communities of participants who share common interests. We propose that these types of programs could be developed for new taxonomic groups, EBVs, and geographic

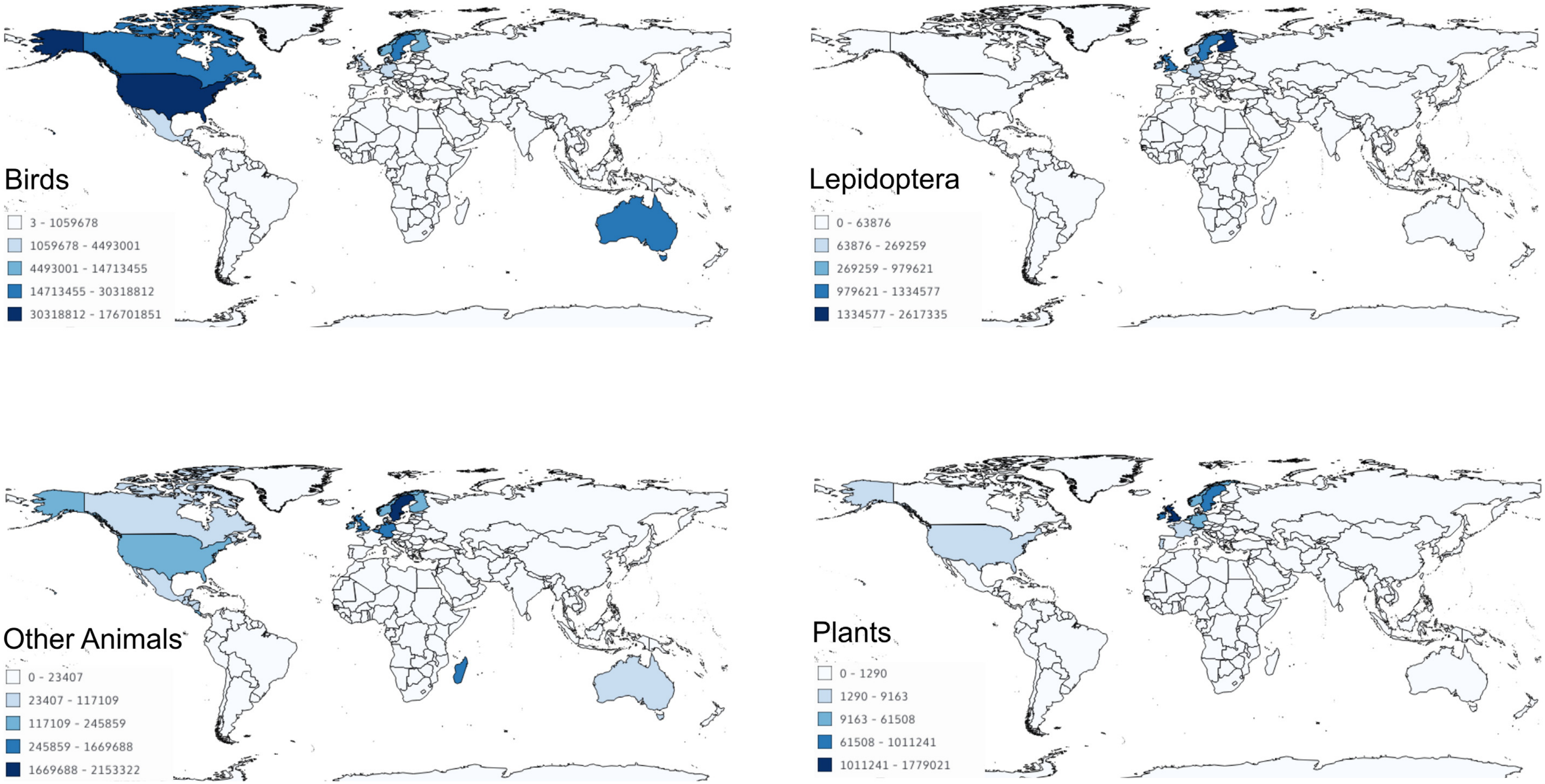

Fig. 2. Distribution of species records made available to the Global Biodiversity Information Facility (GBIF) by citizen science data providers for (a) Aves (b) Lepidoptera (c) Other animals not including Aves or Lepidoptera and (d) plants. Species records categories for each taxon were identified using Jenks natural breaks classification (Jenks, 1967) in QGIS.

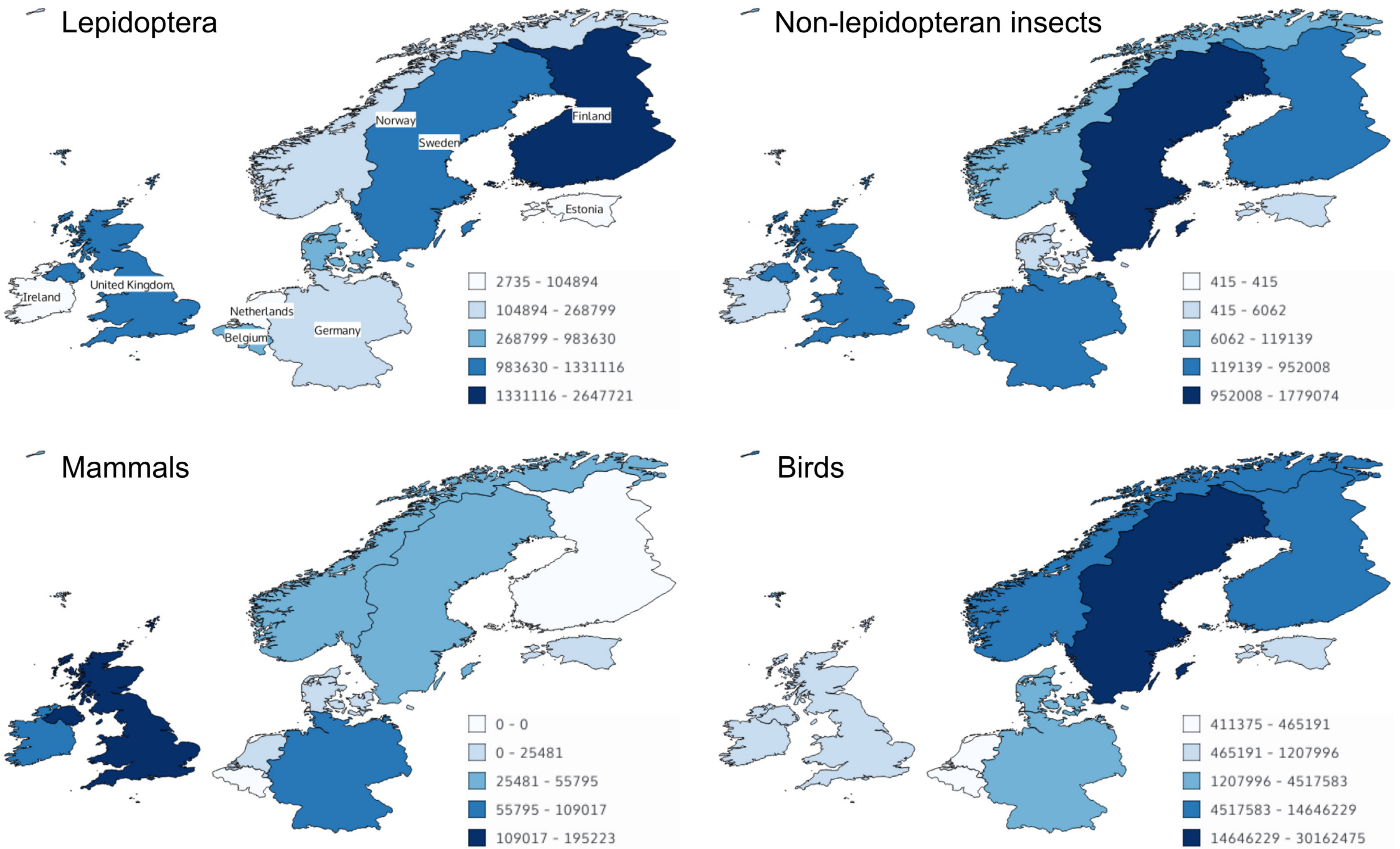

Fig. 3. Distribution of citizen science data published to the Global Biodiversity Information Facility (GBIF) by taxa for countries in Northern Europe (a) Lepidoptera insects (b) Non-Lepidoptera insects (c) Mammals (d) Aves. Species records categories for each taxon were identified using Jenks natural breaks classification (Jenks, 1967) in QGIS.

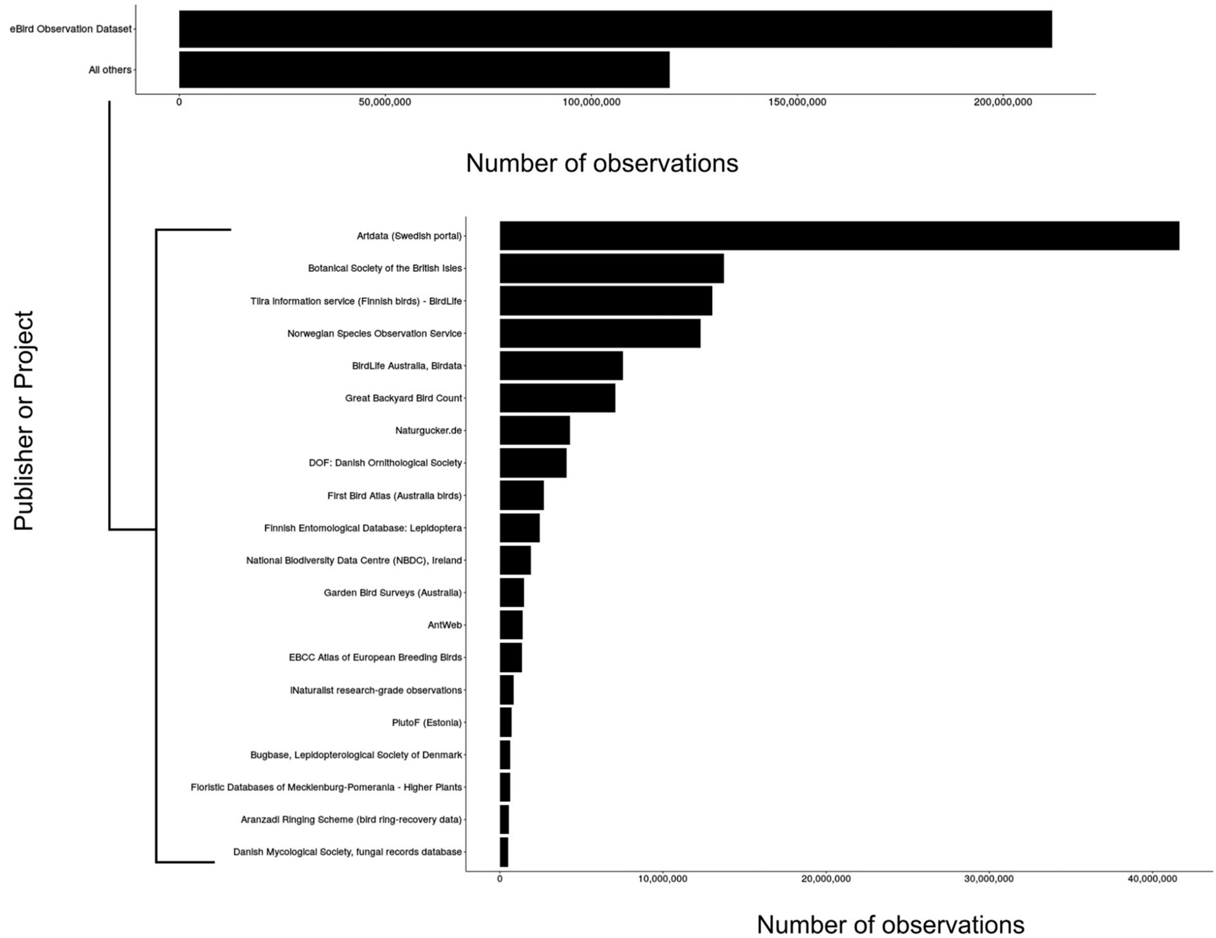

Fig. 4. List of top citizen science data providers to GBIF. Single data providers such as National Biodiversity Data Centre may support multiple projects. Other large portals such as the National Biodiversity Network facilitate contributions to GBIF but are not necessarily recognized as the data provider (data pulled on March 1st, 2016).

locations. However, we note that the model of successful CS programs found in one place (e.g. Sweden) or for one taxon (e.g. Lepidoptera) may be context dependent and thus may not be transferable to regions without the same history or interest groups. Even across countries with vibrant CS programs and well developed infrastructure, there are big differences in which taxa are reported to GBIF (Fig. 3). While seeking citizen experts may seem a short cut to addressing gaps, they may not exist without importing them via travel programs. Instead, CS programs such as iNaturalist, which connect communities of like-minded participants through online tools, or, CBM programs, which are often more collaborative and rooted to local issues and place (Danielsen et al., 2014d; Funder et al., 2013), may be more likely to succeed in collecting data for biodiversity gaps.

