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Citizen Science and Biological Invasions: A Review

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Biological invasions are among the most challenging ecological and conservation riddles of our times. Fortunately, citizen science projects became a valuable tool to detect non-indigenous species (NIS), document their spread, prevent dispersion, and eradicate localized populations. We evaluated the most undisputed definitions of citizen science and proposed that a combination of two of them is a better reflection of what citizen science has become. Thus, citizen science is any environmental and/or biological data collection and analysis, including data quality control, undertaken by members of the general public, as individuals or as organized groups of citizens, with the guidance and/or assistance of scientists toward solving environmental and/or community questions. With this review, we also assessed how citizen science has been advancing biological invasions research and its focus, by analyzing 126 peer-reviewed articles that used citizen science methods or data concerning NIS. Most of the articles studied terrestrial species (68%) and terrestrial plants were the most studied group (22.7%). Surprisingly, most first detection reports were of non-indigenous marine fish probably due to the constraints in accessing aquatic ecosystems which delays the detection of new NIS. Citizen science projects running over broad geographical areas are very cost-effective for the early detection of NIS, regardless of the studied environment. We also discuss the applicability and need to adapt the methods and approaches toward the studied ecosystem and species, but also the profile of the participating citizens, their motivations, level of engagement, or social status. We recommend authors to better acknowledge the work done by contributing citizens, and the putative limitations of data generated by citizen science projects. The outreach planning of citizen science projects is also evaluated, including the use of dedicated web platforms vs. pre-existent and disseminated web platforms, while discussing how such outreach actions can be maximized. Lastly, we present a framework that contextualizes the contributions of citizen science, scientific research, and regional and national stakeholders toward the integrated management of biological invasions.

Keywords: citizen science, invasive species, non-indigenous species, early detection, monitoring, integrated management

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INTRODUCTION

Biological invasions are increasingly exacerbated by human activities and their impacts on the environment, as ecosystem degradation, overexploitation of biological resources, or global trade (Pyšek and Richardson 2010; Canning-Clode 2015). Biological invasions usually go unnoticed by the scientific community during the initial period of low abundance and independently of propagule

pressure (Simberloff and Rejmánek 2011). A similar process is observed with their impacts, which are only acknowledged by the scientific community and public when impacts are already significant (Pyšek and Richardson 2010; Simberloff 2011). In extreme cases, invasive species may lead to the extirpation of native species and shifts in the functioning of ecosystems (Sousa et al., 2011). The estimated economic impacts are tremendous. For example, the estimates of the economic impact in the European Union ranged between €12 and 20 billion per year (Kettunen et al., 2008; Scalera et al., 2012). On a global scale, the impacts of biological invasions were estimated at US$ 1.4 trillion which in the late 1990s corresponded to 5% of the global economy (Pimentel et al., 2001). Recognizably, prevention, early detection, and localized containment are the most effective measures to minimize the impact of non-indigenous species (NIS), including invasive species (Pyšek and Richardson, 2010).

Given the pervasive nature of biological invasions, citizen science emerged as an additional tool for earlier detection and management of biological invasions. Citizen scientists–as individuals or communities–collect and analyze data, helping to conduct research, generate a new hypothesis, or solving unanswered questions (Eitzel et al., 2017). The Oxford English Dictionary defines citizen science as "scientific work undertaken by members of the general public, often in collaboration with or under the direction of scientists and scientific institutions" (Simpson and Weiner, 2014). However, several other terms exist to describe such activities, as volunteer biological monitoring (Lawrence, 2006), community-based and participatory monitoring (Bell et al., 2008; Danielsen et al., 2009), or community science (Carr, 2004). With so many terms to describe the same topic, the information disperses and is more difficult to find. Citizen science initiatives may also be undertaken entirely and independently, by individuals or communities. Yet, the participation or supervision by scientists is advantageous even when the main objective of a citizen science initiative is to increase public literacy or engagement toward biodiversity and science topics. We advocate that citizen science should merge the definitions of Eitzel et al. (2017) and Simpson and Weiner (2014), mainly if data from citizen science produces new scientific knowledge and are intended to be part of decision-making processes where quality control is required. This combined definition describes citizen science as "any environmental and/or biological data collection and analysis, including data quality control, undertaken by members of the general public, as individuals or as organized groups of citizens, with the guidance and/or assistance of scientists toward solving environmental and/or community questions".

One of the main advantages of citizen science is the ability to cover larger geographical areas, at a significantly lower cost when compared to traditional scientific surveys (Carr, 2004; Crall et al., 2010; Tulloch et al., 2013; Pocock et al., 2017; Simoniello et al., 2019). Thus, citizen science can significantly reduce the time until the first detection of a NIS and track its dispersion with a wide network of citizen scientists. Therefore, eradication, containment, and mitigation measures may occur earlier and eventually be more effective (Gallo and Waitt, 2011; Pocock et al., 2017; Eritja et al., 2019).

Quality control is a theme of recurrent discussion regarding the data produced by citizen scientists (Crall et al., 2010; Ellwood et al., 2017). One should always analyze the scope of each research topic and how a specific project or citizen science initiative may be useful. If scientists are aware of the inherent limitations and acknowledge them, such data are of tremendous value (Bird et al., 2014). Communication and exchange of knowledge with those who are on the field on a daily-basis–e.g., professional fishers, farmers, land managers, forest rangers–provide critical insights into species distribution and behavior. The contributions from such citizens, termed Local Ecological Knowledge, quickly increases the acquisition of information by scientists that otherwise could have taken years to obtain (Davis and Wagner, 2003; Gilchrist et al., 2005; Tiralongo et al., 2019). While not always labeled as such, the sole communication between citizens and scientists toward understanding Local Ecological Knowledge should also be regarded as citizen science, as there is an active collaboration between the two to solve a scientific question or hypothesis. As a broad concept, citizen science can embrace several approaches and methods toward a better understanding of scientific hypotheses, as long as authors maintain similar procedures and nomenclatures.

