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Primer

The global reach of citizen science for monitoring insects

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https://doi.org/10.1016/j.oneear.2024.03.009

SUMMARY

Biodiversity is declining rapidly. The most important causes of biodiversity loss are climate change, land- and sea-use change, invasive alien species, pollution, and overexploitation of natural resources. This unprecedented deterioration of the biosphere has profound and far-reaching consequences for insects, who play many important roles within ecosystems, including pollination and decomposition. Declines in the abundance and distribution of insects threaten these essential ecosystem functions. While there is no doubt that urgent and immediate measures are needed to address biodiversity loss and climate change, monitoring of insects is a priority to underpin and inform ongoing conservation action. Citizen science has emerged as an important tool for monitoring insects. In this primer, we explain the application of citizen science for monitoring insects and emerging approaches using digital technologies.

INTRODUCTION

Climate change, land- and sea-use change, invasive alien species, pollution, and overexploitation of natural resources are widely regarded as the major causes of the dramatic recent declines in biodiversity. Biodiversity loss has major implications for nature and the benefits that people derive from nature. Insects play many important roles within ecosystems and benefit people in many ways. As an example, insects are vital to sustainable agriculture, providing pollination and pest control services for crops, and thus play a major role in food security.

Addressing declines in insect diversity, abundance and distribution globally is a major priority. There is sufficient robust evidence demonstrating the need for action including measures to meet the ambitious Kunming-Montreal Global Biodiversity Targets that include specific goals and actions, including halting and reversing biodiversity loss and protecting and restoring ecosystems, to be achieved by 2030. Quantifying trends, understanding causes of decline, and evaluating the impacts of measures to mitigate these declines require accessible and robust information on insects. However, this is challenging because of taxonomic, spatial, and temporal gaps in easy-to-access global datasets that are open to all and appropriate for undertaking relevant analyses. Indeed, the most species-rich regions of the world (e.g., tropical ecosystems) are the ones most lacking accessible data. Solutions to this include deployment of novel monitoring techniques around the world, including citizen science.

WHAT IS CITIZEN SCIENCE?

Citizen science, sometimes also called community science or participatory monitoring, is a term that refers to the engagement of volunteers in scientific research and monitoring. Citizen science comes in many forms. Citizen science projects can be contributory, collaborative, co-created, or community led. Through contributory citizen science, volunteers are involved in data collection, while through collaborative citizen science, participants may also assist with project design, analysis, and reporting. Co-created and community-led citizen science involves scientists and volunteers working together at every stage of the scientific process and often arises from community needs delivering direct benefits for people and empowering communities.

Citizen science has a long history of contributing to our understanding of the natural world. Long-term and large-scale datasets for insects have relied on the sharing of observations by people for centuries. Citizen science has provided insights into the spectacular life histories of insects including awe-inspiring events such as mass migrations of butterflies. Large-scale and long-term citizen science datasets have also provided evidence of the dramatic and ongoing insect declines globally, although it is widely acknowledged that some of the most species-rich regions of the world are the most depauperate in accessible data. Emerging technologies are providing new opportunities to extend the reach of citizen science to address such gaps.

Before embarking on developing a citizen science initiative, it is important to consider the applicability of the approach to