Another potential solution may be to expand the data fields (and hence EBVs) collected by current global CS programs such as iNaturalist, eBird, and antweb, thereby taking advantage of the growing audiences these programs have, as well as their established workflows, and mechanisms for publishing to global databases. Some of these portals (e.g. iNaturalist, eBird, iSpot) already enable CS/CBM program coordinators to tailor the infrastructure to meet their specific needs, including

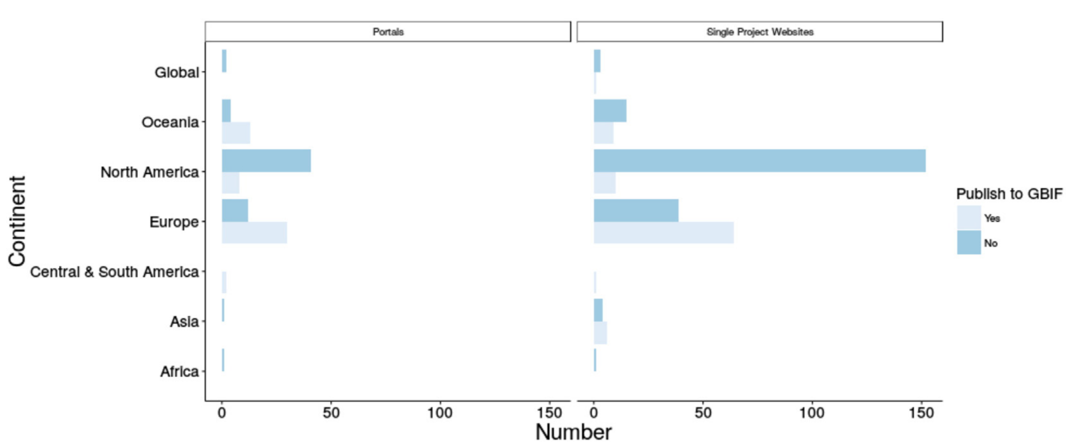

Fig. 5. Proportion of citizen science programs by continent that contribute data available to GBIF further divided by whether they are portals or single project websites.

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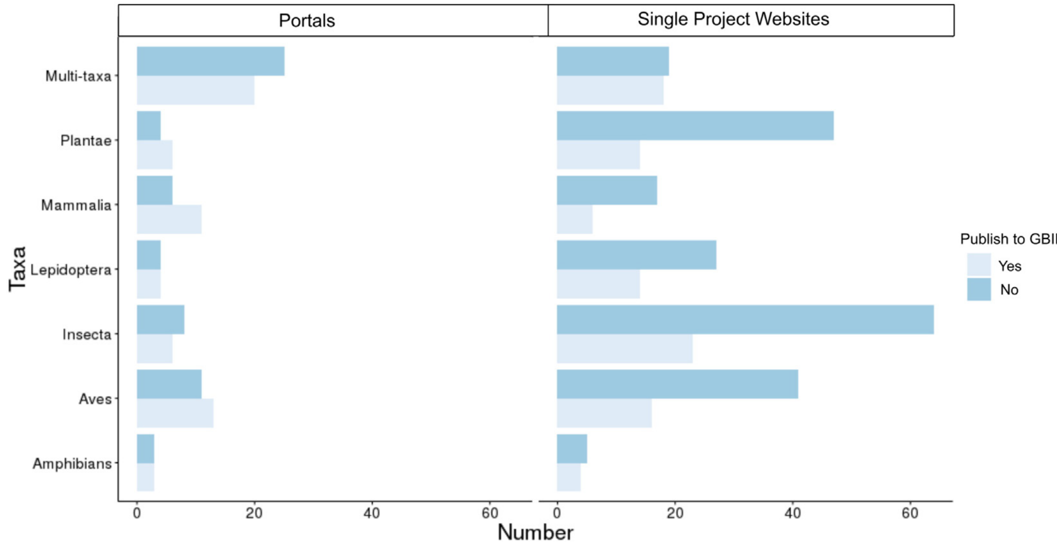

Fig. 6. Proportion of citizen science programs by taxa that contribute data to GBIF further divided by whether they are portals or single project websites.

language. In Mexico, local versions of both iNaturalist and eBird (i.e. Naturalista (http://conabio.inaturalist.org/) and Averaves (http://ebird.org/content/averaves/acerca/) allow for local programming (Ortega-Álvarez et al., 2012). Advances in technology - e.g. image recognition software such as Image-Based Ecological Information System (IBEIS, Berger-Wolf et al., 2015) - may also lower barriers to participation and expand the types of data (taxa identities and other EBVs) that can be extracted from observations.

