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The Role of Community Science in Entomology

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Abstract

Community (or citizen) science, the involvement of volunteers in scientific endeavors, has a long history. Over the past few centuries, the contributions of volunteers to our understanding of patterns and processes in entomology have been inspiring. From the collation of large-scale and long-term data sets, which have been instrumental in underpinning our knowledge of the status and trends of many insect groups, to action, including species management, whether for conservation or control, community scientists have played pivotal roles. Contributions, such as pest monitoring by farmers and species discoveries by amateur naturalists, set foundations for the research engaging entomologists today. The next decades will undoubtedly bring new approaches, tools, and technologies to underpin community science. The potential to increase inclusion within community science is providing exciting opportunities within entomology. An increase in the diversity of community scientists, alongside an increasing taxonomic and geographic breadth of initiatives, will bring enormous benefits globally for people and nature.

Erratum >

1. INTRODUCTION

For centuries, people have been documenting the occurrence of insects and making biological records (3, 101). Indeed, before the late nineteenth century, nearly all scientific research was undertaken by volunteers pursuing topics of personal interest (85). For instance, John Ray (1627–1705), often considered the father of natural history, traveled around Britain noting and cataloguing the species that he observed (103). Today, people volunteering their time to scientific enquiry are often considered to be community or citizen scientists (122). Below, we use the terms community scientist and community science.

Over the past two decades, there has been a rapid escalation in the number and diversity of entomology-focused community science programs. Volunteers have made new insect discoveries, played key roles in monitoring many different species, and contributed to conservation or management actions. Engaging volunteers in entomological science also has the important benefits of combating entomophobia and the growing public mistrust in scientific results. Unfortunately, utilization of community science in the field of entomology and the population trends of some insect species are moving in opposite directions. While the acceptance and adoption of community science is rising, there is increasing, but not unequivocal, evidence that insect populations, including many species that are known for the essential services that they provide, are declining (114, 137). These trajectories are not unrelated. Community science provides the big data (31, 108) observations across time and space that are necessary to detect subtle changes in insect distributions from causes such as climate change and habitat degradation while there remains time to act. These long-term and large-scale observations of species cannot be matched by surveys conducted by professional scientists operating alone. However, further implementation of robust community science is required to address the taxonomic and geographic biases inherent within big data to increase understanding of global patterns of insect populations and distributions (114).

While the increased utilization of community science in entomology is exciting, the practice is at a pivotal developmental crossroad as the number of programs being implemented and amount of data being collected are outpacing the publication and utilization of these data for hypothesis testing and informing management and conservation action. With this review, we aim to highlight the value of information gathered through community science and guide future programs to provide useful data while educating and inspiring participants.

2. DISCOVERIES

Biological specimens collected and curated by volunteers, often referred to as amateur naturalists, have populated museums for centuries (105); indeed, volunteers have contributed to founding, developing, and maintaining natural history collections. Natural history museums represent an important resource for community scientists (120) while also engaging people with entomology and conservation (69). The number of species occurrence records documented by volunteers accelerated with the advent of online reporting sites such as iNaturalist and the Global Biodiversity Information Facility (GBIF) (15). For instance, a search for the class Insecta in GBIF will reveal more than 128 million occurrence records, most of which were contributed by community scientists.

These volunteer efforts have facilitated the discoveries of new insect species (37, 42, 70, 142, 143). For instance, the Swedish Malaise Trap Project collected insects from over 50 locations across the country for three years; after processing just 1% of the catch, which was dominated by Diptera, this project yielded 689 insect species new to science (70) (**Figure 1*a***). In northern China, a new species of bumble bee mimic stiletto fly was serendipitously discovered through a record submitted to iNaturalist (142) (**Figure 1*b***), and parasitoid wasp specimens compiled in databases by community scientists doubled the species records of Microgastrinae known from the

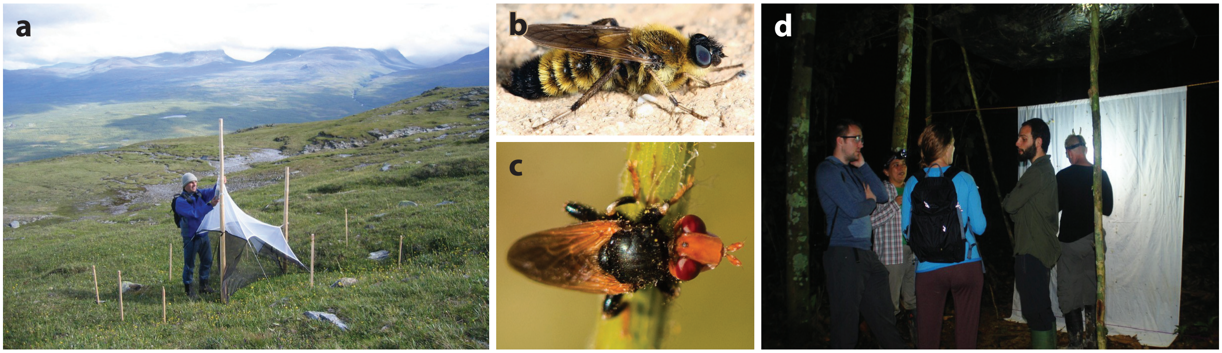

Figure 1

Community science discoveries. (*a*) A volunteer readies a malaise trap at the northernmost sampling point of the Swedish Malaise Trap Project, an ambitious inventory that yielded 20 million specimens and 4,000 species, including hundreds of insect species new to science (70). (*b*) While collecting in China, Dr. Shaun Winterton discovered a new species of stiletto fly, but his specimen was in poor condition and could not be formally described. When examining iNaturalist several years later, he came across images of the same fly posted by an avid nature photographer, Shan Gui, and based on both the specimen and images, formally described this species as *Sinothereva shangui* (142). (*c*) Community scientists rediscovered the thick-headed fly, *Myopa metallica*, 46 years after its prior collection in Chile (6). This discovery collection prompted research into the fly's life history and conservation status, which were unknown at the time of collection (5). (*d*) Ecotourism in Peru yielded new species of neotropical Arctiinae from light traps monitored by resort guests (55).

high arctic (37). Community scientists have also rediscovered many Lazarus species, including the nine-spotted lady beetle, *Coccinella novemnotata* (Coleoptera: Coccinellidae), in the United States (78) and the thick headed fly, *Myopa metallica* (Diptera: Conopidae), in Chile (5, 6) (**Figure 1*c***).

Discoveries occur even within well-studied groups of insects (50). DNA barcodes from butterfly legs collected by schoolchildren increased the diversity of ring butterflies (Nymphalidae: *Ypthima*) known from peninsular Malaysia (66). Likewise, four new species of Arctiinae (Lepidoptera: Erebidae) were described from light trap collections at the Refugio Amazonas Lodge in Peru, where guests participate in community science (55) (**Figure 1*d***). Importantly, the taxonomic discoveries enabled by community science do not always occur in such remote locations. For example, in Los Angeles, California, United States, new species of minute scavenger flies (Diptera: Scatopsidae) were discovered as part of an urban biodiversity project (26).

3. BIOLOGICAL INVASIONS

Many of the first records of an alien species within a new region have been made by community scientists (35, 112). The large data sets of first records of alien species that have underpinned global analyses (118, 119) have only been possible because of the immense efforts of volunteer recorders around the world submitting their observations. Such first records can be critical in informing early warning for invasive alien species. Community scientists have also tracked the rapid spread of alien insects following first detection (9, 49). Two global examples are the harlequin lady beetle, *Harmonia axyridis* (Coleoptera: Coccinellidae) (47, 57, 111, 139), and the brown marmorated stink bug, *Halyomorpha halys* (Hemiptera: Pentatomidae) (60, 79, 80, 125, 136).

Harmonia axyridis is found on all continents except Australia and Antarctica and notably is absent from a few large countries such as Australia (111). Outside of its native range (Asia), it has become very widely established in North America, South America, and Europe and in limited parts of Africa (111). Data sets from community science initiatives have tracked its spread and informed our understanding of the ecology of *H. axyridis*. Indeed, community scientists have provided the data to underpin the evidence of rapid decline of native lady beetles in several European countries (109) and the United States (48) following the arrival of this invasive alien species.

Halyomorpha halys is also native to Asia, and this highly polyphagous insect has caused substantial agricultural losses and acts as a nuisance pest due to its tendency to aggregate in artificial structures to overwinter (80). Community scientists tracked the rapid spread of *H. halys* across North and South America and Europe (136). These efforts facilitated species distribution modeling and informed agricultural scouting programs (79, 125). Community science has highlighted the role of human-mediated spread of *H. halys*, with high abundance of the alien pest reported along main roads and railway lines and volunteer detections of the insect in cars, train stations, and an airport (80). Furthermore, community science has informed our understanding of this insect's overwintering behavior (60). Homes in rural landscapes were found to be more prone to invasions by *H. halys*, and features such as the exterior color and building material of a home influenced the likelihood of invasion (60).

There are many case studies from around the world that highlight the value of volunteer observations in managing and even eradicating biological invaders. As an example, the Asian or yellow-legged hornet, *Vespa velutina nigrithorax*, has been recorded by community scientists in the United Kingdom every year since 2016, and this has informed the successful eradication of this invasive alien species. Surveillance and monitoring systems, including online recording and a smart phone application, were used by thousands of people, leading to the detection and eradication of nests within a few days (56). Predictive models have indicated that, if *V. velutina nigrithorax* had not been managed, it would now occupy a substantial area across the United Kingdom.

The fall army worm, *Spodoptera frugiperda*, is native to tropical and subtropical regions of the Americas but is now found in more than 30 African countries and, more recently, the Indian subcontinent (44, 51). This polyphagous lepidopteran pest feeds preferentially on wild and cultivated grasses including maize, rice, sorghum, and sugarcane. Community science has been utilized by farming communities to identify potential management strategies against *S. frugiperda* (140), but it has been recognized that there is a need to deploy mass media campaigns and training to inform communities more widely about sustainable management options (127).

Although community scientists play a crucial role in the success of management and eradication strategies, ethical dilemmas can arise in some programs when early detection by community scientists results in the use of tactics that they object to, such as the application of pesticides or the felling of trees (99). These possible conflicts must be considered at the onset of projects involving invasive alien species (99), and effective communication is critical to the acceptance of such management strategies.

4. VECTORS

Regional and national vector surveillance programs for mosquitoes, ticks, and kissing bugs frequently employ community science (23, 59, 68). Community scientists have monitored not only vector abundance and distributions but also disease prevalence by submitting photographs (95) or specimens (73, 138) or through trapping programs (10) and bite reports (45). Such collaborations among volunteers, researchers, agencies, and medical practitioners are necessary to study these vectors at large geographic scales, implement integrated pest management programs, and ultimately protect human health (23).

Community scientists have played important roles in mosquito surveillance programs across North America, South America, and Europe (81, 93, 138). For instance, the Invasive Mosquito Project compiled the largest crowdsourced mosquito collection in North America (81), and the Mosquito Atlas program is credited with detecting the first local reproduction and overwintering of the Asian tiger mosquito, *Aedes albopictus* (Diptera: Culicidae), in Germany (138).

Programs in the Netherlands utilized nearly 50,000 crowdsourced tick (Acari: Parasitiformes) bite reports to generate a hazard model that assessed the risk of being bitten based on both tick and human activity (45), and screening 16,080 ticks submitted from across the United States provided species distributions as well as tick-borne pathogen prevalence (89). Similarly, crowdsourcing in Finland revealed that the spatial distribution of ticks has shifted 200–300 km northwards since a previous survey 60 years ago, with climate change proposed as the major factor driving this change in distribution (73).

Chagas disease is a vector-borne zoonotic caused by the protozoan *Trypanosoma cruzi*. Kissing bugs (Reduviidae: Tratominae) are the vector of *T. cruzi*, and community-based surveillance of these insects has been a widespread practice for decades in South and Central America, where some species can establish colonies within homes (23). Within these programs, both passive traps and active searching of dwellings have been important monitoring tools used to inform the application of insecticide treatments for kissing bugs (23). In the southern United States, community scientists have documented the species composition and natural history of kissing bugs and the prevalence of *T. cruzi* infection within populations (23, 34) at a lower cost and higher sensitivity than traditional research methods (34).

Although most programs focus on surveillance, community scientists have also engaged in vector control. In University Park, Maryland, United States, residents and university scientists conducted a mass-trapping intervention that reduced the local abundance of *Ae. albopictus* (67). Volunteers were trained by the National Chagas Service in rural Argentina to monitor and treat homes with insecticides to control kissing bugs (135). These volunteers were tasked with treating homes with insecticides during an attack phase that ran from 1992 to 1996, during which all homes in the focal region were treated, followed by a surveillance phase through 2004, during which only reinfested homes and those nearby were treated (20). The efforts of volunteers during the attack phase did successfully reduce the prevalence of the kissing bug *Triatoma infestans* in homes, which corresponded to a downward trend in the number of reported human cases (135). However, a follow-up analysis suggested that a mixed approach, wherein professional applicators managed spray applications during the attack phase, and volunteers led surveillance and applied any necessary follow-up spray applications, would be the most cost-effective strategy (135). This mixed approach was predicted to reduce human cases of Chagas disease by 1.6–4.0 times compared to a fully horizontal approach to vector control (135).

5. DECLINES

The plight of insects has received considerable attention over the past few years, with headlines such as "Insectageddon" and "Insect Apocalypse" (114) capturing the imagination of people worldwide. However, the need for caution not only around the hype of such headlines but also in the analysis and interpretation of long-term data sets has been widely noted (113). Nevertheless, concerns about the pace and scale of environmental change and consequent effects on biodiversity and ecosystems are well-founded (64). Long-term data sets from community science initiatives have contributed considerably to the current understanding of declines and will undoubtedly continue to do so (86).

5.1. Conservation Targets

Long-term monitoring programs have contributed vast data sets relating to the population status of many butterflies (11, 30, 76), moths (40), beetles (48, 57, 77, 84, 111, 139), and bees (12, 82, 106). Monitoring data across the United States and Europe have been instrumental in demonstrating the severe declines of several aphidophagous lady beetle (Coccinellidae) species (2, 48, 78, 109). Community scientists consider bee decline to be a major environmental issue (54), and their efforts have been pivotal in the long-term monitoring of pollinator populations (12, 82, 106). For instance, nearly a million records of bees and hoverflies compiled by volunteers across the United Kingdom and the Netherlands demonstrated that bee diversity has declined since 1980 (12).

The long-distance migration of the monarch butterfly, *Danaus plexippus* (Lepidoptera: Nymphalidae), from eastern and western North America to overwintering sites in central Mexico (17, 38) has received considerable attention through community science programs (63, 107). The first monarch butterfly community science project was launched in the 1950s, and since then, the volunteers have engaged with a variety of projects (107), from tracking migration patterns (63) to assessing parasite dynamics (7, 90). For instance, data from the Western Monarch Thanksgiving Count have demonstrated the shift to high-elevation overwintering sites by *D. plexippus*, which will ultimately inform conservation strategies (38). Indeed, the evidence to support the petition to federally list the monarch butterfly came from long-term abundance and distribution data suggesting that monarch populations are declining (115).

5.2. Drivers of Biodiversity Change

Long-term data collected by community scientists have been instrumental in the study of climate change. Scientists and volunteers have collected phenology data on hundreds of species across major spatial and temporal scales (22, 117); for instance, in the United Kingdom, Nature's Calendar holds 3 million records spanning 300 years (22). This long-term data set has been used to address many research questions about the effects of environmental change on insects. For instance, both land use and climate change were considered to be important for explaining the decline of 260 macromoth species and the increase of 160 species in the United Kingdom (41). Northern, cold-adapted species were shown to decline, while southern, warm-adapted species increased (41). Similar patterns are seen in studies around the world and at various spatial scales, from beetles within a single protected area (62) to butterflies on a global scale (131). For example, observations for 30 common butterfly species across Ohio, United States revealed the importance of both climate change and urbanization in delaying the first appearance and peak abundance of these insects (32). However, there are geographic and taxonomic biases in these long-term data sets, which are mainly from northern Europe and focused on Lepidoptera (58).

Community science implemented at large spatial scales has illustrated how urbanization can influence insect conservation targets (52). For instance, a nationwide butterfly monitoring scheme in private gardens across France found fewer grassland and forest edge species with increased urbanization (92). Urbanization intensity was also negatively associated with the abundance of aphidophagous native lady beetles in residential gardens across Ohio, United States (48). By analyzing georeferenced photographs of insects on flowers, the Photographic Survey of Flower Visitors program found a significant negative effect of the proportion of urban areas to rural areas on flower visitor richness; this relationship was particularly strong for infrequently observed taxa (27). Importantly, community science data have also demonstrated that the deleterious effect of urbanization can be offset somewhat by local management. For example, butterfly abundances and pollinator richness were positively associated with garden size within urban settings (39) and the concentration of gardens in the landscape (75).

Community science programs have indicated that several forms of pollution are harmful to insects. Data provided by volunteers illustrated the negative impact of pesticides on bumble bee and butterfly abundance in residential gardens (87). Long-term data from the United Kingdom and Ireland illustrated that 69 moth species had declined at sites with a greater intensity of artificial light at night, as compared to historic moth abundances (141), and an increase in lichenivorous macromoths was noted in areas of historically high air pollution, highlighting that these species appear to have increased across the recent period of air quality improvements (97). By hosting bumble bee colonies in their backyards, community scientists demonstrated that heavy metal pollution in the legacy city of Cleveland, Ohio, United States was negatively correlated with bumble bee colony growth (123). The efforts of these volunteers uncovered a potential risk to bee conservation within cities with an industrial past and highlighted a need for further research to identify routes of contamination and effective mitigation measures to advance urban conservation planning (123).

5.3. Community Science Conservation Actions

Beyond monitoring, community scientists have taken collective action to improve the urban environment for insects (121). For example, in Ireland, people were encouraged to create diverse microhabitats in residential gardens to promote moth species richness (8); establishing drought-tolerant vegetation promoted insect species richness in arid Los Angeles, California, United States (1); and a lack of nesting sites, rather than floral resources, was found to limit cavity nesting bees in Leipzig, Germany (36). Within one city in Wisconsin, United States, 435 residents avoided mowing their lawn as part of the No Mow May campaign to provide spring forage for pollinators; bee abundance was five times higher in the unmown yards compared to lawns mown regularly (29). Likewise, participation in a backyard butterfly monitoring project led community scientists to plant additional nectar resources and reduce pesticide use in their own gardens (28).

6. CHALLENGES IN COMMUNITY SCIENCE

Community science has faced scrutiny regarding the quality of data that it produces, and these perceptions of unreliability have created roadblocks to publishing findings of community science studies (16). Errors due to misidentification are of particular concern for entomological initiatives, as insects are small, and many are challenging to distinguish (33, 110). Asking community scientists to undertake visual biodiversity assessments will likely lead to people reporting larger, visually distinctive taxa while underreporting cryptic species and inactive or early life stages (53, 65, 104). For example, the Monarch Larvae Monitoring Project found that volunteers could reliably identify late but not early instar larvae (104). There can be considerable variation in sampling effort, as records may be sparse in certain regions or might be punctuated by periods of intense activity driven by promotion of a particular project. The arrival of *H. axyridis* in the United Kingdom led to considerable media attention, with the promotion of the UK Ladybird Survey as a mass participation community science project, resulting in an approximately fourfold increase in the number of coccinellid occurrence records. Biases in recording behavior can result in overrepresentation of some species and underrepresentation of others within data sets. Community scientists were found to overreport threatened native lady beetles and underreport alien species (47). Likewise, community scientists may be interested in submitting photos of highly charismatic taxa or taxa from remote locations to online reporting sites. These and other forms of bias must be accounted for when making estimations of species' relative abundance or range utilizing crowdsourced data.