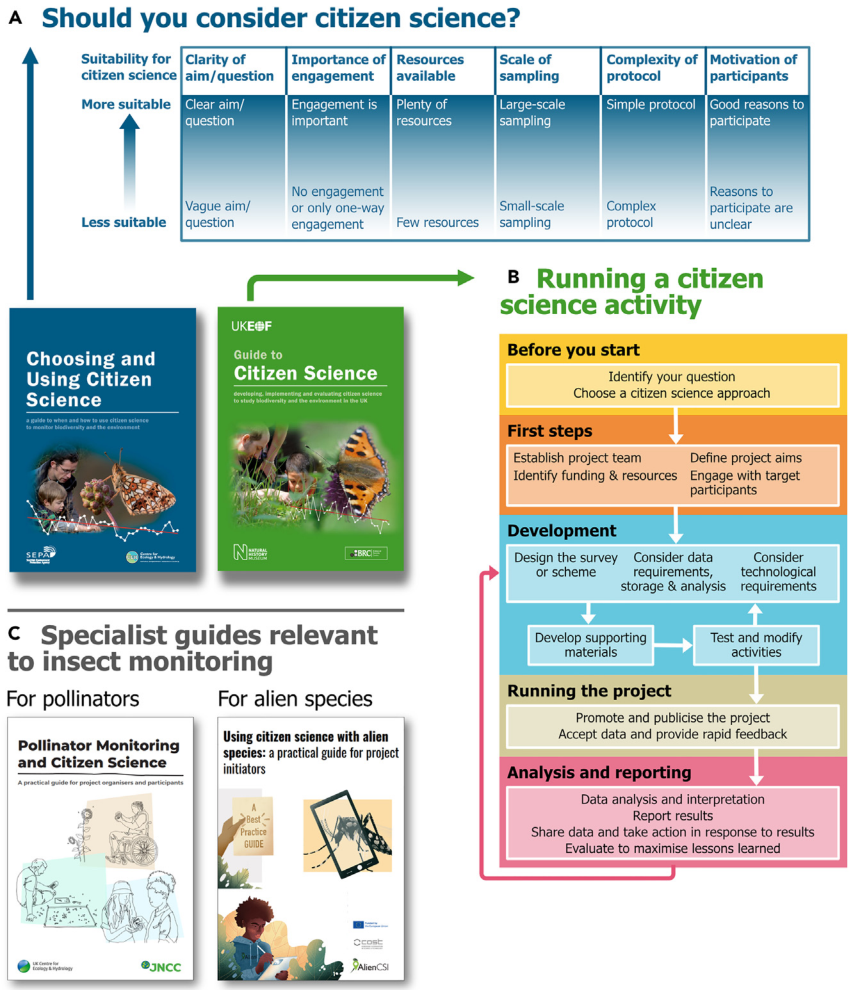

Figure 1. Selected publications outlining approaches to citizen science
There have been many publications outlining approaches to citizen science including (A) guidance on when to use citizen science, (B) how to use citizen science in environmental monitoring, and (C) more specialist guides such as using citizen science for increasing understanding of pollinators or invasive alien species.

achieving the desired aims and outcomes (Figure 1). Projects that have clear aims are particularly suitable for citizen science. Citizen science is not free, and adequate resourcing, including, as an example, to develop materials to guide, engage, and support participants, is often critical to success. Citizen science is particularly suitable for relatively simple survey methods that need to be implemented over very large scales and that might be difficult to achieve without mass participation of volunteers.

ROLE OF CITIZEN SCIENCE IN MONITORING INSECTS

There is a long history of engaging people in entomological research and monitoring through citizen science. For centuries, volunteers have contributed observations (or biological records) of many different insect species, resulting in long-term and large-scale datasets that have value for research to inform policy and conservation action. For insects, citizen science may involve participants following a detailed protocol to monitor insects repeatedly at set locations, providing datasets that can be used to assess change for groups such as butterflies (Box 1) or insect pollinators (Figure 2), sometimes referred to as structured citizen science. Alternatively, citizen science may involve participants submitting observations of insects as and when they choose, often uploading photos of species using smartphone applications. Global-scale projects such as iNaturalist engage hundreds of thousands of people in a relatively simple citizen science approach who submit many millions of records of thousands of insect species annually.

