A Citizen Army for Science: Quantifying the Contributions of Citizen Scientists to our Understanding of Monarch Butterfly Biology

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The first monarch citizen science program was launched in the 1950s and, since then, thousands of volunteers have made fundamental contributions to our accumulating knowledge of monarch biology. We quantified these efforts and the degree to which citizen science has contributed to monarch scholarship. We estimate that, in 2011, volunteers spent over 72,000 hours collecting data useful for monarch research. Of 503 monarch-focused research publications in which new results were presented from 1940 to 2014, 17% used citizen science data. We address persistent gaps in the use and coverage of these data and show that, despite a typical view of volunteers as mere data collectors for scientists, many citizens are deeply engaged in all aspects of monarch research and data use. Finally, we argue that monarchs provide a model system for understanding the impacts of citizen science on scholarship, public engagement, and conservation.

Keywords: public participation in scientific research, citizen science, monitoring, monarch butterfly

The term *citizen science* is used to describe efforts in which volunteers who are generally not professional scientists (or are scientists outside their field of training) collect data for research (Shirk et al. 2012). Public participation in science actually has a long history of naturalists' personal collections and observations contributing to a vast accumulation of specimens and natural history knowledge (Hart et al. 2012, Miller-Rushing et al. 2012). Recently, interest and participation in citizen science have surged, which is evidenced by reports in the popular press, books (e.g., Dickinson and Bonney 2012) and the devotion of an entire issue to this topic by two scholarly journals, *Frontiers in Ecology and the Environment* (August 2012) and the *International Journal of Zoology* (2012). Even the White House recognized the importance of citizen science by naming twelve "citizen science champions of change" in 2013. Here, we describe the contributions that volunteers have made to the scholarship of a single species, the monarch butterfly (*Danaus plexippus*). Our goals are to quantify butterfly monitoring efforts, their importance to our understanding of monarch biology, and—more generally—to encourage increased support for citizen science programs and the use of the resulting data.

Monarchs and citizen scientists

North American monarch butterflies have two fairly distinct migratory populations separated roughly by the Rocky Mountains. Each fall, the majority of those in the east undertake a spectacular migration of up to 4500 kilometers (km) from northern breeding grounds to overwintering habitat in the mountains of central Mexico. The same individuals travel north in the spring to lay eggs in the south central and southeastern United States. Their offspring continue the migration to northern breeding grounds, in which they produce two to three more generations before the final generation migrates back to Mexico (Oberhauser and Solensky 2004). The western North American population also migrates, overwintering in several sites along the California coast; their spring migration expands east and north to breeding grounds in California and beyond (Oberhauser and Solensky 2004). Other populations are found in southern Florida; on islands throughout the

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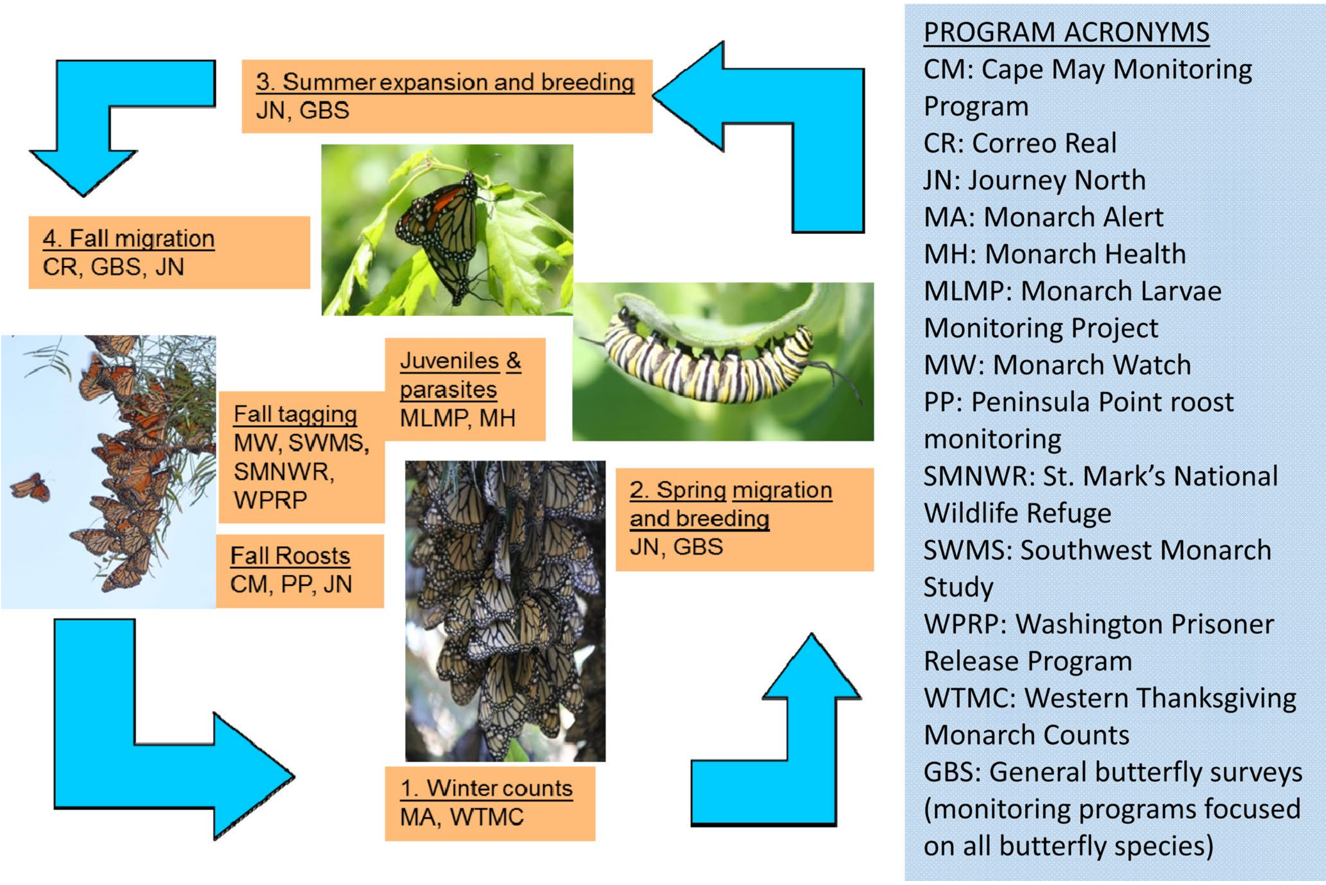

Figure 1. The annual cycle of the migratory monarch butterfly occurs in four main stages: (1) overwintering, (2) spring migration and breeding, (3) summer expansion and breeding, and (4) fall migration. The 12 citizen science programs that collect data solely on monarchs are indicated by acronym at stages at which they collect data. Throughout the year, general butterfly surveys (GBS) collect distribution data. The details and full names for the programs are shown in table 2 and supplemental appendix S1. Photographs: left, Carol Cullar, Rio Bravo Nature Center; top, right, bottom, Wendy Caldwell, University of Minnesota.

Caribbean and Pacific Ocean, including New Zealand and Australia; in Central and South America (CEC 2008); and in Spain and Portugal (Fernández-Haeger and Jordano-Barbudo 2009). These populations are mostly nonmigratory, although some exhibit seasonal movements.

Our evolving understanding of monarchs has benefited enormously from citizen science programs. Indeed, the search for the overwintering grounds of the eastern North American population was a life-long endeavor by Fred Urquhart and his wife Norah, who were aided by hundreds of volunteers who put small, uniquely identified tags on monarch wings starting in the 1950s. Recovery of these tags by the general public allowed the Urquharts to track the flights of individual butterflies and, eventually, led to the discovery of the monarch wintering grounds in Mexico (Urquhart 1976). This program, called the Insect Migration Association (IMA), was an early and still-rare example of a large-scale citizen science effort intended not for basic monitoring but to answer a specific scientific question. The IMA persisted until 1994, and its legacy has continued through Monarch Watch. Recent declines in North American populations (Stephens and Frey 2010, Brower et al. 2012) make tracking monarch numbers and understanding population drivers especially important from a conservation perspective.

Twelve monarch-centric volunteer-based monitoring programs in North America currently collect data on every phase of the monarch's annual cycle (figure 1), including migratory and breeding adults, eggs, larvae, and overwintering clusters. Current monarch citizen science projects are all based in North America, but volunteers were also crucial to the understanding of monarch movement in Australia (e.g., Smithers 1977) and New Zealand (Wise 1980). The programs reach a broad cross-section of society, from school-age children to retirees (Oberhauser et al. 2015b) and one program even operates in a maximum-security prison (David James, personal communication). Although the majority of citizen science projects are focused on fairly simple observations, many recruit and train volunteers who collect more process-oriented data using precise, often time-consuming protocols. These “super citizen scientists” (Hames et al. 2012) engage at intense levels. For example, volunteers for the Monarch Larva Monitoring Program (MLMP) assess monarch egg and caterpillar density and development weekly for up to 15 weeks (or more in the southern United States). These volunteers observe up to several hundred plants per monitoring event, often collect monarch eggs and caterpillars to rear inside their homes for a parasite study, and record weekly data on flowering plants and other characteristics of their site. These examples of process-based data collection reveal how citizen science can move beyond pattern-based exploration.

The contribution of general butterfly monitoring programs

In addition to monarch-centric programs, there are many programs that perform surveys on all species of butterflies, including monarchs. These general butterfly monitoring programs include a wide variety of protocols, from systematic surveys to incidental sightings. The world’s largest and longest-running volunteer-based butterfly monitoring program is the North American Butterfly Association’s (NABA) seasonal count program. Since 1975, thousands of volunteers have counted butterflies in 25-km-diameter count circles throughout North America. Many regional programs do more intensive monitoring with greater replication and stricter protocols. All of these programs are crucial to tracking monarch population dynamics precisely because they are not focused on monarchs; monarch-centric programs tend to be biased toward areas and times at which monarchs are most common.

Assessing the outcomes of citizen science

Citizen science outcomes are generally grouped in three categories: research, individual (impacts on the citizens themselves), and policy or action. These outcomes are often influenced by the level of citizen participation. Shirk and colleagues (2012) described five models that capture the range of participation in public research. Only the model with the least citizen engagement in science (the *contractual* model, in which citizens define a problem and contract scientists to study it) is outside the range of monarch programs. The most typically held perception of citizen science is represented by *contributory* programs, which are designed by scientists, usually affiliated with academic or research institutions, who recruit and engage volunteers largely to collect data. On the opposite end of the spectrum are less well-known *collegial* programs, which are established, designed, and run by the citizens themselves or by organizations focused primarily on outreach and education. Many of these programs recruit volunteers for data collection, and sometimes, professional scientists are engaged to consult or analyze data. In between are programs that represent a mix of engagement, from *collaborative* programs, in which scientists are clearly the leads but volunteers take a more active role in various stages, to *cocreated* programs, which involve fairly equal contributions between scientists and the public.

Here, we focus on research outcomes of citizen science. Although several reviews have shown the importance of citizen science to scholarship (for a review, see Dickinson et al. 2011, 2012), we believe that this is the first study to explicitly quantify how much effort by volunteers goes into collecting data relevant to a single species and the degree to which those data have contributed to the accumulated knowledge of that species. Recent reviews suggest that *contributory* projects produce the most research output (Shirk et al. 2012), and we test this assertion with the monarch system. Our specific goals were to quantify volunteer time investment in monarch citizen science, to determine the proportion of publications that use citizen science data and how data use is influenced by the type of program, and to assess the relative importance of citizen science to different aspects of monarch research and look for emerging potential for data to be more fully utilized.

Quantifying program participation

We compiled an inventory of monarch and general butterfly monitoring programs and quantified the effort made by volunteers during 2011, the most recent year in which the majority of programs had data available for comparison. Our inventory included all monarch programs, including international and defunct programs, but we restricted general butterfly programs to North American programs operating in 2011. We are confident that we included all major programs because both authors have been instrumental in developing organizations to support and connect these programs, one for monarchs (*www.monarchnet.org*) and one for general butterfly programs (*www.nab-net.org*), although some smaller efforts may not be represented. We did not include butterfly atlas projects (in which volunteers document presence and absences across a grid), nor did we include general biodiversity programs (e.g., iNaturalist, Project Noah, or BioBlitzes); the number of monarch observations recorded by these programs in 2011 were trivial, but they could become substantial data contributors in the future. We also did not include locally coordinated efforts to implement national programs, such as when a nature center recruits people to tag butterflies using Monarch Watch tags. We classified each program as to the model of citizen engagement in developing and running the program. Although the level of engagement varied, all programs were heavily tilted toward either scientist or citizen management and therefore all were classified as either *contributory* (run by an academic or research institution, including museums) or *collegial* (designed and managed by nonprofessionals or an outreach institution, including nature centers and butterfly houses).

To quantify the contributions of volunteers in monarch citizen science projects, we needed a metric that allowed cross-project comparisons. The number of data records was not sufficient; what constitutes a record represents different

Table 1. Type of data collection events and the general formula used to calculate volunteer time spent for each.

Data event type	Description	Time estimation formula
Sighting[a]	A monarch sighting is entered into an online database. Only records of monarch sightings are included.	0.25 hours per record
Trip[a]	Trips are "bouts" in which one or several people are doing a search in a limited area and all butterflies are recorded. Trips include "Counts" which are repeated over time and with stricter protocols. Even when no monarchs are observed, this effort is useful for evidence of monarch absences and so all time performing general surveys is counted.	Number of observers * trip duration. For programs that don't record duration, we used a formula of 10 min/species recorded.
Survey	A specific protocol is followed to collect data and searches are usually confined to a transect or plot. As for Trips, time recording these surveys is included even if no monarchs are observed.	Number of observers × survey duration. For programs that don't record survey duration, we consulted with program managers to estimate average time for each survey.
Capture	Programs that require capturing adults include all tagging programs and Monarch Health, in which adults are captured and sampled for disease.	0.33 hours per capture
Rearing	Volunteers bring juvenile monarchs into their home and rear them to study mortality and parasitism.	0.75 hours per juvenile reared

[a]Many people use sightings databases for trip data (evident by multiple species and records of the number of individuals or species). When the databases (eButterfly, NABA, MBC) included both, we designated reports with at least three species recorded as trips; other records were counted as sightings.

levels of effort and information. For example, a general butterfly survey may involve a single individual walking a transect for 30 minutes or dozens of individuals spending all day searching a large area. Another example is a monarch sighting reported to a web site such as Journey North compared with a volunteer who collects a caterpillar in the field and rears it inside to score for parasitism. Each results in a single record, but they require different levels of effort. Therefore, we chose time as our metric.

We defined five types of data collection events—sightings, trips (including counts), surveys, captures, and rearings (table 1)—and obtained activity data from all relevant monarch and general butterfly programs from 2011. We defined a data collection event as one in which data were collected at a specific location on a specific date. When duration information was not recorded, we worked with program managers to develop formulae for estimating time spent for each event (described in table 1). Time estimates do not include travel to and from sites.

From each program, we compiled a database of survey events, including coordinates for all points from which volunteers had submitted data in 2011, the date of the record, the actual or estimated time spent on the observation, and the number of people involved in the survey (when that is known). Note that some smaller programs did not have data compiled for recent years, and we worked with managers to obtain reasonable estimates of where surveys had occurred in 2011 and how much time was spent completing them. We stratified records by seasons, defined on the basis of the monarch migration cycle (Ries et al. 2015): spring (Mar 15–May 16), summer (May 17–Aug 15), fall (Aug 16–Oct 31), and winter (Nov 1–Mar 14). Finally, we mapped the distribution of time spent across North America separately for monarch and general butterfly programs by season, at a 1-degree spatial resolution.

Literature review

To assess the impact of citizen science on scholarship, we tracked the use of citizen science data in the peer-reviewed monarch literature. Although the first publication using data from a monarch citizen science program appeared in 1960 (Urquhart 1960), earlier research included other forms of public participation, such as field notes and museum collections. Therefore, we tracked publications from 1940 through 2014. Papers or books in press as of June 2014 were counted as being published in 2014. We performed Web of Science and Google Scholar searches using the terms "*monarch*" and "*Danaus plexippus*", and supplemented the searches with other papers of which we were aware. We included five peer-reviewed books that presented original research on monarchs: *The Monarch Butterfly* (Urquhart 1960), *Biology and Conservation of the Monarch Butterfly* (Malcolm and Zalucki 1993), *1997 North American Conference on the Monarch Butterfly* (Hoth et al. 1999), *The Monarch Butterfly: Biology and Conservation* (Oberhauser and Solensky 2004), and *Monarchs in a Changing World: Biology and Conservation of an Iconic Butterfly* (Oberhauser et al. 2015a). We counted each chapter as a "paper." All of the papers in our database, and their criteria for inclusion, are listed in supplemental appendix S1.

We assigned each paper to a research category: monarch research, commentary or review (no new analyses presented), supporting research (papers that did not present data on monarchs specifically, but focused on monarch habitat, resources, natural enemies, conservation activities, social dimensions), and techniques (for studying monarchs, including lab or statistical techniques). The complete database is presented in appendix S1, but we only included the monarch research papers in our analyses. The monarch research papers were further classified into ten subcategories (box 1).

Box 1. Research subcategories for papers included in analyses shown in figures 3–5 (the *monarch research* category).

Environmental performance
Individual performance relative to temperature, host plant quality, or other environmental influences. If the primary focus was on the effects of an environmental influence on "population dynamics", then the paper was classified under that category.

Evolution/range
Monarch evolution, range expansion, or island colonization.

GMO/toxin
Impacts of GMOs (genetically modified organisms) or pesticides on monarch performance.

Migration
Patterns of or mechanistic factors related to seasonal migration (other than *orientation*), but not including patch to patch movements within a season (*population dynamics*).

Natural enemies
Predation or parasitism in monarchs. The studies that were focused solely on predator or parasite biology were categorized as *supporting research* and were not included here.

Orientation
Patterns or mechanisms of how monarchs orient their flight.

Overwintering dynamics
Behavior or physiology during the overwintering period, but not on population dynamics (e.g., mortality, classified under *population dynamics*).

Physiology/behavior
Phenomenological studies of mating/development/physical defenses/sequestration/morphology. If these phenomena were studied in relation to *environmental performance* or *overwintering*, they were placed in those categories.

Population dynamics
Any aspect of population trends, including declines, changes in population size from one stage to the next, or small-scale movements (not *migration*).

Resource use
Monarch use of resources in which the focus is on monarch performance (e.g., preference and performance studies were focused on roost choice, host plant choice, etc.). Studies of chemical sequestration were categorized under *physiology/behavior.*

We scored each monarch research paper on the basis of the following factors: setting (lab, field, lab and field, modeling only), field location (when applicable), and citizen science data use (*yes*/*no* and the source program, if that was applicable). We included a *public contribution* category if field notes, collections, or other contributed data were used.

Monarch citizen scientists' contributions

In 2011, eleven programs focused on monarchs and fifteen on general butterflies were active; one new and five defunct monarch programs are also listed (table 2). In 2011, volunteers spent an estimated 35,670 hours collecting data for monarch programs and 36,854 hours collecting data for general butterfly programs (table 2). Volunteer activity, although it is widespread, was more concentrated in the east (figure 2). Monarch program volunteer effort is concentrated in the fall, and general butterfly survey effort is concentrated in the summer, but both collect data throughout the year (figure 2). A breakdown of hours by program indicates that Monarch Watch had the greatest participation for monarch programs and for general butterfly surveys, NABA was the greatest contributor (table 2).

Our literature search yielded 690 peer-reviewed papers published since 1940 that were focused on monarchs or their resources (appendix S1). Of these, 503 were monarch-focused research publications that presented new results. The remaining papers were commentary or reviews (105); research on supporting topics like habitat, conservation, or the monarch's resource base (61); or techniques for studying monarchs (21). Of the 503 monarch research papers, 88 (17%) included data from citizen science programs or other forms of public participation.

The number of publications that have used data from each of the currently running programs is shown in the last column of table 2. The first publication using data from an organized citizen science program was authored by Fred Urquhart (Urquhart 1960). The use of IMA data grew until the program was scaled back in the late 1970s, leading to a

Table 2. Volunteer-based monitoring programs in North America that were focused (a) solely on monarchs or (b) on all butterflies.

Program (Acronym, start year, end year when applicable)	Type	Model[1]	2011 time (in hours)	Data use
(a) Monarch-centric programs: continental				
Journey North (JN, 1994)	Sightings	*collegial*	1893	13
Monarch Health (MH, 2006)	Captures	*contributory*	880	1
Monarch Larva Monitoring Project (MLMP, 1996)	Surveys/rearing	*contributory*	3484	16
Monarch Watch[2] (MW, 1992)	Captures	*contributory*	27,482	7
Insect Migration Association (1950–1994)	Captures	*contributory*	NA	18
Monarch-centric programs: international				
Wanderers Collection Network (WCN, 1967–1970)	Captures	*contributory*	NA	3
New Zealand Tagging Program (NZ, 1968–1974)	Captures	*contributory*	NA	1
Monarch-centric programs: regional				
Cape May Monitoring Program (CM, 1992)	Surveys	*collegial*	61	4
Chincoteague Monarch Program (CMP, 1997–2006)	Surveys	*collegial*	NA	1
Correo Real (CR, 1992)	Sightings	*collegial*	28	
Monarch Alert (MA, 2001)	Surveys/captures	*contributory*	202	
Peninsula Point Monarch Research Project (PP, 1996)	Surveys	*collegial*	91	2
Saint Marks National Wildlife Refuge[2] (SMNWR, 1988)	Surveys/captures	*contributory*	524	
Southwest Monarch Study (SWMS, 2003)	Surveys/captures	*collegial*	915	
Texas Monarch Watch (TMW, 1993–2008)	Sightings	*contributory*	NA	1
Washington Prisoner Rearing Program (WPRP, 2012)	Rearing	*contributory*	NA	
Western Thanksgiving Monarch Counts (WTMC, 1997)	Surveys	*contributory*	110	4
		Total	**35,670**	**71**
(b) General butterfly programs: continental				
Butterflies and Moths of North America (BAMONA, 2005)	Sightings	*collegial*	38	
eButterfly (2011)	Trips/Sightings[3]	*contributory*	387	
North American Butterfly Association (NABA) Counts (1975), Trips (Sightings: 1998, BIS: 2000)	Trips/Sightings[3]	*collegial*	27,139	7
General butterfly programs: regional				
Boulder Open Space (BOC, 2007)	Surveys	*collegial*	499	
Carolina Leps (CLeps, 2000)	Trips	*collegial*	600	
Cascades National Park BMN (C-BMN, 2011)	Surveys	*contributory*	122	
Florida-BMN[2] (FL-BMN, 2003)	Surveys	*contributory*	240	
Iowa-BMN[2] (IA-BMN, 2007)	Surveys	*contributory*	126	
Illinois-BMN (IL-BMN, 1987)	Surveys	*contributory*	649	1
Massachusetts Butterfly Club (MBC, 1992)	Trips/Sightings[3]	*collegial*	1559	
Michigan-BMN (MI-BMN, 2011)	Surveys	*contributory*	51	
Occoquan Monitoring Program (OCC, 1991)	Surveys	*collegial*	2328	
Ohio-BMN (OH-BMN, 1995)	Surveys	*collegial*	1965	2
Rocky Mountain BMN (RM-BMN, 1995–2011)	Surveys	*contributory*	742	
Swengel Monitoring (Swengel, 1985)	Surveys	*collegial*	409	
		Total	**36,854**	**10**

Note: The type (see table 1) and participatory model of program, volunteer time estimate for 2011 (if program was in operation) and data use (the number of peer-reviewed publications that use data from the program) are shown for each. When projects collect more than one kind of data, times for all data types are included. BMN = Butterfly Monitoring Network (a network of fixed survey routes).
[1]Programs started by academics or run out of academic or research institutions (must have a research staff) were classified as *contributory*, programs run by noncredentialed researchers/organizers or out of outreach/education organizations (such as nature centers or local conservation organizations) were classified as *collegial*.
[2]Estimates of time were at least partially based on program officer estimates because not all records are entered.
[3]Because sighting records were minor, time for sightings and trips were combined.

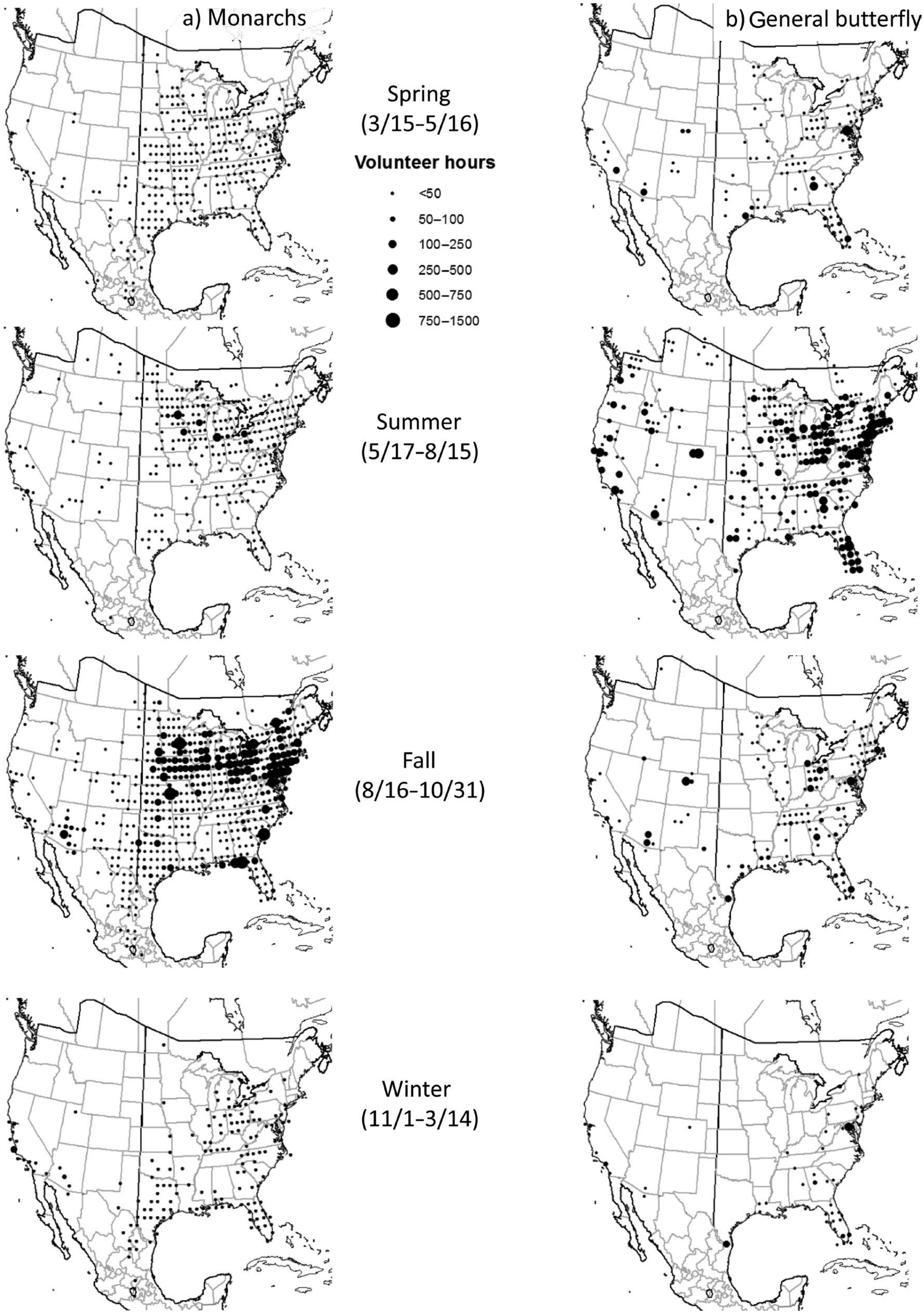

Figure 2. Estimated time spent in 2011 collecting data by volunteers for (a) monarch and (b) general butterfly programs displayed in 1-degree resolution. The monarchs' northern range and the approximate separation between the ranges of the eastern and western North American populations are indicated with dark lines. The point size is scaled to the number of volunteer hours, calculated from the formulae and information in tables 1 and 3. The estimates are stratified by seasons defined by monarch migration biology.

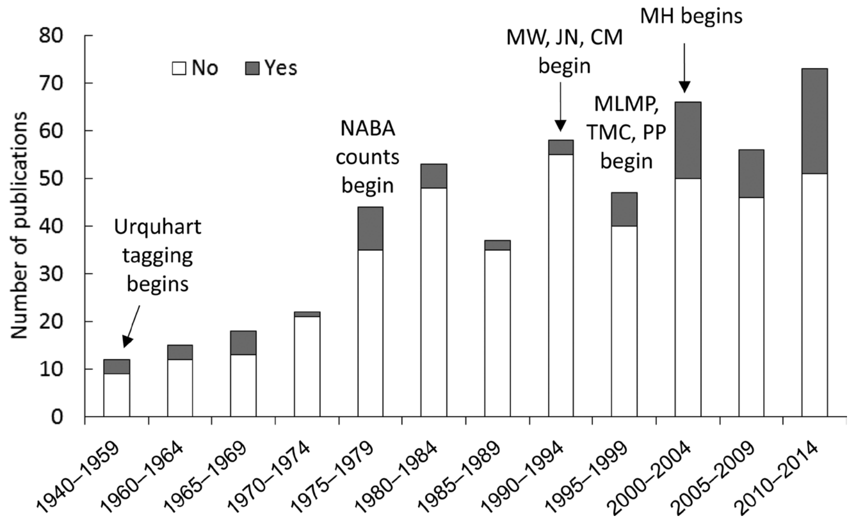

Figure 3. Count of publications presenting new analyses on monarchs (the **monarch research** ***category) over time separated by whether they used citizen science data in their analysis. Initiation time of major monarch citizen science volunteer programs, as well as the NABA count program, is indicated (see table 2 for the acronyms' definitions and for details on each program). See appendix S1 for a list of all of the publications.***

15-year lull in the use of citizen science in published monarch research (figure 3; note years 1980–1994). With the initiation of multiple programs throughout the 1990s and 2000s, the use of citizen science data in the peer-reviewed literature has increased over the past 20 years (figure 3).

The influence of participatory model on research output

Research on models of public participation programs suggest that *contributory* programs are the most likely to produce published results. Interestingly, *collegial* models have not been included in past reviews of research outcomes (Shirk et al. 2012), suggesting these programs may be too rare to quantify. However, many of the programs described here are collegial in nature (table 2) suggesting deep engagement by citizens in butterfly monitoring and research, perhaps more than in other fields. Although data from *contributory* programs have been used in more papers overall, the number of papers using *collegial* program data is still substantial. The proportion of papers using data from *collegial* programs differs on the basis of program focus (30% versus 90% using *collegial* for the monarch-centric and general surveys, respectively). In fact, the scale of the program had a bigger impact, with data from continental-scale programs more likely to be used in research publications than data from regional programs (77% versus 23%, respectively, of the published papers).

Many of the leaders of *collegial* programs are deeply involved in the analysis and publication of their results. Participation in these programs often cause the lines to blur between *scientists* (defined here as people who have an advanced degree and are associated with an academic or research institution) and *nonscientists* (Shirk et al. 2012). For example, the founder of the Journey North project, Elizabeth Howard, does not fit the traditional definition of a scientist—someone who is professionally trained, usually with an advanced degree. However, she is operationally a scientist, organizing the collection and analysis of scientifically valid data and is the senior author on multiple peer-reviewed monarch publications (e.g., Howard and Davis 2009, 2012, 2015, Howard et al. 2010). Another example is that of Ann and Scott Swengel; although Scott has a background in biology and has worked for a conservation organization, neither of the Swengels has an advanced degree nor is currently affiliated with a research institution. Despite this, they set up their own butterfly monitoring program in 1986 and, to date, they have published at least 20 butterfly articles on the basis of their program data in regional and international journals (Web of Science search, July 2014), although none specifically on monarchs (table 2). However, we note that the first paper published on monarchs using general butterfly surveys is by Ann Swengel and reports patterns on population dynamics using NABA data (Swengel 1995).

The most important determinants in level of data use for scientific publications seem to be that data were managed in a way that makes them available and that someone had taken an interest in their analysis, either alone or in collaboration with the program directors. The high output from Journey North resulted from a close collaboration between Elizabeth Howard, the program director, and Andy Davis, a scientist at the University of Georgia. Alternatively, many *collegial* programs provide value simply by collecting data and opening those data for interested researchers to use for analysis (as was done by Ann Swengel). In fact, none of the NABA or Ohio program leaders were involved in the analysis or write up of data that have so far resulted in a total of 9 monarch publications (table 2); in those cases, program leaders were acknowledged in the paper rather than being coauthors.

On the other end of the spectrum, many *contributory* programs have begun to increase engagement with their volunteers, to the point at which volunteers are more involved in the use and dissemination of data. For example, MLMP is a classic *contributory* program established by an academic researcher who actively recruits citizen volunteers for data collection. However, as the program has developed, volunteers have become more engaged and developed independent studies of monarch parasites, survival, and habitat use, and many have presented their findings at scientific meetings and in publications (e.g., Oberhauser et al. 2007). This dynamic is shifting that program toward a more collaborative model of participation.

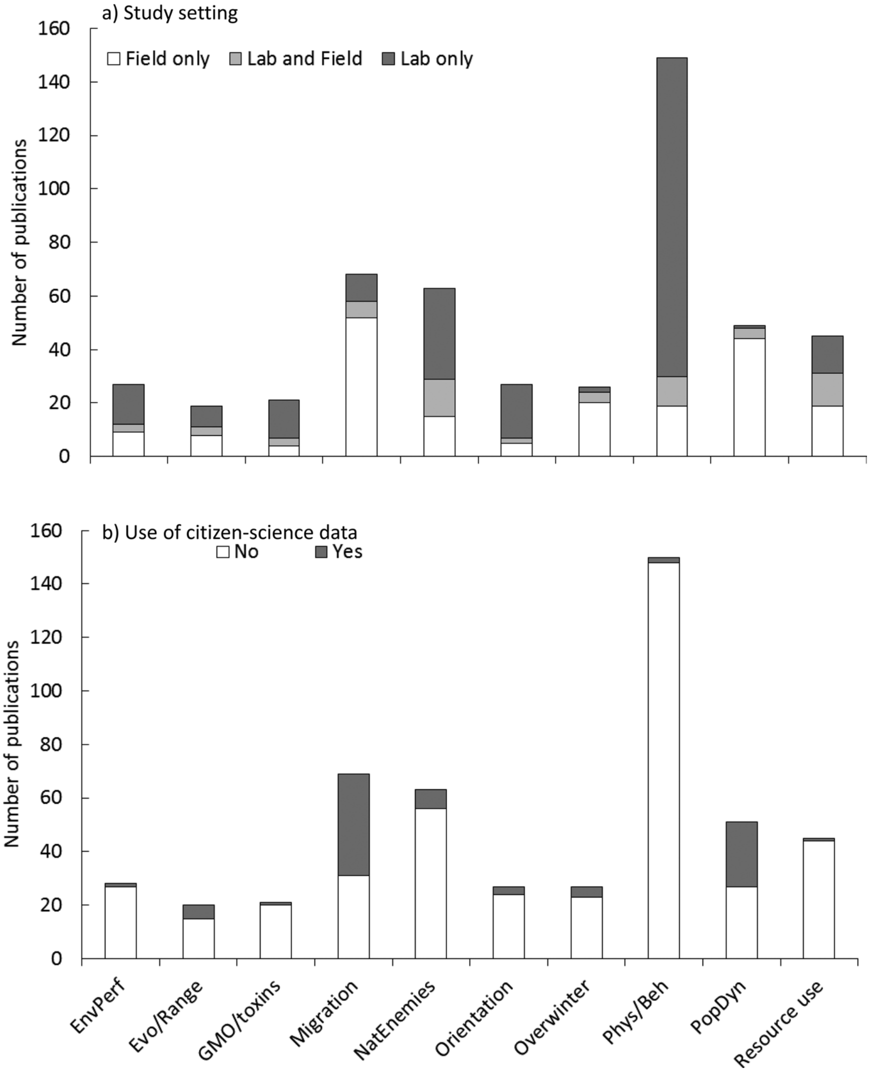

Figure 4. Publications presenting new analyses on monarchs, separated by research topic (see table 2): (a) the number for which data were collected in the lab, field, or both and (b) whether publications used or did not use citizen science data. See supplemental appendix S1 for all of the publications.

field-based research used citizen science data before 2000, but this proportion doubled to almost two-thirds after 2000 (figure 5). Through projects like MLMP and Monarch Health (table 2), field studies with a laboratory component now receive contributions from citizen scientists, with an uptick in the number of lab and field-based papers using citizen science data after 2000 (figure 5).

Citizen science data have allowed us to track patterns in large-scale monarch population dynamics (e.g., Swengle 1995), including robust demonstrations of the underlying drivers of those dynamics such as climate (Batalden et al. 2007, Stevens and Frey 2010, Zipkin et al. 2012) and the use of herbicide tolerant crops (Pleasants and Oberhauser 2012), as well as migratory dynamics during the spring (Davis and Howard 2005) and fall (Howard and Davis 2009). We understand, to a degree that is unparalleled for a nonpest insect, the monarchs' annual migratory cycle, spatiotemporal patterns of pathogens and predators, and year-to-year population fluctuations, all thanks to participants in citizen science projects. This information is key to understanding which regions are important to monarch population viability and what environmental factors drive their movement and, therefore, can provide information that allows informed and effective conservation strategies.

Despite these important contributions, a key question is what we have learned about monarchs that would have been impossible without access to data from citizen science programs. Clearly, volunteers were critical to Urquhart's quest to discover the location of overwintering monarchs (Urquhart 1976), although it would have been discovered through other means eventually (indeed, people in the local area were aware of the colonies, just not the locations from which the butterflies had flown). However, the specific pathways could not have been drawn and the timing of the discovery probably allowed conservation efforts to begin sooner than they would have otherwise. Another example is recent research that linked population dynamics across the entire migratory cycle of the eastern population (Ries et al. 2015). This study used data from multiple programs (NABA, MLMP, Ohio, Illinois) to examine how year-to-year variation in population numbers was driven by dynamics at each stage of the migratory cycle. Clearly, this type of study would be impossible without data at continental scales over several years. In another example,

The impact of citizen science data on monarch scholarship

To determine which aspects of monarch research have been most impacted by citizen science, we first looked at research topic and study setting (figure 4a). Not surprisingly, topics for which research occurs mostly in the field (e.g., population dynamics and migration) include substantial citizen science contributions (figure 4b), but when research is mostly confined to the laboratory (e.g., genetically modified organisms, toxins, orientation, or physiology), citizen science contributions are uncommon. We next looked at studies published before and after 2000, a year associated with the establishment of several large-scale programs. If studies based in the Monarch Butterfly Biosphere Reserve in Mexico are excluded (because only scientists with permits are allowed to collect data there), almost one-third of published

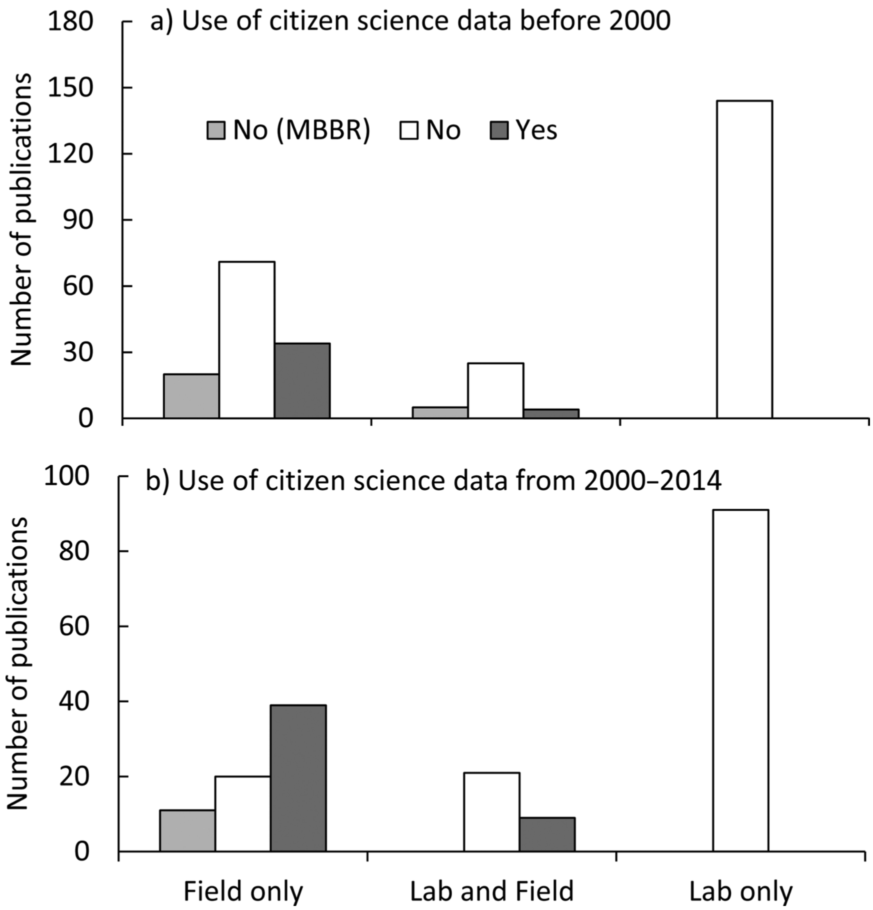

Figure 5. Overall publication use of citizen science data. The studies that took place in the Monarch Butterfly Biosphere Reserve in Mexico are separated because public access is restricted. The data are shown for papers published (a) before and (b) after 2000 to reflect the greater availability of citizen science data as multiple programs began in the 1990s (see figure 3 and table 2).

Cockrell and colleagues (1993) and Malcolm and colleagues (1993) studied the northward movement of monarchs on the basis of local work from a single year and were therefore not able to capture spatiotemporal patterns obvious from Journey North data collected over a wider scale and for many years (e.g., Howard and Davis 2015).

Conclusions: The contribution of citizens to monarch science

We cataloged 88 unique peer-reviewed publications on monarchs that used data from citizen science projects or from some other form of public participation (17% of papers published since 1940). The history of monarch citizen science programs dates back almost 70 years, and the program initiated by Urquhart was quite unusual for the time. Furthermore, it was instrumental in solving a long-held scientific mystery, what happened to monarch butterflies during the winter (Urquhart 1976). More recently, two-thirds of papers on field-based research outside the Mexican Reserve used citizen science data. These studies represent substantial contributions, especially in the areas of population dynamics and migration (figure 4b). Although tracking participation for all 70 years was outside our scope, our snapshot of data collection for 2011 shows that citizens spend considerable amounts of time collecting data (figure 2, table 2) and those numbers are likely to continue growing.

There are many other beneficial outcomes of citizen science programs in addition to scholarly impacts. Project web sites provide summaries of findings, raw data, and information on monarchs to thousands of site visitors and news media, and many findings are summarized in popular press articles and other venues. Goals of the Monarch Joint Venture, a partnership of several organizations with an interest in monarch conservation, include promoting monarch citizen science and the analysis of data from these projects. Data from the Western Monarch Thanksgiving Count have informed management that promotes long-term use of wintering sites by monarchs. Data from a monitoring project on the Chincoteague National Wildlife Refuge informed a plan that included habitat enhancement and management to benefit monarchs (Gibbs et al. 2006).

Monarch citizen science projects have certainly resulted in increased public interest in monarchs and their conservation. Indeed, monarchs are as well-known and valued as many so-called charismatic megafauna (Diffendorfer et al. 2014). This interest is also shown by substantial media coverage, illustrated by the reaction to the January 2014 report that the Mexican wintering population was at an all-time low (Rendon and Tavera 2014).

Despite the incredible contribution of the data accumulating from these programs, we argue that monarch citizen science data are still underused. Many program data have never been used in peer-reviewed publications and most have only been used a handful of times (table 2) or have not been used for large-scale analyses that take advantage of their broad coverage (Davis 2015). Part of the problem is that many of the data were unknown or unavailable to scientists until recently, but this has changed through partnerships like MonarchNet (*www.monarchnet.org*) and the North American Butterfly Monitoring Network (*www.nab-net.org*). Promoting the use of data from these programs could have an immediate and large impact on monarch scholarship, perhaps more so than the initiation of new field studies.

In addition to nonuse, there are spatiotemporal gaps in citizen science data collection (figure 2); filling these gaps could also make a substantial difference in our ability to understand monarch biology (Oberhauser et al. 2015b). Although we cannot dictate where and when data are collected, volunteer recruitment and education could be targeted to increase participation in areas that are not receiving sufficient attention. For example, spring and fall migration activity, and summer breeding are poorly covered in the West (figure 2). General butterfly surveys are poorly represented during the spring, fall, and winter, especially in the south, a region crucial to population dynamics throughout the year (Zipkin et al. 2012, Oberhauser et al. 2015a).

Monarch citizen science as a model system

Finally, we argue that monarch citizen science could be considered a model system for understanding participatory research and its many impacts. In much the same way that *Caenorhabditis elegans* and *Drosophila melanogaster* respectively provide model systems for understanding developmental biology and genetics, the widespread focus of volunteers on a single species provides a unique opportunity to expand our understanding of the practices and outcomes of citizen science. We do not make this claim on the basis of the level of effort compared with other taxa. Indeed, bird monitoring exceeds butterfly monitoring by over an order of magnitude. For instance, here we catalogued 25 active monitoring programs that were focused on monarchs or general butterflies, while the Avian Knowledge Network currently tracks data from 847 bird-focused citizen science programs (*www.avianknowledge.net*). Furthermore, the 467 count circles surveyed in 2011 for NABA's Count Program is far less than the 2,266 surveys in the same year for the directly comparable Christmas Bird Counts (*www.audubon.org*). Finally, eBird has amassed an astonishing 500 million biodiversity records during its short history, and eBird data have already been used in over 120 peer-reviewed publications (*www.ebird.org*). However, the bird monitoring community does not have a single species which dominates its efforts the way the butterfly monitoring world does with monarchs. We contend that having so much focus for butterflies in North America on a single species means that we can more easily understand the complex interplay between engagement, participation, and outcomes. And although the amount of monitoring activity on butterflies is substantial (figure 2), it is not so massive as to make the community intractable to study.

The potential to identify a model system is especially relevant as citizen science is now becoming its own field of research, with a new association and a forthcoming journal. