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Improving and integrating data on invasive species collected by citizen scientists

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Abstract Limited resources make it difficult to effectively document, monitor, and control invasive species across large areas, resulting in large gaps in our knowledge of current and future invasion patterns. We surveyed 128 citizen science program coordinators and interviewed 15 of them to evaluate their potential role in filling these gaps. Many programs collect data on invasive species and are willing to contribute these data to public databases. Although resources for education and monitoring are readily available, groups generally lack tools to manage and analyze data. Potential users of these data also retain concerns over data quality. We discuss how to address these concerns about citizen scientist data and programs while preserving the advantages they afford. A unified yet flexible national citizen science program aimed at tracking invasive species location, abundance, and control efforts could be designed using centralized data sharing and management tools. Such a system could meet the needs of multiple stakeholders while allowing efficiencies of scale, greater standardization of methods, and improved data quality testing and sharing. Finally, we present a prototype for such a system (see www.citsci.org).

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Introduction

Invasive species continue to spread, and the inability of resource managers, scientists, and policy makers to efficiently and effectively control these invasions has resulted in environmental and economic losses worldwide (Mack et al. 2000; Pimentel et al. 2005; Stohlgren and Schnase 2006). This is likely the result of isolated datasets and uncoordinated monitoring and control activities that provide little information on current species locations, making it difficult to

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predict where these species are likely to spread (Crall et al. 2006). Lack of data consolidation and collaboration, among other factors, also hampers early detection and other efforts to minimize invasive species impacts (Myers et al. 2000; Crosier and Stohlgren 2004; Lodge et al. 2006).

Although competition among research groups may sometimes hinder data sharing, the lack of adequate resources to manage and share data is a far more common barrier (Crall et al. 2006; Graham et al. 2008). A survey of 319 invasive species databases within the United States found that only 57% of those were available online (Crall et al. 2006). These results should encourage the expansion of data sharing efforts to include more isolated data contributors who lack their own online databases through mergers with existing online data management systems.

Several data management systems exist to share data solely on invasive species (e.g., National Institute of Invasive Species Science, Early Detection and Distribution Mapping System, Nonindigenous Aquatic Species), and other more comprehensive systems exist that contain data on invasive species (e.g., NatureMapping, FishBase). However, most of these systems focus on a particular region or taxonomic group and many often lack resources (e.g., customer support staff, long-term funding) to accommodate a wider set of users (Crall et al. 2006). These separate and often isolated systems provide few opportunities to collaborate and share data across networks, reducing the effectiveness of early detection and rapid response programs (Graham et al. 2008). Therefore, system designers need to construct features to allow merging early warning data from multiple sources to make the overall system more integrated and effective (Ricciardi et al. 2000).

Many on-line database systems are working to connect via the Global Invasive Species Information Network (GISIN; www.gisin.org). This organization has developed a protocol to link existing on-line invasive species databases across the globe (Graham et al. 2008). Once databases are registered, the data from these providers can be pooled and queried through a common data portal (Graham et al. 2008). Merged data will make patterns of invasion more apparent while exposing monitoring and data gaps. It is through these same cyberinfrastructure tools that scientists can begin harvesting new data to fill these gaps. Given that resources available for professional monitoring are limited, it is important to integrate and coordinate all data sources to provide consistent, year-round monitoring across large areas. Citizen scientists could help fill this role if provided with the capabilities to effectively collect and share data. Such data may improve professional predictions on species' future distributions, allowing the timely dissemination of these results to an educated public (Crosier and Stohlgren 2004; Brossard et al. 2005; Stohlgren and Schnase 2006).

Having citizens participate in collecting scientific data has several additional benefits, including improved science and technology literacy among participants and reduced costs (Jenkins 1999; Trumbull et al. 2000; Danielsen et al. 2005). Studies also suggest that engaging citizen scientists makes it more likely that programs collect data relevant to local conservation and management issues (Danielsen et al. 2005; Measham 2007). Citizen scientists may also have access to lands that may not be accessible to professional scientists, allowing them to discover invasive species not yet detected elsewhere (Lepczyk 2005).