Community science practitioners have evaluated several procedures and tools to estimate, reduce, and account for errors and collector biases (21, 72). Data quality has been found to be positively associated with access to in-person training, detailed protocols, use of specialized data collection equipment, and submission of vouchers such as specimens or photographs (72, 102). For example, in the Buckeye Lady Beetle Blitz program, volunteers submitted yellow sticky card traps to researchers who then counted and identified all coccinellids present (48). However, this verification was time consuming and costly and may not always be feasible for larger-scale programs (72). Researchers have also focused on improving the skills of volunteers through ongoing learning opportunities. For instance, Prysby & Oberhauser (104) found that volunteers who participated in a training workshop produced data of a similar or higher quality to those produced by paid field assistants. Furthermore, statistics and modeling tools have been developed to estimate and account for challenges such as heterogeneity in sampling effort, nonindependent detections, false detections, and volunteer biases (4, 13, 21, 98, 134). For instance, increasing the information content of occurrence records provided by community scientists can inform researchers' understanding of the various sources of bias present in their data and enhance confidence in the analysis of these often noisy data sets (134). Contextual information, such as a volunteer's level of expertise, included within the metadata of occurrence records can assist in verification of an occurrence record by an expert verifier or, indeed, through artificial intelligence (129).

7. GLOBAL FUTURE DIRECTIONS

Going forward, we encourage a community science focus on inclusion, publication, and translating monitoring to action for insect conservation, invasive alien species eradication, and management and vector control. We see reaching diverse communities of volunteers and the study of understudied taxa and regions as essential goals for the field. As community science practitioners, we recognize that providing opportunities for volunteers to act as cocreators, from project inception through the dissemination of the results, is critical. Furthermore, for community science to be part of the scientific record and contribute to our ongoing understanding of our natural world, we must focus on breaking down barriers to the publication of our findings. Finally, we see great potential to coordinate community science monitoring and data collection at global scales to inform conservation and management actions. **Figure 2** highlights questions for practitioners to consider across the stages of project initiation, protocol development, data collection, and dissemination to reach these goals.

7.1. Promote Inclusion via Cocreation

Too often, community scientists are viewed as sensors or data collectors, and the opportunity to engage people in the scientific process beyond data gathering is missed (124). For instance, people submitting species occurrences are often driven by their attachment to a locality or taxonomic group, yet community science does not always empower data collectors to provide their ecological knowledge of the location and the species behind their data points. Furthermore, the demographics of community science are rarely representative of the diversity of people from the many areas where the programs take place (133). Groups that have been historically underrepresented in science make up only a small percentage of community science participants (133), and barriers to access mean that some individuals are less likely to influence the questions asked and methods used by community science, reap the benefits of program findings, or be inspired to seek out a career in science (94, 133). Increasingly, the concept of some communities being hard to reach is being questioned; there is a need to understand why science is difficult for some people to access that moves away from the so-called deficit model, in which audiences are considered to lack relevant knowledge or experience needed to engage, and toward inclusive science practices that facilitate open exchange among scientists and communities (25, 88).

Cocreation of a project from its onset is an important way that we can improve engagement and identify and overcome many historic barriers to inclusion (94). Researchers might engage all participants within cocreation or establish an advisory board of interested community members for large-scale studies. These volunteers can assist with recruitment strategies to ensure that all potentially interested people are aware of the opportunity and feel welcome to participate. When establishing a project's aim, volunteers involved within the cocreation can align the focus of the initiative with their communities' needs and interests. Importantly, the topics identified might extend beyond entomology, and therefore, practitioners must be prepared to build interdisciplinary

EDUCATION AND ENGAGEMENT → COMMUNITY SCIENCE ← RIGOROUS SCIENCE

1. Initiate project and define goals

How can we build community partnerships from the outset?

What is the most inclusive approach to defining our scope and goals?

What steps can we take to create an ongoing inclusive environment to share ideas, opinions, and feedback?

What limitations (obligations to funders, barriers to engagement, time, expertise) exist for project development? How do we overcome these and enable authentic cocreation?

How should we address conflicts that arise in the cocreation process?

What resources and training will volunteers need to fully contribute to project planning?

Have we considered the impact of discrimination and unconscious biases? How can we overcome these challenges?

2. Design and refine approach

What training is required in relation to the protocol development, such as experimental design, for the volunteers? How do we effectively and collaboratively provide it?

