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Species interactions: next-level citizen science

Quentin Groom, Nadja Pernat, Tim Adriaens, Maarten de Groot, Sven D. Jelaska, Diana Marčiulynienė, Angeliki F. Martinou, Jiří Skuhrovec, Elena Tricarico, Ernst C. Wit and Helen E. Roy

Q. Groom (https://orcid.org/0000-0002-0596-5376) ✉ (quentin.groom@plantentuinmeise.be), Meise Botanic Garden, Meise, Belgium. – N. Pernat, Leibniz Centre for Agricultural Landscape Research, Muencheberg, Germany. NP also at: Freie Univ. Berlin, Dept of Biology, Chemistry, Pharmacy, Inst. of Biology, Berlin, Germany and Berlin-Brandenburg Inst. of Advanced Biodiversity Research (BBIB), Berlin, Germany. – T. Adriaens, Research Inst. for Nature and Forest (INBO), Brussels, Belgium. – M. de Groot, Dept of Forest Protection, Slovenian Forestry Inst., Ljubljana, Slovenia. – S. D. Jelaska, Dept of Biology, Faculty of Science, Univ. of Zagreb, Croatia. – D. Marčiulynienė, Inst. of Forestry, Lithuanian Research Centre for Agriculture and Forestry, Girionys, Kaunas, Lithuania. – A. F. Martinou, Cyprus Inst. & Joint Services Health Unit, Nicosia, Cyprus. – J. Skuhrovec (https://orcid.org/0000-0002-7691-5990), Crop Research Inst., Group Function of Invertebrate and Plant Biodiversity in Agro-Ecosystems, Prague, Czech Republic. – E. Tricarico, Dept of Biology, Univ. of Florence, Sesto Fiorentino (FI), Italy. – E. C. Wit, Inst. of Computational Science, Univ. della Svizzera Italiana, Lugano, Switzerland. – H. E. Roy, UK Centre for Ecology and Hydrology, Wallingford, Oxfordshire, UK.

Ecography
44: 1–9, 2021
doi: 10.1111/ecog.05790

Subject Editor: Dominique Gravel
Editor-in-Chief: Miguel Araújo
Accepted 27 September 2021

We envisage a future research environment where digital data on species interactions are easily accessible and comprehensively cover all species, life stages and habitats. To achieve this goal, we need data from many sources, including the largely untapped potential of citizen science for mobilising and utilising existing information on species interactions. Traditionally volunteers contributing information on the occurrence of species have focused on single-species observations from within one target taxon. We make recommendations on how to improve the gathering of species interaction data through citizen science, which data should be collected and how it can be motivated. These recommendations include providing feedback in the form of network visualisations, leveraging a wide variety of other data sources and eliciting an emotional connection to the species in question. There are many uses for these data, but in the context of biological invasions, information on species interactions will increase understanding of the effects of invasive alien species on recipient communities and ecosystems. We believe that the inclusion of ecological networks as a concept within citizen science, not only for initiatives focussed on biological invasions but also across other ecological themes, will not only enrich scientific knowledge on species interactions but also deepen the experience and enjoyment of citizens themselves.

Keywords: data collection, ecosystems, human environment, networks, species interaction

Introduction

Understanding the effects of change on biodiversity and ecosystems requires holistic consideration of both biotic and abiotic factors (González-Salazar et al. 2013). In recent years, the relationship between species distributions and abiotic factors has been studied intensively through the development of sophisticated species distribution models (SDM).

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The results from SDM and their predictive power under different scenarios are increasingly used as the basis for management decisions related to biodiversity, including invasive alien species (IAS) management (Vicente et al. 2016, Barbet-Massin et al. 2018, Fernandez et al. 2019). SDM are able to both work with aggregated data and incorporate future climatic and land-use change scenarios (Kerkow et al. 2019, Roy-Dufresne et al. 2019). However, SDM are for the most part correlatory and obfuscate cause and effect. Mechanistically, these correlations may not be a direct consequence of abiotic factors, but the result of a complicated set of interactions, including among different species (Dormann et al. 2018). There is a risk that these correlations may mislead our conclusions of future change and, therefore, misdirect management decisions.