Even with these benefits, some scientists remain skeptical as to whether citizen monitoring activities can reliably detect and adequately characterize ecological change (Penrose and Call 1995; Brandon et al. 2003; Rodriguez 2003; Bhattacharjee 2005). These concerns stem from research studies that show an increase in variability among data collected by citizen scientists compared to experts (Ericsson and Wallin 1999; Barrett et al. 2002; Genet and Sargent 2003) and the use of simplistic protocols that do not yield useful data (Ericsson and Wallin 1999; Engel and Voshell 2002). In addition, species abundance measures are sometimes under- or over-estimated (McLaren and Cadman 1999; Bray and Schramm 2001) and inconspicuous species are commonly misidentified (Mumby et al. 1995; Brandon et al. 2003; Genet and Sargent 2003).

Researchers have proposed solutions to these issues, stating that the benefits of these programs can outweigh their limitations when properly developed and evaluated. Studies show that many skills needed to do scientific research can be obtained by novices when properly trained (Mumby et al. 1995; Darwall and Dulvy 1996; Bailenson et al. 2002; Barrett et al. 2002; Brandon et al. 2003; Janzen 2004;

Cohn 2008). Proper sampling design has been considered essential when designing and implementing a citizen science program (Yoccoz et al. 2003), yet (ironically) few studies have compared data collected by citizen scientists to those collected by experts (Danielsen et al. 2005).

These research findings suggest that we should cautiously seek to expand citizen science programs to track distributions of invasive species while ensuring the quality of the data they generate. In particular, we should strive to standardize and improve methods to ensure data quality and build a cyberinfrastructure capable of integrating local data into regional and eventually national or global databases (Danielsen et al. 2005). Therefore, the National Institute of Invasive Species Science (NIISS; www.niiss.org) has begun to develop a national citizen science program for invasive species. To better understand the current situation and existing programs, we surveyed citizen scientist programs currently monitoring invasive species populations. Here, we report results from those surveys with the goal of improving the design and implementation of existing cyberinfrastructure resources to best meet the needs of both local organizations and scientists.

Methods

In 2007, we conducted a comprehensive Google web search using several keywords (e.g., citizen science, invasive species, non-native species, volunteer monitoring) to identify potential citizen science program coordinators. Therefore, our search was limited to those programs with existing websites. We then emailed each potential coordinator ($N = 921$) a letter describing the NIISS program and survey. The email asked recipients to respond to the email by either replying that they had been misidentified as an invasive species citizen science program coordinator or to access the link to an online survey. The survey included questions in four areas:

(1) available resources (i.e., their number of volunteers, levels of funding, and available education tools);
(2) data collection, in particular, their use of global positioning system technology, the types of data collected, and sampling design;
(3) data management, including data dissemination, data format, and data availability; and
(4) data quality in terms of their data quality assurance or control (QA/QC) procedures.

We included definitions of key terms to ensure clarity. We analyzed the survey responses using basic query tools (e.g., counts of programs per question per response) available in Microsoft Access. To obtain more detailed responses, we further interviewed 15 of these citizen science program coordinators representing small (i.e., 5 volunteers) to large (i.e., >1,000 volunteers) programs. Selection of programs to interview included those well-known in the citizen science community and those in close proximity to NIISS staff.

To estimate any bias inherent in our survey results, we performed a non-respondent bias test (Barnette 1950). We selected four questions from the original survey (i.e., How many volunteers does your group manage?; What percentage of your group's monitoring effort focuses on non-native species?; Have your data been taken through a quality assurance/quality control process; and Where do you house data collected by your volunteers?) that highlighted key findings from the initial responses and randomly selected thirty non-respondents from the initial sample pool to interview. We tested for significant differences between answers provided by respondents and non-respondents using a two-tailed Chi-square test.

Results

We received responses from 249 programs in 35 states, a 27% response rate. Of those who responded, 128 (51%) participated in the survey. Other respondents either had no citizen science program ($N = 34$; 14%), were not currently working with invasive species ($N = 31$; 12%), were only participating in removal or treatment activities ($N = 9$; 4%), forwarded their request to a colleague ($N = 32$; 13%), or participated in our interview process ($N = 15$; 6%). Our non-respondent bias test showed that 7% of those contacted did not work with invasive species and 20% were doing removal or treatment activities only. This suggests that many programs did not respond to the initial email request that they had been misidentified as an invasive species citizen science program collecting data related to invasive species monitoring.