Second, in terms of how we can make more from our existing data coverage, this review found only a small fraction (<10%) of CS and CBM programs contributing to global analyses of biodiversity, despite the fact that many CS and CBM programs collect data on underrepresented taxa in remote regions, or observe underrepresented EBVs. This is partly because these programs suffer from many disadvantages common to other biodiversity monitoring efforts, namely, they are poorly resourced, with limited communication and visibility to participants and researchers (Costello et al., 2015, 2013; Michener, 2015; Johnson et al., 2016). Increasing the impact of CS and CBM is now an active area of interest, including the development of tools and networks to build capacity both for individuals and institutions. Organisations such as U.S.-based Citizen Science Association (CSA), the European Citizen Science Association (ECSA), and the Australian Citizen Science Association (ACSA) as well as national or regional Biodiversity Observation Networks should help to improve communication, integration, and scaling of CS and CBM programs (Bonney et al., 2014; Wetzel et al., 2015). Toolkits (e.g. BON in a Box - http://geobon.org/bon-in-a-box/what-is-bon-in-a-box/), online resources and guidelines can also increase capabilities for sharing standardised data (Schmeller et al., 2015; Johnson et al., 2016).

Data repositories for underrepresented EBVs should continue to be established that can facilitate CS and CBM programs monitoring EBVs and to make their data available to international databases (Costello et al., 2013; Peters et al., 2014; Michener, 2015; Kullenberg and Kasperowski, 2016, e.g. EOL's TraitBank (Parr et al., 2015), GloBI (Poelen et al., 2014), Ocean Biogeographic Information System (http://www.iobis.org/OBIS), and TRY (www.try-db.org). Web-based portals have been developed that collate data from multiple CS and CBM projects, and increase data interoperability (Schmeller et al., 2015) and the amount of data submitted to biodiversity databases. Our analysis of GBIF-mediated data indicated how effective data sharing can be in the increased use of data in analyses (Kissling et al., 2015; Kullenberg and Kasperowski, 2016; Figs. 4 and 5).

Networked portals or platforms can use resources more efficiently, bundling tools, services and support for multiple projects while directing investment towards processes and workflows that increase sharing of accessible, discoverable and interoperable data (Wetzel et al., 2015). These investments are difficult for individual CS and CBM projects to make on their own because of their cost and the technical expertise required. Portals are emerging in both India and Africa (Table A4).

The positive effect of a regional portal is exemplified by the Atlas of Living Australia (ALA), which links numerous CS programs to GBIF. ALA enables hundreds of small- to medium-sized programs to tap into a robust and easy-to-use infrastructure with workflows that automate data syndication and synchronization with GBIF. Several members of the GBIF network have either adopted or are considering the adoption of ALA's open-source tools to develop their national portals. This may represent a transferable model for regions currently without well-organized and self-sustaining CS programs.

Third, while addressing taxonomic and geographic data gaps for the EBVs will take time and resources, there is great potential in leveraging the synergies from combining CS/CBM and remote sensing approaches (Pereira et al., 2013; O'Connor et al., 2015; Skidmore et al., 2015), particularly for EBVs well suited for CS and CBM (e.g. species distribution, species abundance, and phenology) and in situations in which fine-scale spatial or temporal heterogeneity is important (Danielsen et al., 2005; Devictor et al., 2010). However, some EBVs can only be partially monitored by remote sensing (Table 1), while others, such as Natal Dispersal Distance, Population structure, Physiological Traits and the four EBVs in the Genetic Composition Class, cannot be remotely sensed and thus require ground-based measurements (Table 1). In-situ monitoring by CS and CBM can therefore help to fill the gaps in monitoring those EBVs that are not easily remotely sensed.

Predictions of forest-level response to climate change would be impossible using either data type in isolation. Efforts are underway to combine CS-derived species composition maps and other data with remote-sensing data from satellites and cameras in forest canopies to improve models of land surface phenology, carbon budgets, and ecosystem function (Melaas et al., 2016).

