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Participatory monitoring drives biodiversity knowledge in global protected areas

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Protected areas are central in strategies to conserve biodiversity. Effective area-based conservation relies on biodiversity data, but the current biodiversity knowledge base is insufficient and limited by geographic and taxonomic biases. Public participation in biodiversity monitoring such as via community-based monitoring or citizen science increases data collection but also contributes to replicating these biases or introducing new ones. Here we examine how participatory monitoring has changed the landscape of open biodiversity knowledge in protected areas using biodiversity data shared on the Global Biodiversity Information Facility. We highlight a growing dominance of participatory monitoring within protected areas. We find that patterns in geographic, taxonomic, and threatened species coverage differ from non-participatory monitoring, suggesting complementarity between the two approaches. The relative contribution of participatory monitoring varies with characteristics of both protected areas and monitoring programs. We synthesize these results to derive context-specific strategies for extending the conservation impact of participatory biodiversity monitoring.

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The target to protect 30% of the earth's habitats by 2030 is central in the international conservation strategy established by the post-2020 Global Biodiversity Framework[1]. However, there remain concerns about how to define and manage protected areas to meet the needs of the many people living near and relying on conservation lands[2–4]. There is also debate about the most effective indicators for evaluating the effectiveness of protected area management strategies[5–8]. Indicators rely on biodiversity monitoring data, but resources for monitoring are limited and inequitably distributed[9,10]. A global paucity of data, along with steep geographic and taxonomic biases in biodiversity research, mean that there are insufficient data to assess the conservation status of and develop conservation strategies for the majority of species worldwide[10–14]. The evidence base is most limited in the Global South, where biodiversity is highest and conservation stakes often greatest[15–17].

Strengthening the assessment and management of protected areas will rely on integrated action across scales from international to local[18–20]. Because conservation challenges are driven by multiple socio-ecological drivers that interact across spatial scales, engagement with the local context is critical for developing, implementing, and evaluating science-based conservation strategies[21–27]. Insufficient spatial resolution and coverage in biodiversity data can therefore be a limiting factor in developing conservation strategies at the scale of individual protected areas and regional protected area networks[28]. At the same time, community-based monitoring has long generated biodiversity knowledge and informed active management on a local scale, though practices for integrating this knowledge across scales are still developing[29–32]. In light of this, there are growing calls for localization of conservation efforts and furtherance of community engagement to inform protected area management and assessment[20,21,26,33].

Participatory monitoring, including both citizen science and community-based monitoring, is regularly highlighted as a way to fill gaps in the global biodiversity evidence base while engaging local communities[34–39]. It produces vast amounts of structured and unstructured data that are increasingly relied upon for biodiversity research and conservation[35,40], aided by growing accessibility of digital tools[30] and advancements in analytical approaches for unstructured data[41–43]. However, participatory monitoring risks replicating the taxonomic and spatial biases that are currently associated with biodiversity research or introducing new ones, which may limit its effectiveness[10,12,44,45]. Participatory monitoring varies greatly across ecological and social contexts, so effective monitoring programs cannot be defined in a one-size-fits-all approach. Therefore, an overview of the role of participatory monitoring across protected area contexts is needed to guide its continued expansion and increased use in conservation.

Here, we explore the varying contribution of participatory monitoring to the biodiversity evidence base for global protected areas. We focus on the extent to which patterns in data from participatory monitoring replicate or differ from patterns associated with non-participatory monitoring. The assessment is based on all biodiversity data shared on the Global Biodiversity Information Facility (https://www.gbif.org/) between 2000 and 2021 within the boundaries of all terrestrial protected areas identified by the World Database on Protected Areas (https://www.protectedplanet.net/), a total of 486 million species occurrence records. We first classify protected areas according to the relative contribution of participatory monitoring, examining differences across taxa and geographic regions. Second, we explore how the contribution of participatory monitoring in protected areas has changed over time. Third, we assess the contribution of participatory monitoring within distinct taxonomic groups, with a particular focus on threatened species.

Fourth, we identify characteristics of protected areas and participatory monitoring programs that are associated with high relative contribution. Finally, in the discussion, we contextualize our findings to suggest priorities for the expansion of participatory monitoring in protected areas.

Results

Contribution of participatory biodiversity monitoring in protected areas. Since 2000, participatory monitoring has produced 77% of all biodiversity data available on the Global Biodiversity Information Facility (GBIF) for the world's terrestrial protected areas (Fig. 1). It is the sole source of GBIF data from that time period for 25% of all terrestrial protected areas. Among the 61% of protected areas for which there are available data on GBIF, participatory monitoring contributes the majority of data in 75% of areas and nearly all (over 90%) of the data in 59% of areas. This reliance on participatory monitoring developed rapidly; until 2008, the contribution of participatory monitoring data grew at a similar rate to the overall growth rate of data on GBIF. Around 2008, two shifts caused the proportion of data derived from participatory monitoring to climb: the annual growth rate for participatory monitoring data increased sharply, while the rate at which non-participatory data were added to GBIF began to decline (Fig. 1). The contribution of participatory monitoring continues to grow up until today (Fig. 1).

