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Citizen science and invasive alien species: An analysis of citizen science initiatives using information and communications technology (ICT) to collect invasive alien species observations

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A B S T R A C T

Owing to the huge number of species observations that can be collected by non-professional scientists, "citizen science" has great potential to contribute to scientific knowledge on invasive alien species (IAS). Citizen science has existed for centuries, but the recent adoption of information and communications technology (ICT) in this field (e.g. web- or mobile application-based interfaces for citizen training and data generation) has led to a massive surge in popularity, mainly due to reduced geographic barriers to citizen participation. Several challenges exist, however, to effectively utilize citizen-generated data for monitoring IAS (or other species of interest) at the global scale. Here, we conducted a systematic analysis of citizen science initiatives collecting IAS data using ICT, hoping to better understand their scientific contributions and challenges, their similarities/differences, and their interconnections. Through a search of the Scopus database, we identified 26 initiatives whose data had been used in scientific publications related to IAS, and based our analyses on these initiatives. The most common scientific uses of these citizen science data were to visualize the spatial distribution of IAS, better understand their behaviour/phenology, and elucidate citizen science data quality issues. To alleviate data quality concerns, most initiatives (19/26) had mechanisms for verifying citizen observations, such as user-submitted photographs. While many initiatives collected similar data parameters for each species observation, only 54% of the initiatives had a practice of data sharing. This lack of data sharing causes fragmentation of the citizen-generated IAS data, and is likely inhibiting the wider usage of the data for scientific studies on IAS involving large geographic scales (e.g. regional or global) and/or broad taxonomic scopes. To reduce this fragmentation and better consolidate the collected citizen science data, finally we provide some general data sharing guidelines for citizen science initiatives as well as individual volunteers.

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1. Introduction

Invasive alien species (IAS) can have major impacts on the ecosystems they invade, e.g. through predation or interspecific competition with native species (Cooper et al., 2007; Skálová et al., 2013; Vilà et al., 2011; Yu et al., 2018), and have been identified as one of the most common drivers of native species extinctions (Bellard et al., 2016). Cases do exist where IAS contribute to protecting or enhancing native biodiversity, e.g. by providing habitat or food resources for native species (Schlaepfer et al., 2011; Vilà et al., 2011), but generally their impacts on native plant/animal diversity and abundance are negative (Vilà et al., 2011). At the global scale, the economic impacts of IAS are significant. For example, invasive insect species alone are thought to be responsible for more than 70 billion USD/year in lost ecosystem goods and services, and 6.9 billion USD/year in health costs, far outweighing the economic benefits of these species (Bradshaw et al., 2016). Moreover, many IAS affect nonmarket values, such as landscape aesthetics and biodiversity, indirectly affecting tourism and other recreational businesses (Hanley and Roberts, 2019; Holmes et al., 2009). From these figures, it is clear that IAS management and control is an important environmental, social, and economic issue.

Due to the global significance of IAS, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) started a three-year global thematic assessment on IAS and their control (IPBES, 2018a) in 2019. Previous IPBES thematic assessment reports on pollinators, pollination, and food production (IPBES, 2016) and on land degradation and restoration (IPBES, 2018b) have generated public and policy interest in the concerned topics, so there will likely also be increased public interest in IAS following the release of this new assessment. This wider public interest can, in turn, result in greater citizen contributions to IAS monitoring and management.

One way for the general public to contribute to IAS monitoring and management is through participation in "citizen science" initiatives, e.g. by reporting sightings of IAS in their locality. Citizen science can be generally defined as "the engagement of non-professionals in scientific investigations" (Miller-Rushing et al., 2012). Typically the citizens involved are unpaid, and contribute out of their own personal interest in the topic of the investigation. Although citizen science has a centuries-long history, it has seen a recent surge in popularity due to advances in information and communications technology (ICT) (Miller-Rushing et al., 2012), including mobile smartphones with internet, GPS, and camera capabilities. Use of ICT has made it much easier for citizen volunteers to interact with professional scientists (e.g. through online videos or message boards) and to generate data (e.g. through web interfaces or mobile applications) (Dickinson et al., 2012; Goodchild, 2007; Miller-Rushing et al., 2012; Washitani et al., 2015). Because of this newfound popularity, hundreds of biodiversity-related citizen science projects, many which of which collect IAS observations, have been initiated within just the last decade (Theobald et al., 2015). Despite some data quality issues, the data collected through these citizen science initiatives has been recognized as having great potential to contribute to biodiversity research due to the number of species observations that can be collected by the public (Bradter et al., 2018; Chandler et al., 2017; Klemann-Junior et al., 2017). The large number of ongoing initiatives with varying taxonomic/geographic/scientific focuses, however, may confuse potential volunteers as to which initiative(s) they should participate in. Further, the fact that many citizen science initiatives are independently collecting IAS data may also pose a problem for researchers trying to analyse the data for large-scale scientific studies (e.g. IAS studies with broad geographic and/or taxonomic scopes), as the collected data will be highly fragmented (i.e. divided among many disparate sources) unless there is collaboration/data sharing between initiatives.

Due to the great potential of citizen science and ICT for IAS monitoring, in this study we conducted a review and analysis of citizens science initiatives using ICT to better understand their contributions to the broader scientific knowledge on IAS (through use of the data in peer-reviewed publications); their general characteristics, and the interconnections between different initiatives (i.e. through data sharing). Finally, from our analysis, we developed some general recommendations for data sharing to ensure that the species observations collected by these various ongoing citizen science initiatives are consolidated into a small(er) number of data sources.

1.1. IAS data collection through citizen science: potential and challenges

For the effective management of IAS, their early detection and consistent monitoring over time and space are essential. Traditional field-based monitoring approaches, in which small teams of researchers or government staff conduct ground surveys to locate IAS, however, can be very time-consuming and costly to conduct over large geographic areas. To extrapolate from sparse field-based observations, some past studies have utilized remote monitoring technologies, e.g. satellite images (Johnson et al., 2013; Visser et al., 2014) or environmental DNA analysis (Ardura and Zaiko, 2018) to estimate and map species' distribution(s). Other studies have used statistical models ("habitat models") to estimate and map species occurrence (Jordt et al., 2016; Kuzivanova et al., 2017) or abundance (Bradley et al., 2018; Potts and Elith, 2006) based on field observation data and various environmental parameters (e.g. land use/land cover type, elevation, temperature, precipitation, or distance to roads). These remote monitoring/modelling techniques, however, still require in-situ observation data for model training and validation; i.e. data on the locations at which a specific IAS is present, and preferably an estimate of the abundance of the species (e.g. number of individuals of an animal species, or the area cover of a plant species). Citizen science data can provide this much needed in-situ observation data. Although there are some concerns over the quality of in-situ data collected through citizen science initiatives (e.g. inaccurate species identifications), particularly if there is no means for professional scientists or other fellow citizen scientists to verify the observations (e.g. based on photographs taken of the observed species), the data that they generate has the potential to drastically increase the quantity of species observations available for biodiversity research (Gallo and Waitt, 2011; Young et al., 2015).

Although many biodiversity-related citizen science projects have been initiated in recent years, few have had their data used in scientific publications, and therefore contributed to the generation of new scientific knowledge. For example, Theobald et al. (2015) found that data from only 12% of the 388 biodiversity-related citizen science projects they identified were used in scientific publications. According to our re-analysis of their data, only 14% of the 56 projects considering IAS were used in scientific publications. These statistics suggest that the majority of biodiversity/IAS citizen science projects are somewhat disconnected from the academic community. In this case, simply creating more independent initiatives may have limited scientific benefits.

The proliferation of citizen science projects was realized as an issue as far back as 2011, when it was suggested that, instead of continuously "reinventing the wheel" and creating new IAS citizen science databases/projects, efforts should focus on promoting the continuity of existing long-term projects, so-as to improve the temporal scale of the data and give volunteers the confidence to be loyal to a particular set of data collection protocols (Bois et al., 2011). Quantitative evidence to support this claim can also be seen in Theobald et al. (2015), who found that citizen science project longevity and geographic extent positively affected the likelihood of the data being used in scientific publications. The large number of IAS-related citizen science projects may not be a major problem if it does not lead to fragmentation of IAS data collection efforts, e.g. if all projects are contributing their collected data to a centralized web database. However, the fragmentation of IAS data collection was realized as a problem even before citizen science projects became popular (Ricciardi et al., 2000), as invasive species data collection efforts by professional scientists have also historically been quite fragmented. While many studies have investigated the benefits (Malek et al., 2018) or challenges (Bradley et al., 2018; Cross et al., 2017) of using citizen science data for IAS monitoring, to our knowledge none have assessed the degree of fragmentation of the ongoing citizen science-based data collection efforts.

1.2. *Objectives of this study*

The main objectives of this study are to:

- Review and synthesize the contributions of citizen science data to scientific knowledge on IAS;
- Evaluate and summarize the ongoing citizen science initiatives collecting IAS data, in terms of their geographic and taxonomic scopes, and the data parameters they collect;
- Determine to what degree these different initiatives are interconnected through data sharing; and
- Develop guidelines for better data sharing between initiatives, with the aim of consolidating the collected observations.

Rather than compile an exhaustive list of citizen science initiatives related to IAS (e.g. as was done for biodiversity citizen science initiatives in Theobald et al. (2015) and Chandler et al. (2017)), we focused specifically on those initiatives with demonstrated scientific utility, as indicated by the use of their collected data in one or more peer-reviewed journal publications. Although this somewhat limited our focus to relatively large and well-established initiatives, we do not mean to imply that other citizen science projects are not also valuable. Indeed, many smaller, local initiatives may be quite successful in terms of community participation, local knowledge generation, and possibly even physical removal of IAS. These smaller initiatives, however, often face constraints (e.g. limited time, budget, or computing resources) which make the storage, analysis, and distribution of their collected observations difficult (Crall et al., 2010). One intention of our study was to help these smaller citizen science initiatives and individual volunteers identify opportunities to collaborate with larger biodiversity/IAS data collection initiatives, so that their local efforts can also contribute to IAS knowledge at a broader scale.

2. Materials and methods

To identify the relevant citizen science initiatives for our analysis, we performed a title/keyword/abstract search in Scopus, an abstract and citation database of peer-reviewed literature covering ~36,000 journals (https://www.scopus.com/). We used the search query: "invasive*" AND ("citizen science" OR "citizen sens*" OR "crowdsourc*" OR "volunteered geographic" OR "web 2.0″), with the intention of identifying any studies that used citizen science data for their research on IAS. Some of the less obvious terms were included in the search query because citizen science data is sometimes alternatively (or additionally) referred to as "crowdsourced information/data", "volunteered geographic information/data", or "web 2.0 data", depending on the scientific field. Papers that satisfied these search criteria were first screened to remove any duplicates. The remainder were then categorized into three groups: (A) **irrelevant papers**, unrelated to citizen science and IAS; (B) **somewhat relevant papers**, related to IAS but involving citizen science dataset(s) that lacked a web- or mobile application-based data submission interface; and (C) **directly relevant papers**, related to IAS and involving citizen science dataset(s) with a web- or mobile smartphone application-based data submission interface (i.e. citizen science initiatives).

After sorting the papers, we compiled a list of the citizen science initiatives belonging to the third category, and collected various types of information for these initiatives, including:

i. How the data contributed to new knowledge of IAS: The scientific discoveries or predictions made using the collected citizen science data (alone, or in combination with other datasets);
ii. The geographic and taxonomic scope: The type(s) of species observations recorded, the number of georeferenced observations recorded (up to February 2019), and the geographic area covered;
iii. The data parameters collected: Species name, latitude/longitude coordinates, species abundance information, species absence information (i.e. whether the absence of a particular species was reported, or could be determined), animal behaviour/plant phenology information, habitat information, and multimedia evidence of the observation (photographs or audio recordings); and
iv. Data sharing information: Whether or not the data had been shared with another relevant IAS or biodiversity monitoring initiative, and the name of this initiative.

All of this information was collected through our review of the relevant paper(s) as well as the initiative's own website and/or mobile application. The values of (ii) were used to understand the scope and data volume of each initiative, while the information for (iii) was used to identify similarities and differences between different initiatives in terms of the types of data parameters collected, and information on (iv) was used to help quantify the degree of fragmentation of the data collected by these initiatives.