Available resources

Citizen science programs concerned with invasive species monitoring vary considerably in their size (number of volunteers), funding, and available educational resources. Fifty-nine percent of programs consisted of small groups (<50 volunteers). Only 15% manage 500 or more volunteers each, with 27% managing 50–500 volunteers. Non-respondents showed only marginally fewer volunteers managed ($X^2 = 12$; $P = 0.07$). Fifty-three programs work with people under the age of 18. Other programs work with adults aged 19–30 ($N = 103$), 31–50 ($N = 109$), and >50 ($N = 108$).

Forty-four percent of the survey groups reported spending at least 75% of their time on invasive species activities. Here, non-respondents differed strongly from respondents being less involved in non-native species monitoring (a majority spent <25% of their time on this; $X^2 = 14$; $P = 0.01$) further suggesting that many of the groups not responding may not consider themselves a suitable candidate for completing the survey. Many respondents (40%) obtain a majority of their funding from grants. The short-term nature of such funding presents a clear barrier to sustaining these monitoring programs (more than half our interviewees emphasized this). Only nine coordinators have annual budgets of $100,000 or more to manage and maintain their programs.

Most citizen scientist organizations have educational materials available to their volunteers, providing training workshops (73%), field guides (72%), and/or volunteer manuals (58%). Fewer provide web-based education tools (43%) or access to herbarium/museum collections (30%). Only 9% of the groups had no educational resources available.

Data collection

The tools available to citizen science data collectors can help determine their capacity to contribute to invasive species monitoring programs. Some 60% of groups surveyed had access to global positioning system units, and 13% used personal digital assistants (PDAs) in the field. Most groups concentrated their data collection on only a single taxon (65%) or on invasive plants (92%). However, all taxonomic groups were represented, with 35 groups collecting data on invertebrates, 30 on vertebrates, five on pathogens, and two on fungi.

Survey designs varied considerably, ranging from simple random (8%) and stratified random (15%) to random systematic (i.e., a random or stratified-random starting point followed by systematic sampling; 18%) and systematic sampling (20%). Survey respondents described the types of data collected by their citizen scientists by choosing among a list of attributes and data variables (Fig. 1). Participants most often noted the presence of a species (95%), followed by its absence (56%). Common auxiliary data included habitat type (41%) and level of disturbance (37%). Most groups (70%) collected these data opportunistically, often along roads, trails, and other easily accessible locations.

Data management

Many citizen science programs lack the resources to manage data effectively. Sixty-three percent of survey respondents rated their computer support as sufficient, but only 20% had databases accessible via the internet. Only 13% used an enterprise level database (allowing separate single-users to access multiple datasets); whereas, 23% used a personal database and 27% relied on spreadsheets (Fig. 2). A minority (12%) maintained only hard copies of their data. Non-respondents generally showed similar patterns, but the use of hard copy formats may be exaggerated (Fig. 2). Few analyses are performed on any of these data, with 36% of groups not being able to create species distribution maps from the data they collected.

The availability of data to external groups could also limit data sharing, but only 23% of the survey respondents said their data were not publicly available. Groups not sharing their data may be concerned about data sensitivity as 27% reported that issues exist with publishing their data online. Half of the interviewees further expressed concerns regarding how to protect private property and/or sensitivity to threatened and endangered

