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Advancing research on alien species and biological invasions

Eyes on the aliens: citizen science contributes to research, policy and management of biological invasions in Europe

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Abstract

Invasive alien species (IAS) are a key driver of global biodiversity loss. Reducing their spread and impact is a target of the Sustainable Development Goals (SDG target 15.8) and of the EU IAS Regulation 1143/2014. The use of citizen science offers various benefits to alien species' decision-making and to society, since public participation in research and management boosts awareness, engagement and scientific literacy and can reduce conflict in IAS management. We report the results of a survey on alien species citizen science initiatives within the framework of the European Cooperation in Science and Technology (COST) Action Alien-CSI. We gathered metadata on 103 initiatives across 41 countries, excluding general biodiversity reporting portals, spanning from 2005 to 2020, offering the most comprehensive account of alien species citizen science initiatives on the continent to date. We retrieved information on project scope, policy relevance, engagement methods, data capture, data quality and data management, methods and technologies applied and performance indicators such as the number of records coming from projects, the numbers of participants and publications. The 103 initiatives were unevenly distributed geographically, with countries with a tradition of citizen science showing more active projects. The majority of projects were contributory and were run at a national scale, targeting the general public, alien plants and insects, and terrestrial ecosystems. These factors of project scope were consistent between geographic regions.

Most projects focused on collecting species presence or abundance data, aiming to map presence and spread. As 75% of the initiatives specifically collected data on IAS of Union Concern, citizen science in Europe is of policy relevance. Despite this, only half of the projects indicated sustainable funding. Nearly all projects had validation in place to verify species identifications. Strikingly, only about one third of the projects shared their data with open data repositories such as the Global Biodiversity Information Facility or the European Alien Species Information Network. Moreover, many did not adhere to the principles of FAIR data management. Finally, certain factors of engagement, feedback and support, had significant impacts on project performance, with the provision of a map with sightings being especially beneficial. Based on this dataset, we offer suggestions to strengthen the network of IAS citizen science projects and to foster knowledge exchange among citizens, scientists, managers, policy-makers, local authorities, and other stakeholders.

Keywords
biological recording, community science, crowdsourcing, non-native species, public engagement, survey

Introduction

The history of citizen science, broadly defined as the practice of involving members of the public in scientific research, can be traced back centuries (Silvertown 2009). However, in recent decades the field of citizen science has grown and transformed with capabilities enhanced by the use of new technologies (e.g., smartphones) (Howard et al. 2022). As citizen science expands and reaches new audiences, its potential for impact and engagement also grows. Large and diverse audiences across the globe now contribute to initiatives carried out on scales ranging from short-term and local, to generational and international. The role of the citizen scientist is equally variable and as a result, the definition of citizen science has been subject to debate (Heigl et al. 2019; Haklay et al. 2021). In many ecological projects, citizen scientists merely collect and submit field observations to be analysed by professional scientists (Bonney 1996); however, in this paper we also consider more in-depth involvement of citizen scientists, such as collecting experimental data. The definition of citizen science that we will use, based on the definition by Wiggins and Crowston (2011), is the active involvement of citizens in scientific inquiry generating new knowledge or understanding.

One area in which citizen science has seen an increase in contributions is the domain of alien species science and policy (Adriaens et al. 2015; Roy et al. 2018; Schade et al. 2019; Johnson et al. 2020). Alien species are defined as species introduced into a new geographic range by human intervention, either intentionally or accidentally (Blackburn et al. 2011). While alien species may have a positive, neutral, or negative impact on their new environment (Cox and Lima 2006; Goodenough 2010), the term invasive alien species (IAS) refers to species whose introduction and spread has been found to threaten or adversely impact global biodiversity, ecosystem services, society and the economy (Seebens et al. 2017, 2020; IPBES 2019; EU Regulation 1143/2014). Concerns over the impacts of IAS have led to policy responses internationally, nationally, and locally. For example, as well as being an important target (Target 9) in the Convention on Biological Diversity (United Nations 1992), the UN's Sustainable Development Goals (SDGs) include a specific target on IAS (target 15.8). Similarly, in 2014, in response to the CBD target, the European Union published the EU Regulation 1143/2014 (European Union 2014) to control the spread of IAS in all Member States through prevention, early detection, rapid eradication, and management. This Regulation identifies a list of IAS of Union Concern which pose a threat to biodiversity and related ecosystem services, and require concerted action at the European Union level. Accessible information on these IAS and implementation of associated policies is provided by the European Alien Species Information Network (EASIN; Katsanevakis et al. 2015; Schade et al. 2019). The core function of this system is to gather and integrate data on alien species occurring in Europe from data partners and scientific literature (Katsanevakis et al. 2012). Data originate from official monitoring programmes and research projects, but also from several IAS-focused citizen science projects active throughout Europe. These projects either deliver data to EASIN directly or publish to open data repositories like the Global Biodiversity Information Facility (GBIF), where they are harvested by EASIN.