Have we considered participation barriers such as time, language, transportation, physical abilities, and financial limitations in protocols and plans for training?

Can we use focus groups to review and improve our plans prior to launching the project?

Did a review of our protocol highlight challenges to data quality that could prevent publication, such as response rate, accuracy, or biases? How can we overcome these?

3. Launch, collect, analyze

How can we publicize broadly to reach and attract a diverse audience of potential volunteers?

How do we maintain open communication to share knowledge, answer questions, and develop relationships during data collection and processing?

How can we empower our volunteer cocreators to train new recruits?

How can we engage volunteers in sample processing and data analysis?

What procedures are volunteers interested in learning? What training and permits (e.g., to work within university laboratories or visit field sites) are necessary?

4. Share, take action, reflect

How can we ensure that all volunteers are informed about the results of the study in a timely and accessible manner?

How can we engage volunteers in the dissemination of project findings? Are volunteers interested in co-authorship, writing popular press articles, posting on social media, or presenting in workshops? What training and tools can we provide to facilitate this?

What is next? Do the results of a monitoring project inform testable hypotheses? How can we engage a growing team in cocreation as the project moves forward? How can we balance new ideas with ongoing research without overwhelming our volunteers with too many responsibilities?

Do our data highlight the value of a conservation practice or mitigation measure that aids imperiled biota, improves environmental quality, or reduces human health risks? Are community scientists interested in participation in such actions? How can we initiate, manage, and fund such a program?

Were we successful in recruiting a volunteer pool reflecting the local community? If not, why? How can we apply what was learned to enhance diversity in future community science programs?

a Cocreating project aims

b Training

(Caption appears on following page)

Figure 2 (*Figure appears on preceding page*)

Guiding questions for community science practitioners. Community science aims to balance rigorous scientific enquiry with the engagement and education of volunteers. Looking ahead, we see four major challenges to achieving this balance. First, we must all do better to create an environment of inclusivity in our programs and think about how we can remove barriers to participation. Second, we should aim to engage volunteers in cocreation throughout the lifecycle of a project. For instance, photo A illustrates teachers and ecologists coming together to develop an approach for school children to monitor pollinating insects in Cyprus. Working together to define a project's goals, state hypotheses, and synthesize and disseminate the results allows volunteers to fully experience scientific enquiry. This group of cocreators might be a subset of all community science participants, who then work to recruit and train additional participants. For instance, in photo B, an expert in identifying bees is assisting teachers in gaining the field skills necessary to deliver a pollinator monitoring approach for school children in Cyprus. Third, we must overcome the challenges faced in publication of community science data by focusing on improving accuracy, identifying biases, and adopting new statistical tools while recognizing the needs and motivations of the community. Finally, we see opportunities to move community science beyond monitoring to engage in hypothesis testing and management actions to improve environmental quality and protect human health. Although this figure is far from exhaustive, we highlight guiding questions for community science practitioners throughout the stages of a project aimed at addressing these challenges.

teams to address the emerging topics of interest (94). When developing protocols, volunteers can assess the logistical commitments anticipated, such as reviewing whether the time commitment necessary to complete data collection is reasonable, allowing for any needed modifications during development. If necessary, the team can consider shifting onerous tasks from volunteers to paid researchers to aid participant retention (71) and potentially increase the amount of data submitted to the project. Volunteers can also provide leadership in assessing language, technological, or economic barriers and guide actions that promote inclusion of diverse participants. For example, volunteers could assist with the translation of program materials into additional languages, removing this common barrier to participation (100). Likewise, use of technology, such as social media sites and smartphone digital photography, as part of data collection might promote inclusion of volunteers in remote areas (126); however, these tools can also act as a barrier where access to them remains limited (100). Although community scientists are typically unpaid, compensating lower-income volunteers for time that they invest away from work should also be considered (96), and volunteers involved in project cocreation can advise on whether this strategy is likely to promote inclusion of underrepresented groups within their community.

Furthermore, engaging volunteers within cocreation will help to address the geographic biases that exist within community science. Currently, most published entomology studies emerge from the United States and the United Kingdom (**Figure 3*a***). Few data sets from high altitudes or tropical regions, where most insects live, exist; both of these habitats are critical areas for further investigation into the effects of climate change on insects (46). The formidable challenges to conducting community science in understudied regions can be tackled if local residents, funders, policy makers, and researchers work together to identify compelling, locally relevant questions that address community needs and values (100). For example, Tengö et al. (128) highlight the importance of connecting Indigenous peoples as knowledge holders with community science practitioners and provide a roadmap of tools and approaches for practitioners to engage with these communities. Many opportunities for community science were identified in a conference held in East Africa, where increasing people's awareness of environmental issues, empowering young people, and providing the data necessary to take actions to protect habitats and species were identified as key benefits of such programming (100).