We have now come to a period when citizen science reached maturity. It is then imperative to understand what we have learned on the use of citizen science to study biological invasions. And above all, what opportunities exist to advance the study of biological invasions with the contribution of citizen science. Thus, in this review, we analyze peer-reviewed articles that used citizen science methods or data applied to study or manage NIS–detection, rate of dispersion, control, and restoration. We discuss the applicability and need to adapt the methods and approaches toward the ecosystem and studied species, but also the profile of participating citizens–motivations, level of engagement, education, and social status. The need for data verification and random audit procedures is addressed, exemplified by different methods where the results obtained by volunteers are compared to those obtained by scientists to evaluate accuracy and efficiency. The outreach plans of citizen science projects are also evaluated, as the use of dedicated web platforms vs. pre-existent and well-established web platforms. The goals of this review are to 1) understand the effective contribution of citizen science toward the detection and monitoring of NIS across a wide range of ecosystems 2) identify the main trends of citizen science focused on NIS, and 3) quantify the efficiency of citizen science (participation of citizens, number of detected NIS) and monitoring outcomes.

BIBLIOGRAPHIC ANALYSIS

We conducted a bibliographic search with SCOPUS on July 9, 2019, to retrieve research and review articles using three combinations of keywords: "invasive species" and "citizen science"; "non-indigenous species" and "citizen science"; "non-native species" and "citizen science". The search retrieved 233 bibliographic references. The analyzed list consisted of 126 articles after eliminating the articles that do not contain data

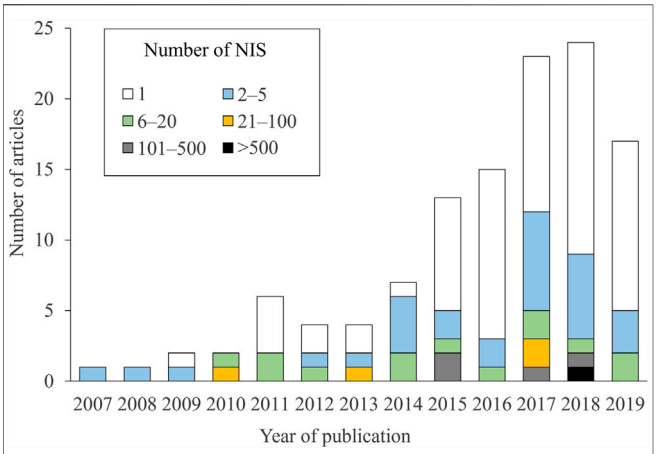

FIGURE 1 | Number of articles published on citizen science and non-indigenous species (NIS) since 2007. The number of species studied in each article is also shown and divided into six categories. A total of 126 studies reported information with this issue. Data were retrieved from a bibliographic survey made in July 2019 with SCOPUS using a combination of keywords: "invasive species" and "citizen science", "non-indigenous species" and "citizen science", and "non-native species" and "citizen science".

about citizen science or invasive, non-indigenous, and non-native species. Subsequently, we analyzed the articles according to 18 fields of information:

- Geographic: 1) studied ecosystem (Terrestrial, Freshwater, Marine); 2) country of affiliation of the first author; 3) country where data were gathered; 4) continent where data were gathered; 5) geographic range of the citizen science campaign, divided into five categories according to the maximum distance between data points (<5 km; 5–100 km; 101–500 km; 501–1,000 km; >1,000 km).
- Species: 6) total number of species studied; 7) total number of NIS, divided into six categories (1; 2–5; 6–20; 21–100; 101–500; >500); 8) if species were all NIS or not (yes or no); 9) NIS scientific name list (up to five species; or "Several" if more than five); (10) taxonomic group of NIS (if more than one, classified as "Several").
- Citizen scientists: 11) training provided to citizens (yes or no); 12) number of citizen scientists that participated in the study; 13) role of citizen scientists in the study (descriptive field on what tasks and actions were performed by participating citizen scientists toward the research question).
- Citizen science initiative or project: 14) duration of data collection (in months); 15) number of records gathered by citizen scientists; 16) how records were transferred from citizen scientists to scientists (personal communication; digital platforms; e-mail or social media post; or combinations of several methods); 17) use of a database to store data (yes or no); 18) source of citizen science data (field sampling campaigns; existent citizen science databases; independent report of data by citizen scientists; questionnaires; evaluation of citizen science projects or data quality; or combination of several methods).

Chi-square tests were done to investigate if the proportions of each category were similar or not, and the results are available as **Supplementary Material**.

We will mainly use the term non-indigenous species (NIS), often also referred to as non-native species, because it embraces both invasive and non-invasive species. However, when appropriate, we will mention if a species is invasive or not. Regarding the type of citizen science activities, our nomenclature will mainly be "citizen science projects" whenever there is an established project behind the data collection, usually with a specific denomination, but not necessarily funded. Still, other actions as one-off data collections will, whenever relevant, be referred to as "citizen science initiatives".

OVERVIEW OF PUBLICATIONS

Of the 126 articles analyzed, 76.2% were exclusively on NIS (n = 96), while the remaining also focused on native species. The total number of publications increased consistently since 2007 (**Figure 1**). Significant increases in the number of articles regarding a single NIS ($\chi^2_{(12,68)}$ = 70.4, p= < 0.001) and between two and five NIS ($\chi^2_{(12,29)}$ = 26.1, p = 0.010) occurred since 2007 (**Figure 1**). After 2015, most studies focused mainly on one NIS (**Figure 1**).

Most studies delved into terrestrial ecosystems (68.0%, n = 83), followed by marine ecosystems (21.3%, n = 26) (**Figure 2**). Articles on terrestrial ecosystems were the only ones displaying a significant increase with the increase of the study range ($\chi^2_{(4,83)}$ = 11.4, p = 0.022). On the other side, the marine ecosystems showed a trend of reduction in the number of published articles with the increase of the study range (**Figure 2**).

Plants were the most studied group of NIS (22.7%, n = 27), followed by insects (19.3%, n = 23), mammals (10.9%, n = 13), and fish (10.1%, n = 12), while several studies delved into multiple taxonomic groups (11.8%, n = 14) (**Figure 3**). Plants are mostly studied in North America (12.7%, n = 16), while Insects are studied mainly in Europe (11.1%, n = 14). Europe is the continent with most studies (44.4%, n = 56), followed by North America (32.5%, n = 41) (**Figure 3**). Significant changes in the number of published articles across the various taxonomic groups were identified for three study locations: North America ($\chi^2_{(15,41)}$ = 97.5, p= < 0.001), Central and South America ($\chi^2_{(15,7)}$ = 27.3, p = 0.026), and Europe ($\chi^2_{(15,56)}$ = 76.0, p= < 0.001) (**Figure 3**).

Citizen science databases were the most used source of data (25.4%, n = 32), followed by field sampling activities (22.2%, n = 28), and independent reports by citizens (17.5%, n = 22) (**Figure 4**). The studies that involved some sort of field sampling activity carried out by citizens, were the ones where the highest percentage of training preceded the activities (11.9%, n = 15) (**Figure 4**). Significant differences in the number of published articles across the different data sources were identified for activities with training ($\chi^2_{(6,29)}$ = 44.1, p= < 0.001) and without training of citizens ($\chi^2_{(6,97)}$ = 40.3, p= < 0.001) (**Figure 4**).

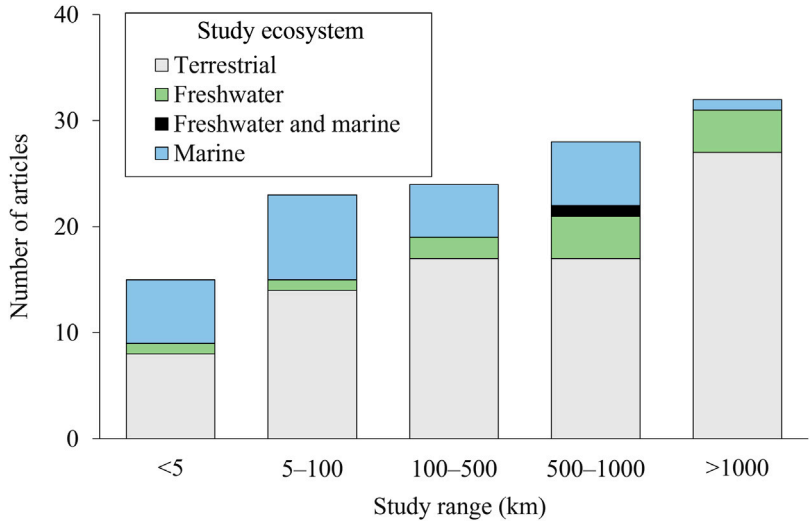

FIGURE 2 | Study range of articles published on citizen science and non-indigenous species according to four ecosystem categories (terrestrial, freshwater, freshwater and marine, marine). A total of 122 studies reported information on this issue. Data were retrieved from a bibliographic survey made in July 2019 with SCOPUS using a combination of keywords: "invasive species" and "citizen science", "non-indigenous species" and "citizen science", and "non-native species" and "citizen science".

Data has been transferred to scientists mainly through a digital platform (33.0%, n = 3) (**Figure 5**), either a dedicated website, e-mail, mobile app or a combination of these. Unfortunately, 20.6% of the articles (n = 26) did not specify which type of data transfer method was used, but likely some sort of personal communication was established. Personal communication is the third most common method to report data (16.0%, n = 15). We included in this category the articles that gathered data through in-person surveys or interviews. The reduced diversification of data transfer methods, which reflects how data was gathered in the first place, translates into a significant difference in the number of published articles across these various methods ($\chi^2_{(6,94)} = 55.8$, $p = < 0.001$). Diversifying the communication channels between citizen scientists and scientists should be established more often, namely combining digital and personal communication, to increase the number of interactions because the use of several methods of communication only represents 9.6% (n = 9) of all published articles (**Figure 5**).

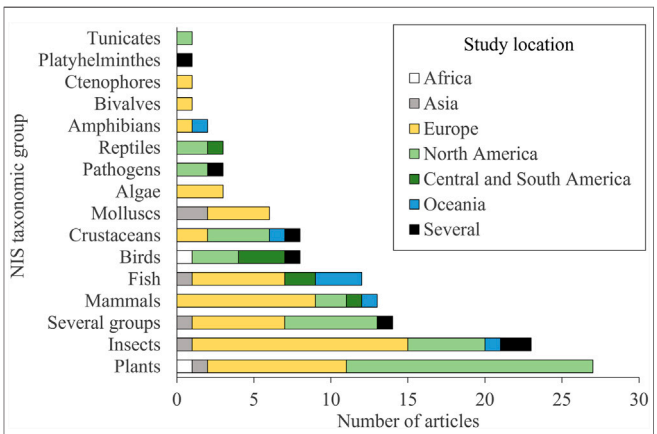

FIGURE 3 | Number of articles published on citizen science and non-indigenous species (NIS) according to 16 taxonomic categories. The continent where the studies were made is also included. A total of 126 studies reported information on this issue. Data were retrieved from a bibliographic survey made in July 2019 with SCOPUS using a combination of keywords: "invasive species" and "citizen science", "non-indigenous species" and "citizen science", and "non-native species" and "citizen science".

UNRAVELING NON-INDIGENOUS SPECIES DISTRIBUTION WITH DIFFERENT CITIZEN SCIENCE APPROACHES

Supervised Field Actions

A more traditional approach to citizen science projects consists of recruiting citizen scientists, provide them informative materials, develop training sessions, and then finishing with the participatory activities in the field, supervised, or in collaboration with scientists. Yet, only 17.5% (n = 22) of the articles in our bibliographic survey followed this traditional approach. One example consisted of a group of 12 citizens that received a 15-min training session before the one-day field sampling campaign with scientists to document the spread of the hemlock woolly adelgid *Adelges tsugae* (Animalia, Hemiptera) in a forest in Massachusetts (United States) (Fitzpatrick et al., 2009). This type of approach, named bioblitz, is increasingly popular. They are defined as participatory actions to quickly and intensively survey a given area to provide a biodiversity snapshot (Robinson et al., 2013). For example, during the "Marine

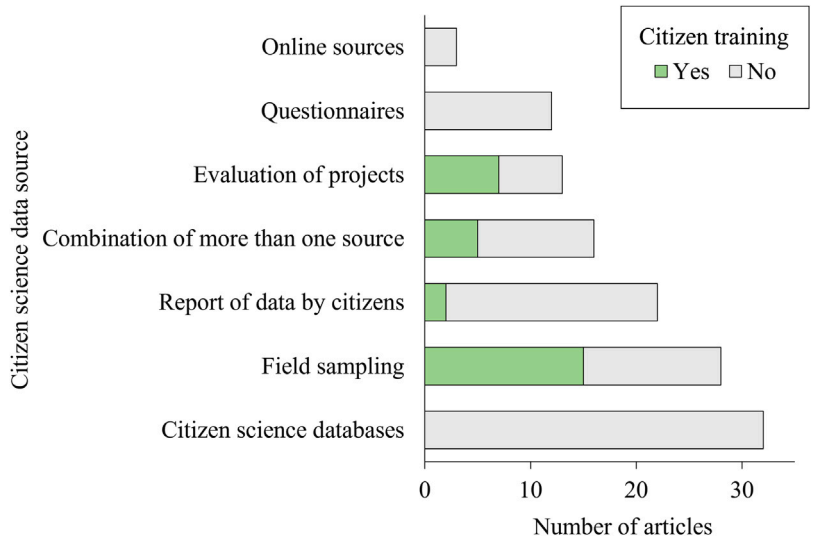

FIGURE 4 | Number of articles published on citizen science and non-indigenous species according to the data source used in the study (seven categories) and if citizen scientists received training under the scope of the study. A total of 122 studies reported information on this issue. Data were retrieved from a bibliographic survey made in July 2019 with SCOPUS using a combination of keywords: "invasive species" and "citizen science", "non-indigenous species" and "citizen science", and "non-native species" and "citizen science".

Invasive Species Bioblitz" in Sitka (Alaska, United States), participants received training on the identification of several target NIS which resulted in the detection of a 1000-km northward expansion of the invasive tunicate *Didemnum vexillum* (Animalia, Aplousobranchia) during the 2-days sampling (Cohen et al., 2011). The development of user-friendly tools and metrics enables the participation of a wider range of people. For example, the Metric of Aquatic Invertebrates for Volunteers (MAIV) enabled elementary and middle school students from Southern Portugal to evaluate the ecological status of streams (Pinto et al., 2020).

Independent Surveys Across Broad Geographical Areas

Citizen science projects may improve the information on the distribution range of known NIS or infer about locations where NIS may expand their distribution. The sampling process of projects studying the distribution range of a NIS, across a broader geographical range, is usually undertaken independently by citizen scientists.

In terrestrial ecosystems, the "Invaders of Texas" project from the United States aims at monitoring invasive plants across the state. Every year, hundreds of citizens receive training through frequent workshops and online training programs. Citizen scientists identified several new locations where the giant reed *Arundo donax* (Plantae, Poales) is present in Texas. In many locations, the new discoveries were done without support from scientific literature or species lists. Then data were submitted to the "Invaders of Texas" database and later validated by professional scientists through photographic evidence (Gallo and Waitt, 2011).

There are numerous examples from aquatic ecosystems–e.g., two gelatinous NIS in the Western Mediterranean Sea (Boero et al., 2009) or freshwater crayfish across Greece and Italy (Faraone et al., 2017; Perdikaris et al., 2017). One of the more successful projects aimed at the early detection and monitoring of the invasive European green crab *Carcinus maenas* (Animalia, Decapoda) along the northern Pacific coast of the United States. Here, trained citizen scientists deployed baited traps and carry visual surveys along 3,000 km of shoreline. Citizen scientists documented the expansion of the European green crab across the state of

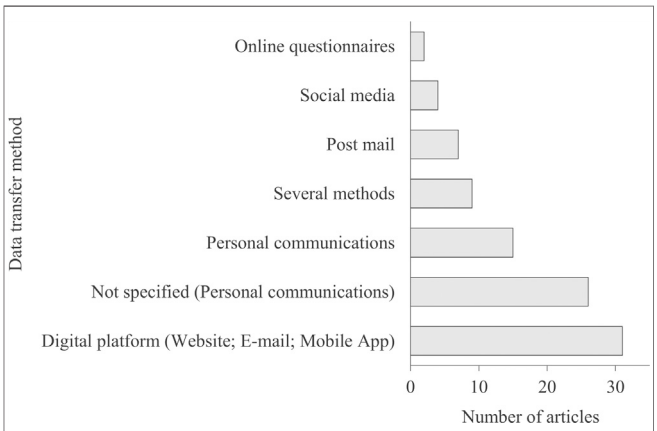

FIGURE 5 | Number of articles published on citizen science and non-indigenous species according to the method used by citizen scientists to transfer data to scientists. A total of 94 articles reported information on this issue. Articles based on citizen science databases and evaluations of citizen science projects (n = 32) were not included in this figure because data were not gathered throughout the process of the specific study. Data were retrieved from a bibliographic survey made in July 2019 with SCOPUS using a combination of keywords: "invasive species" and "citizen science", "non-indigenous species" and "citizen science", and "non-native species" and "citizen science".