Every species on the planet interacts with other species, whether that is in a trophic cascade as predator or herbivore, in some kind of symbiosis, such as mutualism, commensalism or parasitism; through interspecific competition; through transmission of disease agents; through spatial proximity or other forms of energy, biomass and nutrient flux, or simply as an epibiont. In recent years, research on, and application of, ecological networks has gained momentum as methods and access to interaction data have improved (Poelen et al. 2014, Poisot et al. 2016a, b, Delmas et al. 2019). These networks are not only research and simulation tools but also an instrument to communicate results to the scientific community, policymakers and the public (Pocock et al. 2016). In addition, networks can be presented so that people can see themselves as part of the network and understand the concept of nature's contribution to people (Pocock et al. 2016, Díaz et al. 2018). For example, the shifts in entire systems may become apparent when interactions are disrupted through biological invasions and other drivers of environmental change.

Of particular interest to the authors is invasion biology, a field in which there are several keystone hypotheses related to biotic interactions. For example, the 'enemy release hypothesis' predicts fewer negative interactions on invaders in their invaded range compared to within the native range (Maron and Vilà 2001). Species interactions are one of the primary means by which IAS have a negative impact on other biodiversity (Blackburn et al. 2014). These interactions include predation, herbivory, toxicity, disease transmission and competition, thereby emphasizing how relevant a holistic understanding of ecological networks is to prevent, manage and control IAS (Zavaleta et al. 2001). Furthermore, when IAS invade ecosystems, they can alter networks, potentially resulting in the loss of interactions and species (Penk et al. 2017).

Furthermore, invasion success has been linked to specific novel, unforeseen ecological interactions such as the presence of naïve prey (Cox and Lima 2006) and the availability of empty ecological niches (Darwin 1859) and to the priority effect, whereby the order and timing of arrival of an alien species can shape the community structure (Dickson et al. 2012). The complex chains of ecological interactions and the cascades of effects highlight the need for data on the spectrum of interactions, their strength, periodicity and frequency to inform understanding of invasion success.

Much of what we know about the distribution of biodiversity comes from citizen scientists, and the data they collect are essential to research on environmental change (Chandler et al. 2017) including biological invasions (Roy et al. 2015). Citizen science or the 'active public involvement in scientific research' (Irwin 2018) has made a major contribution to ecological research, but occurrence datasets gathered by volunteers also contribute to policy through instruments such as the European Common Bird Index (Gregory et al. 2005), the European Grassland Butterfly Index (van Swaay et al. 2016) and the Marine Strategy Framework Directive (Nascimento et al. 2018).

Even before the term citizen science was coined in the 1990s (Eitzel et al. 2017), amateur naturalists asked research questions, collected data and produced results (Strasser et al. 2019). Of course, the Internet and smartphones have increased the possibilities for public involvement in scientific data collection, and so have the types of projects and of data gathered (Newman et al. 2012, Theobald et al. 2015, Hamer et al. 2018, Braz Sousa et al. 2020). Citizen science is making an ever-growing contribution to biodiversity databases (Chandler et al. 2017, Poisson et al. 2019) and has also proven itself as a method for monitoring biodiversity, especially at large scale, for example, not only in passive surveillance for early warning of biological invasions but also on local or regional scales to monitor the range expansion of the invaders (Goldstein et al. 2014, Andow et al. 2016). Citizen science is also important in underpinning IAS management. The involvement of different stakeholders in the process of gathering information will increase understanding of the specific invasion syndrome (combination of pathways, alien species traits and characteristics of the recipient ecosystem which collectively result in predictable dynamics and impacts) and so can prioritise management actions (Novoa et al. 2018). Information on species interactions could enrich understanding of IAS, for example, interactions of an IAS within its native range could help predict the potential impacts of the species within an invaded range. Also, Haelewaters et al. (2017) suggested involving citizens in reporting interactions to identify potential biocontrol agents.

Despite the value of including species interactions within studies, the majority of citizen biodiversity monitoring projects focus on the observations of single taxa. In some cases of obligate dependency, a species interaction can be inferred from the co-occurrence of organisms; however, co-occurrence is generally a poor surrogate for actual evidence of an ecological interaction (Blanchet et al. 2020, Peterson et al. 2020). In only a few projects have people, directly or indirectly, been asked to report what the species is doing and with whom in the moment of observation, such as recording an insect visiting a flower or recording the activity of an observer preceding a tick encounter (Kremen et al. 2011, Porter et al. 2019). However, some citizen science data are aggregated in the Global Biotic Interactions Database (GloBI, Poelen et al. 2014). For example, the iNaturalist platform is used for surveys on specific interactions. Projects include *sea otter prey*, *Odonata as prey*, *pollinator association*, *jumping spider meals* and others. Many of these surveys can be regarded as community-based monitoring programmes sensu Chandler et al. (2017).