Geographic patterns in the participatory monitoring data on GBIF for protected areas broadly follow known patterns in the distribution of biodiversity research: as has been shown elsewhere, participatory monitoring data are collected in the greatest quantities in wealthier nations[12,17,44] (Fig. 2, SI Figure 2.1). Still, many nations with an overall low quantity of available data derive a high proportion of that data from participatory monitoring (Fig. 2, SI Figure 2.1). Regardless of a nation's overall contribution from participatory monitoring, there is a great deal of variation between individual protected areas (Fig. 2). Nevertheless, variation across national boundaries suggests that national-level policies (regarding, e.g., participatory monitoring, standardized biodiversity monitoring, or open data) do impact the knowledge base of open biodiversity data for protected areas.

Taxonomic trends in participatory biodiversity monitoring. The proportion of data derived from participatory monitoring continues to increase for all taxonomic groups (Fig. 1). To date, participatory monitoring has contributed more than half of all GBIF data since 2000 for birds, invertebrates, fungi, reptiles, and amphibians within protected areas (Fig. 3). Within most taxonomic groups, our findings support the common expectation that participatory monitoring data will have a highly skewed distribution of the number of observations per species[46,47]. However, we show that for birds, reptiles, and amphibians, data from participatory monitoring are similarly or less skewed towards a small number of species than data from non-participatory monitoring (Fig. 3). Among species that have been evaluated for the IUCN Red List, data on threatened species are recorded less frequently through participatory monitoring than through non-participatory monitoring on GBIF (Fig. 4). However, participatory monitoring records different Red List species than non-participatory monitoring; 47% of the threatened species recorded through participatory monitoring within protected areas were not recorded by any other means.

Contexts associated with high participatory monitoring contribution. We evaluated how three characteristics of protected areas (area size, IUCN protection category, and governance structure) relate to the contribution of participatory biodiversity
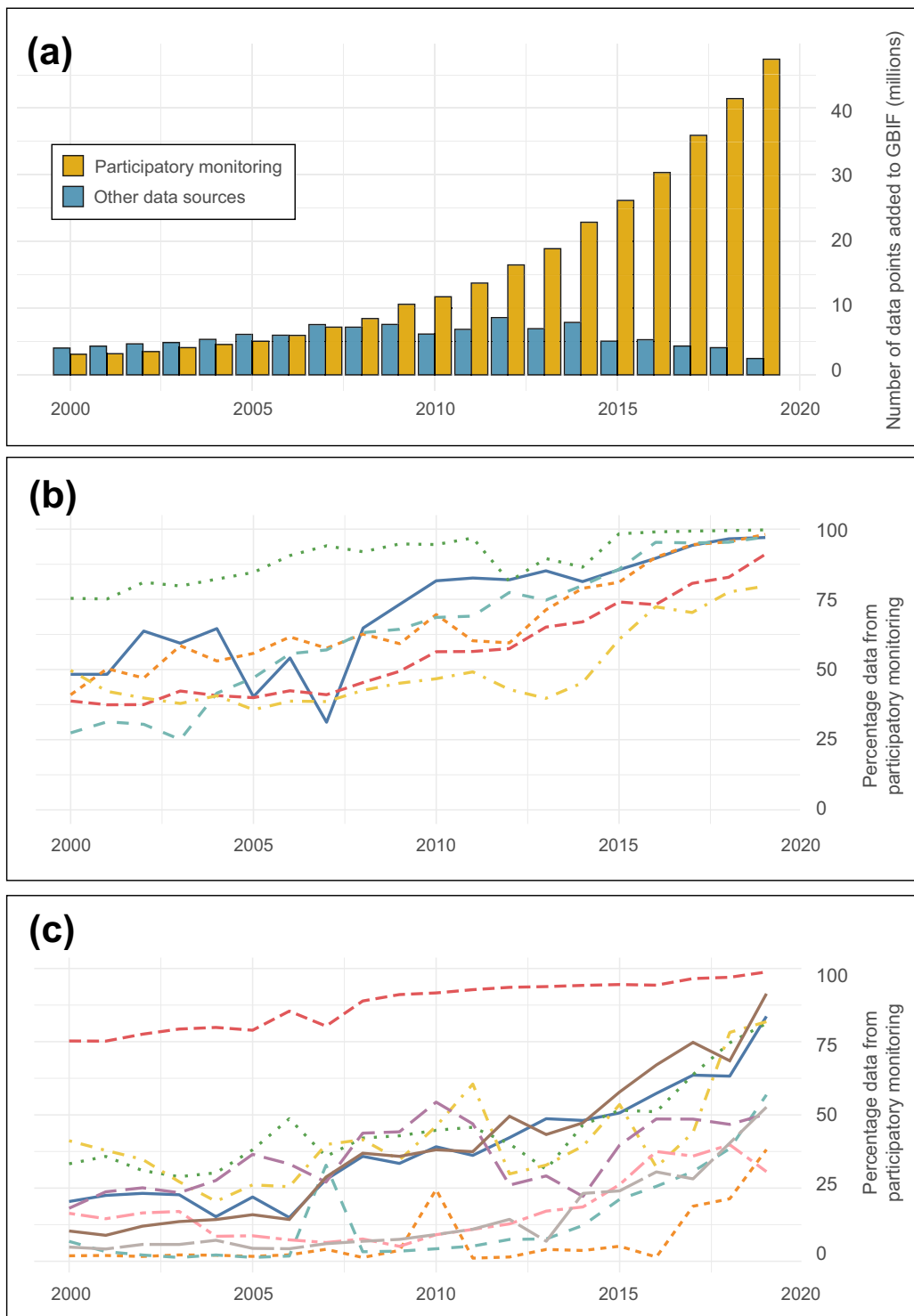
Fig. 1 Changes in the contribution of participatory monitoring from 2000-2020. a The amount of data contributed to GBIF annually from participatory monitoring (yellow) and non-participatory monitoring approaches (blue) for global protected areas; **b** the annual percentage of data derived from participatory monitoring across global regions; **c** the annual percentage of data derived from participatory monitoring across broad taxonomic groups.