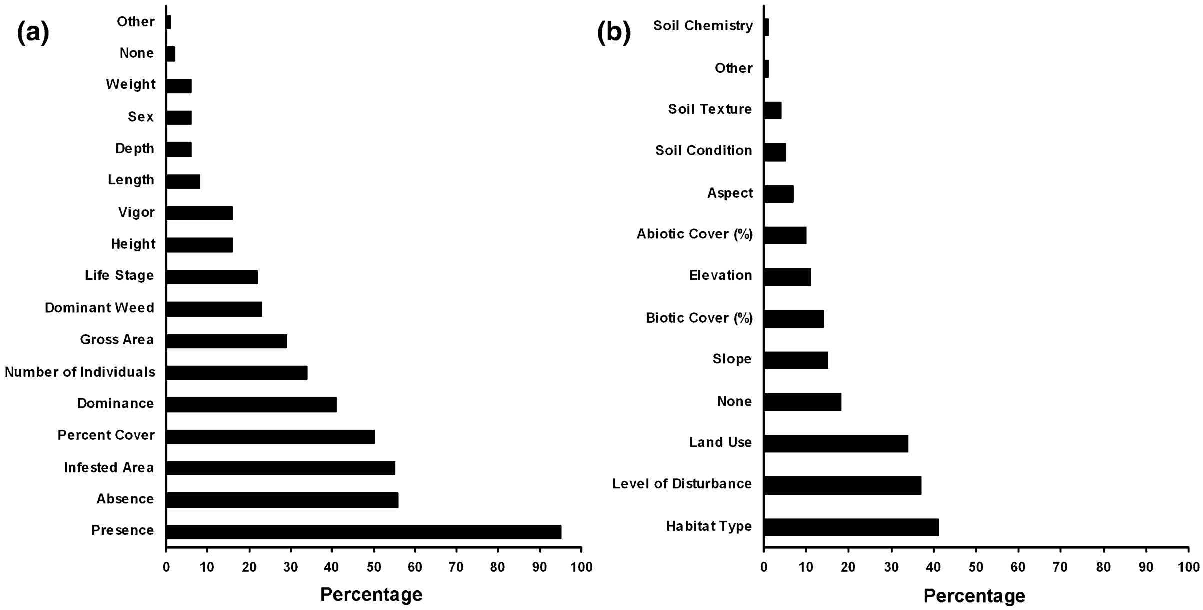

Fig. 1 Percentage of groups ($N = 128$) collecting data on a list of invasive species attributes (**a**) and auxiliary variables (**b**)

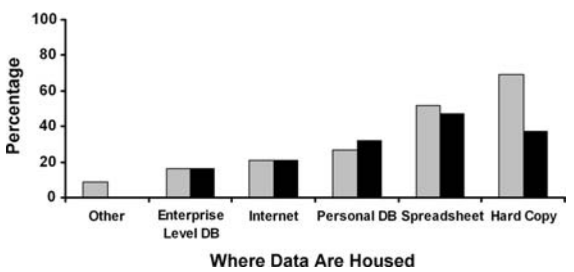

Fig. 2 Percentage of respondents (*grey*) and non-respondents (*black*) that house their data in the different formats. Some survey participants selected more than one option

species locations. Only one of the 15 interviewees expressed concern over releasing data prior to publication.

Data quality

Data quality appears to be of concern in many programs. Only 39% of the citizen science programs have any data quality checks in place (with similar rates for non-respondents; $X^2 = 1.0$, $P = 0.3$). Data quality procedures varied across programs. Qualitative data showed that common methods included volunteer training, expert validation of species identification, validation of species locations, and deletion of any suspect data.

Discussion

The many citizen science programs that exist to monitor invasive species across the United States vary considerably in size, resources, and the quality and quantity of data they are able to collect. Collectively, they show great potential for being able to collect extensive data on several taxa at low cost across large areas. Most face constraints, however, that limit their abilities to check, store, share, analyze, and interpret these data. These limitations weaken the value of the datasets collected when sampling designs are inadequate, suitable training and data checking procedures are not in place, or constraints on data handling and sharing limit access to the data generated. More standardized data collection coupled with quality assurance protocols and an accommodating national data infrastructure could go a long way towards improving invasive species distribution maps and detecting their occurrence and spread early enough to limit the environmental and economic losses they cause.

Our survey underscored the small size of many citizen science programs and the consequent need for additional data management resources to better utilize the data they collect. Citizen science programs have the potential to contribute greatly to local and regional efforts to monitor and control invasive species. To do this most effectively, however, they will need additional resources. Most immediately, these programs could be improved by integrating them more effectively into regional and national networks designed to ensure high data quality, statistically reliable methods, extensive coverage, and coordinated data sharing and analyses. We next discuss these issues in turn.