Here we argue that citizen science can make a major contribution to our understanding of the effects of environmental change on biodiversity and ecosystems and, indeed, human health and well-being by collecting species interaction data. We believe that the existing benefits of citizen science can be built upon and traditional single taxon recording can be taken to a new level by additionally collecting data on species interactions. We identify some of the difficulties in this approach and present potential solutions in three key elements: 1) project design and incentives for next-level citizen science; 2) possibilities and limitations in interaction data collection by volunteers; and 3) data integration and use on open data platforms.

The challenges of involving citizens in monitoring ecological interactions

There are many ways and contexts in which interested people could collect data on species interactions. As examples, we consider potential opportunities and challenges (Table 1) of integrating species interactions within citizen science approaches using examples of two contrasting themes:

Pollination services – monitoring flower visitation, to support an understanding of pollination as an ecosystem service, but noting that flower visitation is only a proxy for pollination.

Public health – understanding the behaviour and habitat use by mosquitoes (Fig. 1).

1) Project design and incentives for next-level citizen science

Eliciting an emotional connection

The motivation that people have to report single-species observations may also apply to reporting interactions (Domroese and Johnson 2017). Jarić et al. (2020) suggest that a species' charisma affects the public's attitude towards it. To kindle interest in species interactions we, in fact, believe that the target species merely needs to be emotive, rather than only charismatic. The connection to the participant could be positively emotive, e.g. by exploiting the appealing physical appearance of species (Sequeira et al. 2014) such as ornamental plants and pets, or negatively emotive, such as IAS that threaten native flora (Gallo and Waitt 2011), disease vectors (Palmer et al. 2017, Porter et al. 2019) or pathogens (Meentemeyer et al. 2015). Alternatively, in addition to eliciting an emotive response to the target species or when an emotive connection is not directly available, interactions are particularly suited to building a story that links emotions and experiences (Hecker et al. 2018, Richter et al. 2019). How species interact is in essence natural history with the potential to trigger motivational curiosity for participants (Everett and Geoghegan 2016).

Keep it simple and fun

Designing programmes for public participation in scientific research requires a tradeoff between maximising participation, outreach and learning outcomes and complexity of the research

Table 1. A summary of the problems associated with collecting species interaction data and their potential solutions, particularly as these related to citizen science data.

Objective	Problems	Solutions
Motivation and design	No interest in monitoring interactions	• Eliciting an emotional connection • Incentives to record interactions/mitigating fears of complexity
	Citizens do not understand why they should record interactions	• Visualisation of networks, particularly if they incorporate their data • Active communication about the need for data and the research goals
	Citizens may be put-off by complex protocols	• Improvements to current systems of single species recording • Simple methods • Integration within existing projects or platforms • Focus on the peri-domestic environment, such as gardens • Prompting contributions with automatic suggestion, for example with the aid of AI (Pocock et al. 2016)
Data	Recording bias and invisible interactions	• Improved statistics to detect and account for bias • Field protocols to reduce bias (Kelling et al. 2019) • Adequate collection of metadata
	Missing data	• Leveraging what already exists in the literature and elsewhere (see Supporting information for examples). • Including data from the native range of alien species could be potentially useful • Open data
	Availability and accessibility of analysis tools	• Providing tools in popular Open Source platforms such as R • Build in network visualisation into online platforms used by citizen scientists
	Lack of data on human–wildlife interactions	• Look to alternative sources of information, such as public health, social media and medicine
Integration	Transferability of interaction data between native and introduced range	• Taking advantage of gardens where non-native plants mingle with native organisms
	Doubling the scientific names in an observation compounds the potential taxonomic confusion	• Work with names resolution services and aggregated taxonomic authorities

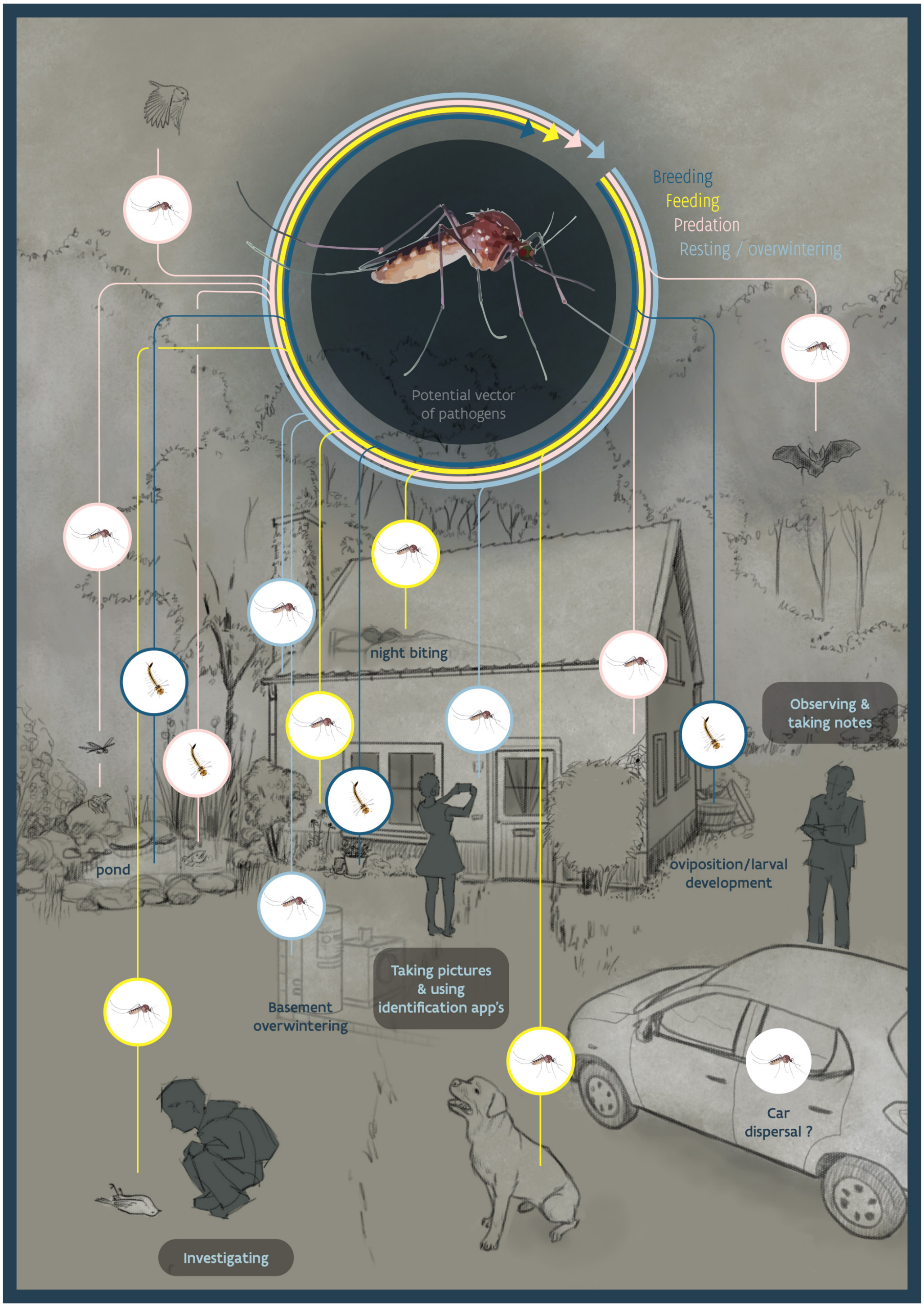

Figure 1. An illustration of some of the ways in which mosquitoes and humans interact and where citizen scientists can contribute to our understanding by providing additional data on species interactions (breeding = dark blue; feeding = yellow; predation = white; resting/overwintering = pale blue). The actual interactions depend not only on the particular mosquito species but also on the landscape structure in which the observations are made, such as urban, semi-natural or agricultural land. Drawn by Sven Bellanger.

question addressed. Project designers who wish to reach large audiences need to keep projects simple (Bonney et al. 2009, Parsons et al. 2011, Bloom and Crowder 2020). With increasing complexity of citizen science protocols, the number and persistence of participants decreases as does the quality of data (Dickinson and Bonney 2012) although there are projects addressing more complicated questions by recruiting a subset of 'super citizen scientists' (Dickinson et al. 2012).

Furthermore, co-creation, social interactions and reward systems are among the ways to foster a sense of membership of the project (Rotman et al. 2012).

One solution to obtain interaction information is to extend existing projects with additional protocols, such as allowing participants the opportunity to select the observed interaction from a list of possible interactions using the 'tick the box' approach or with a free-form response describing the presence of the species and its behaviour (Sequeira et al. 2014, Porter et al. 2019). For example, this could be used to prompt participants to report the presence of a pollinating insect while recording flowering plants or conversely to record the plant name while observing an insect visiting a flower.

Data should also be collected that are free from interpretations. For example, we can directly observe which flowers an insect visits and which species a cat brings home, but we cannot so directly infer pollination or predation from these observations.

Analysis and visualization tools

Visualization is a powerful tool in science communication and can provide feedback to the general public. Citizen science platforms often show maps, photographs and graphs but invariably do not present networks, even if they collect suitable data. If the visualization of interactions networks is dynamic, participants get an instant view of their contribution and how their contribution supports the underlying science (Bonney et al. 2009, Hochachka et al. 2012).

Users could examine pollinator interaction networks from their own area, see the range of pollinators that plants in their garden attract, or examine when and where mosquitoes bite. Yet, care needs to be taken to make such visualisation approachable to a general audience, who are perhaps unused to seeing data represented as a network. Indeed, Fig. 1 was designed specifically with the intension that it could be used for a broad audience to communicate on mosquitoes, without that audience needing further explanation.

2) Possibilities and limitations

In my backyard, please – taking advantage of urban habitats

Projects that relate to the daily life and experience of participants are particularly successful. Programs empowering people to respond to potential threats to their health, such as ticks (Porter et al. 2019), mosquitoes (Palmer et al. 2017, Walther and Kampen 2017, Braz Sousa et al. 2020), or pollution of the immediate environment, activate many people and more often result from grass-roots movements of the affected communities (Commodore et al. 2017). Projects that can take place in the house or adjacent garden seem especially popular because of the participants' inherent interest and the justifiable amount of effort (Catlin-Groves 2012, Pergl et al. 2016, Dehnen-Schmutz and Conroy 2018).

In homes, not only can mosquitoes be observed, but also information about their behaviour and environment can be recorded. While many of the interactions of mosquitoes are undetectable through citizen science, mosquitoes intending to feed on humans or pets are easily observed (Fig. 1). For such a personal event as a mosquito bite, citizen science is one of the few approaches to gather the intimate details of the event (Caputo et al. 2020). To monitor flower visitation, a short term 'GardenBlitz', in which people record species within gardens in a given time-frame (usually a short period of time), could be more suitable for the snapshot of all interactions over a certain period of time. With respect to pollinators, we need observations of the plants they visit and the frequency of visits to better understand the roles that different insects play in pollination (Osborne et al. 2008, Roy et al. 2016).

Furthermore, we must include cultivated plants (agriculture, horticulture and gardens) and domestic animals (farm animals, bee hives, pets, aquarist collections) within such studies. They are under direct care of people and have a direct impact on human well-being. Yet they also have a direct impact on wild organisms (Groom et al. 2021).

Human–wildlife interactions are important to our understanding of the societal impact of IAS (Crowley et al. 2017). Many invasive populations are commensal with humans, and their invasion success can partly be explained by human activity. For example, alien squirrels often profit from supplemental feeding in urban environments. Recording such interactions between humans and IAS could inform social or economic impact assessments (Lioy et al. 2019).

Think big and be open to observing the whole ecosystem

Worldwide coalitions of projects including citizen science approaches are excellent examples of thinking big. 'Global Mosquito Alert' brings together a number of mosquito-related citizen science monitoring programmes that focus mainly on IAS to share tools, knowledge and data (Tyson et al. 2018). The idea of establishing national hubs, as proposed by Dunn and Beasley (2016) for citizen science-supported evolutionary entomology, would go one step further and could also be applied to the collection of interaction data on IAS. Another example are botanic gardens that represent collections of alien plants in the ecological context of a native animal and fungal community. Observations of any interaction could be useful when those same native animals and fungi become invasive in another location where the plant is native (Barham et al. 2015), but care must be taken to document the environmental context of each interaction to be able to evaluate the transferability of such data.