The data gathered through IAS-focussed projects are eminently actionable, as they hold potential for use in early warning and rapid response, control programmes at various spatial scales, and policy implementation. Citizen science is especially valuable in an IAS context since tackling the spread of these species necessitates upscaled recording both temporally and geographically, improved understanding of the IAS problem, and increased awareness at all levels of society, objectives for which citizen science is well suited (Roy et al. 2018). Ultimately, citizens who become involved in IAS citizen science projects gain a voice in promoting decision-making and policy implementation, thereby supporting the development of IAS policies (Groom et al. 2019). However, there is no updated and systematic analysis of IAS citizen science projects across Europe. This would allow a better understanding of the potential reach and gaps of such projects for European science and policy. Here, we present the first comprehensive overview of European IAS citizen science initiatives. Unlike earlier work (Johnson et al. 2020), we focus on European alien species-specific citizen science projects and journal publication is not used as a criterion for inclusion. Since Europe adopted a common Regulation on IAS (the above mentioned EU Regulation 1143/2014) we wanted to assess the policy relevance of projects with a particular emphasis on the implementation of this Regulation.

In addition to developing a database of European alien species citizen science projects, we were interested in determining if there were geographic differences in three parameters of project scope (target taxon, target audience and environment type), as an indicator for international cooperation. We further evaluated the performance of projects considering their numbers of participants, number of alien species records they yielded and the publications derived from them, in order to understand how various engagement, feedback and support parameters contributed to project performance.

Materials and methods

Data collection

This survey was developed within the scope of the European Cooperation in Science & Technology (COST) Action CA17122 – "Increasing understanding of alien species through citizen science (Alien-CSI)", which includes participants from all EU Member States and a few neighboring countries. This COST Action sets out six research coordination objectives, to be first approached through a European wide analysis of existing IAS citizen science initiatives (Roy et al. 2018).

The first version of the survey was tested, revised and validated in a COST Action workshop in Akrotiri, Cyprus, 25 – 28 February 2019. Representatives from 25 countries in the COST Action attended. The survey (Price-Jones et al. 2021) was shared as a Google Form with all COST Action participants, and disseminated online. Responses were collected from June 27, 2019 to April 6, 2020. For each country, existing citizen science projects involving alien species were contacted and requested to complete the survey. All projects are/were active in EU Member States and/or neighbouring countries. A list of projects was compiled, including from a web search and previously available lists of European citizen science projects (e.g., EASIN, Kus Veenvliet et al. 2019), and the missing projects in the survey database were contacted. Finally, to increase reach, the survey was also disseminated through the European Citizen Science Association (ECSA) newsletter and mailing list and respondents were asked to share it with colleagues and local networks via snowball sampling.

Survey questions and attribute values were developed using JRC metadata standards for citizen science projects (European Commission, Directorate-General for Environment 2018) and the project metadata model of PPSR Core, a set of global, transdisciplinary data and metadata standards for Public Participation in Scientific Research (PPSR Core). The survey included 62 questions (Price-Jones et al. 2021), in nine sections: 1) Contact information of the respondent (a project coordinator); 2) General characterization of the project, including a brief summary, geographical scope, time scale, hosting entities, funding, etc.; 3) Information on project scope, including target audience, taxonomic and environmental scope, project aims, type of data collected, etc.; 4) Policy-related information, i.e., policy relevance and inclusion of species listed in the EU IAS Regulation; 5) Information on engagement, such as type of involvement of the general public in the design of the project, engagement methods and social media used, skills needed to participate and frequency of contributions; 6) Information on feedback and support provided to participants by the project, e.g., if the project provides materials for species identification, guidelines, training activities, information on how data from the project are used, feedback mechanisms and support; 7) Data quality and data management, namely validation mechanism for records, registration type, methods of recording, whether data are open and accessible to the general public, data form used to store data, data standards and data licence used, whether a public data management plan was in place; 8) Performance indicators of projects, namely usage of smartphone applications, number of participants and number of records, whether learning is assessed, number and type of publications using data from the project; and 9) Notes and remarks.

Preprocessing

Only projects that simultaneously fulfilled the following criteria were included in the analyses: 1) a clearly citizen science-focused project; 2) alien species included in the main scope; and 3) projects developed in Europe (even if not exclusively). As such, national biodiversity networks and portals collecting data on all species were only considered if they had a clear alien species focus. Projects needed to have specific forms of public engagement related to alien species, so projects solely devoted to improving IAS policies but without a typical citizen science component (e.g., data collection using target groups, interaction with volunteers) were not considered. However, projects where data gathering was less relevant, but which had clear educational and outreach goals on IAS, were included.

Due to response rates below 100% for particular questions and the prevalence of responses "Unknown" or "Not applicable", the number of projects that provided a definite response was determined and used for calculations of percentages for each question.

Statistical analysis

Exploratory analysis of project parameters

Of the nine survey sections, six asked for information about project parameters, or characteristics. These sections are: General characterisation of the project, Information on project scope, Policy-related information, Information on engagement, Information on feedback and support, and Data quality and data management strategies. To explore the parameters of all surveyed projects, the frequency of each multiple choice or written answer was determined for each question within the above sections. Additionally, we were interested in determining if an association existed between target audience and target taxonomic group, or between target audience and target environment. Fisher's exact tests were conducted with a significance level of 0.05 to test for these associations.