Washington, which was later confirmed by scientists with rapid assessment surveys (Grason et al., 2018). Such kind of data collection over broad geographical areas may also help predict the areas to where a NIS will expand through species distribution modeling–e.g., two NIS of insects in Sweden (Widenfalk et al., 2014) and several invasive plant species in the United States (Crall et al., 2015) and Portugal (César de Sá et al., 2019).

Records of Non-Indigenous Species Made by Informed Citizens

Informed citizens should be regarded as citizen scientists that have a strong interest in providing data to scientists even if there is no citizen science project in progress. Frequently, citizen science projects and databases help assess the presence and distribution range of NIS after the first detections were done by scientific surveys–e.g., Asian paddle crab *Charybdis japonica* (Animalia, Decapoda) in Australia (Hourston et al., 2015); Joro spider *Nephila clavata* (Animalia, Araneae) in North America (Hoebeke et al., 2015); monk parakeet *Myiopsitta monachus* (Animalia, Psittaciformes) in Mexico (Hobson et al., 2017). However, extremely relevant information may also arise from sporadic reports made by informed citizens. Such reports may contribute to specific citizen science projects, as the single record reports of two fish NIS in the Mediterranean Sea–the sergeant major *Abudefduf saxatilis* (Animalia, Perciformes) record submitted to the project "Seawatchers" (Azzurro et al., 2013), while the white-spotted puffer *Arothron hispidus* (Animalia, Tetraodontiformes) record was uploaded to the Facebook group "Mediterranean Marine Life" (Bariche et al., 2018). On the other hand, sporadic reports may also trigger the onset of a citizen science project. For example, the first record of weakfish *Cynoscion regalis* (Animalia, Perciformes) in southern Portugal was reported by a fisherman to scientists (Morais and Teodósio, 2016). This led to the development of a citizen science project–through social media and traditional media–which revealed that the species was going unnoticed by the scientific community for years in several locations across Portugal (Morais et al., 2017). Similarly, the first record of Asian bush mosquito *Aedes japonicus* (Animalia, Diptera) in Spain was submitted to the project "Mosquito Alert", triggering scientific surveys that confirmed the presence of the species and suggesting that the establishment had occurred a long time ago (Eritja et al., 2019). Overall, the contributions from informed citizens should be encouraged because it provides unique information that may even trigger the onset of in-depth studies on NIS species.

SUITABILITY OF CITIZEN SCIENCE METHODS IN DIFFERENT CONTEXTS

Terrestrial *Versus* Aquatic Ecosystems

The access to different ecosystems requires different logistics and dictates the methods used, both to engage participants and gather data (Cigliano et al., 2015). The number of participants and the amount of data gathered are greater in terrestrial ecosystems (Gallo and Waitt, 2011; Bradley et al., 2018) than in aquatic ecosystems. Still, the number of articles about first records of NIS in marine ecosystems is almost the double of those in terrestrial ecosystems. A search for the keywords "first/new" and "record/occurrence" in the titles of the retrieved articles disclosed five articles done in terrestrial ecosystems (Hoebeke et al., 2015; Maistrello et al., 2016; Mori et al., 2016; Eritja et al., 2019; Schüttler et al., 2019) and nine articles done in marine ecosystems (Boero et al., 2009; Azzurro et al., 2013; Hourston et al., 2015; Bariche et al., 2018; Fernández-Vilert et al., 2018; Giovos et al., 2018; Jurgens et al., 2018; Kleitou et al., 2019; Pearson et al., 2019). This may reflect the inherent difficulty in accessing the aquatic ecosystems by scientific community.

In aquatic ecosystems, data may need to be obtained through SCUBA diving (e.g. Zenetos et al., 2013; Cigliano et al., 2015; Anderson et al., 2017) or fishing (e.g. Danielsen et al., 2009; Morais and Teodósio, 2016; Tiralongo et al., 2019). Our bibliographic survey disclosed that 41 articles (32.5%) delved into an aquatic ecosystem (Marine or Freshwater) (**Figure 2**), but only 25 involved field sampling or the report of observations by citizens. Of these, 11 articles obtained data from marine subtidal areas, either through SCUBA diving (32.0%; n = 8) and/or fishing (20.0%; n = 5). In subtidal aquatic ecosystems, sampling is typically only possible through SCUBA diving which limits the number of participants (Cigliano et al., 2015). Yet, there are several successful examples. Citizen scientists monitored the macroalgae of the Bay of Seine (France) and identified 14 NIS over nine years (Verlaque and Breton, 2019). Also, seven non-indigenous fish were detected on the southern coast of Turkey by volunteer divers across three years of monitoring (Bodilis et al., 2014). The remaining 13 articles included data from shore habitats or intertidal zones. The "Plate Watch" project trained citizen scientists to deploy PVC settlement panels from floating docks and monitor sessile marine invertebrates. The main result was the detection of two invasive colonial ascidians, *Botrylloides violaceus* (Animalia, Stolidobranchia) and *Botryllus schlosseri* (Animalia, Stolidobranchia) (Jurgens et al., 2018).

Digital Outreach *Versus* Personal Communication

The ease of access to information, through social media platforms, websites, and e-mail, opened new forms of communication between citizen scientists and scientists, as observed in our bibliographic survey. Outreach campaigns, supported by easy-access communication channels, resulted in several opportunities for citizen science projects to obtain new and relevant data, resulting in the detection of invasive species for the first time in several cases–fish species in the Mediterranean Sea (Azzurro et al., 2013; Zenetos et al., 2013; Bariche et al., 2018; Giovos et al., 2018) and in the NE-Atlantic coast and estuarine ecosystems (Morais et al., 2017), crustaceans in the NE-Atlantic (Morais et al., 2019; Encarnação, unpublished data), an invasive mosquito species in Spain (Eritja et al., 2019), or an invasive

garden slug in several new locations in Japan (Morii and Nakano, 2017).