Mitigating recording bias

Citizen observations of biodiversity are not evenly distributed taxonomically but are strongly focused on certain taxa, such as birds (Amano et al. 2016). It is well known that records collected by volunteers are temporally and spatially biased, including uneven sampling effort and uneven species detectability (Isaac et al. 2014, Isaac and Pocock 2015, Geldmann et al. 2016, Callaghan et al. 2019), and this is to be expected for interaction records too. Approaches to mitigating such biases can parallel those of single-species observations, such as aggregating observations across time and space, modelling observer behaviour, including detectability within models, normalising data to observer effort and by training observers. However, the subject of bias specific to observations of species interaction records has received little attention. One is left to speculate on what interaction biases may exist. Certainly, there are large differences in the detectability of interactions. Some important interactions happen infrequently, rapidly or at night. Flower visitation and predation events vary considerably in their duration, phenology, diel rhythm and frequency (Jędrzejewski et al. 2002, King et al. 2013, Klecka et al. 2018, De Cuyper et al. 2019).

Nevertheless, it is important to recognise that biases are also a potential advantage of citizen science, working with taxa that people are predisposed towards is easier than trying to work on unpopular taxa and in inhospitable habitats. Not all interactions are suitable to build citizen science projects around. Only by understanding, designing for, controlling for and leveraging these biases can the value of citizen science data be understood and increased through appropriate design of projects.

3) Data integration and use on open data platforms

The frequency, impact, magnitude and direction of the interaction are highly relevant to ecology (Delmas et al. 2019). Rarely are all these elements known for any system, and so data must be integrated from a number of sources. However, there are difficulties in integrating species interaction data, a few of which are mentioned below.

Data standards

The difficulty of integrating such data may partly be explained by the lack of a data exchange standard, or indeed agreed protocols, for ecological interactions (Poisot et al. 2019). In some platforms, observations can be annotated with an interacting species (e.g. iNaturalist and observation.org). However, the stated interaction does not necessarily conform to a standard controlled vocabulary and this hampers their aggregation and further use. Moreover, there is no validation mechanism currently available for community review or other forms of quality control. In the aggregator GloBI, interaction terms from source datasets are first mapped onto the Relation Ontology before they can be incorporated (Smith et al. 2005, Poelen et al. 2014).

Different sources of data

Information on different aspects of an interaction network can come from many sources, including stable isotopes (Layman et al. 2012), environmental DNA (Larson et al. 2020), machine observations (Johnson et al. 2020) and machine learning (Tran et al. 2018). Each method provides a unique insight into a network, yet combining data from such sources, visualizing those and analysing those will be challenging. However, recent developments in analytical approaches combining datasets through, as an example joint species distributions models or data integration, are an encouraging development (Ovaskainen et al. 2016, Isaac et al. 2020).

Interaction data can also be extracted from the photographs that people post to social media. This approach has been used to examine the diet of eagles (Naude et al. 2019), flower visitation (Gazdic and Groom 2019) and human interaction with wildlife (Van der Jeucht et al. 2021). In these examples, this has been done by the researcher viewing the pictures manually. However, there is potential to use machine learning to extract additional information from photographs that would allow this to be scaled up to the millions of pictures now available (Bonnet et al. 2020).

Transferability of data between native and introduced range

Documenting species interactions could inform IAS impact and risk assessments and horizon scanning, by identifying species sensitive to the alien species impact or functional groups at risk (Andersen et al. 2004, Sutherland and Woodroof 2009, Roy et al. 2014). An alien species may be able to realize a wider part of its fundamental niche outside its native distribution (Broennimann and Guisan 2008, Beaumont et al. 2009). Therefore realised niches in the native range are often poor predictors of the potential fundamental niche which can often be explained by ecological interactions (Bidinger et al. 2012, Hof et al. 2012, Filazzola et al. 2017). Understanding the ecological interactions of an IAS might be used to evaluate the relative magnitude of impacts and, hence, could help prioritise action. In particular, backyard science could shed light on the range of interactions in cultivated environments, such as between non-invasive captive or cultivated and native species, and help fill the gaps in our understanding of how IAS form a bridgehead to a new ecosystem.