Geographic differences in project scope

In these series of analyses, we were interested in whether there were geographic differences in the distribution of projects, and whether project scope had a geographic component. For this, we divided Europe into five regions: Northern Europe, Eastern Europe, Southern Europe, Western Europe, and the United Kingdom and the Republic of Ireland (the UK and ROI). The UK is considered as a separate region with the ROI due to an extensive history with citizen science (Silvertown 2009). These divisions are commonly used in ecology, with minor variability in the countries in each region (e.g., Bilton et al. 1998). To normalise the quantity of projects according to the different number of inhabitants per region, the number of projects was expressed per million inhabitants using population data from the United Nations (United Nations 2019). Project distribution maps were created using ESRI ArcGIS Pro 2.7. Then, for each of three project scope parameters (target taxon, target audience and environment type), a two-way chi square test was conducted to test for association with geographical region. The tests were carried out with a significance level of 0.05.

Impact of engagement, feedback and support on project performance

To test whether parameters which related to engagement, feedback and support had an effect on project performance, we selected 11 explanatory variables (project duration, four variables related to engagement, and six variables related to feedback/support) and defined three project performance indicators: the number of participants taking part in the project, the number of species records (observations) gathered by the project and the number of publications related to the project reported by the respondent (Table 1). Three cumulative link models (CLMs) were conducted in RStudio version 3.3.3 using the package "ordinal" (Christensen 2018) in R version 4.2.0 (R Core Team 2022) to determine if engagement, feedback/support and project duration had a significant effect on performance indicators. Each of the three tests used a different performance indicator - number of participants, records and publications - as a response variable. All models were carried out with a significance level of 0.05. R code for these tests is published on Zenodo (Price-Jones et al. 2021).

Results

Exploratory analysis of selected project parameters

General characterisation of the project

In total, 129 projects/initiatives completed data for the survey and, of these, 103 fitted the criteria for inclusion and were considered for analysis. Of the 26 that were excluded, 17 were not alien species-focused, seven had no specific forms of public engagement on alien species and two were duplicate entries.

The number of new projects has increased over the past fifteen years with the oldest project recorded beginning in 2005 (Brown et al. 2008) while 21 began in 2019 (Fig. 1). Most projects (76 of 103 projects) are still ongoing. A total of 42 countries were represented in the survey. A majority of projects (66%, 68 of the 103 respondents to this question) were run at the national level, and 85% (87/103) were active in a single country. However, one project, a survey of alien species of Union Concern on iNaturalist, was active in 38 countries. In four countries (Estonia, Malta, Montenegro, and North Macedonia) this represented the sole project.

Table 1. Variables used in the Cumulative Link Models.

Explanatory variables	Response variables
Project duration	Number of participants
Project design (collaborative/contributory; engagement factor)	Number of records
Use of social media (engagement factor)	Number of publications
Level of skill/knowledge required (none/low/advanced; engagement factor)	
Expected contribution frequency (one-off/irregular/regular; engagement factor)	
Provision of guidelines (feedback and support factor)	
Provision of training (feedback and support factor)	
Provision of sightings map (feedback and support factor)	
Provision of active informing (feedback and support factor)	
Provision of feedback (feedback and support factor)	
Provision of support (feedback and support factor)	

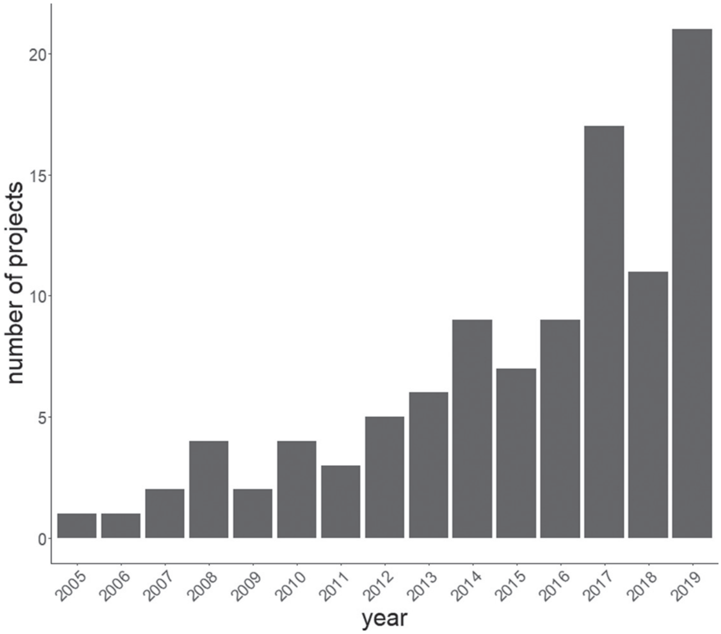

Figure 1. Number of new citizen science projects per year on alien species in Europe according to responses to the survey.

The type of organisation responsible for the projects varied between governmental (29%, 30/103) and non-governmental organisations (22%, 23/103), universities (28%, 29/103), public research organisations (22%, 23/103), and private companies, non-profit organisations and individual persons (12%, 12/103). Most projects were fully (54%, 56/103) or partially (19%, 20/103) funded, but 26% (27/103) reported having no funding. Governments were the largest source of funding, although only 36% of projects (28/78) report governments as being their sole source of funding. Otherwise, funding was provided by public entities, the EU LIFE program, NGOs or private sources, or a combination of the above.

Project scope

Plants were the most common target taxonomic group (30%, 31/103; Fig. 2a), the general public was the most common target audience (89%, 92/103; Fig. 2b), and terrestrial habitats the most common environment considered in the projects (57%, 59/103). There was no association between target audience and taxon ($p = 0.2779$), but an association was observed between target audience and environment ($p = 0.0049$). Two trends in the data included the prevalence of terrestrial projects aimed at land managers, and freshwater and marine projects aimed at fishers. The marine environment was also the environment type most frequently involving scientists and students.