To quantify and visualize the degree of similarity between each of the 26 initiatives in terms of their collected data parameters (out of the nine parameters from (iii)), we also generated a 26×26 cell matrix for each data parameter, with the cells in each matrix indicating whether or not two initiatives had the same data collection characteristics. If two projects both collected (or both did not collect) a specific data parameter, a value of 1 was assigned to the cell, indicating a similarity between the initiatives. On the other hand, if one initiative collected the data parameter and the other did not, a value of 0 was assigned to the cell, indicating no similarity between the initiatives. For the sake of simplicity, we did not differentiate between whether a data parameter was “required” or “optional” to report for an initiative (i.e. if a parameter was required for one initiative and optional for another, we still assigned a value of 1 to indicate a similarity between the two initiatives). Finally, we generated a matrix showing the overall degree of similarity between each project by calculating the average of the values from nine individual data parameter matrices. An overall similarity value of 1 indicates 100% similarity between two initiatives in terms of the data parameters collected, while a value of 0 indicates no similarity between the two initiatives. Initiatives with high degrees of similarity have a high potential for data sharing, particularly if the geographic and taxonomic scopes of the initiatives are also overlapping.

3. Results

3.1. Results of scopus search

Our Scopus search returned 198 papers, of which 81 were found to be irrelevant or duplicates. Of the remaining papers, 87 were identified as somewhat relevant, being related to IAS but involving citizen science initiatives that lacked a web-/mobile app-based data submission interface, and 31 papers were identified as directly relevant, being related to IAS and involving an citizen science initiative. From these directly relevant papers, we identified 26 different citizen science initiatives (data from some initiatives was used in multiple papers). Table 1 provides general information on these initiatives, including their names, websites, number of observations collected (if available), and which scientific studies the data were used in. These 26 initiatives were used as the basis for our subsequent analyses.

3.2. What was discovered/predicted using these citizen science datasets

To better understand how these citizen science datasets contributed to new scientific knowledge on IAS, we reviewed each of the 31 papers and noted how the data were used to make a new discovery or prediction. We found 27 instances in which the data contributed to a new discovery/prediction. These scientific contributions could be divided into five general categories, as shown in Fig. 1. The most common usage of the data (8/27 cases) involved overlaying the citizens’ IAS observations onto a map (based on their latitude/longitude coordinates) to visualize the spatial distribution of the observed species. Although this represents the simplest way in which the data can be used, it may not capture the full picture of the species distribution, as areas lacking observations may represent an absence of volunteers rather than the absence of a particular species.

In six studies, new discoveries were made regarding the behavioural (animals) or phenological (plants) characteristics of an IAS. For example, by studying audio recordings of yellowhammer birds *Emberiza citrinella* in their native (United Kingdom) and invaded (New Zealand) habitats, it was discovered that, due to convergent cultural evolution, song dialects that had disappeared from the native habitat still existed in the invaded habitat (Pipek et al., 2018). As another example, using Project Budburst data, it was discovered that invasive plants in North Carolina typically underwent earlier leafing and earlier flowering than the native plants, potentially giving them a competitive advantage (Wolkovich and Cleland, 2011).

In six studies, new methodological or data issues related to citizen science data were identified. For example, by investigating citizen observations in EDDMaps, Bradley et al. (2018) found that two data parameters essential to reporting of plant

Table 1
Citizen science initiatives identified through our Scopus search. Code: "S", single species; "M", multiple species; * Statistic taken from the initiative's website (as of February 2019), ** statistic taken from the Global Biodiversity Information Facility website (https://www.gbif.org/), *** statistic taken from the iNaturalist website (https://www.inaturalist.org/).

	Alien plants	Native plants	Alien animals	Native animals	Number of observations	Home page	Data used in
EDDMapS	M		M		3,483,966*	https://www.eddmaps.org/	(Bois et al., 2011; Bradley et al., 2018; Cross et al., 2017; Falk et al., 2016)
Waarnemingen.be	M	M	M	M	32,393,358*	waarnemingen.be	Swinnen et al. (2018)
BugMap			S		n/a	https://www.facebook.com/pages/category/Community/Bugmap-1926843807640177/	Malek et al. (2018)
Pl@ntnet	M	M			709,411*	https://plantnet.org/en/	(Botella et al., 2018; Joly et al., 2016)
Yellowhammer dialects			S	S	9345*	http://yellowhammers.net	Pipek et al. (2018)
UK Ladybird Survey			S		48,510 (Roy et al., 2018)	http://www.ladybird-survey.org/	(Roy et al., 2018; Roy and Brown, 2015)
eBird			M	M	361,429,888**	https://ebird.org/home	Hobson et al. (2017)
iNaturalist	M	M	M	M	16,727,397*	https://www.inaturalist.org/home	(Ciceoi et al., 2017; Hobson et al., 2017; Mori et al., 2016; Spear et al., 2017)
iMapInvasives	M		M		44,943 (Cross et al., 2017)	https://www.imapinvasives.org/	Cross et al. (2017)
Invasoras.pt	M				15,245**	http://invasoras.pt/en/	Marchante et al. (2017)
Rasprostranenie Invasionnyh Vidov Rastenij ("RIVR")	S				18,347*	https://ib.komisc.ru/add/rivr/en/	Kuzivanova et al. (2017)
Invasive Mosquito Project			M	M	n/a	http://www.citizenscience.us/imp/index.php	Cohnstaedt et al. (2016)
Vildsvin og Vandløb ("Wild boar and Water Courses")			S		n/a	http://www.gis34.dk/map.aspx?caseid = 106	Jordt et al. (2016)
Southern African Bird Atlas Project			M	M	n/a	http://sabap2.adu.org.za/ (website down in February 2019)	Broms et al. (2016)
Ontario Reptile and Amphibian Atlas			M	M	17,101***	https://ontarionature.org/programs/citizen-science/reptile-amphibian-atlas/	Seburn (2015)
Mosquito Alert (formerly AtrapaelTigre.com)			S		4160*	http://www.mosquitoalert.com/en/	Kampen et al. (2015)
That's Invasive!	M		M		291 (Adriaens, 2015)	http://www.rinse-europe.eu/resources/smartphone-apps/	Adriaens (2015)
KORINA			M		7770 (Adriaens, 2015)	www.korina.info	Adriaens (2015)
Redmap			M		n/a	http://www.redmap.org.au/sightings/	Robinson et al. (2015)
Artportalen	M	M	M	M	32,000,000 (not all from citizens) (Preuss et al., 2014)	https://www.artportalen.se/	Preuss et al. (2014)
Project FeederWatch			M	M	n/a	https://feederwatch.org/	(Cooper et al., 2007; Koenig et al., 2013)
Invaders of Texas	M				21,826*	https://www.texasinvasives.org/invaders/	Gallo and Waitt (2011)
Project BudBurst	M	M			17,808*	https://budburst.org/	Wolkovich and Cleland (2011)
North American Breeding Bird Survey			M	M	n/a	https://www.pwrc.usgs.gov/bbs/index.cfm	Cooper et al. (2007)
Christmas Bird Count			M	M	n/a	https://www.audubon.org/conservation/science/christmas-bird-count	Cooper et al. (2007)
Invasive Pest Atlas of New England/Outsmart	M		M		72,165*	https://www.eddmaps.org/ipane/	(Bois et al., 2011; Cross et al., 2017; Starr et al., 2014)

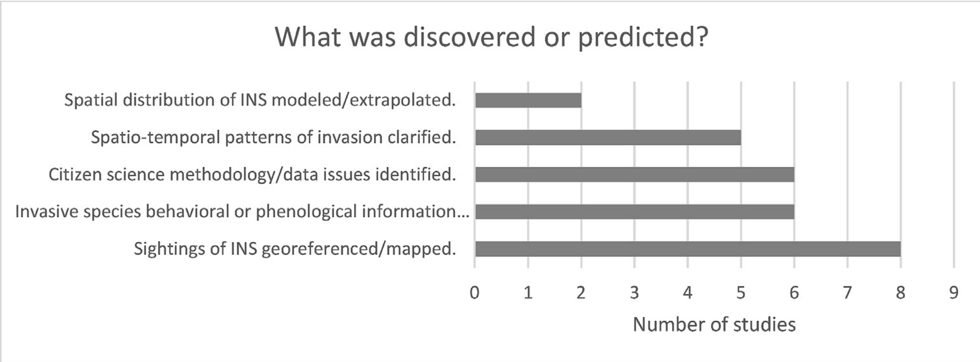

Fig. 1. Number of studies in which a specific discovery or prediction was attributed to the use of the citizen science data (alone, or in combination with other non-citizen science datasets).

species abundance (area cover and percent cover) were rarely both reported by volunteers, which limited the utility of the data for modelling species abundance. Also in relation to species abundance, Cross et al. (2017) found that the number of observations of an invasive plant at a given location was not a suitable proxy for its abundance. As another example, Starr et al. (2014) compared the effectiveness of three different methods for training volunteers to identify invasive plant species in Massachusetts, USA (in-person trainings, app-based videos, and app-based images/text), and found that in-person and video trainings had similar levels of effectiveness, while images/text alone were not sufficient.

In five studies, the spatio-temporal patterns of a species' invasion was clarified. By studying citizen sightings of monk parakeets (*Myiopsitta monachus*) in eBird and iNaturalist over time, Hobson et al. (2017) found that the species spread widely throughout Mexico after an increase in pet imports between 2008 and 2014. Using data from Redmap (as well as other non-citizen science data sources), Robinson et al. (2015) found that eight marine animal species had extended their geographic range to Tasmania in recent years, potentially due to increasing surface water temperatures.

In two studies, the spatial distribution of IAS were modelled using the citizen observations. Chadin et al. (Kuzivanova et al., 2017) predicted the spatial distribution of the invasive plant Sosnowsky's hogweed (*Heracleum sosnowskyi*) in the Komi Republic, Russia, using a generalized linear multiple regression model. Citizen and professional scientists' observations as well as various environmental and bioclimatic datasets (e.g. vegetation maps, monthly temperature and rainfall data) were used as the explanatory variables for this model. Jordt et al. (2016) also used a regression model to predict the habitat suitability of wild boar (*Sus scrofa*) in Denmark based on citizen observations from the Wild Boar and Water Courses Project as well as questionnaire surveys, official government statistics, and vegetation maps. In both of these studies, species presence/absence was predicted rather than species abundance. This is significant in that spatial abundance data are necessary to understand IAS′ population distributions, which are the main determinants of the species' environmental and economic impacts (Bradley et al., 2018). The lack of studies using citizen science data for species abundance modelling is likely due to the fact that the submission of abundance information is either optional, or not recorded at all, in many projects (see Section 3.3.2. for more details).

3.3. *Characteristics of the identified citizen science initiatives*

3.3.1. *Geographic and taxonomic scope*

Most (13) of the 26 initiatives identified were conducted at the national scale, followed by subnational (7), global (3), and regional (3) scales (Fig. 1). Of the three regional initiatives, one focused on the Americas (North/Central/South America and the Caribbean), while another focused only on North America, and the third focused on Northwest Europe. The national and subnational scale initiatives were also highly focused on Western Europe and North America, with very few initiatives focusing on other geographic regions (Fig. 2). Notably, no citizen science initiatives had a geographic focus on Asia, despite the rich biodiversity and high number of invasive species in this region. Some of the regional discrepancies detected may, however, have been due to our use of English language terms for the literature search in Scopus.

The taxonomic scope of the initiatives also varied widely. Six initiatives limited their focus to a single invasive plant or animal species (Table 1). Five initiatives focused specifically on bird species (eBird, Southern African Bird Atlas Project, Project FeederWatch, North American Breeding Bird Survey, and Christmas Bird Count), while another two limited their focus to mosquito species (Invasive Mosquito Project, Mosquito Alert), and one more focused only amphibians and reptiles (Ontario Reptile and Amphibian Atlas). A few studies limited their taxonomic scope to the several priority invasive species within the geographic area of interest (e.g. EDDMapS, That's Invasive!), and for these initiatives the organizers typically developed very detailed training materials to help volunteers identify the species of main concern. Finally, three initiatives (iNaturalist, Waarnemingen. be, and Artportalen) had a very wide taxonomic scope, allowing observations to be submitted for any native

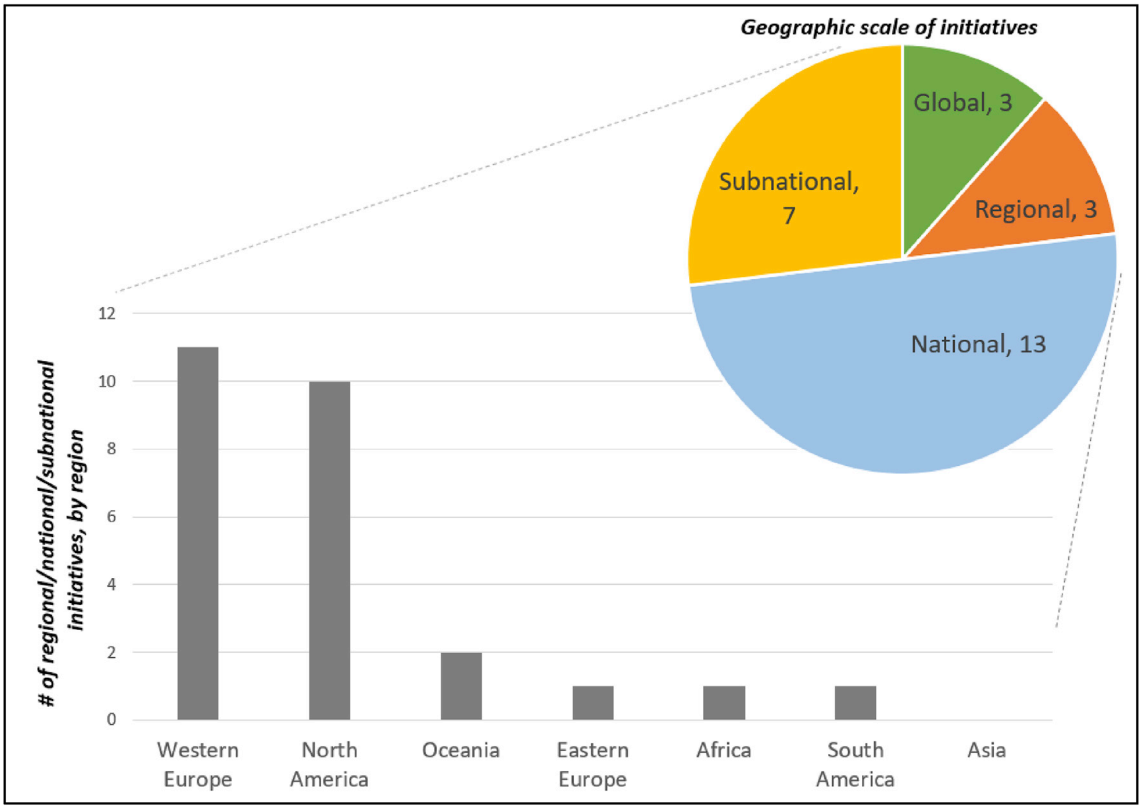

Fig. 2. Geographic scales and focuses of the 26 identified citizen science initiatives.

or non-native plant or animal species. As shown in Table 1, the initiatives with the highest number of recorded observations were generally those that did not limit their focus specifically to collecting invasive species observations. For these broader initiatives, however, it is difficult to identify exactly how many of their observations were of invasive species. The eBird initiative had more observations (~361 million) than the rest of the initiatives combined, which illustrates how popular citizen science is within the bird watching community (and how popular birdwatching is in general).

3.3.2. Data parameters collected by each initiative

The 26 initiatives varied in terms of the data parameters collected for each volunteer observation, as shown in Table 2. Some data parameters, however, were collected by many of the initiatives. Species name was the most commonly collected data parameter, being a required parameter for 22 projects and an optional parameter for the remaining four projects. In the initiatives where the species name was an optional parameter, a photograph of the observed species was required, presumably so that a fellow citizen scientist or professional scientist (or a machine-learning algorithm in the case of (Joly et al., 2016)) could help identify the species at a later stage. Latitude/longitude coordinates were either required or optional in 24 initiatives, and these coordinates were, in most cases, recorded automatically using GPS functionality built into the mobile app. The remaining two initiatives possibly lacked this latitude/longitude parameter for privacy reasons; The Invasive Mosquito Project is mainly intended to be conducted by school children and teachers as a class science project, while Project FeederWatch involves volunteers recording the species of birds visiting the feeder(s) in their home garden). When latitude/longitude coordinates were not recorded, other coarser identifiers were used to help georeference the observations (e.g. postal code or city name). Species abundance information, typically either the number of specimens observed (for animals), or the area extent and percent cover (for plants), was required by a majority of projects (15) and optional for five. Photographs were required for 12 projects and optional for six, and they were important both for helping to confirm that volunteer observations were correct, and for assisting volunteers unable to identify the species observed. Other parameters were less commonly recorded, including habitat descriptions (7 projects), species absence data (5 projects), animal behaviour/plant phenological information (4 projects), audio recordings of the observed species (4 projects), and weather information (3 projects). Some additional types of data were collected by a single project, but for the sake of brevity they are not reported here.

From the matrix showing the degree of similarity between the initiatives in terms of their data parameters collected (Fig. 3), it can be seen that in 14 cases, two different initiatives were collecting exactly the same information for each volunteer

Table 2
Data parameters recorded by each initiative. Code: “x”, required data parameter; “o”, optional data parameter. The SUM row shows the number of initiatives having a parameter as either required or optional.

		Species monitored				Data parameters collected									Method of submission	
DID	Name of citizen science initiative	Non-native plant(s)	Native plant(s)	Non-native animal(s)	Native animal(s)	Species name	Latitude/longitude coordinates	Abundance	Absence information	Photo(s)	Audio	Behavioural/ phenological information	Habitat information	Weather information	Website	Mobile application
1	EDDMapS	x		x		x	x	o		o			o		x	x
2	Waarnemingen.be	x	x	x	x	o	x	x		x					x	
3	BugMap			x		x	x	x		x			x			x
4	Pl@ntnet	x	x			o	o			x					x	x
5	Yellowhammer dialects			x	x	x	o				x				x	x
6	UK Ladybird Survey			x		x	o	x		x			x		x	x
7	eBird			x	x	x	o	x		o	o				x	x
8	iNaturalist	x	x	x	x	o	o			x	o				x	x
9	iMapInvasives	x		x		x	x	o		x					x	x
10	Invasoras.pt	x				x	x	x		x		o	x		x	x
11	RIVR	x				x	x			x					x	
12	Invasive Mosquito Project			x	x	x		x							x	
13	Wild boar and Water Courses			x		x	o								x	x
14	Southern African Bird Atlas Project			x	x	x	x	x	x						x	
15	Ontario Reptile and Amphibian Atlas			x	x	x	x	x		o	o				x	x
16	Mosquito Alert			x		o	x			x					x	x
17	That's Invasive!	x		x		x	x	x		x						x
18	KORINA			x		x	o	x		x						x
19	Redmap			x		x	x	o		o			o	o	x	x
20	Artportalen	x	x	x	x	x	x	o		o		o			x	
21	Project FeederWatch			x	x	x		x	x			x			x	
22	Invaders of Texas	x				x	x	x	x	x			x		x	x
23	Project BudBurst	x	x			x	x	x				x			x	
24	North American Breeding Bird Survey			x	x	x	x	x	x					x	x	
25	Christmas Bird Count			x	x	x	x	x	x					x	x	
26	Invasive Pest Atlas of New England/Outsmart	x		x		x	x	o		o			o		x	x
	SUM	**12**	**5**	**21**	**11**	**26**	**24**	**20**	**5**	**18**	**3**	**4**	**7**	**3**	**23**	**17**

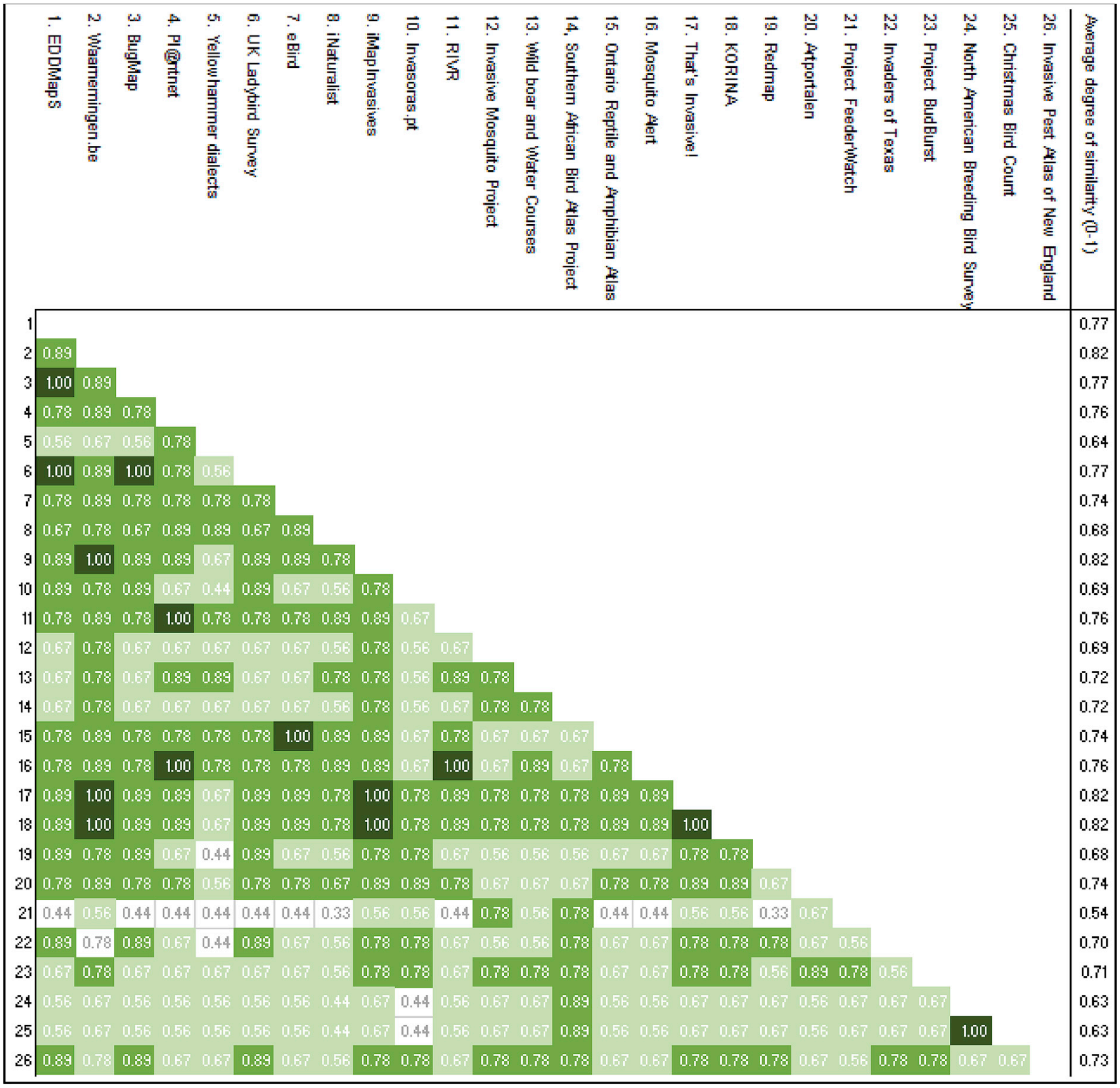

Fig. 3. Degree of similarity (0–1) between each of the 26 citizen science initiatives, in terms of the collected data parameters. Row and column numbers correspond to the project ID's in Table 2.

observation (i.e. value of 1 in the matrix). The average degree of similarity between different initiatives (i.e. average of all the values in Fig. 3 matrix) was 0.73, indicating a 73% overlap of the data parameters collected by different initiatives. This relatively high degree of similarity between initiatives in terms of the data they collected suggests a strong potential for data sharing between initiatives. The main outliers, representing more “niche” initiatives, that can be seen in this matrix were Project Feederwatch (ID #21; average degree of similarity = 0.54), Yellowhammer Dialects (ID #5; average degree of similarity = 0.64), and Invasoras. pt (ID # 10; average degree of similarity = 0.69). Project Feederwatch was dissimilar from the other initiatives in that it did not record the geographical coordinates of observations, lacked a functionality for photo submission, and required behavioural information to be provided. Yellowhammer Dialects was dissimilar from the other initiatives (although not nearly to the same degree as Project Feederwatch) mainly because it required submission of audio recordings and lacked the functionality for photo submission. Invasoras. pt was dissimilar in that required habitat information and requested behavioural/phonological information; both of which were uncommon data parameters. Although their uniqueness makes these initiatives interesting on their own, their difference from other citizen science initiatives may make it more challenging for them to identify opportunities for collaboration and data sharing.

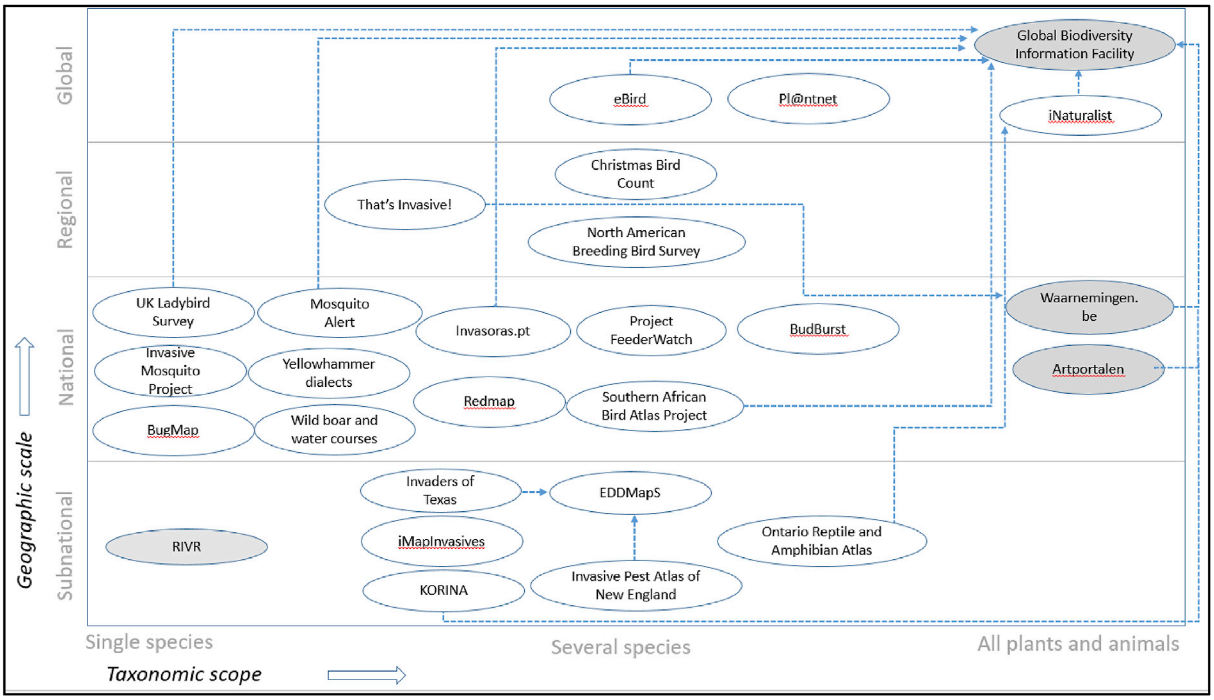

Fig. 4. Data sharing between different citizen science initiatives, indicated by the blue arrows. Gray circles indicate datasets that contain observations from both citizen scientists and professional scientists. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.4. Collaboration and data sharing

Although the different citizen science initiatives generally collected similar data parameters, we found that only 14/26 (54%) of the initiatives shared their collected data with other initiatives/other biodiversity databases (Fig. 4). This indicates that citizen science IAS data collection efforts are still quite fragmented in terms of geographic and taxonomic coverage. Of the 14 initiatives that shared data, some did so with other citizen science initiatives, while others shared data with more general biodiversity databases (i.e. those containing data contributed by citizen scientists as well as professional scientists). For visualization, Fig. 4 shows the instances of data sharing between the initiatives, as well as general information on the geographic and taxonomic scopes of the initiatives. As can be seen in Fig. 4, most cases of data sharing involved subnational or national initiatives transferring their data to global databases with wide taxonomic scopes, i.e. iNaturalist or the Global Biodiversity Information Facility (GBIF). The next most common cases were data sharing between subnational initiatives, and this only occurred between subnational initiatives located within the same country (due to their similar or overlapping geographic scopes). Other types of data sharing were uncommon.

Although it is not a citizen science initiative, GBIF was by far the largest recipient of data contributed by the citizen science initiatives. GBIF is a web database containing various types of biodiversity data, including citizen and professional scientists' observations of IAS, and it is now the largest species occurrence database in the world (Chandler et al., 2017). As the name implies, its geographic scope is global, and the taxonomic scope includes all species. GBIF permits the submission of a wide range of data parameters, and it also provides functionality for public download of all of its raw data. For these reasons, it has high utility for scientific studies related to IAS. Unlike the citizen initiatives analysed in this study, however, GBIF does not allow observations to be submitted directly by individuals, and only institutions can contribute data. On the other hand, the organizers of citizen science initiatives – often an academic, scientific, or non-profit organization – are typically eligible to submit data to GBIF.

4. Discussion and conclusions

4.1. Consolidating the collected IAS observations

One of the most significant results of our analysis was that, as indicated in Section 3.5., nearly half of the citizen science initiatives we analysed were not sharing data with other initiatives or other IAS/biodiversity databases. All of these initiatives already store their collected data online (since the data is collected through websites or mobile apps), so it should be easier for them to share data as compared to citizen science initiatives that do not utilize ICT (e.g. those that rely on hard copies). Previous studies have also highlighted this issue of data sharing. Crall et al. (2010) conducted a survey of 249 IAS citizen science initiatives' organizers, and found that most 77% were willing to share their data, although the authors did not assess many actually shared their data online (and how many shared data only by request). Theobald et al. (2015) found that 37% of biodiversity citizen science initiatives provided all of their collected data via public download, while another 50% made some of the data available (e.g. viewable as a map or aggregated into figure/table). We should note that several of the initiatives in our study which did not actively share data with another initiative/database, did allow for data download from their project website (e.g. EDDMapS, Project BudBurst). Several others, however, did not (e.g. Yellowhammer Dialects, Invasive Mosquito Project), although some may share this data upon request. In either case, large-scale analysis of collected observations (e.g. to better understand IAS at the global or regional level) would greatly benefit from the consolidation of the data into one (or a few) database so that the data does not need to be downloaded from many separate project websites. To help promote greater consolidation of the collected IAS data, here we formulated some general guidelines, which fall into three categories:

1) **Geographic information consolidation**: An initiative should aim to contribute its data to other initiative(s) having a broader (or equivalent) geographic scope, provided that the geographic range of the smaller initiative is included in that of the larger initiative.
2) **Species information consolidation**: An initiative should aim to contribute its data to other initiative(s) having a broader (or equivalent) taxonomic scope, provided that the species observations of the smaller initiative are within the taxonomic scope of the broader initiative.
3) **Data parameter consolidation**: An initiative should aim to contribute its data to other initiative(s) that are collecting more (or an equivalent number of) data parameters, provided that the "key" data parameters (as determined by the smaller initiative) collected by the smaller initiative are also included in the broader initiative. This guideline is necessary to avoid losing valuable information when data is shared between initiatives. Additionally, it is recommended to clarify whether a species is invasive at each observed location (e.g. by tagging these observations as "invasive") when sharing data to allow for greater compatibility for IAS monitoring.

Based on these guidelines, GBIF seems to provide a good candidate for smaller/more specific citizen science initiatives to share their data with, as it is a global database with a broad taxonomic scope, and allows for submission of a large number of data parameters.

For individual citizen scientists interested in contributing to large-scale (e.g. global or national) IAS observation databases, however, the choice of which initiative to participate in is less clear. As already mentioned, GBIF does not provide a direct outlet for individual citizen scientists to provide their data. It is possible, however, for individuals to contribute data to GBIF indirectly, by participating in a citizen science initiative that provides its data to GBIF. For observations of invasive bird species, eBird seems a logical choice for individuals to contribute their data to due to its large geographic scope, high number of contributors, and collection of most important data parameters (including species abundance information). eBird contributes its data to GBIF, which is another advantage. For other animal and plant species, the choice for citizens is less clear. Most of the initiatives with broad taxonomic scopes are national or subnational in scale (Fig. 4), so they don't provide valid options for citizens outside of these countries. iNaturalist was the only citizen science initiative we found with a global geographic scope and broad taxonomic scope, so it seems a valid option for the majority of citizens interested in contributing to a global IAS database (especially considering that it also shares its observations with GBIF). iNaturalist, however, currently only formally supports the collection of species presence data, as its definition of an observation is "an encounter with an individual organism at a particular time and location" (https://www.inaturalist.org/pages/getting+started). That said, it is possible for contributors to create customized observation fields (https://www.inaturalist.org/observation_fields) and informally report abundance or other phenomenon of interest.

Aside from these biodiversity-related initiatives, other more general citizen science initiatives and platforms (i.e. collections of initiatives hosted on a single website) exist. One example is CitSci.org, a website that hosts citizen science projects with many different types of objectives. CitSci.org was previously suggested as a common platform for different IAS-related initiatives (Crall et al., 2010), but as of yet the data from this platform (and other similar platforms) does not seem to have been utilized in scientific studies on IAS (at least based on our Scopus search).

Finally, we should mention that, aside from consolidation of the collected IAS observations (which we have focused on in detail here), data standardization is also an important issue that has been recognized in past works (Bradley et al., 2018; Crall et al., 2010). For example, citizen science initiatives may use different sampling schemes for the collection of species observations (e.g. systematic vs. opportunistic data collection) (Crall et al., 2010). Similar data parameters may also be collected in slightly different ways. For example, IAS plant species abundance may be estimated using different descriptors of the infested area and/or percent cover (i.e. qualitative vs. quantitative descriptors) (Bradley et al., 2018). This can hinder the usefulness of the shared data for large-scale scientific studies on IAS. Hence, future studies may want to focus greater attention on this data standardization issue.

4.2. Conclusions

In this study, we analysed citizen science initiatives collecting invasive alien species (IAS) observations, with a focus on initiatives utilizing web- or mobile application-based interfaces for citizen training and data submission. From a search of Scopus, we identified 26 relevant initiatives that had their data used in peer-reviewed studies on IAS. Although this search certainly missed some relevant initiatives, our analysis of these 26 initiatives provided a general overview of how citizen science data and information and communications technology (ICT) are being used to generate IAS data, what the scientific contributions of this data have been, what similarities/differences exist between initiatives, and how different initiatives have become interconnected through data sharing.

In terms of the ICT utilized by these initiatives, all had web- and/or mobile application-based interfaces, while nearly all (24/26) employed GPS technology to record the coordinates of the citizen observations, and most (21/26) allowed for photos and/or audio recordings to be uploaded so that the accuracy of the citizen observations could be verified. Most of the initiatives had a geographic focus on Western Europe or North America, despite a great need in other regions (e.g. developing countries and island countries). Although the collected data has already made significant contributions to scientific knowledge on species invasions, further efforts are required to ensure that the data is consolidated into a small number of (or even a single) web databases containing biodiversity-related information (e.g. GBIF). This data consolidation would greatly enhance the utility of the data for regional- and global-scale scientific studies on IAS, including the upcoming IPBES thematic assessment on IAS and their control.

The main source of uncertainty in our study was the limited sample size (26 initiatives), and this was due to our focus on a very specific subset of the citizen science initiatives collecting IAS data (those using ICT and having already been utilized in peer-reviewed publications). In future work, it may be beneficial to expand our analysis to citizen science initiatives that have not yet had their data used in peer-reviewed literature, to understand if differences exist in terms of their collected data parameters and data sharing practices. It would also be worthwhile to investigate how IAS citizen science data (or other biodiversity-related citizen science data) can be incorporated into broader citizen science initiatives like OpenStreetMap (www.openstreetmap.org), e.g. to better analyse the relationships between IAS observations (or other species observations) and land-use features.

Role of the funding source

We declare that the funding source had no involvement in the study design; in the collection, analysis and interpretation of data; in the writing of the report; and in the decision to submit the article for publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gecco.2019.e00812.

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