monitoring. Larger areas were associated with the largest participatory datasets (Kruskal-Wallis $H = 18167$, $p < 0.001$), but in smaller areas, participatory monitoring contributed a greater proportion of total data (Kruskal-Wallis $H = 12824$, $p < 0.001$; Fig. 5). Similarly, areas classified in stricter IUCN protection categories were associated with more participatory monitoring data (Kruskal-Wallis $H = 1263$, $p < 0.001$), but participatory monitoring contributed a greater proportion of the total data in

less strictly protected areas (Kruskal-Wallis $H = 581$, $p < 0.001$; Fig. 5). These trends were consistent across most global regions (SI Figures 2.2, 2.3). Though trends in governance structure were weaker, areas managed by local communities were associated with the greatest overall contribution from participatory monitoring and areas managed by non-profit organizations derived the greatest proportion of data from participatory monitoring (SI Figure 2.4).
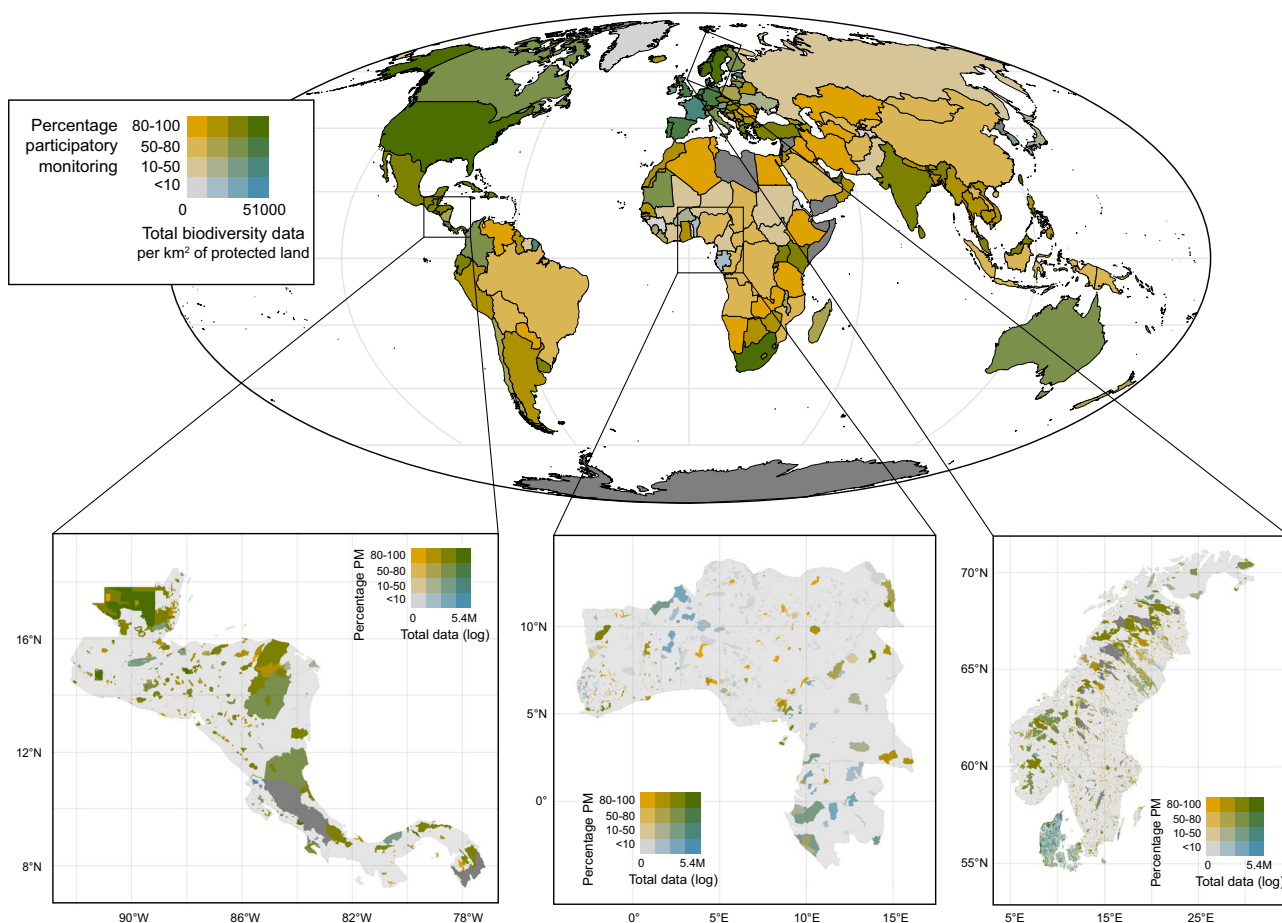
Fig. 2 A global overview of the contribution of participatory monitoring to open biodiversity data. A bivariate scale illustrates the total biodiversity data available on GBIF and the percentage of this data that is derived from participatory monitoring. The global map illustrates variation between nations and the inset maps illustrate variation between protected areas within three global regions.