84% of projects (87/103) focused solely on alien species and 9% (9/103) focused partially on alien species; 7% (7/103) responded that alien species were not the main focus, yet alien species data were collected and received some emphasis. Most projects had multiple aims, the most common being mapping of alien species distribution (Fig. 2c). Most projects also collected more than one type of data, with species presence and/or abundance being the most common.

Policy-related information

75% of projects (59/79) claimed to have policy relevance, with 79% (77/97) including species on the list of IAS of Union concern (EU Regulation 1143/2014), whether exclusively or partially.

Information on engagement

In terms of project design, 39% of projects (41/97) were categorised as collaborative (citizen scientist input was possible in project design) and 53% (56/97) as contributory (projects were designed only by scientists). The top three ways to engage citizens with the projects were through websites (83%, 83/99), social media (64%, 64/99) and live training (41%, 41/99). Newsletters, school engagement, exhibitions, bioblitzes and gaming were also common methods, each used by six or more projects. Of the projects that used social media and stated the platform, Facebook was the most popular platform, used by 65% of projects (63/96), but Twitter, Instagram and YouTube were also used. Almost 95% of projects (94/99) responded that participants needed "None" or "Limited" prior skills or knowledge to participate.

Information on feedback and support

The number of projects that provided species identification materials, guidelines, training, sighting maps, active informing, feedback and support is shown in Table 2. Of the 67% of projects (64/95) that offered training, 47% (45/95) offered group training, 31% (30/95) offered online training, and 7% (7/95) provided training through bioblitzes.

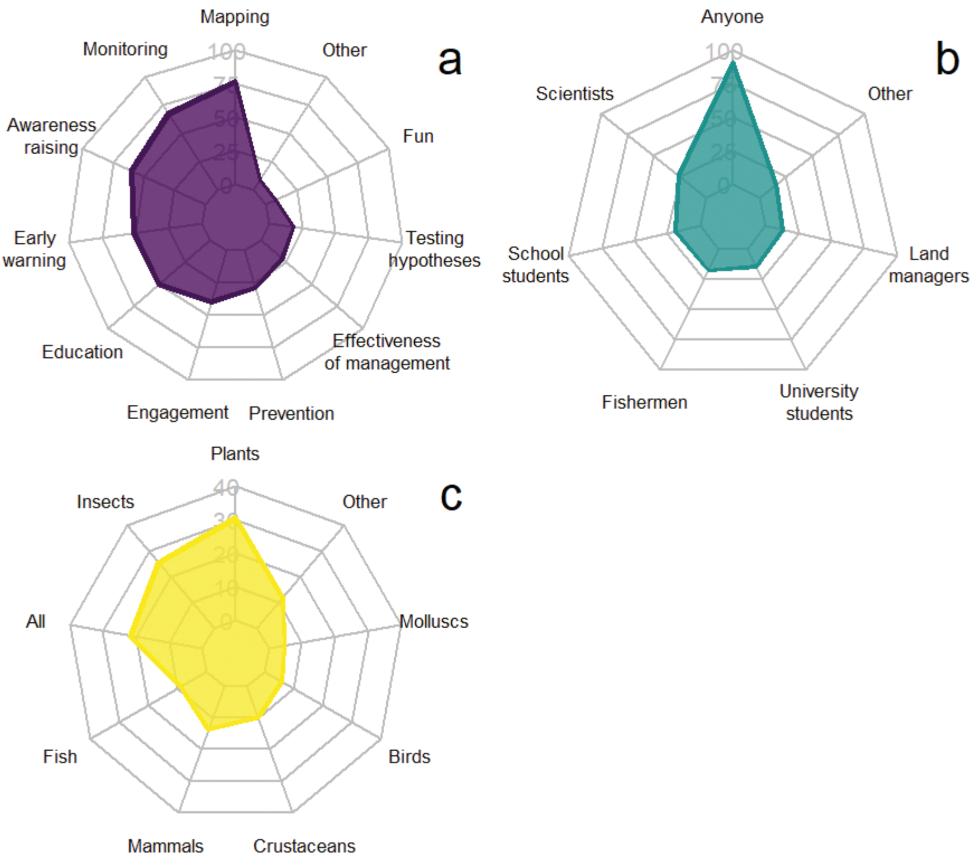

Figure 2. Percentage (indicated by numbers on radar plots) of projects that gave selected responses to project scope questions: **a** target taxon **b** target audience, and **c** stated project aim.

Table 2. Responses to survey questions concerning various feedback and support factors.

Factor	Percentage of projects		
	Yes	No	Partial (if applicable)
Provision of species identification materials	76% (74/98)	7% (7/98)	17% (17/98)
Provision of guidelines	87% (85/98)	13% (13/98)	–
Provision of training	67% (64/95)	33% (31/95)	–
Provision of sightings map	86% (78/91)	14% (13/91)	–
Provision of active informing	69% (64/93)	7% (7/93)	24% (22/93)
Provision of feedback	89% (71/80)	11% (9/80)	–
Provision of support	93% (85/91)	7% (6/91)	–

Data quality and data management

The large majority (86%, 89/103) of the projects surveyed had validation systems in place, and 6% (6/103) had partially implemented validation systems. An additional 6% (6/103) of respondents indicated that the validation system was unknown to them and only 2%

(2/103) responded they did not have validation in place. Within the subset of projects implementing validation procedures, expert validation was most commonly used, by at least 93% (93/100) of projects. Validation was either performed solely by experts (77%, 77/100), aided by automated systems (3%, 3/100) or peer validation (9%, 9/100), or a combined approach was used (3%, 3/100). Peer validation and automated validation without expert validation were only used by a minority of projects (2%, 2/100).

