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REVIEW PAPER

Overcoming biases and identifying opportunities for citizen science to contribute more to global macroinvertebrate conservation

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Abstract
Citizen Science (CS) provides valuable data to assist professional scientists in making informed decisions on macroinvertebrate conservation. However, CS is not developed nor implemented uniformly across the globe, and there are biases and challenges in the extent that it can contribute to global macroinvertebrate conservation. Here, a meta-analysis was performed using 107 Citizen Science Projects (CSPs) to identify underlying biases related to taxon representativity, country wealth, and demographic participation. Macroinvertebrate orders with the highest representativity were Lepidoptera and Hymenoptera, accounting for 53% of represented macroinvertebrate groups. The orders Scorpiones, Parasitiformes, and Spirobolida had proportionately the highest IUCN threat statuses, but significantly lower CSP representation, indicating that these orders require more public attention. Hymenoptera, Odonata, Coleoptera, Hemiptera, Diptera and Clitellata had the highest levels of Data Deficient species, suggesting that the primary objective of CSPs targeted at these orders should be collecting distribution and abundance data to improve Red List assessments. Global distribution of CSPs was uneven and the number of CSPs per country was positively correlated with national Gross Domestic Product (GDP) and GDP per capita, suggesting that countries with relatively low GDP face challenges to successfully establish and maintain CSPs. Establishing new CSPs can assist macroinvertebrate conservation in these countries, where biodiversity levels are often high. To accommodate these biases, CSP development should adopt a bottom-up approach, in which CSPs are designed to address data gaps, and to address local socio-economic limitations and cultural ideologies. Guidelines for such development are presented here, with emphasis on addressing societal variations and inter-disciplinary communication gaps to ensure equitable opportunities for CSP participation.

Keywords Macroinvertebrates · Public awareness · Public engagement · Global threats · Conservation strategies

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Introduction

While conservation biology is essentially a biocentric science, it is governed by the social perspectives and conventions of our anthropocentric world (Bickford et al. 2012; Jiménez et al. 2014; Jordan et al. 2011). Therefore, it is important for conservation practitioners not only to realize but to utilize this largely undervalued social element to maximise the influence of their work in both the biological and social spheres of conservation (Devictor et al. 2010; Chandler et al. 2017). One way to achieve this, is through the rapidly growing field of citizen science (CS).

Broadly, CS is the involvement of civil society in scientific projects, often in geographic areas where relatively little is known about biodiversity levels, but also in those areas where biodiversity is well-known but conservation directives not fully understood. During the CS engagement process, participants (i.e., citizen scientists) collect some type of data, which are used to further baseline science, species monitoring programmes, and/or may be used to inform policy decisions (Domroese and Johnson 2017; Jordan et al. 2011; Kobori et al. 2016). Citizen science is effective, and the socio-ecological benefits stem from its ability to foster a sense of stewardship in the general public (Campanaro et al. 2017; Jordan et al. 2011; Lewandowski and Oberhauser 2016). Citizen science projects (CSPs) are categorised based on their objectives, and these categories include A (Action), B (Conservation), C (Investigation), D (Virtual), and E (Education). For involvement of civil society in biological sciences, the most common CSPs are those that fall under categories B and E (Wiggins and Crowston 2011).

Biological data collection by citizen scientists reduces time and overcomes some accessibility constraints that often impede data collection by professional scientists (Campanaro et al. 2017; Domroese and Johnson 2017; McKinley et al. 2017; Saunders et al. 2018). To some extent, CS also addresses the barriers that hinder effective communication between scientists and the public by increasing the scientific literacy of non-scientists (Bickford et al. 2012; Didham et al. 2020; Jordan et al. 2011; Lynch et al. 2018). Technological advances have enhanced the application of CS in conservation, indicated by the establishment of multiple CSPs across several branches of conservation (Bonney et al. 2009; Caley et al. 2020; Fan et al. 2014; Schaefer et al. 2020). However, some technological advances may be inaccessible to some groups of people, such as certain age groups, low-income households, or those with limited understanding of natural systems (Newman et al. 2012).

Despite macroinvertebrates comprising a significant percentage of all life on earth, they receive much less conservation attention compared to large mammals and birds (Cardoso et al. 2011; McKinley et al. 2017; Sanderson et al. 2021). Only a fraction of the estimated global macroinvertebrate species have been identified, with only a small proportion of identified species having been assessed in terms of their threat status (Sanderson et al. 2021). Citizen science can be employed to address these scientific challenges related to macroinvertebrates, specifically through addressing the Wallacean (lack of species distribution data) and Prestonian shortfalls (lack of data on the changes of species and their abundance over space and time).

From a social perspective, CS also helps to address the public dilemma through raising public awareness of the importance of macroinvertebrates, and their roles as ecological service providers. The knowledge and experience gained during participation in CSPs, as well as increased interaction between citizen scientists and researchers, help bridge the gap between science and society, making macroinvertebrate conservation science more appealing and interesting to the public (Bonney et al. 2009; Jordan et al. 2011; Druschke and Seltze 2012; Saunders et al. 2018). It is imperative to macroinvertebrate conservation for public and scientific dilemmas to be overcome, as this knowledge is needed to inform basic management plans, resource allocations, and policy decisions (Girardello et al. 2019).