Improving data quality

This and other surveys (Crall et al. 2006) expose concerns over data quality when data quality procedures are inadequate. Detailed data quality checks are necessary to ensure that the data are collected by qualified observers, checked for errors, and entered reliably into databases suitable for further analyses and sharing. Because citizen scientists sometimes misidentify species or fail to measure other data accurately (Bray and Schramm 2001; Brandon et al. 2003; Fitzpatrick et al. 2009), an obvious first step to improve data quality is to design and test simple and reliable data collection procedures. We should also seek to train citizen scientists adequately using workshops, on-line instruction, and field lessons on species identification. In many programs, they also need to learn how to use maps, global positioning system units, and/or other devices for collecting environmental data accurately. The monitoring protocols themselves should be standardized whenever possible by distributing designs created by professionals experienced in statistical ecology and already field-tested using citizen scientists working under realistic conditions (Delaney et al. 2008).

Studies that have compared the accuracy of invasive species data collected by volunteers versus experienced professionals are also instructive. Brandon et al. (2003) found no significant difference between these groups in their ability to collect data on the abundance and distribution of seven invasive shrubs (*Lonicera japonica*, *Lonicera maackii*, *Lonicera morrowi*, *Lonicera tatarica*, *Rhamnus cathartica*, *Rhamnus frangula*, *Rosa multiflora*). Identifying native species accurately, however, depended on the species being monitored (Brandon et al. 2003). Citizen scientists commonly misidentified genera lacking simple distinguishing characteristics among species (e.g., *Ulmus* and *Quercus*) and rarer species with limited distributions. Providing additional training and only using more experienced volunteers for specific tasks would improve this program as would continuously assessing error rates to improve performance and advise data users on potential data limitations.

In testing a protocol for detecting the invasive species *Bythotrephes longimanus* (spiny water flea), Boudreau and Yan (2004) determined that the program succeeded when seven or more monitoring stations were sampled. Delaney et al. (2008) assessed the ability of volunteers to correctly record the presence and gender of native and two invasive crab species along the New England coast. Accuracy measures were used to set eligibility criteria for program participants. Education best predicted accuracy, with those having 2+ years of college reaching 95% accuracy. Finally, Fitzpatrick et al. (2009) found that experienced individuals were better able to detect small infestations of the *Adelges tsugae* (hemlock wooly adelgid) than volunteers, potentially biasing occupancy models. Such studies should be extended to include additional species and community types being used routinely in citizen science programs to assess their accuracy and limitations.

User-friendly tools to record data in the field could also reduce errors in data collection, but few studies have been conducted to show this (Stevenson et al. 2003; Prytherch et al. 2006; Williams et al. 2006). A majority of groups surveyed collect data on paper, which could lead to skipped data fields or mis-recorded data such as transposing digits in a coordinate. Such data eventually need to be transferred to a computer for processing and analyses, inserting a step that could take months and introduce errors. If data are entered by individuals unfamiliar with the species or who have trouble reading the field forms, additional errors may be introduced. Online data entry forms have automatic error checking to limit errors and allow for each data collector to input his/her own data. Online data entry also allows dispersed data providers to access these forms anywhere, potentially speeding data entry and rapid dissemination of the results.

Pre-programmed PDAs and multipurpose ‘smart phones’ could also enhance field data collection methods and improve QA/QC needs by correcting errors at the time of input in the field, but only 17 of the survey participants currently use PDAs for field data collection. Digital field guides can be loaded onto PDAs to aid in field species identification (Stevenson et al. 2003). Many PDAs and phones can take photographs in the field, allowing identifications to be verified (or spot checked) by expert taxonomists. These devices can also be linked to a global positioning system (GPS) to automatically collect and enter accurate location information and many smart phones may integrate GPS location technology and mapping software into the device. Furthermore, data from such devices can be quickly uploaded to a personal computer or may allow a user to enter data via an internet connection directly to a website, avoiding manual data entry and potential for errors in data transcription and loss of data forms.