For data storage, projects used national repositories (38%, 34/89), hard drives (34%, 30/89), GBIF (30%, 27/89) and institutional repositories (23%, 21/89). 58 projects offered participants direct access to their own data. Excel (65%, 44/68) was the most common data form and Darwin Core (50%, 18/36) the most popular data standard. The license Creative Common Attribution (CC BY; 57%, 16/29) was the most common, followed by CC0 licence waiver (10%, 3/29) and Creative Commons Non-Commercial licence (7%, 2/29). Finally, most projects did not draft a data management plan (73%, 40/55).

Project performance

The usage of applications, number of participants, number of records and number of publications all show a distribution of responses that peaked in lower numbers and fell off quickly at higher numbers (Fig. 3), but these values were often unknown or not applicable. Only 33% of projects (21/63) assessed learning of the participants. A similar number of projects produced scientific peer-reviewed publications (94%, 33/37) and science communication publications aimed at the general public (85%, 30/37). Most of these publications directly presented data from the project (47%, 24/51) or were descriptive in nature (43%, 22/51).

Geographic differences in project scope

According to responses to our survey, the UK had more alien species citizen science projects (21) than any other country, followed by Italy (13), Portugal (9) and France (9) (Fig. 4a). However, when project counts per region are normalised by population, Northern Europe has the highest ratio, followed by the UK and ROI, Southern Europe, Eastern Europe and Western Europe (Fig. 4b). There was no association between geographic region and the target audience ($p = 0.51$), taxon ($p = 0.41$) or environment ($p = 0.16$).

Engagement methods and performance

Project duration had a significant, positive impact on the three performance indicators tested, i.e., number of participants ($z = 2.78$, $df = 1$, $p = 0.0054$), publications ($z = 3.38$, $df = 1$, $p = 0.00073$) and records ($z = 3.01$, $df = 1$, $p = 0.0026$). Projects that provided a map also outperformed projects that did not in number of participants ($z = 2.13$, $df = 2$, $p = 0.033$), publications ($z = 2.77$, $df = 2$, $p = 0.0056$) and records ($z = 2.84$, $df = 2$, $p = 0.0045$).

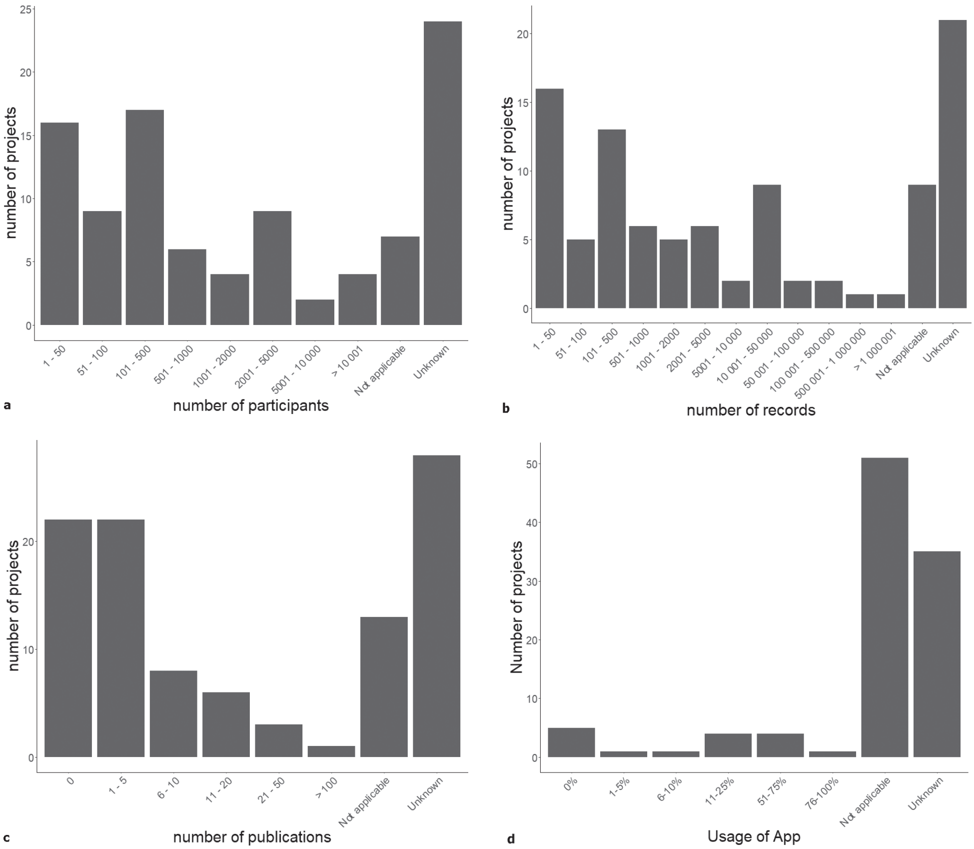

Figure 3. Survey responses concerning project performance, participation and publication. **a** number of participants (n = 72) **b** number of records (n = 73) **c** number of publications (n = 62) and **d** percentage of usage of App (n = 17).