We highlight a need for community science to consider a greater diversity of arthropods as targets for research. A survey of entomology studies published using community science data illustrates a strong taxonomic bias toward butterflies and moths, bees, and lady beetles (**Figure 3*b***). Increasing public understanding can improve science literacy and demystify entomology (116, 121), which may ultimately increase the taxonomic coverage of community science (132). For

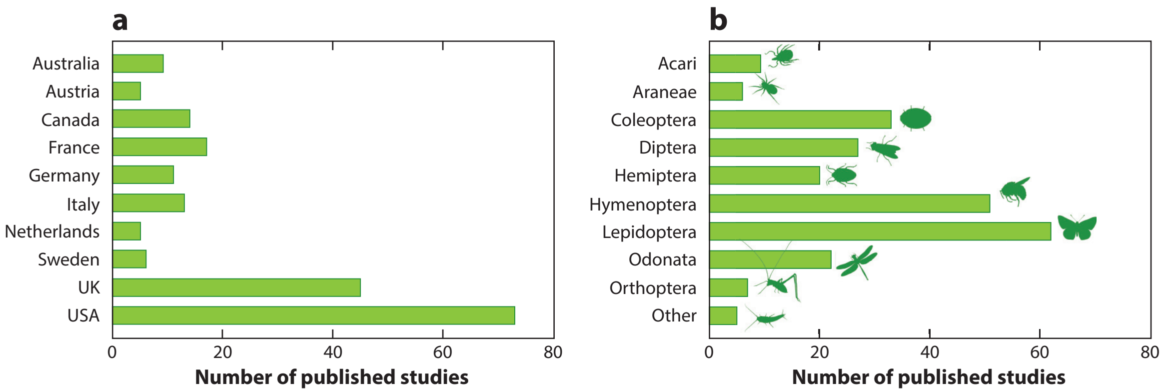

Figure 3

Taxonomic and geographic focus of published community science initiatives. Web of Science searches of the terms "citizen science" and "entomology" and "citizen science" and each arthropod order individually yielded 245 research publications (**Supplemental Table 1**). (*a*) To date, the majority of community science data have been collected within the United States and the United Kingdom, with few publications highlighting data collected outside of North America and Europe. (*b*) Nearly half of the studies focused on three insect orders: Lepidoptera (24.0%), Hymenoptera (20.2%), and Coleoptera (11.6%). Arthropod icons were obtained from the website **http://phylopic.org**, with credit to the following creators: Henry Lydecker (Acari), Lafage (Aranea), Melissa Broussard (Coleoptera), and Gareth Monger (Diptera, Odonata, and Zygentoma) (license: **https://creativecommons.org/licenses/by/3.0/**).

Supplemental Material >

example, after learning of the threats posed by illegal harvesting for the pet trade and habitat loss to baboon spider communities, community scientists across southern Africa engaged in a community science program by collecting photographs of these large arachnids to estimate their current ranges (19). Likewise, hairworms might not appear to be an ideal target for community science, but these parasites evoked the curiosity of people who found these 30-cm-long worms in water sources around their homes and went online to learn more about them (61). By engaging these individuals with the Report-a-Worm community science project, researchers were able to collect the specimens needed to conduct a taxonomic revision of the group (61). Indeed, research to understand, and strengthen, the connections between people and insects should be prioritized to underpin advances in community science. The extraordinary and diverse life histories of insects offer many opportunities for engagement, and community science approaches promoting empathy and curiosity toward insects will have a multitude of benefits (74).

7.2. Contributing to the Scientific Record

A small fraction of data collected by community scientists is published in peer-reviewed publications (130). Publication costs for open access journals is a significant barrier for many community science programs. Data quality, either real or perceived by peer reviewers; data quantity; and biases (including temporal and spatial extents), as well as the scientific novelty of the study, are also known publication barriers (18, 130). For example, some peer reviewers may exhibit bias against data collected by young people, as they are new to the field (43). Use of pilot studies or focus groups to evaluate protocols, measuring and accounting for error, and meeting the training needs of a volunteer pool are key steps that practitioners can take to increase publication rates (18, 43, 130) (**Figure 4**). The inclusion of volunteers as coauthors is suggested as a best practice for community science, yet practitioners have voiced frustrations over barriers faced when they attempt to credit volunteers' contributions. These include limits on the number of coauthors or challenges obtaining the necessary permissions to include young participants, resulting in the contributions of

OPPORTUNISTIC SIGHTINGS
(e.g., biological records)

1978: Bees, Wasps and Ants Recording Society

Aim: To gather **distribution and biological data** on the aculeate Hymenoptera, to provide advice and training to society members and the general public, and to promote understanding of aculeates

Approach: Recording of all aculeate Hymenoptera

Geographic scope: UK (but similar schemes in Belgium and the Netherlands)

www.bwars.com/home

2010: SpiPoll

Aim: Gather information on pollinating insects

Approach: Take photos of pollinating insects on flowers and submit records

Geographic scope: France

www.spipoll.fr/

2014: Bumblebee Watch

Aim: Track and conserve bumblebees of North America

Approach: Recording bumblebee sightings

Geographic scope: North America

www.bumblebeewatch.org/about/

2014: Save our bumblebee

Aim: Track *Bombus dahlbomii*

Approach: Recording bumblebee sightings

Geographic scope: Chile

https://salvemosnuestroabejorro.wordpress.com

2017: Record Pollinators

Aim: Establish how insect pollinator populations are changing across Ireland

Approach: Record various pollinators

Geographic Scope: Ireland

pollinators.ie/record-pollinators/

STRUCTURED OBSERVATIONS
(e.g., flower-insect timed counts)

2008: The Great Sunflower Project

Aim: Understand cause and impact of declines in bee populations

Approach: Flower-insect timed count

Geographic scope: North America

www.greatsunflower.org

2016: Wild Pollinator Count

Aim: Build a database on wild pollinator activity

Approach: Flower-insect timed count

Geographic scope: Australia

wildpollinatorcount.com

2017: Pollinator Monitoring Scheme

Aim: Establish how insect pollinator populations are changing across the UK

Approach: Flower-insect timed count

Geographic scope: UK (adapted for Cyprus and ongoing EU-wide)

www.ukpoms.org.uk

www.ris-ky.info/poms-ky

2017: Record Pollinators

Aim: Establish how insect pollinator populations are changing across Ireland

Approach: Flower-insect timed count

Geographic scope: Ireland

pollinators.ie/record-pollinators/

2021: X-POLLI:NATION

Aim: Monitor interactions between plants and visiting insect pollinators, and collect information in new countries

Approach: Flower-insect timed count

Geographic scope: UK and Italy

xpollination.org/about/

STRUCTURED SURVEYS
(e.g., transects)

2008: BeeWalks

Aim: Monitor abundance of bumblebees on transects across Britain

Approach: Transect walk on fixed route (1–2 km) once a month

Geographic scope: Britain

www.beewalk.org.uk/

2011: Bumblebee Monitoring Scheme

Aim: Monitor abundance of bumblebees on transects across Ireland

Approach: Transect walk on fixed route (1–2 km) once a month

Geographic scope: Ireland

www.biodiversityireland.ie/projects/monitoring-scheme-initiatives/bumblebee-monitoring-scheme/

2017: Pollinator Monitoring Scheme

Aim: Establish how insect pollinator populations are changing across the UK

Approach: Standardized pan-trap samples within series of 1 km squares

Geographic scope: UK

www.ukpoms.org.uk

Figure 4

The global reach of pollinator community science. Community science initiatives for monitoring bees and other important pollinators use different approaches, from documenting opportunistic sightings to structured observations and surveys. Outputs from these initiatives include distribution maps, biodiversity indicators, peer-reviewed publications, popular science articles, increased taxonomic knowledge, public engagement, understanding the motivation of participants, and evidence underpinning policy (e.g., indicators on the status of pollinating insects). The geographic breadth of these programs and the widespread concern for bees among the public showcase the scale at which community science practitioners and participants could collaborate to inform pollinator conservation at a global scale.

community scientists often appearing as an acknowledgment (43). In one discouraging account, Gadermaier et al. (43) note that a manuscript led by a young community scientist was deemed "not scientific enough" by reviewers who suggested a technical rewrite. We must advocate for the normalization of community scientists as authors of peer-reviewed publications and always facilitate other opportunities for volunteers to synthesize their findings, such as blogs, websites, and podcasts.

7.3. Coordinate and Act

When volunteers are engaged within project cocreation, they can contextualize project findings and propose and communicate actions to address major environmental problems and human health threats (24). Community scientists have demonstrated a willingness to report conservation targets, vectors, and invasive alien species across the globe; by standardizing protocols, we could improve risk mapping and better target management interventions. One critical example in which community scientist contributions were important is the decline of pollinators and pollination services. The links between insect diversity and ecosystem functions and services can be better understood when community science practitioners and volunteers work together to monitor pollinators and measure pollination services (14, 91). There are community science programs around the world monitoring pollinating insects (**Figure 4**), and considerable potential exists to build on these programs globally to develop standardized protocols to estimate species and functional trait diversity of habitats, measure derived ecosystem functions and services, and examine the influence of stressors as well as conservation measures on pollinator communities. For instance, tens of thousands of people have participated in the Great Sunflower Project, making timed observations of bees visiting sunflowers (*Helianthus annuus*) coupled with counts of seeds to estimate pollination services across North America (91). If an international standardized monitoring protocol could be developed, then the data generated would ultimately inform actions to conserve pollinators and pollination services globally (29, 83). Similar approaches could be employed at various temporal and spatial scales for other taxa, demonstrating and quantifying the immense and inspiring contributions of insects to people and nature globally.

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AUTHOR CONTRIBUTIONS

M.M.G. and H.E.R. both contributed original text and editing to this manuscript and worked jointly to prepare the figures.

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