Digital outreach should be complemented, whenever possible, with in-person questionnaires to obtain Local Ecological Knowledge from digitally-excluded citizens. Such approach proved its value in detecting and reconstructing the invasion of several freshwater fish in Northern Spain (Clusa et al., 2018), coastal fish in the Mediterranean Sea (Tiralongo et al., 2019), marine mollusks in Greek waters (Crocetta et al., 2017), mammals in the sub-Antarctic Cape Horn Archipelago (Schüttler et al., 2019), and several NIS in the Andaman archipelago, India (Mohanty et al., 2018).

DATA MANAGEMENT

Data Quality and Verification Strategies

Several biases may occur when combining data gathered by scientists and citizen scientists. The level of expertize of the participants involved should be accounted for when assessing the presence and identification of a species. First, scientists can detect low-abundant invasive species more frequently than less experienced citizen scientists (Fitzpatrick et al., 2009). Second, the rate of correct identifications is generally higher among citizen scientists that received some sort of training, but this does not exclude the need for the implementation of validation protocols (Crall et al., 2011; Jordan et al., 2012; Goczał et al., 2017). Overall, the amount of data, but also the participation of citizens, will likely be higher when dealing with large, unique, or charismatic NIS, than with small and cryptic species. Regardless data quantity all gathered data are of the utmost importance, particularly at the beginning of a biological invasion when abundances are low. In all cases, data quality protocols should always be implemented, either during or after data collection, and regardless of the project dimension, geographical scope, or methodologies used for data collection (Crall et al., 2010).

In many projects, the validation of NIS records is made with photographs sent to scientists (Gallo and Waitt, 2011; Justine et al., 2018; Eritja et al., 2019; Tiralongo et al., 2019; Johnson et al., 2020). In other cases, all samples may be checked by scientists. For example, the samples collected by 1,000 volunteers to monitor two invasive crustaceans–the European green crab *Carcinus maenas* (Animalia, Decapoda) and the Asian shore crab *Hemigrapsus sanguineus* (Animalia, Decapoda)–were checked and re-counted by the research team after each sampling campaign (Delaney et al., 2008). Another strategy is for scientists to participate in the field sampling along with citizen scientists to make a quality control assessment of a subset of samples and compare it with the data gathered by citizen scientists (Jordan et al., 2012). A third strategy is to analyze a subset of samples once the field sampling is concluded (APA, 2020).

Dedicated Web Platforms

The use of digital communication channels and new technologies, like smartphone apps, increases participation and engages participants to keep active and motivated (Graham et al., 2011). The importance of digital communications is undeniable since 33.0% (n = 31) of published articles relied on it (**Figure 5**). However, the diversity of communication channels may challenge scientists and data managers on how to standardize this type of data. Indeed, several authors stressed out that standard protocols for gathering and sharing data on public databases must be implemented (Crall et al., 2011; Crall et al., 2012; Adriaens et al., 2015; Johnson et al., 2020). Such recurrent concerns can be partially addressed with an initial assessment of pre-existent standardized protocols and platforms, and an evaluation of their suitability to a new project, resulting in the subsequent integration of citizen science data into public databases and in the decision-making process (Delaney et al., 2008; Crall et al., 2011).

Here are a few examples of the diversity of methods used to collect information provided by citizen scientists. Smartphone apps have been used to detect and monitor NIS in several ecosystems. The app "FrogID" was designed to record and identify the callings of frogs in Australia (Rowley et al., 2019). The app "RINSE That's Invasive" and "KORINA" were designed to record plant and animal NIS across Europe (Adriaens et al., 2015). The apps "Tigatrapp" and "iMoustique" were developed to detect mosquito NIS in Spain and France, respectively (Kampen et al., 2015). However, the creation and maintenance of a dedicated smartphone app, or a website to submit observations, is expensive and may discourage researchers from exploring such tools. An alternative approach has been the use of generalist and free citizen science online platforms, such as iNaturalist (iNaturalist, 2020). This online platform can be used by any project to record the submissions of citizen scientists. The iNaturalist platform has been chosen by many citizen science projects, including to study the presence of marine species expanding their distribution range and NIS in southern Portugal (Encarnação, unpublished data), the invasive Eastern gray squirrel *Sciurus carolinensis* (Animalia, Rodentia) in Italy (Mori et al., 2016), or reptiles and amphibians in North America (Spear et al., 2017).

ENGAGEMENT OF CITIZENS

Managing Expectations and Motivations

Scientific activities involving citizens may fall under three project categories (Bonney et al., 2009): 1) contributory projects–scientists define the research questions and citizens collect data according to pre-defined protocols; 2) collaborative projects–citizens are involved in several research steps, as sample collection and analysis, interpreting data, and presenting results; and 3) co-created projects–citizens usually determine the research question and then work with scientists to solve a specific problem, usually on issues of community concern as environmental or public health.

In each project category, the expectations and motivations of citizens are inherently different and should be accounted for by project managers. The most common motivations to participate in citizen science projects are to learn more about the

environment and biodiversity, protect a local area or natural resource, spent more time in nature, or help with community activities (Crall et al., 2012; Tulloch et al., 2013; Merenlender et al., 2016; Frensley et al., 2017). For example, the motivation of Australian fishers to fish the invasive common carp *Cyprinus carpio* (Animalia, Cypriniformes) relied on their desire to remove this invasive species. The common carp is likely to disrupt aquatic ecosystems and removal actions were regarded as socially acceptable–the "ends justify the means" (Atchison et al., 2017). Interestingly, there was a significant difference among fishers' motivations depending on their origin; overseas-born fishers' motivations were mostly based on the joy for recreational fishing, while Australian-born fishers were mainly motivated by environmental reasons due to the species' invasiveness (Atchison et al., 2017).

Although many citizens may be motivated to participate and contribute to a citizen science project, the willingness to spend time making such contributions change from person to person and according to what is expected from citizens. In many contributory projects, participants are not required to attend meetings or training sessions, which simplifies their participation and may increase the amount of data collected (Zenetos et al., 2013; Jordt et al., 2016; Morii and Nakano 2017; Tiralongo et al., 2019). In participative methodologies, as collaborative or co-created projects, citizens receive a higher number of tasks and have more responsibility, which requires that substantial information must be transmitted to participants to keep their motivation high and demonstrate how their actions can impact science and conservation (Jordan et al., 2011). Also, citizen science projects where citizens are active volunteers–i.e., they actively search for citizen science projects to participate–reach higher levels of engagement and retention (Bonney et al., 2009; Andow et al., 2016; Davis et al., 2018).

Finally, once citizen science projects make significant progress, scientists should contact citizen scientists and disclose the scientific progress they helped achieve. This simple action motivates citizen scientists and keeps them engaged with the current project while increasing the chances of having them participate in future projects.

Becoming Part of the Solution

The implementation of activities to control or eradicate invasive species increase the level of engagement of citizen scientists because they feel being part of the solution. Sometimes of a very noticeable environmental problem. Several examples from our bibliographic survey show this. Motivated volunteer divers and fishers are fundamental in the removal of the invasive lionfish *Pterois volitans* and *Pterois miles* (Animalia, Scorpaeniformes) in the Caribbean Sea, while providing data on the distribution and abundance of the species (Carballo-Cárdenas and Tobi, 2016; Anderson et al., 2017). In the Aviles estuary (Northern Spain), a group of 20 citizen scientists removed 774 individuals of the invasive pygmy mussel *Xenostrobus securis* (Animalia, Mytilida). This removal action effectively controlled the population as confirmed by posterior visual census and eDNA analysis (Miralles et al., 2016). In Portugal, participatory ecosystem restoration efforts to remove the invasive iceplant *Carpobrotus edulis* (Plantae, Caryophyllales) and the giant reed *Arundo donax* (Plantae, Poales) have been regularly performed by citizen scientists, including elementary and middle school students (APA, 2020). Several examples of innovative approaches propose the use of invasive species for human consumption while partnering with Chefs and news media channels to increase awareness on biological invasions (Chapman et al., 2016; Carrillo-Flota and Aguilar-Perera, 2017; Mancinelli et al., 2017; Cerveira, 2019; Leone et al., 2019; Ulman et al., 2020).

Nevertheless, several obstacles may arise when planning the removal or eradication of certain invasive species. For example, public empathy with species may undermine removal actions, namely with species that the public perceives as "beautiful", "domestic", or "useful" (Courchamp et al., 2017)–e.g., invasive gray squirrels *Sciurus carolinensis* (Animalia, Rodentia) in Italy (Bertolino and Genovesi, 2003), feral cats *Felis catus* (Animalia; Carnivora) in Australia (Nogales et al., 2013), or freshwater game fish like the smallmouth bass *Micropterus dolomieu* (Animalia, Perciformes) in several European countries and South Africa (Loppnow et al., 2013).

DISCUSSION

A Roadmap to Citizen Science Success

Citizen science is not a perfect science, but perfection is the enemy of good. As described throughout this review, many citizen scientists have contributed significantly to the knowledge of biological invasions and their management. In the following paragraphs, we propose six action items that any citizen science project could adopt to maximize the chances of success.

First, know your audience. At the onset of a citizen science project identify the social, cultural, and environmental awareness background of potential participants. This action will pave the road to success or failure. Bear in mind that a successful citizen science project cannot be mimicked anywhere else because the sociological fabric is different and mutates through time. Even the same project has different levels of success within a population owing to the intrinsic characteristics of the individuals (e.g., age, education, environmental awareness, motivation) and, consequently, also between different regions and countries (Crall et al., 2010; Ganzevoort et al., 2020; Larson et al., 2020).

Second, cherish the contributions from informed citizens and strengthen that partnership. The records provided by informed citizens on non-indigenous and uncommon species are precious information that often ignites research efforts (Morais et al., 2017; Morais et al., 2019), so they must be encouraged. However, given the sporadic nature of such records, they must be part of a broader effort to complement citizen science projects and scientific research.

Third, combine multiple methods of communication with citizen scientists. The methods used in citizen science projects should strive to maximize the reach and engagement of a broader audience (e.g., field sampling, social media, in-person interviews/questionnaires). For example, digital platforms of communication between citizen scientists and scientists

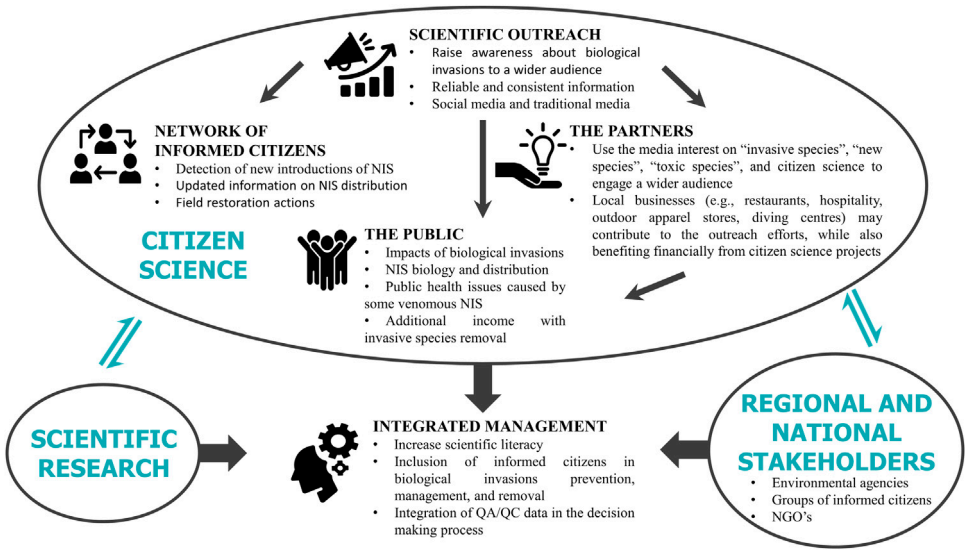

FIGURE 6 | Diagram proposing how outreach activities promoted by scientists can be boosted with the aid of the media and local businesses to reach a higher audience and inform several segments of the public with credible information about biological invasions. The media and the public, but also a network of informed citizens, are essential for building a solid citizen science project. The contributions from citizen science and national and regional stakeholders complement those from scientific research to attain a more solid integrated management of biological invasions. Icons retrieved from the Noun Project (www.thenounproject.com).

exclude those that are not technologically savvy, despite being very effective and essential in modern citizen science projects (Spiers et al., 2019). This is a simple example of why multiple methods must be set in place.

Fourth, KIS–Keep It Simple. We advocate that a citizen science project should be kept as simple as possible, regardless of the dimension or scope. The participatory activities of a project should not overload participants with too many tasks or demand a long-term commitment. This will allow citizens with different experiences, motivations, and expectations to custom-tailor their participation and commitment to a project. For example, citizen scientists are generally uncomfortable in making advanced scientific decisions, regardless of their motivations and engagement, so, such kind of requests may limit the number of submitted observations (Gallo and Waitt, 2011).

Fifth, describe the methods clearly and acknowledge the contributions made by citizen scientists. Many articles covered by our review failed to describe basic information on the process of data gathering–i.e., 1) the number of participating citizen scientists, 2) how citizen scientists contributed or gathered data to the project, 3) the amount of data gathered by citizen scientists, and 4) how data were transferred from citizen scientists to the scientists. This undermines the public and other scientists from understanding the role of citizen scientists, the engagement of a project, and its impact. Ultimately, mentioning how each citizen participated and contributed to advance scientific knowledge will encourage citizen scientists to participate in future projects and recruit new volunteers. The outreach channels used to call citizen scientists for action should be used at a later stage of the project to communicate how data gathered by them advanced scientific knowledge.

Sixth, use existing citizen science digital platforms. While conducting this review, we questioned the cost-benefit of developing an app or web platform for the submission of observations in each new citizen science project. Such an approach–one app *per* project–will potentially reduce the participation of citizens in more projects (Johnson et al., 2020). Additionally, the lack of data uniformization can undermine the value of data on biological invasions, while data sharing-policies on commonly available databases will facilitate access to a wider scientific audience and managers. Citizen science projects should firstly consider ready-to-use and free apps, with mobile and desktop interfaces, as these are advantageous in many aspects. For example, it standardizes submission protocols, data-sharing policies, and allows highly engaged citizens to participate in multiple projects while using the same platform. Adopting existing and free platforms (e.g., iNaturalist, Zooniverse, Project Noah) will contribute to advance citizen science as a whole. The platform iNaturalist is one of the best citizen science platforms because it has a user-friendly interface for multiple devices, it features automated suggestions for the identification of species, the validation of species identification is made by a wide array of experts, and the validated records are regularly exported to the Global Biodiversity Information Facility (GBIF) database (iNaturalist, 2020). Automated export of data to centralized databases, such as GBIF, should be a standard procedure, regardless of the used platform (Adriaens et al., 2015). The use of generalist platforms will still require the establishment of QA/QC protocols by each research team before the use of data on a specific project.

Integrated Management of Biological Invasions

The interest of citizen science in biological invasions has increased steadily, as reflected by the increased number of articles published since 2015 (**Figure 1**). Citizen science has benefited from the easier access of citizens to novel technologies and digital platforms (Eritja et al., 2019; Simoniello et al., 2019), but also to increasing efficiency of the outreach actions of citizen science projects (Nuñez et al., 2012; Chapman et al., 2016; David et al., 2018; Encarnação, unpublished data). As highlighted throughout this review, choosing a method to engage citizens in gathering data will mainly depend on the target taxonomic group, study ecosystem, and social context of the citizen scientists. We do not see this variability in approaches and sociological contexts as negative, but rather as an opportunity to adapt each citizen science project to specific scientific questions, different NIS, ecosystems, and regions/countries.

Several actions can be merged to increase the outreach of citizen science projects and the chance to convey the "right" message about biological invasions to the public and maximizing integrated management of biological invasions (**Figure 6**). Thus, informed citizens with their intrinsic Local Ecological Knowledge can be recruited as citizen scientists and early warning agents to detect the introduction of NIS and track their expansion (Boero et al., 2009; Gallo and Waitt, 2011; Azzurro et al., 2013; Hoebeke et al., 2015; Morais and Teodósio, 2016; Hobson et al., 2017; Grason et al., 2018; Eritja et al., 2019; Encarnação, unpublished data). They can also be recruited to eradicate species during field restoration actions to reduce the impact of invasive species in highly invaded ecosystems-e.g., invasive terrestrial plants (Crall et al., 2010), intertidal invasive invertebrates (Miralles et al., 2016), marine invasive fish (Peiffer et al., 2017). It should be noted that the eradication of edible invasive species may provide additional revenue for local populations, encouraging all stakeholders to contribute to the reduction of invasive species (Chapman et al., 2016; Mancinelli et al., 2017; Rotter et al., 2020), although everyone must be continuously reminded that the overall goal is the effective reduction of invasive species abundance (Nuñez et al., 2012). Again, a well-structured outreach plan will ensure that the "right" message is conveyed to all stakeholders.

Bringing a citizen science project to the next level–i.e., contributing to official national and international monitoring networks of NIS–requires the setup of independent and regular audits (Delaney et al., 2008; Crall et al., 2010). Citizen science should also strive to reduce the gap between the scientific community and the general public and promote scientific literacy while increasing the information obtained by scientists (Bonney et al., 2009; Crall et al., 2012). Reducing this gap should be the overarching goal of any citizen science project while empowering citizens to make effective contributions for integrated management plans of biological invasions.

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