We further evaluated how four characteristics of participatory monitoring programs (program size, taxonomic focus, geographic focus among areas, geographic focus among nations) relate to the programs' focus on threatened species and to the types of areas where they are active. Small programs and programs with a narrow geographic or taxonomic focus were slightly more likely to collect data on threatened and data deficient species (SI Figures 2.5–2.7). Such programs were more active in large areas and areas with less strict protection. In contrast, data in small and strictly protected areas were more likely to be collected by large, taxonomically and geographically diverse monitoring programs (SI Figures 2.5–2.7).

Discussion

Participatory monitoring has changed the nature of biodiversity monitoring in protected areas, with a large and growing majority of biodiversity data in protected areas now coming from participatory monitoring. This contribution exceeds previous estimates of the proportion of this data type on GBIF[38,48,49]. This is a substantial step towards increased inclusion of the public in protected areas management and it offers immense opportunity to expand the evidence base for biodiversity research and conservation[35]. At the same time, a growing reliance on participatory monitoring will bring new challenges.

The most direct contribution of participatory biodiversity monitoring is a vast increase in the amount of available biodiversity data. In the last twenty years, over three times more data has been added to GBIF from participatory monitoring than from all other sources. Participatory monitoring expands biodiversity monitoring in protected areas that have lower coverage by non-participatory monitoring, including small areas and those with less strict protection schemes, as illustrated by the 25% of areas for which participatory monitoring is the sole source of biodiversity data on GBIF. Because participatory monitoring is most common in protected areas with higher human impact, such as those that are near population centers, directly relied upon for natural resources, or highly accessible for recreation, its contribution in fragmented landscapes and small and multi-use protected areas will likely continue to grow[50–52].

Though our results generally support the expectation that participatory monitoring emphasizes charismatic and easily identified species and thus results in a skewed distribution of data across species[46,47], we find that participatory monitoring achieves a similar distribution compared to non-participatory monitoring for reptiles and amphibians, and a less skewed distribution for birds. The strong coverage of these groups may be supported by advances in technological and community support for taxonomic identification and quality control in participatory monitoring data[47,53,54]. Participatory monitoring expands the range of species covered by biodiversity monitoring rather than simply replicating the species monitored with other approaches, including many Red List species that have been reported exclusively through participatory monitoring.
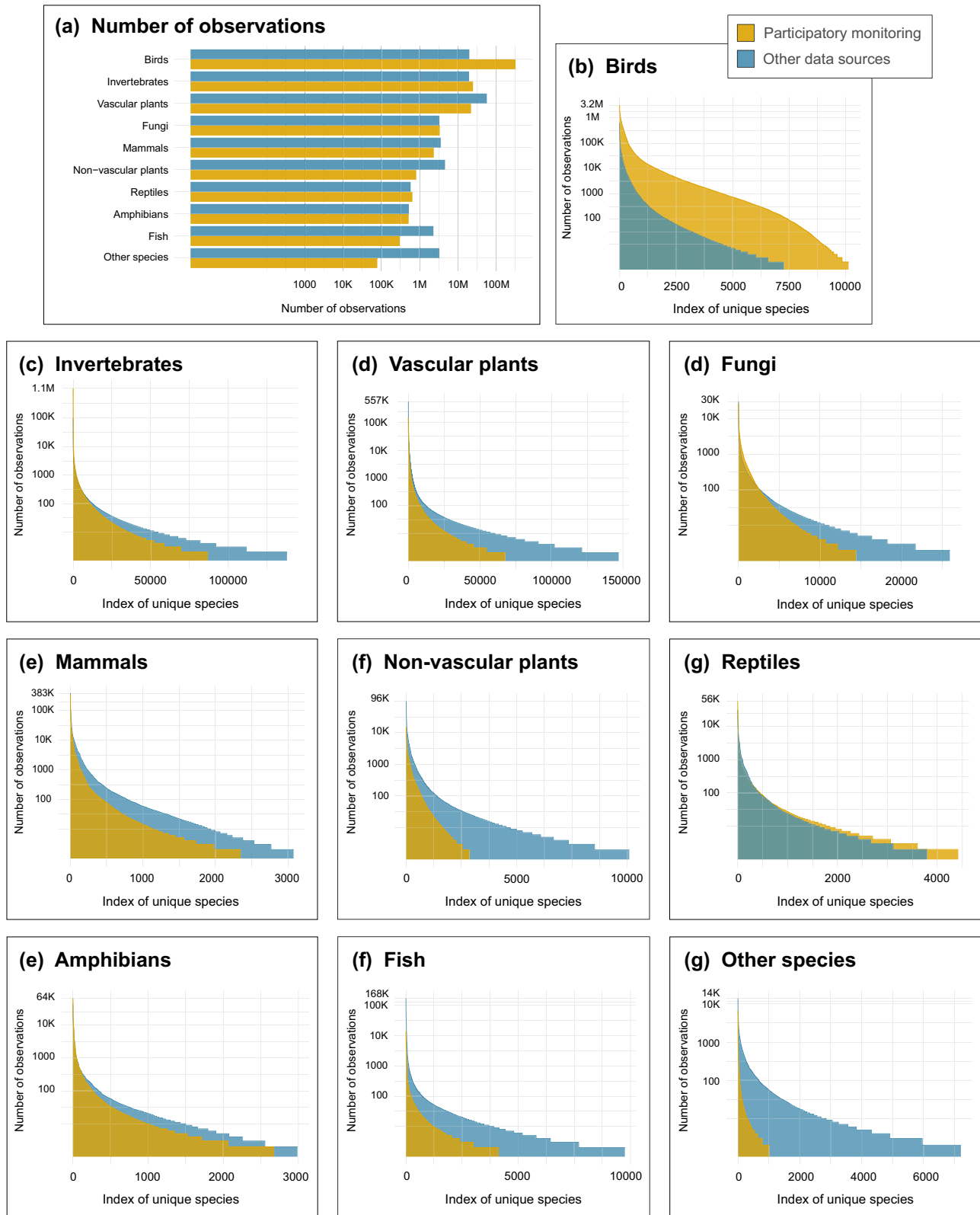
Fig. 3 Contribution of participatory monitoring across taxonomic groups. a The total amount of data contributed to GBIF within protected areas during the study period via participatory monitoring and non-participatory monitoring for each broad taxonomic group. In **b–g**, curves for participatory monitoring (yellow) and non-participatory monitoring (blue) indicate the distribution of the number of observations per species within taxonomic groups. Each point along the x-axis indicates a unique species within the taxonomic group, ordered from most- to least observed, and the y-axis values indicate the number of observations of that species included in the GBIF data. Note that the x- and y-axis ranges differ between plots.
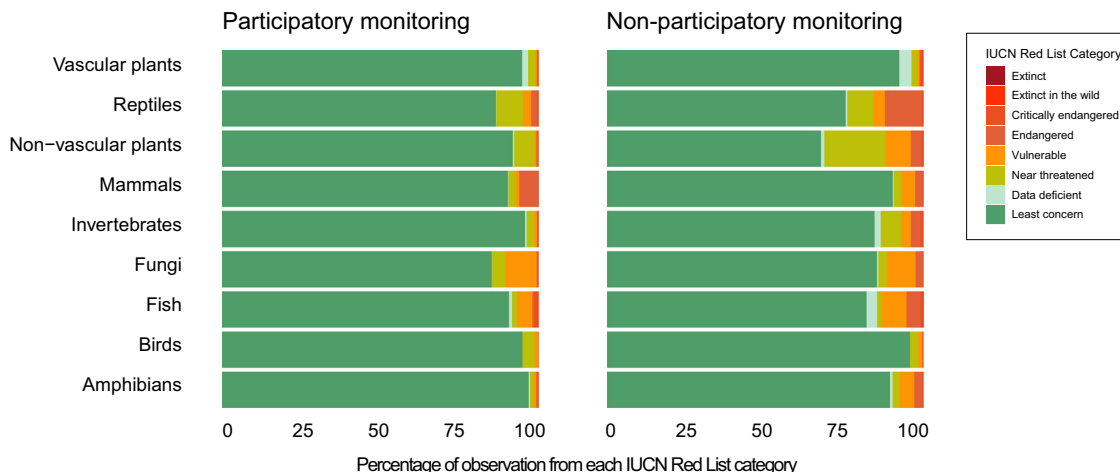
Fig. 4 Coverage of IUCN Red List species. The number of observations of species within each IUCN Red List category for participatory monitoring and non-participatory monitoring approaches. Among species that have been evaluated for the IUCN Red List, data on at-risk species are recorded less frequently through participatory monitoring than through non-participatory monitoring on GBIF (Kruskal-Wallis $H = 279$, $p < 0.001$).
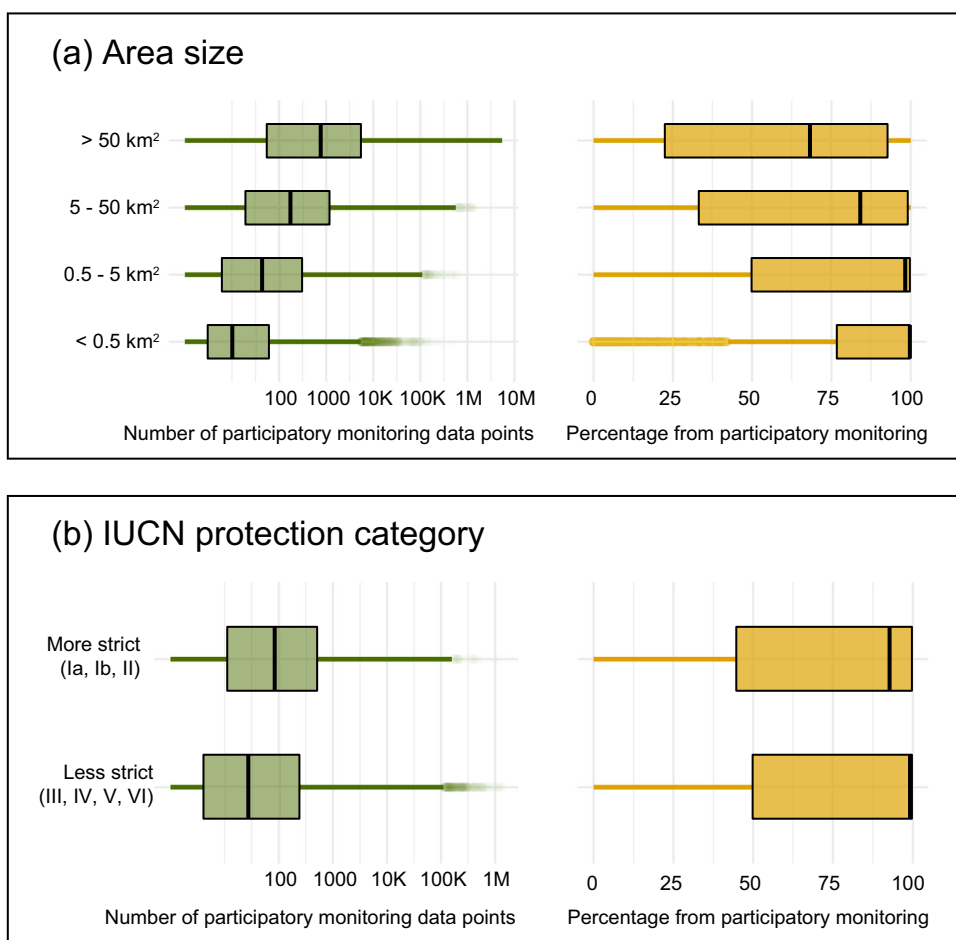

Fig. 5 Contribution of participatory monitoring across protected area characteristics. The amount of participatory monitoring data (on the left, in green) and the percentage of overall data that it comprises (on the right, in yellow) available on GBIF associated with protected areas of varying **a** size; **b** IUNC protection category. Bars indicate median values, box indicates interquartile range, whiskers indicate data within 1.5 times the interquartile range, and points indicate outliers.

The impacts of a growing reliance on participatory monitoring will be exacerbated by the parallel decline in the publication of biodiversity data from other sources to GBIF that was revealed by our results (Fig. 1), which could be driven by either a true decline in data collection or a decline or time lag in the publication of data to GBIF. Indeed, biodiversity monitoring is regularly conducted in protected areas to directly support area management[55] as well as by academic researchers[56], and much of the resulting data are not published on GBIF[57]. Nevertheless, because GBIF data are increasingly relied upon in global syntheses and assessments[49], the decline in the publication of data from other monitoring approaches to GBIF is noteworthy. Because they have different strengths and weaknesses, participatory data offer the greatest potential as a complement rather than substitute to structured, long-term biodiversity monitoring[43,58]. Furthermore, participatory monitoring offers the potential to fill gaps in data collection in the many protected areas that have limited resources to support professional monitoring[59].

Like biodiversity data as a whole, the contribution and growth of participatory monitoring are globally uneven and biased towards wealthier countries, largely in the Global North[12,16,17,38]. However, our results reveal some deviations from this general trend. Community-based monitoring plays a strong role in generating biodiversity knowledge in many developing countries, which may explain the especially high proportion of participatory data in some countries with otherwise overall little data on GBIF[34]. Because practices for sharing and integrating knowledge generated through community-based monitoring are still developing, this contribution is poised to grow[30,31,50]. Our results reveal variations across national borders, which may be driven in part by national policies that can enable or impede both participatory monitoring and open data sharing[60–62].

The role of participatory monitoring is also context-dependent on a finer scale. Our results show that in large protected areas, participatory monitoring is building biodiversity datasets of unprecedented size. These can fuel analyses to detect high-resolution spatial and temporal biodiversity trends[41]. In smaller protected areas, relatively small amounts of participatory monitoring data are often the primary or sole information available to inform urgent conservation decisions[63,64], support prioritization of management actions[65,66], or inform future sampling[67]. Small areas are increasingly seen as essential to meet international area protection targets and address local-scale environmental threats[19,68,69], but they often have limited resources for biodiversity monitoring[70,71]. Participatory monitoring can help fill this gap. Our results show that areas managed by local communities and nonprofit organizations have some of the highest contributions from participatory monitoring. Small and locally managed protected areas with robust participatory monitoring can be a model to emulate as other effective area-based conservation measures (OECMs), many of which are small and locally managed, become a greater focus of area management targets[71–74].

Though small and less strictly protected areas rely on the greatest proportion of participatory monitoring data, they are less likely to receive data from small monitoring programs or programs with a specific focus on taxa or areas of interest. This may be due to the limited capacity of smaller protected areas to support locally-managed participatory monitoring programs[70,75,76]. As a result, small areas may miss out on some of the benefits of small, focused participatory monitoring programs, including a focus on threatened and data-deficient species. Locally-led monitoring programs often have greater capacity to implement tailored study designs, sampling protocols, and quality control, all of which can mitigate some of the spatial biases that are typical of unstructured biodiversity data collected with digital monitoring platforms[50,51,77,78]. Further strengths of locally-focused programs include increased likelihood of conservation outcomes[79,80] and increased civic engagement around area management[81,82].

Our analysis is limited by its restriction to monitoring programs that add data to GBIF. There are many participatory and non-participatory monitoring programs that do not use GBIF to share data[30,57,83], and these are not included in this analysis. For participatory data, this means that we have probably underestimated the contribution of small, taxonomically focused, and geographically focused monitoring programs. Unlike large monitoring programs, which often have digital data workflows that are integrated with GBIF, many smaller and thematically focused monitoring programs apply data directly to local management without publishing it externally[37,83,84]. These programs often have substantial local impact, but their contribution could be expanded even further by facilitating greater sharing of these data through infrastructure development, incentivization, and awareness raising[30,31,80], while respecting limitations introduced by sensitive data, privacy concerns, and Indigenous data sovereignty and local data governance[32,85,86]. These data can be especially valuable because many small and focused monitoring programs support structured sampling that alleviates bias or targets specific research questions[35,87]. Other emerging forms of participatory biodiversity data, including data gathered from social media, online forums, and search engine usage, are also likely underestimated in our dataset due to limited integration with GBIF[88].

Although data from participatory monitoring offer immense potential to inform science-based conservation strategies while making these strategies more responsive to the priorities of the people who rely on protected areas[34,89], studies show that participatory monitoring data shared on GBIF have historically been underutilized in the research and management of protected areas, particularly at finer spatial scales[42,51,90]. Extensive recent advancements in analytical approaches for participatory monitoring data have greatly expanded their fitness for diverse research purposes, and there is much potential to further extend their utility for informing the management of individual protected areas and area networks[41,43]. By revealing the extent to which biodiversity knowledge in protected areas relies on participatory monitoring, our findings emphasize the importance of continued research to maximize its relevance for the management and assessment of these areas.

Our results also highlight opportunities to share best practices in biodiversity data collection and sharing at multiple scales. Thirty-nine percent of protected areas have no data on GBIF, and many of these share characteristics and proximity with areas that have robust participatory monitoring; protected areas with active monitoring might be used as models to extend participatory monitoring into similar areas in a way that is tailored to the areas' specific conservation needs. Our results also reveal substantial variation across national boundaries. Nations with low contribution from participatory monitoring can follow national-level guidance to create an enabling policy environment for participatory monitoring to facilitate its emergence, perpetuation, and impact[27,61]. National support can both facilitate local engagement and also allow for national-level coordination, which can increase the structure and fitness-for-purpose of participatory monitoring data[31]. Further, nations can enact policies supporting open data infrastructure and incentivization for both participatory and non-participatory monitoring data[62,91]. Such policies can, for example, open new funding mechanisms, build incentivization into existing funding schemes, address legal and structural barriers to data sharing, and establish new capacity building opportunities[92]. Increased data sharing can expand the potential impact of even small datasets by allowing them to contribute to regional or international assessments, syntheses, and other analyses[31,49]. We show that the amount of non-participatory data from protected

areas published annually on GBIF has declined, pointing to a need for continued support for both biodiversity monitoring and open data sharing.

As the contribution of participatory monitoring grows, its explicit recognition in publications, reports, and other data applications will be important for justifying its continued funding as well as for identifying opportunities to share best practices among participatory monitoring practitioners and data users[40,75,87]. In particular, small participatory monitoring programs may struggle to sustain resources despite their unique responsiveness to local contexts and their strong role in collecting data on threatened and data deficient species. Our results demonstrate clearly that participatory monitoring has great current and future potential to expand the biodiversity knowledge base within protected areas to regions and taxa that are underrepresented by non-participatory monitoring methods. Therefore, increased recognition and continued development of participatory monitoring will be critical for strengthening the conservation outcomes of protected areas and meeting ambitious but necessary international targets for area-based conservation.

Methods

Protected areas data. We accessed polygons representing global protected areas from the World Database on Protected Areas (WDPA; https://www.protectedplanet.net/)[93]. The full dataset consisted of 254,526 areas. We retained all terrestrial areas, resulting in 236845 areas. All variables used to characterize protected areas in our study (area size, IUCN protection category, and governance structure) were included in the WDPA database.

Biodiversity data. We accessed all biodiversity data available on the Global Biodiversity Information Facility (GBIF; https://www.gbif.org/)[94]. The data were downloaded to a spatially enabled SQL database (PostgreSQL 10.22 with PostGIS 3.0.1) also holding the protected area polygons described above. GBIF occurrence data within the boundaries of global protected area polygons were then extracted. We restricted the data to years between 2000 and 2021 for further analyses because we were interested in capturing recent trends in participatory monitoring. Of the WDPA protected areas, 143,510 areas were associated with data on GBIF while the remaining 93,335 were not. Biodiversity data were summarized by unique combinations of taxon ($n = 778,949$), dataset ($n = 11,242$), protected area ($n = 143,510$), and year. Each taxon was associated with an IUCN Red List classification[95].

Each dataset was classified according to whether or not it was considered to be participatory monitoring, which was defined in this study as the voluntary participation by members of the public, acting outside of their typical professional or academic capacity, in biodiversity data collection, including both structured and unstructured sampling. Datasets were classified through an iterative process. First, all datasets tagged in the GBIF API with the machineTag "citizenScience" ($n = 494$) were classified as participatory monitoring[96]. Second, we accessed the full GBIF record for each remaining dataset via the GBIF Registry API and performed a keyword search for a list of terms relating to participatory monitoring through several descriptive text fields associated with each dataset. We derived the list of search terms from recent publications related to terminology in participatory monitoring: Kullenberg and Kasperowski 2016[97], Eitzel et al. 2017[98], and Cooper et al. 2021[99]. We further used translations of the European Citizen Science Association "Ten Principles of Citizen Science"[100], which so far includes thirty-five global languages, to derive terms related to participatory monitoring in languages indicated to be included in the set of datasets in our GBIF download. The full list of search terms used and dataset fields considered is found in the SI (SI Tables 1.1, 1.2). All remaining datasets whose descriptive text fields contained one or more search terms ($n = 4806$) were manually screened for consistency with the definition of participatory monitoring used in this study. Because some datasets contained data from both participatory and non-participatory monitoring, we followed the approach of Chandler et al.[38], classifying datasets as participatory monitoring if it seemed that at least 50% of the associated data came from participatory monitoring. Through this process, 970 datasets were classified as participatory monitoring while the remaining 10,272 were not. We expect that our approach resulted in a conservative estimate of the contribution of participatory monitoring, because it could not account for any data providers that used participatory monitoring but either did not describe it in the metadata or described it in terms not captured by our search.

Analysis. We summarized the amount (total number of participatory monitoring observations) and ratio (total number of participatory monitoring observations divided by the total number of observations) of participatory monitoring data, first using nations as the unit of analysis and second using protected areas as the unit

of analysis. We further summarized this information within global regions and within broad taxonomic groups, and summarized the number of observations per species and per IUCN Red List category within broad taxonomic groups. We summarized the quantity of data collected via participatory and non-participatory monitoring by year to examine change over time within regions and broad taxonomic groups.

Using the amount and ratio of data from participatory monitoring as response variables, we used Kruskal-Wallis non-parametric tests to relate these variables to three characteristics of protected areas: area size, IUCN protection category, and governance structure (these characteristics are further defined in SI Table 1.3). The correlation between these three characteristics was minimal (all Cramer's $V < 0.24$). We further derived four characteristics of participatory monitoring programs: monitoring program size, taxonomic focus, the geographic focus among protected areas, and geographic focus among nations (these characteristics are further defined in SI Table 1.4). The correlation between these four characteristics was minimal (all Cramer's $V < 0.30$). We used chi-squared tests to relate these characteristics to the area size and IUCN protection category of the protected areas in which each program was active, as well as to the IUCN Red List category of the species monitored by each program. All analyses were conducted in R version 4.1.2[101].

Data availability

All data are from open databases and publicly available for download: protected area data were obtained from the World Database on Protected Areas (https://www.protectedplanet.net/)[93] and biodiversity data were obtained from the Global Biodiversity Information Facility (https://www.gbif.org/)[94]. Processed data used to make figures are available on Open Science Framework: https://osf.io/fm6e2/[102].

Code availability

R scripts used in analyses are available on Open Science Framework: https://osf.io/fm6e2/[102]. Analyses were conducted in R version 4.1.2[101].

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Author contributions

A.G.F. and I.H. led the biodiversity data acquisition and management. C.P.M. led the conceptual development, data analysis, and writing. C.P.M., E.B.N., I.H., and A.G.F. contributed to conceptual development and writing.

Competing interests

The authors declare no competing interests.

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