Datasets comprising observations of species or biological records are an immensely valuable source of information for monitoring trends in insect distributions. Biological records are often extremely precise in terms of the location and time of collection. Additionally, the identification of the species reported is accurate because either a species expert has made the record or checked and verified the record. However, such datasets need careful analysis because of some of the biases inherent within them. Volunteers make biological records at specific places and times that they chose for various reasons: a site that is of interest to them or one conveniently near to where they live or at times of the year when they are most likely to see a species of interest, for example, when the species is known to be most active and at life stages most easy to detect (for example, adults rather than larvae). Decisions on when, where, and what to record can lead to a variety of challenges for researchers: uneven sampling over space and time, uneven sampling effort per visit, and abilities to detect a species, noting that some are more easily seen and recognized than others. As such, datasets comprising biological records can be difficult to analyze, but there are examples of statistical approaches that have been successfully adopted to overcome and transparently acknowledge some of the biases.

Semi-structured approaches invite people to take part in insect recording when and where they choose but following a simple protocol. These activities remain accessible to volunteers but may provide additional power for subsequent analyses than biological recording alone. Other projects are going a step further by using "adaptive sampling," whereby volunteers are encouraged to maximize their contributions by recording insects in the places where species observations are most needed to improve ongoing biodiversity analyses. All in all, the range of citizen science approaches available allow many people to contribute to insect monitoring in many different and engaging ways.

Box 1. Monitoring butterfly migrations

Line transects are the primary method for monitoring butterflies in many parts of the world and the foundation of butterfly monitoring schemes that sample butterflies in a consistent way at multiple sites across seasons and years. The first such scheme was initiated in 1976 in the UK. The UK Butterfly Monitoring Scheme has been incredibly successful, with volunteer participants now counting butterflies from over 4,000 sites each year, and arguably represents the world's largest spatiotemporal dataset on insect abundance. This citizen science approach and the resulting dataset has generated a wealth of research insights, including the impacts of climate change on butterfly numbers, distribution, phenology, and migration. Indeed, long-term population monitoring by volunteers in the UK and Catalonia has helped reveal the remarkable Afro-Palearctic migration of Painted Lady butterflies (*Vanessa cardui*) in response to weather patterns.

When combined with new technologies such as smartphone applications and innovative data visualizations, citizen science offers huge potential for involving large numbers of people in tracking pan-continental insect migrations. The ButterflyCount mobile application has implemented a specific survey for the Painted Lady butterfly to allow the collection of data to deepen understanding of its migratory ecology (see https://butterfly-monitoring.net/painted-lady-migration). The approach is being extended to other species such as the Caper White (*Belenois aurota*) that can occur in spectacular numbers in Africa and migrates from the northeast over the interior of the continent. Dedicated surveys through tools such as the ButterflyCount application offer the collection of structured data on much wider spatial and temporal scales than has previously been possible and enable the involvement of naturalists (e.g., bird watchers and wildlife photographers) alongside researchers working on insect migration. Documenting insect migrations through citizen science is an important approach for understanding source populations, migration routes and stopovers, host plant use by egg-laying females, and male territorial behavior and to understand the roles of environmental conditions (such as wind conditions or resource availability) in insect migrations.

EMERGING TECHNOLOGIES FOR INSECT MONITORING

Over the last decade, there has been an expansion in the deployment of technologies for insect monitoring, and some of these advances have transformed the opportunities for citizen science initiatives on insects. As an example, biological records were often captured in notebooks or on pre-printed recording cards; however, although biological recording remains much the same as it has been for centuries, the technology revolution means that records can be made and shared rapidly and more easily from smartphone applications and other online tools.

Indeed, new tools and technologies provide opportunities to increase capacity, expand the breadth of biodiversity observations, and consequently enrich our understanding of the natural world. From the use of molecular tools, such as environmental DNA, to the deployment of acoustic sensors and camera traps and exploring the signals from remote sensing technologies, including radar, citizen science activities are embracing technology to address complex ecological questions. Traditional approaches to undertaking insect surveys will remain a critical component of monitoring capability, but technologies provide additional opportunities to increase participation through citizen science.