However, several other factors influence the success of CSPs and in turn, their contribution to macroinvertebrate conservation (Domhnaill et al. 2020). Many have underlying social, economic, and political ties that affect how CS is, or is not, utilized in certain geographic areas (Blake et al. 2020; Bonney et al. 2009; McKinley et al. 2017). Some of these factors include country wealth, political stability, social convention, and biophobia associated with some macroinvertebrate groups (Soga et al. 2023). It is important to understand all factors and biases to maximize the efficacy of CS to benefit researchers, community members, and macroinvertebrate conservation initiatives (Domhnaill et al. 2020).

Here, we perform a meta-analysis, aiming to identify the underlying biases of CSPs targeted at terrestrial macroinvertebrates across the world. Our objectives were to: (1) determine terrestrial macroinvertebrate representation, and identify the factors that affect the success of CSPs, (2) review the public footprint of CSPs across the world, and the associated implications for macroinvertebrate conservation, and (3) provide recommendations for future directions to improve macroinvertebrate conservation efforts through the effective use of CSPs. We hypothesise that representation is uneven across macroinvertebrate taxonomic groups. We also hypothesise that the establishment and success of macroinvertebrate focused CSPs are strongly related to national wealth, while social media participation greatly improves the success rates of CSPs.

Materials and methods

Gathering citizen science projects

This meta-analysis was performed as per guidelines of Basu (2019). A sample list of CSPs focused on documenting macroinvertebrate occurrences and distribution across the world was collated via SciStarter (www.scistarter.org), an online CS database in the public domain that includes over 3000 projects worldwide. A shortlist of compatible projects was made using Boolean search criteria: “invertebrate” AND “insect” AND “arthropod”. The “Topic” field was left blank to include all CSP topics irrespective of discipline. Thereafter, the search results were individually examined and selected for final inclusion, based on the following criteria: (i) macroinvertebrates were the only group included in the CSP, and (ii) macroinvertebrates were terrestrial and/or amphibiotic. CSPs focusing on invasive macroinvertebrates, behaviour, or those that report findings from single bioblitz events, were excluded.

The SciStarter platform is one of the most popular databases for finding CSPs and was used as our primary data source. Yet, to ensure a large enough dataset covering countries across the world, we followed the same search protocol on other popular platforms, including EU Citizen Science, CitizenScience.gov, CitizenScience.org, AnecData, Zooniverse, and the Australian Citizen Science Association. We acknowledge that large platforms such as iNaturalist and Biodiversity4All hosts a plethora of collections on the distribution of macroinvertebrates, but due the difficulty in tracing the origins and motivations of these collections, they were excluded for the purpose of this study, unless these collections hosted data from one of the shortlisted CSPs. A limited number of well-known CSPs from reference literature and personal recommendations were also included in this assessment. Each shortlisted CSP was studied in detail to extract additional relevant information.

Additional information

Macroinvertebrate representation

The macroinvertebrate orders represented by each CSP were listed. For each order represented, the IUCN Red List of Threatened Species (IUCN 2021) metrics were extracted for each threat category. We were specifically interested in the proportions of Data Deficient (DD), Least Concern (LC), Near Threatened (NT), Vulnerable (VU), Endangered (EN), Critically Endangered (CR) and Extinct (EX) species within each order, at the global scale.

Relationships between citizen science projects and country wealth

From the final list of eligible CSPs, the number of CSPs per country was counted. For each country with at least one active CSP, the Gross Domestic Product (GDP) and GDP per capita was identified, as of 2023 (World Population Review 2023). The number of active CSPs per country was then compared relative to GDP and GDP per capita.

Citizen science project success

Where available, the current number of verified records of a project were noted and the number of records for a CSP was taken as an indication of the success of the CSP (i.e., the higher the number of records, the greater the success of the project). Citizen science projects were categorized based on the number of records, and CSPs with < 500 records were classified as 'Low success', CSPs with between 500 and 1000 records were classified as 'Moderate success', and CSPs with > 1000 were classified as 'High success'. The CSPs for which the number of records were undisclosed, were classified as 'Unspecified'.

Social media

Use of social media (primarily Facebook and Twitter), as indicated by online sources, was noted for each CSP. If no listing of any social media platforms for a particular CSP could be found, the CSP was categorised as 'no active social media'.

Statistical analyses

All statistical analyses were performed in RStudio (RStudio Team 2019). Overall representation of macroinvertebrate orders in CSPs, and the descriptive statistics of the proportionate representation (as a percentage value) of each threat category within each macroinvertebrate order was calculated, as a factor of the total number of CSPs that qualified for our study. These proportions were then graphically illustrated.

Generalised linear modelling, using the *lme4* package (Bates et al. 2014) was performed to determine the relationships among the following: (i) the proportionate values of overall macroinvertebrate representation, and proportionate representation of threat categories within each macroinvertebrate order, (ii) GDP, GDP per capita, and the number of CSPs per country, and (iii) the influence of social media on the success of a particular CSP. All test variables were interrogated for normality prior to generalised linear modelling.

Results

Macroinvertebrate representation

A total of 107 CSPs were identified and analysed (Supplementary Material A), and a total of thirteen main focus macroinvertebrate orders were identified from the sampled CSPs (Fig. 1). Overall, 90 of the 107 considered CSPs (84%) targeted a single macroinvertebrate order, with the remaining 17 CSPs (16%) targeting multiple macroinvertebrate orders. Just over half (53%) of the sampled CSPs were dominated by two macroinvertebrate orders,

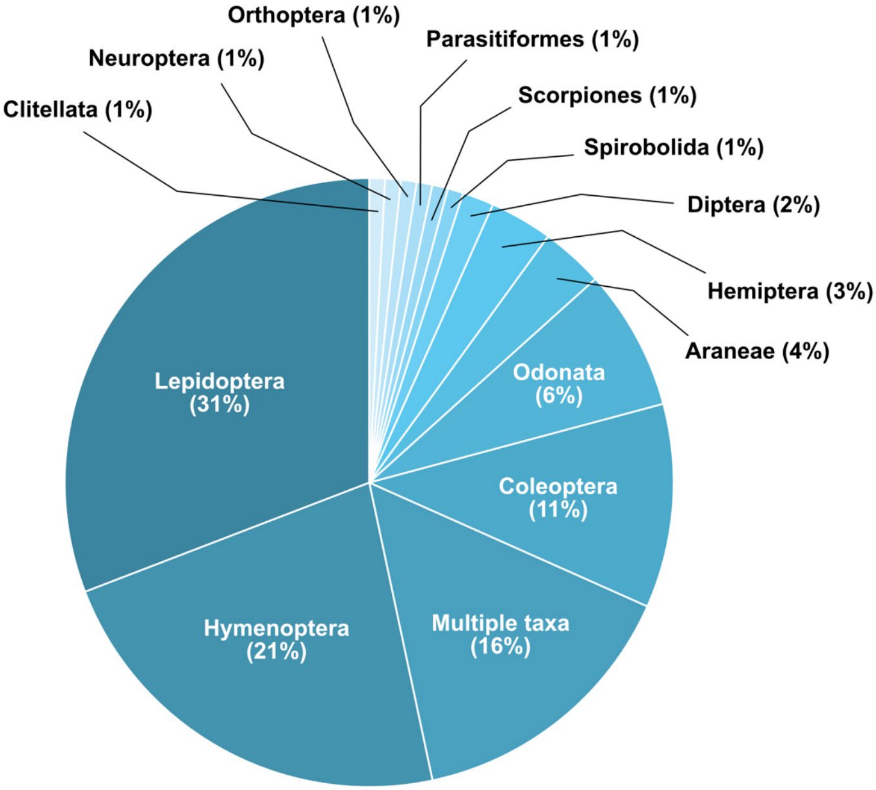

Fig. 1 Proportions of macroinvertebrate groups represented by the selected citizen science projects

with Lepidoptera, making up 31% of CSPs, and Hymenoptera accounting for 22%. Within the Lepidoptera, 26 CSPs (79%) were focused on butterflies, while only three CSPs (9%) were focused on moths, and four CSPs (12%) included moths along with butterflies. Within Hymenoptera, thirteen CSPs (56%) were focused on bees, five CSPs (22%) were focused on ants, while five CSPs (22%) included wasps. Coleoptera, Odonata, and Araneae accounted for 11%, 6%, and 4% of CSPs respectively, while all other individual macroinvertebrate groups each made up 3% or less of the total number of considered CSPs.

Overall, the ‘Least Concern’ category represented the largest proportion of species for more than half of the focal macroinvertebrate groups (Fig. 2). Exceptions were Hymenoptera, Coleoptera and Clitellata, where the largest proportion of species were in the ‘Data Deficient’ category. In the case of Spirobolida most species were ‘Near Threatened’, while for Parasitiformes most species fell in the ‘Critically Endangered’ category. For Scorpiones, an equal proportion of species were in the ‘Vulnerable’, ‘Endangered’, and ‘Critically Endangered’ categories. Parasitiformes also had the greatest proportion of ‘Critically Endangered’ (50%) and ‘Extinct’ species (25%), while Spirobolida had the highest number of ‘Near Threatened’ species (30.3%). Scorpiones had the greatest proportion of ‘Vulnerable’ and ‘Endangered’ species, each at 33.3%. Clitellata had the greatest proportion of ‘Data

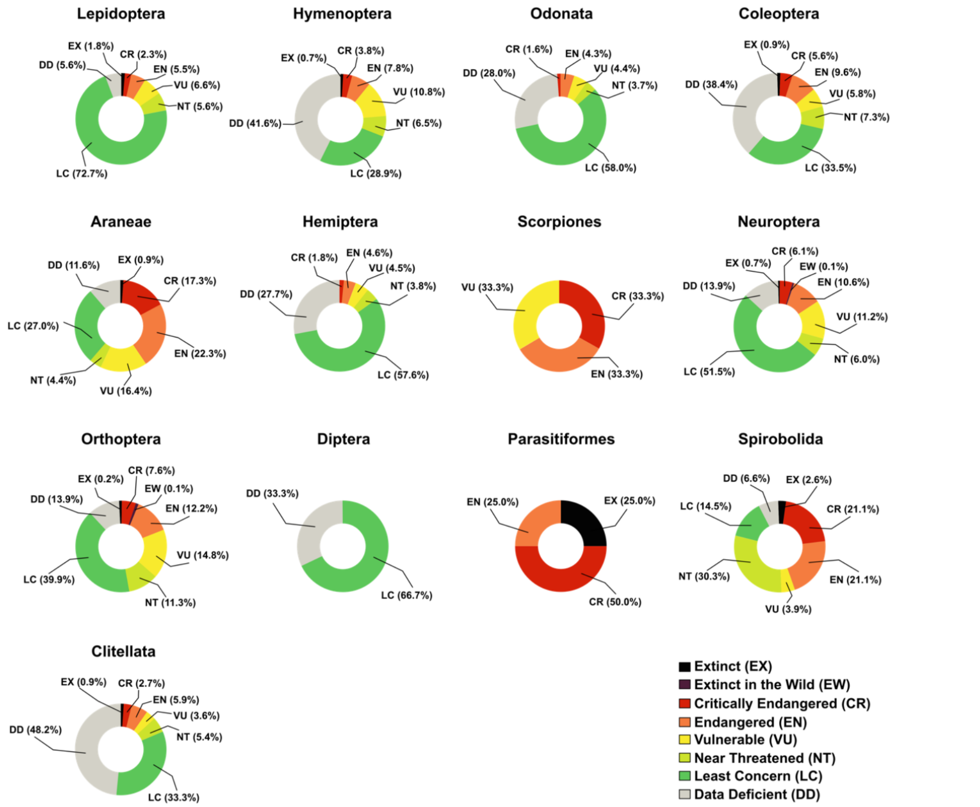

Fig. 2 IUCN Red List categories for the macroinvertebrate orders represented in the selected citizen science projects (Adapted from IUCN (2021))

Deficient' species (48.2%), followed by Hymenoptera (41.6%). For all focal macroinvertebrate groups, 'Extinct in the Wild' and 'Extinct' had the lowest proportion of species overall.

The number of CSPs globally had a weakly positive correlation with the proportion of 'Least Concern' taxa across all focal macroinvertebrate groups ($R^2=0.019$; $p<0.001$; Table 1). Interestingly, the number of CSPs globally had a moderately strong and significant negative correlation with the proportion of 'Endangered', 'Critically Endangered', and 'Extinct in the Wild' taxa ($R^2=0.192$; $p<0.001$, $R^2=0.246$; $p<0.001$ and $R^2=0.135$; $p<0.01$, respectively). The number of CSPs globally had no significant correlation with the 'Data Deficient', 'Near Threatened', 'Vulnerable', nor 'Extinct' taxa.

Citizen science projects and country wealth

At least one CSP was identified from all continents except Antarctica. 15% of CSPs were operational on a global scale, while eighteen countries were identified with country specific CSPs. Generalised linear modelling results showed a moderately strong and positive relationship between GDP and the number of CSPs per country (Z-value = 10.449, adjusted $R^2=0.480$; $p<0.001$; Fig. 3a), and between GDP per capita and the number of CSPs per country (Z-value = 7.644, adjusted $R^2=0.423$; $p<0.001$; Fig. 3b).

Citizen science project success

Fifty out of the 107 total selected CSPs did not disclose the number of records gathered throughout the lifetime of the project (Fig. 4). However, from the CSPs for which the number of records were available, 33% had a high success rate (> 1000 records), while 14% had moderate success (500–1000 records). The remaining 8% was found to have a relatively low success rate (< 500 records).

About half of the countries investigated here had proportionally high success rates of 50% or more. The USA, the UK, and Ireland were the only countries to have CSPs with a low success rate, even though these made up a small proportion of the CSPs in America and the UK (13% and 12%, respectively). For Canada, Australia, Italy, Kyrgyzstan, Spain, Andorra, Belgium, Serbia and New Zealand, more than 50% of the national CSPs did not disclose the number of records.

Table 1 Generalised linear model results indicating statistical relationships between the number of citizen science programmes for each focal macroinvertebrate group, and the individual categories of the IUCN Red List. Only global statuses were considered. Significance levels: *: $p<0.05$, **: $p<0.01$, ***: $p<0.001$

IUCN Threat Category	Direction of correlation	Z-value	Adjusted R^2	Significance level
Data Deficient (DD)	(+)	1.747	0.019	
Least Concern (LC)	(+)	5.239	0.197	***
Near Threatened (NT)	(–)	-0.849	0.005	
Vulnerable (VU)	(–)	-1.189	0.010	
Endangered (EN)	(–)	-4.810	0.193	***
Critically Endangered (CR)	(–)	-4.467	0.246	***
Extinct in the Wild (EW)	(–)	-3.091	0.136	**
Extinct (EX)	(–)	-1.928	0.036	

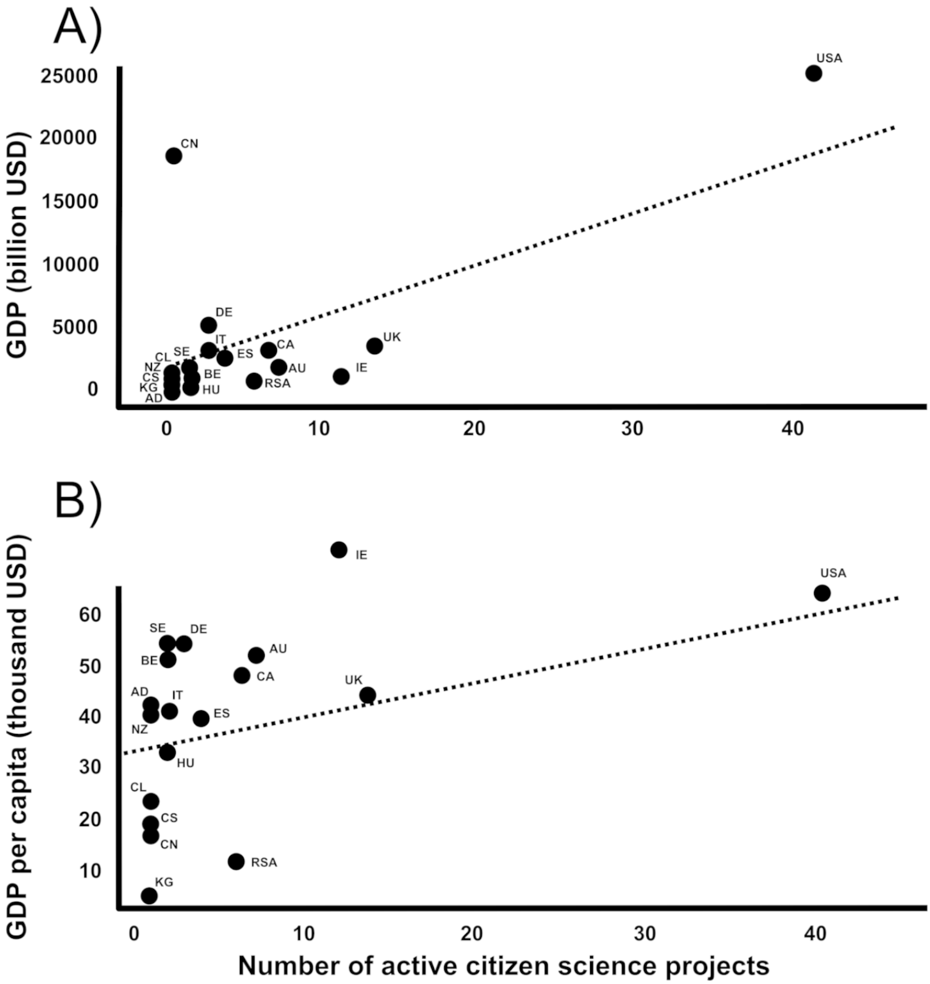

Fig. 3 Linear relationship between number of citizen science programmes and (A) Gross Domestic Product, and (B) Gross Domestic Product per capita, per country. AD: Andorra; AU: Australia; BE: Belgium; CA: Canada; CL: Chile; CS: Serbia; CN: China; DE: Germany; HU: Hungary; IE: Ireland; IT: Italy; KG: Kyrgyzstan; RSA: South Africa; ES: Spain; NZ: New Zealand; SE: Sweden; UK: United Kingdom; and USA: United States of America

Influence of social media

Overall, 67 out of the 107 selected CSPs did not have an active social media campaign, while the remaining 40 CSPs had active social media campaigns via Facebook, Twitter, or both. We found no statistically significant differences between the success rate of CSPs that made use of social media, compared to those that did not (t-value = 1.585; $p > 0.05$). Interestingly, for the categories of low and high success rates, the CSPs that did not make use of social media outnumbered those that did use it in both cases. However, the category of 'Moderate success' contradicted this observation, as CSPs that used social media were dominant. Most CSPs for which records were unspecified made no use of social media.

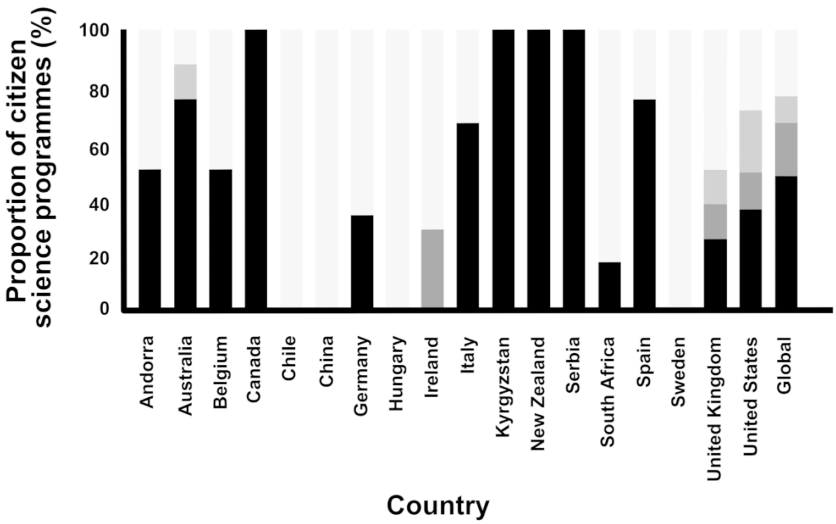

Fig. 4 Relative success of selected citizen science programmes for each country. Black: unspecified; dark grey: low success (< 500 records); light grey: intermediate success (500–1000 records); and clear: highly successful (> 1000 records)

Discussion

The overall aim here was to identify the underlying biases that influence CS worldwide, and how this may influence current and future macroinvertebrate conservation. Confirming our first hypothesis, we found that macroinvertebrate groups with high IUCN threat statuses are weakly represented by current CSPs, while those with low threat statuses are more common focal organisms for CSPs globally. The number of CSPs per country was positively correlated to national GDP and GDP per capita, partially supporting our second hypothesis. Interestingly, the active use of social media had no significant impact on the success CSPs, which was in partial disagreement with our second hypothesis.

Representation of macroinvertebrate orders in citizen science projects

Lepidoptera and Hymenoptera were the macroinvertebrate orders best covered by the subset of CSPs identified here. These findings were to be expected, as these insect orders are among the most familiar to the public, while simultaneously being conspicuous, and being recognized for the important ecological services they provide. Overall, the public feels more enthusiastic towards these insects, particularly butterflies (Lewandowski and Oberhauser 2016) and bees (Domroese and Johnson 2017; Mwebaze et al. 2018). Other popular insect groups included Odonata and Coleoptera, presumably also related to the comparatively high level of attention they draw from the public. This is as opposed to some cryptic macroinvertebrates such as Clitellata which are rarely observed by the public. Furthermore, for nuisance arthropods such as certain Diptera and Araneae, or common plant pest arthropods such as certain Orthoptera, their nuisance outweighs their importance as ecological service providers in the public eye. These findings support the notion that the public dilemma and perception challenge can in some cases be significant barriers to macroinvertebrate conservation (Cardoso et al. 2011; Johansen et al. 2013). Yet, these barriers can be overcome by raising public awareness on the importance of these macroinvertebrate groups, and recognising that they have an important place in modern society (Simaika and Samways 2018).

From a biodiversity loss perspective, analysis of the relationships between IUCN Red List status and macroinvertebrate representativity by current CSPs indicated that macroinvertebrate groups with high relative proportions of species with low IUCN threat statuses and/or unassessed species are the best represented by CSPs. The prevalence of data deficiency across multiple macroinvertebrate groups yielded mixed results. While Lepidoptera (which was the best represented order) displayed the lowest levels of data deficiency, Hymenoptera (the second most represented order) displayed among the highest levels of data deficiency, which is not surprising given exceptionally high biodiversity of the order, and taxonomic impediments especially among wasps and ants (Forbes et al. 2018). Perhaps this is partly related to overarching focus on bees (Apidae) and willingness to fund bee-related research programmes, having strong ties with food security (Porto et al. 2020). There is less recognition that other families in this order are equally important, both economically and for ecosystem functioning (Samways 2020). Likewise, Odonata, Coleoptera, Hemiptera, Diptera, and Clitellata had high proportions of undocumented and unassessed species, creating significant barriers to their conservation ("…all studies on global insect extinctions to date clearly reflect our ignorance of exactly how many species there are…", Cardoso and Leather 2019). There is great opportunity for current and future CSPs to address the conservation dilemmas and shortfalls for these megadiverse and data deficient orders (Bried et al. 2020; Reid et al. 2020; Fagan-Jeffries and Austin 2021).

A general theme was that the groups least represented by CS are those that stand to benefit from it the most. These are the macroinvertebrate groups with a great proportion of species that fall within high IUCN Red List threat categories (i.e., Endangered, Critically Endangered, Extinct in the Wild, and Extinct). In particular, the arthropod orders Scorpiones, Parasitiformes and Spirobolida, had the highest proportions of Endangered and Critically Endangered species, but collectively only made up 4% of the selected CSPs. These findings suggest that there is a high level of disconnect between the CSPs and the urgency of avoiding future species extinctions, with biophobia undermining the success rates of CSPs specifically related to these arthropod groups (Soga et al. 2023). It may also be that funders are more willing to support research on groups that have direct ties with growing economies, such as those that provide pollination services, or in some cases, those which are pests to crops, so enhancing food security. However, CSPs focused on threatened macroinvertebrate groups, among others, can greatly enhance their conservation to avoid future extinctions.

Perhaps to improve representativity among all terrestrial macroinvertebrates is to follow a more habitat-focused approach, so including multiple macroinvertebrates under the same CSP. There is however, a trade-off here: while habitat-focused approaches generate valuable information on the importance of certain habitat types for maintaining macroinvertebrate assemblage diversity (e.g. assemblages in home gardens, green spaces in urban areas, nature reserves, etc.), taxon-specific information might be diluted, especially for species that are locally rare or cryptic (Franklin 1993). A further challenge is to practice CS across whole biogeographic ranges, due to funding constraints and/or constrained accessibility.

Citizen science projects relative to economic factors

Analyses of the relationships between the number of active CSPs, GDP, and GDP per capita indicated a positive correlation. This is almost certainly due to relatively wealthy countries having greater socio-economic welfare and political stability, in turn allowing for more opportunities to allocate time and resources towards environmental education and nature conservation (Pocock et al. 2014; McClanahan and Rankin 2016). Higher GDP is also associated with higher education levels and better access to technology, so improving general scientific literacy and environmental awareness (Pandya 2012). Aside from influencing the presence and success of CSPs in a country, these factors also affect the willingness and ability of the public to participate in scientific programmes, through greater investment to support volunteers (Pocock et al. 2014). This is a major challenge for developing countries, where conservation issues are often of low priority due to resource constraints (Rose et al. 2018). Instead, resources may rather be allocated to a developing economy, rather than environmental management. This is problematic, since several developing countries, especially in Africa, South America, and Asia, have exceptionally high levels of irreplaceable biodiversity that is at high risk from future infrastructural and agricultural development (McClanahan and Rankin 2016; Simaika and Samways 2018).

An exception is South Africa, a developing country with a relatively low GDP, but with three biodiversity hotspots (Williams 2011). These hotspots are at high risk through economic development and agricultural expansion in social or political systems where nature conservation cannot always be a top priority. However, South African biodiversity receives much more attention from local and international researchers, compared to many other developing countries on the continent. South Africa also has a variety of CSPs, specifically focused at terrestrial arthropods, that aid in raising public awareness of the important ecological roles they play (e.g., Edge and Mecenero 2015; Underhill et al. 2016). These CSPs are instrumental for biodiversity conservation in the country, especially for the highly endemic and mega-diverse taxonomic groups. It also indicates that the number of CSPs, and in turn environmental education, need not be governed by the net income of a country. Citizen science projects with clear guidelines, aims and application of data, can also go a long way in support of biodiversity conservation in developing countries (Bried et al. 2020).

Conversely, in many Asian countries, political restrictions are a huge impediment to the establishment and longevity of CSPs, especially those directed towards recording the distribution of macroinvertebrates. Political factors in large parts of Asia obfuscates digital mapping services, challenging CSPs to accurately record macroinvertebrate distribution. Yet, CS has proved to be invaluable to conservation science, and has led to the discovery of rare and threatened macroinvertebrates (So et al. 2022). This implies that CS can rapidly contribute to prioritizing regions of Asia for conservation, and engagement through CS can be instrumental for gathering information on rare species. Recently, great strides have been made by non-governmental and non-profit organizations to catalyse CS across Asia, which is an important milestone to improve conservation science through public participation.

Citizen science project success and influence of social media

The success of CSPs may be affected by the quality as well as the quantity of records, which in turn, are primarily driven by participant accessibility to CSPs, range of operation, time required for participation, frequency of participation and data submission, and skills and resources required for participation (Kobori et al. 2016; Newman et al. 2012; Turrini et al. 2018). Here, CSP success was taken as a measure of the number of verified records, which is the simplest form of measuring successful deployment of CSPs.

Surprisingly, we found that the use of social media had no influence on the success of CSPs. Acorn (2017) found that citizen scientists had mixed views towards having to contribute to a project via social media platforms, such as Facebook or Twitter. Most negative stances were due to a concern over security, with some participants apprehensive of scrutiny from others. Conversely, some participants may feel more motivated when seeing what others have recorded or photographed. Social media may also help organisers or hosts to engage on recent findings and monitor progress, while also communicating with participants on the importance of their voluntary work (Bried et al. 2020). Due to the sheer volume of CSPs globally, social media can in most cases be an effective way of promoting specific CSPs, and in turn, increase participation. Whatever the case, social media participation might be appealing to certain participants (e.g., certain age groups), while being unappealing to others, and this should be carefully considered by CSP hosts.

The way forward

The results of this meta-analysis showed that terrestrial macroinvertebrate-targeted CSPs are not uniformly distributed across the world, with wealthy countries having more active CSPs compared to developing countries, overall. Also, there were significant biases towards iconic macroinvertebrate groups that are viewed as important service providers in the public eye, consequently leading to uneven representation among the various macroinvertebrate groups.

We recommend that CSP development should take a bottom-up approach, to maximize the efficiency and efficacy of CS in macroinvertebrate conservation. The root of CS lies in its societal influences, suggesting that Category B (Conservation) and E (Education) CSPs should be tailored to suit the region-specific social variables. In turn, this approach to CSP development and implementation amplifies both the social and the scientific outcomes of a given project. Collectively, CSPs should also aim at covering a diverse suite of macroinvertebrate groups, while having well-defined programme aims and objectives, and fostering a clear understanding of the conservation issue that is being addressed. It is also important to regularly engage with participants. Doing so will keep participants motivated, and improve on the usability and relevance of the data gathered. These interventions will go a long way towards addressing the current data deficiencies and improving conservation efforts across multiple macroinvertebrate groups.

The task of promoting awareness of macroinvertebrate-related conservation matters is primarily ascribed to governments, research institutions, and NGOs, and it is their responsibility to create a foundation of awareness and interest, no matter how slight, upon which CS can develop (Samways 2020; Haddad 2021). Previous studies have shown that most citizen scientists have some pre-existing appreciation, understanding of the subject macroinvertebrates, or resonate with the study taxa (e.g., pest species which impact participants directly) (Kobori et al. 2016; Lewandowski and Oberhauser 2017, Richardson et al. 2022). As a result, the primary objective, pre-CSP, should be to foster appreciation and emphasise the value of the undertaken project. As Bickford et al. (2012) pointed out, we should localize issues and build upon people's personal experience to show why they should care about the environment. One of the most effective ways to accomplish this is to incorporate this objective into educational syllabi (Bickford et al. 2012; Saunders et al. 2018). By doing so, CS has potential to become a self-sufficient field of science, where well-informed nature enthusiasts drive the success of CSPs, and consequently, contribute to the conservation and protection of macroinvertebrates across space and time. This also means that detectability of CSPs on online platforms should be maximised to improve public participation.