Open data

Finally, open licencing of interaction data allows reuse globally wherever they are needed, not just in the countries where they are collected. Gradually, the scientific and citizen science community are moving towards an open-by-default philosophy (Groom et al. 2015). The use of standard open licenses allows the building of aggregations and visualizations that can themselves be licenced openly. If readers are interested we have listed some sources of interaction data in the Supporting information. These are published under a number of different licences and formats.

Next steps for 'Next-level citizen science'

To summarize, here are our key messages to improve our collection of species interaction data through citizen science, particularly as it relates to IAS and their management but with relevance to other contexts as well.

- Extend existing citizen science platforms to include interactions in a standardized way and communicate the results as network visualizations (Pocock et al. 2016).
- Combine single species observations with known interactions to create rich visualizations of potential interaction networks to support and encourage data contributions.
- Adopt new methods, metrics, standards and tools to study and communicate on interaction networks (Poisot et al. 2015, Lau et al. 2017, Delmas et al. 2019). Particularly on those that simplify communication on networks and network properties to a general audience.

- Develop citizen science projects to collect targeted high-quality interaction data specifically to parameterise models, such as those described in Delmas et al. (2019).
- Use the unique features of citizen science to focus data gathering on the human ecosystem.
- Leverage the power of image analysis and machine learning to extract additional data from shared sounds and photographs to support the public's collection of interaction, co-occurrence and behavioural data.

Collection of species interaction data by citizens could take ecology to a new level of understanding. The engaged public would develop their observational skills and increase their understanding of ecosystems, while researchers would be provided with new data sources to complement professional field and laboratory methods. Citizen science has unique features, particularly related to the access to anthropic ecosystems, that mean it is well placed to contribute to environmental issues related to policy, such as on invasive species. For these reasons we see great potential for the use of citizen science in this area. Furthermore, we also believe that the people themselves will enjoy and learn from the experience.

Acknowledgements – We acknowledge Jan Pergl for hosting the workshop on "Increasing understanding of invasion dynamics through citizen science" in Průhonice, Czech Republic.
Funding – This publication is based upon work from COST Action CA17122 - Alien CSI supported by COST (European Cooperation in Science and Technology) <www.cost.eu>. QG and TA acknowledge the Belgian Science Policy Office under the TrIAS project (BR/165/A1/TrIAS). HER is supported by the Natural Environment Research Council award number NE/R016429/1 as part of the UK-SCAPE programme delivering National Capability.

Author contributions

Quentin Groom and **Nadja Pernat** share first authorship. **Quentin Groom**: Conceptualization (lead); Funding acquisition (lead); Project administration (lead); Visualization (equal); Writing – original draft (lead); Writing – review and editing (lead). **Nadja Pernat**: Conceptualization (equal); Visualization (lead); Writing – original draft (lead); Writing – review and editing (lead). **Tim Adriaens**: Conceptualization (equal); Project administration (equal); Writing – original draft (equal); Writing – review and editing (equal). **Maarten de Groot**: Conceptualization (equal); Project administration (equal); Writing – review and editing (equal). **Sven D. Jelaska**: Conceptualization (equal); Project administration (equal); Writing – review and editing (equal). **Diana Marčiulynienė**: Conceptualization (equal); Project administration (equal); Writing – review and editing (equal). **Angeliki F. Martinou**: Conceptualization (equal); Project administration (equal); Visualization (equal); Writing – review and editing (equal). **Jiří Skuhrovec**: Conceptualization (equal); Project administration (equal); Writing – review and editing (equal). **Elena Tricarico**: Conceptualization (equal); Project administration (equal); Writing – review and editing (equal). **Ernst C. Wit**: Conceptualization (equal); Project administration (equal); Writing – review and editing (equal). **Helen E. Roy**: Conceptualization (equal); Funding acquisition (lead); Project administration (lead); Visualization (equal); Writing – original draft (equal); Writing – review and editing (equal).

Transparent Peer Review

The peer review history for this article is available at <https://publons.com/publon/10.1111/ecog.05790>.

Data availability statement

No new data were created or analyzed in this study.

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