Integrating emerging technologies with citizen science is increasing the involvement of people in monitoring insects. The most widely applied example is artificial intelligence used to assist participants with the identification of species. Indeed, artificial intelligence is becoming routinely integrated within recording applications to provide users with support for identification of the species in the photographs that they have taken. Advances in computing power are also providing benefits for enhancing biodiversity monitoring through citizen science. Clusters of computers are being used to provide the power for complex modeling techniques such as adaptive sampling approaches that maximize the contributions of volunteers making biological records to improve species maps and biodiversity models to inform policy and conservation decision-making.

MOVEMENT OF INSECTS: INDIVIDUALS AND POPULATIONS

Understanding the detailed life histories of insects, including patterns of movement, can inform management such as controlling pest species or conserving threatened species. Furthermore, the stories revealed through entomology can be engaging, inspiring people to contribute to citizen science initiatives to further increase knowledge of these captivating creatures. Detection of swarms of insects using radar is not new, but modern radars have the capability to provide information on the movement of individual insects far above the surface of the Earth at high resolution. While citizen science observations on the ground provide valuable information on the status and trends of insects, these citizen science datasets can also be used to check and validate information from radar. A citizen science dataset from the Ladybird Survey in the UK was used in combination with vertical facing radar data collected over 10 years to reveal that two species of ladybird (7 spot, *Coccinella septempunctata*, and harlequin, *Harmonia axyridis*) were flying up to 1,100 m above ground level and at speeds of up to 60 km/h. Seasonal trends in the movement of ladybirds were also revealed, with high temperatures and low aphid prey abundance driving ladybirds to take to the skies. Ladybirds are capable of long-distance dispersal usually in the range of tens of kilometers. However, there are awe-inspiring examples of insects migrating over much greater distances including, perhaps most famously, the millions of eastern North American monarch butterflies (*Danaus plexippus*) that travel staggeringly long distances, up to 4,500 km, to reach overwintering sites in Mexico. In so doing, they avoid the adverse low temperatures and demise of their host plants in more northern locations while also reducing the prevalence of a virulent parasite. Citizen science, including studies tagging butterflies from the 1970s, has played an important role in unraveling the ecology of the spectacular migration of monarch butterflies in North America. Indeed, citizen science has a long history in understanding butterfly migrations and is being made more accessible through new technologies (Box 1).

MOVEMENT OF INSECTS: RESPONDING TO ENVIRONMENTAL CHANGE

Citizen scientists have mapped the distributions of many species globally by sharing their observations or biological records. Such datasets have demonstrated that an ever-increasing number of insect species are needing to shift their distribution ranges as regions in which these insects previously thrived become increasingly unsuitable because of climate change, habitat degradation, and landscape fragmentation. Dispersal and migration are critical for the continuation of some insect populations to counter the adverse effects of environmental change.

Environmental change is leading to the movement of species in various ways. Assisted migration, whereby species are intentionally moved to new regions, may be an important approach to conserving some insects that cannot naturally disperse to new habitats. Robust assessment of risk is critical before any activity involving the movement of species is initiated. Climate change and land-use change might also create opportunities for some species, and in some cases, this may not be desirable. Invasive alien species may benefit from increases in temperatures and habitat disturbance. For example, some species of insects, such as the Argentine ant, *Linepithema humile*, and mosquitoes (Box 2), which have been introduced by human activities into new regions where they would not otherwise occur, are now thriving as invasive alien species in many countries.

TRACKING INVASIVE ALIEN SPECIES

Invasive alien species are one of the major causes of biodiversity loss. Preventing the introduction of alien species into new regions is the most effective way to manage biological invasions, but when this fails, rapid control is critical. Early warning and rapid response of invasive alien species depend in part on the commitment of citizen scientists to report their observations of species of concern. The Asian hornet, *Vespa velutina*, arrived in France in a pottery consignment in 2004. It spread rapidly through France and into neighboring countries. Communication campaigns in many countries raised awareness of the threat of the Asian hornet to biodiversity, particularly as a predator of pollinating insects, and called on people to report any sightings of this invasive alien species. In the UK, the citizen science initiative Asian Hornet Watch receives thousands of reports from citizen scientists. Most are native species, but the confirmed sightings of the Asian hornet enable rapid action and have so far led to its eradication in the UK. The incredible engagement of people with the Asian Hornet Watch campaign is inspiring, but managing the much-welcomed large number of reports is time consuming. Technologies such as artificial intelligence have the potential to assist by automatically identifying the species within the photographs that accompany many of the reports. If the species is identified as an invasive alien species, then this information can be rapidly conveyed to decision-makers who can take appropriate action.