However, increasing awareness of the high conservation value of macroinvertebrates is multi-faceted, and to ensure that the potential of CSPs is maximized, they need to be tailored to the socio-economic limitations, as well as the cultural ideologies of a particular region in which they are implemented. Advances in CS should be aimed at representing a more diverse demographic by encouraging participation from all social and ethnic groups (Blake et al. 2020; Pandya 2012). Effective communication between professional scientists and citizen scientists is essential here, using various forms of media including online social media platforms, printed media, and verbal communication. This will ensure that the general public is presented with equal opportunities for participation, while fostering a psychological responsibility to protect natural systems and their macroinvertebrate inhabitants, so leading to increased longevity and higher success. This is most pertinent for, but not limited to, developing countries, often with high levels of biodiversity, and/or ethnic communities in regions that are adjacent to protected areas or habitats for threatened species (Bickford et al. 2012; McClanahan and Rankin 2016; Newman et al. 2012).

Pandya (2012) presented a general framework for developing CSPs. The main premise is to invite participants to have input at every step of the scientific process, including the formulation of the main research questions and objectives. This can empower local people by enabling them to tackle the ecological issues that resonate with them the most (Clausnitzer et al. 2017). This also gives researchers and conservationists some insight into the perspective of non-scientists, which may positively influence their ability to communicate their scientific findings to the broader public. This approach also creates a positive relationship between CS participants and scientists, which may encourage further participation in CSPs.

Other general considerations that may help overcome the barriers to participation include facilitating social interactions between CS participants and scientists, giving formal recognition to participants, and providing hands-on training in the use of data-gathering methods to participants where needed (Brossard et al. 2005; Druschke and Seltze 2012; McKinley et al. 2017; Turrini et al. 2018). Kobori et al. (2016) also suggest introducing participants to CS by means of short-term or once-off CSPs (e.g., bioblitzes) as an effective way to recruit participants for other long-term CSPs.

Finally, to ensure its long-term success and efficacy, it is imperative that CS and CSPs within a region are evaluated regularly, along with regular updates to participants on the current status of a given CSP. Kobori et al. (2016) outline four evaluation tools (logic models, front-end evaluation, formative evaluation, and summative evaluation) that can be used to evaluate the human dimensions of CSPs. Not only will this ensure the sustainability of CSPs, but it is also likely to positively influence the quality and frequency of data collected by citizen scientists (Bonney et al. 2009; Lovell et al. 2009).

Study limitations

We did not include CSPs that document macroinvertebrates alongside vertebrate or plant taxa, and only included those which focus exclusively on macroinvertebrates, whether single species, single groups, or multiple macroinvertebrate groups. While macroinvertebrates often form part of larger CSPs that document various taxa across set geographic areas, quantifying how many records pertain to macroinvertebrates is challenging. However, this does not mean that macroinvertebrates are of lower importance relative to other taxa included in larger CSPs, but extracting all relevant information is difficult, especially since larger CSPs commonly aims at capturing general biodiversity as opposed to information only relating to certain taxa. For these reasons, we also excluded projects exclusively hosted on general biodiversity platforms such as iNaturalist and Biodiversity4All. We acknowledge that these general biodiversity platforms have gained much momentum in recent years and contains countless projects and records of macroinvertebrates, but their origins, aims, and objectives are often difficult to track.

We included only CSPs which document macroinvertebrate distribution and abundance, and excluded those which document macroinvertebrate invasions, behaviour, and online platforms employing volunteers to identify macroinvertebrates from museum specimens. We acknowledge that CSPs focused towards these aspects of biodiversity also have high value, but including this level of information was beyond the scope of the study. In short, we encourage a range of CS initiatives, and one should not be weighted more valuable relative to others, granted that the incentives and aims are clear. A further challenge is to collate information across multiple CS platforms. This should be done with care to ensure that all extracted information fits the conservation intention at hand.

We also only included CSPs with information given in English, to ensure that the information given here is accurate. However, several European and most Asian countries have primary languages other than English, yet online search engines prioritizes search results according to input language, meaning that CSP information given in other languages can easily be missed. Listing CSPs in languages other than English is advantageous, as it opens opportunities for native communities to participate in CSPs with which they are comfortable. The trade-off is that listings in native languages other than English obscures visibility to global readership.

Conclusions

Citizen science programmes related to terrestrial macroinvertebrates are developed and implemented disproportionately around the world, with high-income countries having comparatively more CSPs compared to low-income countries, where conservation efforts are arguably needed most. Citizen science programmes targeted at terrestrial macroinvertebrates are biased towards charismatic, publicly favoured insects, such as lepidopterans and hymenopterans, while other important macroinvertebrate groups are greatly underrepresented. Furthermore, many of these underrepresented groups are those that are highly threatened or have high levels of data deficiency, providing increased opportunity for the involvement of CS in their conservation. To maximize the contribution of CSPs to macroinvertebrate conservation, several social and conservation biases need to be addressed.

These biases include, but are not limited to, macroinvertebrate public appeal, representativity, and holistic demographic group involvement. These biases can be accounted for by implementing a bottom-up approach in CSP development, in which CSPs are designed to match the social interests and limitations of a particular geographic region to ensure that both biological and social objectives are met. Additionally, local, regional, or national conservation agencies, NGOs, and research institutions should take the initiative to promote awareness on the exceptional ecological importance of whole macroinvertebrate assemblages as important ecological service providers.

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Data Availability All datasets generated during this study are disclosed in the supplementary files.

Declarations

Competing Interests The authors declare no conflict of interest.

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