Additionally, there is great potential to connect CS and CBM programs to other in-situ monitoring efforts—e.g. protected areas and long-term ecological research sites (Tulloch et al., 2013) and, thereby to cross-fertilize scientist-executed and community-based observations and knowledge (Magnusson et al., 2013). Connecting CS/CBM and scientist-executed monitoring (e.g. Earthwatch field expeditions) can allow for assessment of many EBVs including in underrepresented and remote regions such as tropical forests and the Arctic (Chandler et al., 2016b; Johnson et al., 2016; Magnusson et al., 2013).

Finally, addressing the question regarding limitations of CS and CBM, the most likely ones are the availability of funding and adequate resources—CS and CBM are not free, and are not considered a high priority in many parts of the world. The primary obstacles to expanding the taxonomic, geographic and EBV-relevant scope of CS projects are whether volunteers can observe particular challenging taxonomic groups and EBVs in new locations, and whether programs are developed with the necessary infrastructure to support this. Some taxonomic groups may be too challenging although the abundance of CS data on insects and Fungi suggests that volunteer contributions to some groups difficult for novices is indeed possible. Some EBVs—like Genetic Composition—may become possible when field-based gene sequencing technologies have matured (Thomsen and Willerslev, 2015). EBVs dealing with ecosystem functioning could be covered by CBM programs but by definition the primary focus of CBM programs is on affecting local management with less interest in collecting standardised data useful for other purposes (Conrad and Hilchey, 2011).

Concerns have also been raised that when scientists "assimilate local ecological knowledge within Western worldviews" (Mistry and Berardi, 2016), there is a risk that it may further marginalize indigenous and local people. For organizers of CBM programs to effectively share their data with global repositories, suitable modus operandi of cooperation must therefore be established. Agreements on cooperation between CBM programs and the global repositories should address principles of intellectual property rights, Free Prior and Informed Consent, respect for knowledge holders, and reciprocity (Danielsen et al., 2014b; United Nations, 2008).

Finally, there are issues of concern surrounding the bias of CS/CBM-derived data (Riesch and Potter, 2014; Nature, 2015). However, many examples show that volunteer-collected data in well-designed studies are no more problematic than those collected by professional scientists (Newman et al., 2003; Danielsen et al., 2014a; Lewandowski and Specht, 2015; Meentemeyer et al., 2015). Maintaining high data quality can be time and resource intensive (Buesching et al., 2015) so project managers must consider this expense when monitoring biodiversity; CS/CBM is not always the most cost-effective monitoring approach, despite the participation of volunteers and many other strengths (McKinley et al., 2016).

5. Conclusions

Our findings suggest that CS already make substantial contributions to large-scale international biodiversity monitoring. The EBVs currently used at international scale include species occurrence, abundance, and phenology. A few taxa and variables are also extensively monitored at scale (e.g. birds, Lepidoptera and plants/trees), while other taxa garner strong interest in selected regions including Fungi, amphibians, reptiles and coral reef taxa. Some of these data already contribute to international biodiversity monitoring databases.

The biodiversity monitoring community can expand the taxonomic, geographic, and EBV coverage of CS and CBM programs, if they can make citizens and community members interested in it. By building on the interests and needs of participants and providing existing communities (e.g. naturalists, concerned citizens and community members) with the tools and services they need (Bell et al., 2008; Shirk et al., 2012), most EBVs and taxa could potentially be covered by CS and CBM programs.

Several strategies can facilitate further scaling up of CS and CBM contributions to international biodiversity monitoring. One is to include making better use of CS and CBM associations, online toolkits, data repositories, and network portals that coordinate and support CS and CBM projects and increase data interoperability. Another is to encourage successful existing projects to expand their data collection fields to other EBVs. It would also be useful to develop further synergies between CS/CBM and remote sensing and scientist-executed monitoring programs to expand and enhance the monitoring of EBVs.

Despite its potential, real limits remain for scaling CS/CBM contributions to international biodiversity monitoring. Chief among those limits is the availability of resources. CS and CBM are not free. Relying on volunteer contributions can make them seem cheap, and CS and CBM are frequently more cost efficient than paying professionals to do the same monitoring (Danielsen et al., 2005; Theobald et al., 2015). However, ultimately, CS and CBM programs require investment to maximise their potential contributions to international biodiversity monitoring.

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