IMPORTANCE OF CITIZEN SCIENCE FOR NATURE RECOVERY

While there has been considerable focus on insect declines and, indeed, stark reports of an impending insect apocalypse, there is cause for optimism. The Kunming-Montreal Global Biodiversity Framework comprises ambitious targets to underpin nature recovery worldwide: its target 3 commits to ensuring and enabling "at least 30% of terrestrial, inland water, and coastal and marine areas, especially areas of particular importance for biodiversity and ecosystem functions and services, are effectively conserved and managed by 2030." Appropriate ways of measuring progress toward these targets, and ultimately nature recovery, are crucial. Distribution, abundance, and richness are important indicators of the status of insects. However, the interactions among species within complex ecological networks underpin the functioning and resilience of ecosystems. For example, pollinating insects span many different groups (bees, flies, beetles, and many others), but even within one group, there will be considerable variation in the flowers they visit, the habitats they occupy, and the time of year when they are active. This diversity in life histories can support the resilience of ecosystems and nature recovery.

Studying interactions among multiple species at large scales is exceptionally time consuming and, in many cases, simply impractical because of the numbers of species and range of interactions involved in complex networks. Engaging citizen scientists in studying insects through initiatives such as flower-insect timed counts (Figure 2), where volunteers count all the insects visiting a specific flowering plant within a quadrat over a given time period, is providing robust and invaluable datasets for assessing change over time and across large scales. The use of smartphone applications to guide citizen scientists, taking them step by step through the survey method and assisting with species identification through artificial intelligence alongside automated feedback, which can provide additional information on their observations, is revolutionizing citizen science.

Figure 2. Flower-insect timed counts through a program organized by the Anguilla National Trust
Photo credit: H.E.R.

Box 2. Monitoring mosquito populations and distributions

Mosquito monitoring is an essential part of any integrated mosquito management or control program. Traditionally, mosquito monitoring relies on locating mosquito breeding sites where the aquatic stages of mosquitoes live and sampling mosquito species through a method known as "larval dipping." There are also a variety of traps available for monitoring adult flying mosquitoes alongside any associated risks from mosquito-borne diseases. Sampling is often undertaken by medical entomologists or public health professionals. However, citizen science is becoming an increasingly important component of mosquito monitoring, particularly for invasive alien mosquito species within the genus *Aedes* that are anthropophilic and live near humans. Studies on these citizen science projects have shown the high accuracy and value of citizen science compared to professional monitoring. The use of mobile phone applications by citizen scientists is becoming popular for recording disease vectors or assessing the need for mosquito control in specific neighborhoods or regions. For example, the Mosquito Alert project includes a mobile phone application for citizen scientists to record mosquitoes that can then be reviewed and verified by experts. The project also provides analysis and visualization tools that provide feedback to participants while, importantly, assisting local mosquito control agencies that may have limited capacity to monitor mosquito populations themselves.

Flower-insect timed counts have been designed to be adaptable to any local situation and have already been developed in Western and Eastern Europe and in countries in the Caribbean and South America, in collaboration with local stakeholders. Furthermore, such techniques can be deployed for monitoring the effectiveness of conservation measures implemented to address biodiversity declines including assessing changes to insect communities as species move. Citizen science in combination with deployment of emerging technologies offers exciting opportunities to increase the rigor of biodiversity metrics used to assess the success of conservation actions, such as ecosystem restoration and nature recovery, by increasing their taxonomic, spatial, and temporal coverage.