Provision of training was positively related to the number of publications (z = 2.85, df = 1, p = 0.044), as was use of social media (z = 2.35, df = 1, p = 0.019) and provision of guidelines (z = 2.01, df = 1, p = 0.045). Projects that required advanced prior knowledge resulted in more publications than projects that required limited (z = -2.80, df = 2, p = 0.0052) or no (z = -2.74, df = 2, p = 0.0061) prior knowledge. The same result was seen in terms of number of records, with projects that required advanced prior knowledge performing better than projects that required limited (z = -2.47, df = 2, p = 0.014) or no (z = -2.02, df = 2, p = 0.043) prior knowledge.

Provision of feedback positively impacted the number of publications (z = 2.01, df = 1, p = 0.044) but negatively impacted the number of records (z = -2.01, df = 1, p = 0.044). Provision of support negatively impacted the number of publications (z = -2.59, f = 1, p = 0.0096).

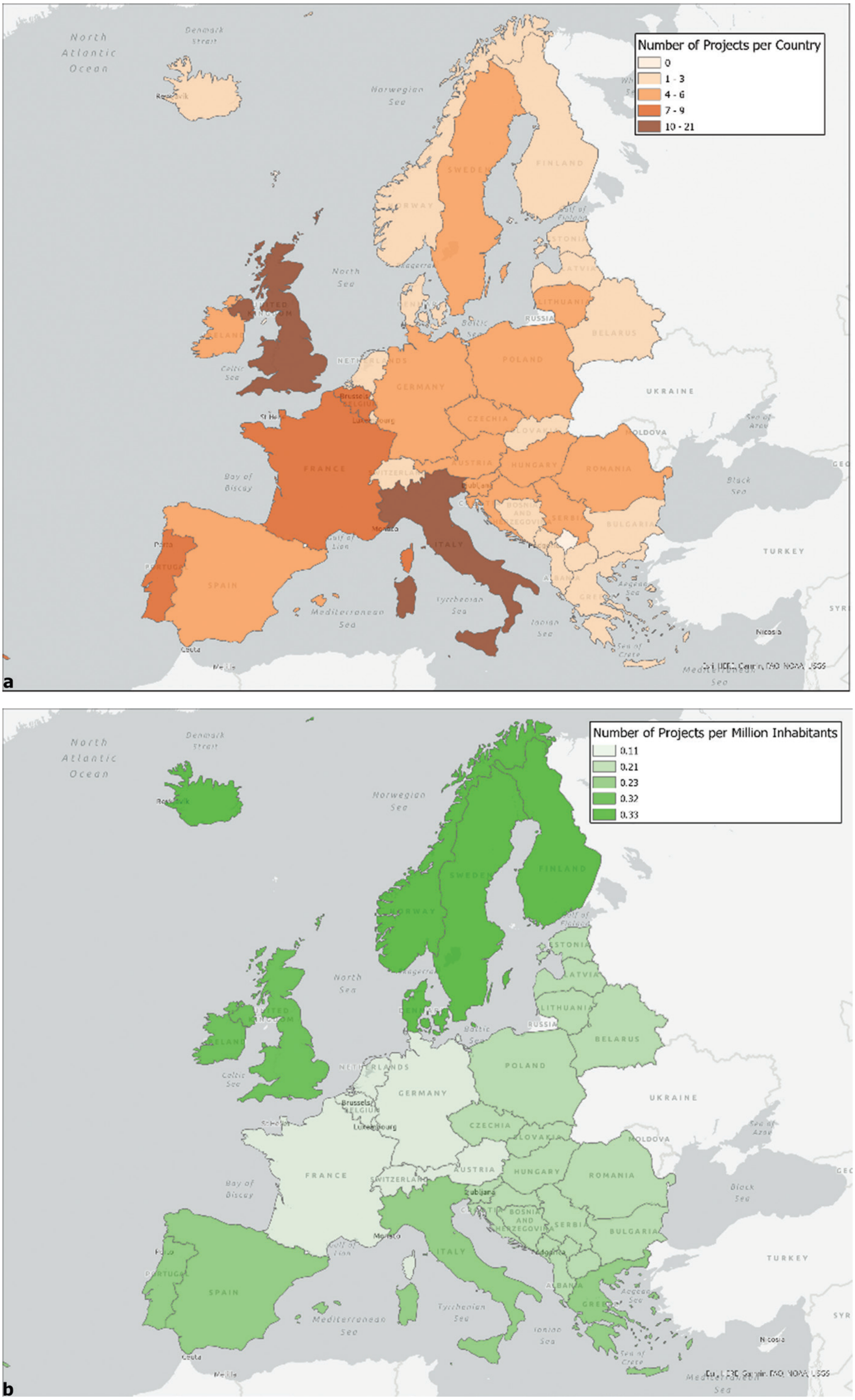

Figure 4. Geographic distribution of projects: **a** number of projects by country and **b** number of projects per million inhabitants by region.

Discussion

Project scope and regional variation

The dominance of national projects in our results is consistent with that observed for other research on management of biological invasions (Hulme et al. 2008). Several factors contribute to this tendency, including nationally-derived funding, differing degrees to which countries are exposed to or aware of alien species, species alien in one country being native to another, logistical convenience (Hulme et al. 2008) and uneven distribution of expertise (Hulme et al. 2009). However, international coordination is necessary to better protect native ecosystems from IAS (Perrings et al. 2010; Katsanevakis et al. 2013), as reflected by international agreements, from the Convention on Biological Diversity (United Nations 1992) to EU Regulation 1143/2014. There was a small degree of international coordination evident in our dataset, with most multinational initiatives being active in six or fewer geographically clustered countries.

Most projects target the general public, which is logical given our inclusion criteria. This strategy aligns with the philosophy of informing (Genovesi et al. 2015), engaging with and inspiring a passion for nature in as many participants as possible (Roy et al. 2015). Plants and insects are the most common target-taxa of projects, possibly because both are broad and speciose groups and are among the taxa containing the most invasive species with recorded ecological and/or economic impacts (Vilà et al. 2010; Haubrock et al. 2021). Furthermore, they can be easily accessible, with many urban species. The under-representation of groups such as birds is notable, and is likely a result of the concentration of data specific to these groups on large crowd-sourcing platforms that did not fit our criteria.

The prevalence of projects in the terrestrial environment similarly reflects convenience for the public, as reported for other citizen science projects (Aceves-Bueno et al. 2017). It is also highlighted by the association we found between target audience and target environment.

The most common aim is mapping of alien species, and participants are often asked to submit species presence and/or abundance data. Species presence is easy to observe, report and validate (Hyder et al. 2015), and works well in conjunction with mapping (e.g., Malek et al. 2018; Dissanayake et al. 2019; Kumar et al. 2019). Nonetheless, presence-only data have limitations: for example, the lack of absence reporting and the assumption that species were not present because they were not observed (Johnson et al. 2020).

The region with the most recorded projects is the United Kingdom and the Republic of Ireland, reflecting a long history of citizen science in ecology (Silvertown 2009). After this region, more projects in Western and Southern Europe may reflect a higher level of IAS awareness in these regions due to a relatively higher number of funded IAS projects (e.g., LIFE projects in Italy). On the other hand, a low number of projects, e.g., in the Netherlands and Belgium, may be explained by the presence of single, dominant national biodiversity portals not being included in our survey. For example, in Belgium, biodiversity recording is dominated by the general reporting portal www.waarnemingen.be which has a dedicated app and upon which early warning tools for IAS are built (Vanderhoeven et al. 2015; Swinnen et al. 2018). Additionally, there is a possible language bias, if projects from non-English speaking countries were not reached or not motivated to participate in the survey, which was only available in English.

Data quality and management

Studies evaluating data quality and management in citizen science projects sometimes have contradictory conclusions (Crall et al. 2011). Overall, volunteer contributions have been regarded favourably by scientists, e.g., 73% of papers positively described in analysis by Aceves-Bueno et al. (2017). Various tangible benefits have been noted, such as increases in the predicted spatial distribution of IAS by models trained with data from citizen science (César de Sá et al. 2019). However, Aceves-Bueno et al. (2017) also concluded that differences between volunteer data and professional data were significant in 38.4% of projects. In addition, some projects use their data for removal or management of regulated IAS, and as such correct species identification is of utmost importance. The most prominent approaches to validate citizen science data are peer and expert validation, often aided by automatic filtering techniques (Balázs et al. 2021). This is clearly also the case for IAS citizen science in Europe (Adriaens et al. 2021), with our results showing that most projects use expert validation.

Data generated by citizen science are often referred to as dark data: unreproducible, becoming more valuable over time, and at high risk of being lost (Costello and Wieczorek 2014). The implementation of a well-defined data management plan (DMP) can be used to prevent such loss of data. Nonetheless, few of the surveyed projects claimed to have a DMP and our survey did not assess adherence to the DMP for projects that had one. Many citizen science projects are relatively small scale and probably lack experience and/or access to tools for data management planning (Schade et al. 2017). Data management planning could improve the accessibility of data, an important component of FAIR (Findability, Accessibility, Interoperability, and Reusability) data management (Wilkinson et al. 2016; Reyserhove et al. 2020).

Opening alien species data is important to unlock their full potential for science, policy and management (Groom et al. 2015, 2017a,b). However, although some projects deposit their data on national or institutional repositories, less than one third make them freely available on an open data repository, e.g., through GBIF publication. We also found that most alien species citizen science projects produced peer-reviewed papers, but these were not necessarily open access; however, most also produced scientific communications aimed at the public. Reasons for avoiding open data may be multiple, including licensing issues, funding limitations, technical barriers or the privacy of the participants (Ganzevoort et al. 2017). Ganzevoort et al. (2017) found that half of the citizen scientists they surveyed believed that data collected by the citizen science organisation was a public good, but only 12% supported unconditional use. The question of data ownership is complex and can be addressed in legal terms by choice of license. We found that 92% of projects that provided licence information had a licence allowing public use. Overall, these parameters around data accessibility are consistent with the findings of Wiggins and Crowston (2011) and Schade and Tsinaraki (2016), indicating a willingness to provide access to data.

Optimisation of engagement

We anticipated that higher levels of feedback, support and engagement would improve performance, e.g., the number of participants, records and publications, through the generation of commitment and empowerment. As expected, provision of maps, training and guidelines related positively to one or more of the performance indicators. Unexpectedly, provision of feedback related positively to the number of publications, and negatively to the number of records; provision of support also negatively related to the number of publications. While citizen scientists often claim that receiving feedback is important to their continued participation (Geoghegan et al. 2016; Anđelković et al. 2022), a reduced sample size and the fact that many projects are relatively new (17 started in 2017 and 21 in 2019), may have influenced the results. In addition, the number of publications may be influenced by several other factors such as the publishing dynamic of the project team, or the level of knowledge of the survey respondent on the publications stemming from the project. Also, the many missing values in the survey responses might partly explain some of these results.

Only 39% of the projects were designed collaboratively, thus in most cases citizens were contributing in a predetermined way (usually data collection). Even so, *a priori* fewer projects were expected to be collaborative (e.g., Pocock et al. 2017 analysed more than 500 ecological and environmental citizen science projects and only 4% were collaborative) and so we suspect that this question may have been misunderstood. We define a collaboratively-designed project as a project with citizen scientist participation in the initial conception of the project and all subsequent steps. However, respondents may have considered other roles, such as feedback from participants on project design, as collaboration.

Surveyed projects mostly required low levels of time commitment for learning and participation, possibly recognising that most citizen scientists are amateur observers (Bonney et al. 2016). However, from the authors' own experience, even though many projects target the general public, in reality many of the participants do have some level of expertise in the taxonomic group they report. Another unexpected result was that projects with limited or no skill requirements were related with a significantly lower number of records and publications. Possibly, participants with advanced skill levels, having already invested the time in learning, have a stronger commitment to contributing. Nevertheless, encouraging anyone to participate is highly relevant to the goal of reconnecting people with nature (Devictor et al. 2010) and increasing the chances of prevention and early detection of IAS. Furthermore, if a contributor can both learn and teach (e.g., through peer validation), knowledge is transferred without the need for training or prior expertise. It should be noted, however, that the lessons that can be drawn from this result are limited by how the levels 'none,' 'low' and 'advanced' skills/knowledge were not defined in our survey, and so may have been interpreted differently by different respondents.

Although it depends on project goals, besides engaging participants, projects often encourage continued participation (Penner 2002). The positive relation between provision of maps, training and guidelines and some of the performance indicators suggest that these investments may encourage participation. It has been shown that publicly displayed maps allow recognition of citizen scientists' efforts (Williams and DeSteno 2008; Crowston and Prestopnik 2013).

Finally, the majority of projects used an internet-based engagement method, such as a website or social media, reflecting the ubiquity of these technologies in Europe (Kemp 2021).

Applications and recommendations

Several lessons can be drawn from the results of our survey. First, sustainability of projects is key to their performance in terms of the number of records they gather, participants they involve and publications derived from them. Second, many citizen science projects apparently have not yet opened their data. Open data publication maximises the use of the data in policy processes, such as their use by EASIN in the implementation of the EU IAS Regulation (Schade et al. 2019) and provides better return to citizen scientists on their contribution and value of their data.

One partial solution to openness and data management issues might be the drafting of DMPs, which are missing in many projects, despite these facilitating better storage, maintenance, and use of data. Although small projects may struggle to create their own, they may take advantage of existing plans, and strategies can be designed to make data openly accessible, for example on the platform GBIF. Few respondents provided information about their scientific outputs, and there is often no information on project web pages about where they publish their datasets.

To further improve outreach and onboarding of new citizen scientists, and sustained participation, our results suggest that the provision of maps with sightings and the provision of training are important. Future work could also be undertaken to compare the performance of different validation procedures and provide recommendations to new projects to improve data quality (Probert et al. 2022).

Our results show an increasing number of new alien species citizen science projects in the last few years that contribute to IAS mapping and policy implementation, but some regions still hold untapped potential for new citizen science initiatives related to alien species. Existing projects may be made accessible to new audiences through language translation or simplification, and through tailoring of aims and species lists to geographic regions (e.g., Invasive Alien Species in Europe application; Trichkova et al. 2021).

The UN's SDGs provide an excellent model for how citizen science can be relevant to setting and achieving goals at a global level. Although SDGs were not initially developed with citizen science in mind, data gathered through citizen science can be used directly for feeding SDG indicators (Fritz et al. 2019; Bishop et al. 2020), can increase the temporal and spatial scale of data collection (Schade et al. 2019) and can engage people with science and the environment (Pocock et al. 2014). Nonetheless, Fraisl et al. (2020) noted poor alignment of citizen science initiatives with target 15.8 on IAS.

Conclusions

The number of citizen science projects dedicated to alien species has been on the rise in Europe in the last decade, yet some regions in Europe still hold untapped potential for new initiatives. Citizen science initiatives often yield data on policy-relevant species, including species of the list of IAS of Union concern, and the data generated by these projects are used for science and management. Despite this, many projects face sustainability problems and only a minority of the data finds its way to open data repositories. Future work could explore the added value of specific alien species projects as compared to general citizen science biodiversity reporting portals, as well as the actual relevance of citizen science data in decision making on IAS. Also, the value of alien species citizen science in terms of increased engagement, learning outcomes and environmental awareness, needs to be further explored. To further foster active alien species citizen science across the continent, we suggest that strategies could be developed i) to support regions where alien species citizen science is currently only emerging and ii) to strengthen the links between projects and entities around the EU IAS Regulation. One way to do so is to provide networking opportunities where projects can exchange experiences.

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