Improving statistical rigor

Scientists working to assemble geographically extensive datasets and maps of invasive species presence and spread face a dilemma. Most prefer to apply statistically rigorous designs using either random or stratified random sampling designs, but new invasions could be missed by simple random sampling or small sample sizes (Stohlgren and Schnase 2006). Models seeking to predict species occurrence and spread usually require more widely dispersed data than these sampling designs can provide (Fortin et al. 1989). Citizen science programs can provide more geographically extensive and dispersed data at low cost to improve model performance. However, such programs usually collect data opportunistically (as found by this survey), and subjective sampling can either exaggerate species presence or cause new invasions to be missed in localized random samples (Stohlgren and Schnase 2006; Fitzpatrick et al. 2009).

Stohlgren and Schnase (2006) described an iterative design for sampling invasive species occurrences that demonstrates how data collected in different ways can be used to meet multiple research and management objectives. This iterative sampling design was developed with the knowledge that resources are limited, typically allowing <1% of any given area to be monitored (Jarnevich et al. 2006). In this scheme, the initial collection of opportunistic data is used to construct more statistically rigorous sampling and to focus further opportunistic searches into particular areas. These phases involve iterative adjustments to the sampling design, nicely integrating the roles of scientists and citizen scientists (Fig. 3; Stohlgren and Schnase 2006; Evangelista et al. 2008).

In the preparation phase existing data on species presence, absence, and density are combined with available ancillary data on site characteristics like elevation, soil type, etc. These initial data allow resource managers to identify both currently invaded sites and gaps where future sampling would be most useful. The next phase seeks to fill these gaps by adding new known occurrence locations via subjective sampling. The addition of opportunistic samples helps define the range of environmental conditions that exist at each species location (i.e., environmental envelope; Jarnevich et al. 2006; Evangelista et al. 2008). The second phase integrates stratified-random sampling to provide data for more statistically rigorous analyses that can be extrapolated to additional unsampled locations. Gradient sampling further refines the environmental envelope of each species (Jarnevich et al. 2006). The final iterative phase integrates different sampling designs and the collection of data variables as deemed most appropriate by the best available data for a particular species. To be most effective, scientists need to work closely with citizen science programs to inform them on which data are most important to collect using this iterative process.

Our interview with the Southern Appalachian Man and the Biosphere program (www.samab.org) provided an example of an iterative sampling design. Multiple monitoring levels integrate the knowledge and skills of scientists, land managers, and citizen scientists to maximize the resources available from each group. Level one surveys are conducted by citizen scientists along roads and trails. The data collected include presence/absence, area of infestation, and number of stems for 15 species of concern (selected by the Exotic Plant Council of the Southeast; A. Brown 2007, *pers. comm.*). Level two surveys assume that populations found in level one act as seed sources for new populations in the forest interior, so resource managers prioritize sampling locations from the level one data. More experienced volunteers then collect additional data on disturbance, soil moisture, light levels, forest community type, soil chemistry, and litter depth at these priority locations. Level three surveys employ the use of formal vegetation plots by local resource managers. Citizen scientists contribute by helping with monitoring

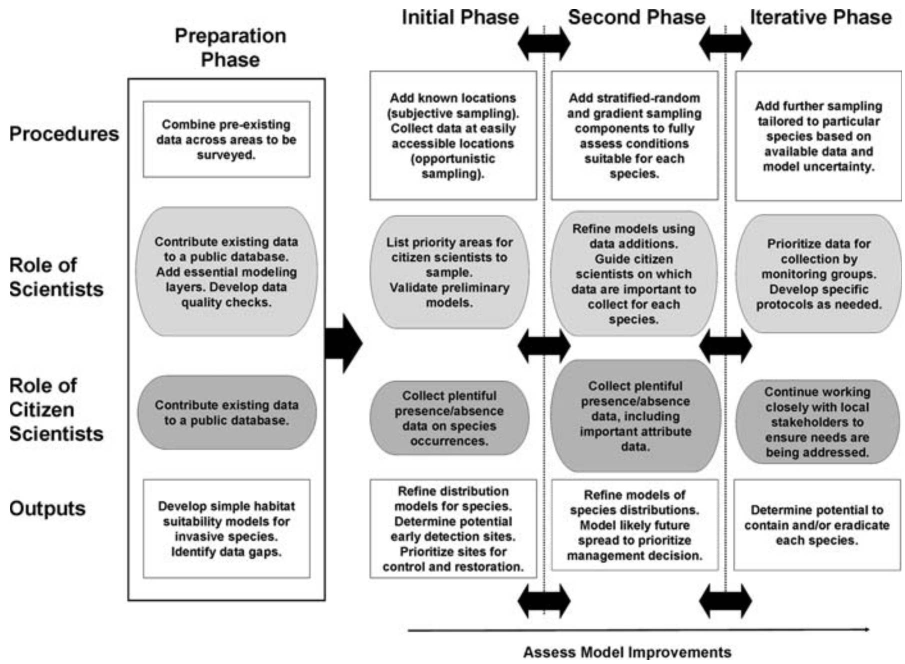

Fig. 3 Iterative sampling design for invasive species (Stohlgren and Schnase 2006), including the role of scientists and citizen scientists throughout each phase of the sampling design

equipment and laying out plots (A. Brown 2007, *pers. comm.*). This example demonstrates how scientists and land managers can guide sampling by citizen scientists to maximize limited resources while collecting the best available data for research and local managers.

Merging data and mitigating data sensitivity concerns

When distribution maps for invasive species remain incomplete, scientists lack the crucial baseline needed to design efficient monitoring and control measures. Merging data from multiple programs can help to alleviate these inadequacies. Our survey showed that many citizen science programs lack the funding and expertise to develop their own data management system, with issues ranging from a lack of computer support or the inability to use complex mapping and statistical software to lacking the resources to fund and maintain a data management system.

To address this need, NIISS developed a user-friendly website to assist citizen science programs with data management, dissemination, and analyses (www.citsci.org). The underlying database is connected to the International Biological Information System maintained by NIISS, facilitating nationwide data sharing for all taxa via a shared online data management system (www.niiss.org; Graham et al. 2007). This system allows registered users to upload, view, and download datasets on invasive species using a variety of web tools and also includes an early warning feature which notifies users via email when a new invasive species is sighted or new data are added for an area of interest (Graham et al. 2007; Jarnevich et al. 2007).

The citizen science website allows project managers to create customizable data entry forms for approved data contributors (Graham et al. 2007). These customized forms are then accessed from a user's profile page for printing or downloading to a PDA. The field data are subsequently uploaded using the same system with the data quickly available for viewing and mapping (Jarnevich et al. 2007). These data can ultimately be merged with other existing online datasets to create regional databases. These features provide for the rapid data entry and dissemination crucial for detecting and tracking new invasions. Future development will include online tutorials to train users in field tested data collection protocols, data analyses, and website use, reducing the need for in-person training. All features will be thoroughly tested prior to public release.

Several citizen science groups (27%) expressed concerns over sharing data due to data sensitivity. Data can be sensitive for several reasons including devaluation of private property, property fines, and concerns over species of cultural and/or biological significance (Jarnevich et al. 2007). To address these concerns, the citizen science website includes features to protect sensitive data and to facilitate greater data sharing across political boundaries. When users register with the website, they sign a data sharing agreement stating that the appropriate permissions are in place from the original data owners. In addition, all uploaded data must be assigned to a specific project created by an approved project manager. If a data contributor marks shared data as sensitive, project members can see exact locations of a species occurrence but anyone not a member of the project sees the sensitive data at a low resolution (see Jarnevich et al. 2007 for details). This allows for these data to be included in statistical analyses and early warning systems without compromising the security of data uploaded by these groups.

Future directions

Our survey of existing citizen science monitoring programs make clear that these groups face several distinct challenges including funding, expertise, and data checking, protection, organization, and analysis. Although no program can address all these needs, the particular resources reviewed above can provide citizen science programs with improved monitoring protocols and cyberinfrastructure tools, enhancing their ability to collect, manage, and disseminate data on invasive species. These resources can thus extend the power of citizen scientists to monitor the spread of invasive species, improving our knowledge of their current and potential future distributions. These improvements will also make monitoring data more readily available to scientists, allowing them to build more effective predictive models and early warning systems for these species. This, in turn, will aid local and regional managers and empower citizen scientists to participate more actively in local conservation and management decisions. Active collaborative efforts that include scientists, land managers, and citizen scientists will allow us to develop and implement more effective solutions for invasive species at a national scale.

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