Excitingly, emerging technologies, specifically computer vision, which enables computers to identify and understand objects in images, are also beginning to show potential for real-time monitoring of insect interactions with flowering plants. Convolutional neural networks are deep learning models, a type of artificial intelligence that can recognize complex patterns from images and learn to differentiate between them. Time-lapse cameras can be placed above flowering plants to record insects visiting flowers across entire seasons, with computer vision documenting in real time the insects observed. There is considerable potential to increase the capacity of such technologies to explore other species interactions including predator-prey dynamics, herbivory, and more. This could help to transform the potential of citizen science to support insect monitoring. Documenting the ways in which insects move through changing landscapes and understanding the barriers to dispersal could also inform conservation action including the creation and effectiveness of wildlife corridors.

CONCLUSION AND OUTLOOK

There is no doubt that people and nature are facing major challenges as a consequence of the ongoing unprecedented scale of environmental change. Calling on people to act in support of wildlife through participation in citizen science initiatives provides hope. There are many examples of the ways in which citizen science has been used to monitor insects around the world, from mass participation observations of specific insects to structured approaches monitoring plant-insect interactions. The value of the information and data from citizen science is being increasingly recognized within policy and research. Importantly, there are well-being benefits for citizen science participants that come from connecting with nature and contributing to measures to safeguard biodiversity.

There are opportunities to expand the reach of citizen science globally and, in doing so, increase data flow for underrepresented taxa and regions, such as the Global South. Priorities include the following:

(1) Ensuring adequate and sustained funding for citizen science and biodiversity monitoring.
(2) Establishing networks to share and collaborate with educational institutions (including universities and schools to integrate citizen science into curricula) but also national parks and existing citizen science groups to maximize participation and ensure projects are locally relevant (including co-development of relevant resources and materials in an accessible format to guide and support target audiences).
(3) Providing a variety of ways for volunteers to participate; as an example, WhatsApp and other social media can be useful for gathering records in some countries and contexts.
(4) Building capacity in the use of emerging technologies, such as computer vision, through regional and international networks. It is important to acknowledge that the detection and identification of insects using computer vision has many challenges. For example, in many regions, there is a paucity of training data available to optimize the deep learning models and validate species identifications. Citizen science participants can assist in providing the information needed to inform the refinement of the models.
(5) Openly sharing innovations, infrastructures, and datasets including online databases and recording platforms and following FAIR (findability, accessibility, interoperability, and reuse) data principles for digital datasets and CARE (collective benefit, authority to control, responsibility, and ethics) principles for Indigenous data governance.

Citizen science connects people to the natural world and contributes much-needed biodiversity data and information, closing gaps in knowledge. Together, we can address the biodiversity crisis, but there is no time to wait. Action must come now.

ACKNOWLEDGMENTS

With thanks to the many, many volunteers who have made inspiring contributions to our understanding of insects for centuries. H.E.R., D.B.R., and M.J.O.P. were funded by UK Natural Environment Research Council award number NE/R016429/1 as part of the UK-SCAPE programme Delivering National Capability. Through the GLOBMS project, D.B.R. was also supported by the Natural Environment Research Council as part of the NC for Global Challenges programme NE/X006247/1 delivering national capability. H.E.R. also acknowledges support from UK Natural Environment Research Council grant NE/V006533/1 Global Insect Threat-Response Synthesis (GLiTRS): a comprehensive and predictive assessment of the pattern and consequences of insect declines. H.E.R., A.F.M., D.B.R., and M.J.O.P. gratefully acknowledge funding opportunities from Darwin Plus, including DPLUS175 "Enhancing monitoring and prevention of invasive non-native species across UKOTs," which have provided many insights into citizen science initiatives on the UK Overseas Territories. H.E.R. and A.F.M. acknowledge COST Action CA22129 InsectAI (Using Image-based AI for Insect Monitoring & Conservation) for networking opportunities.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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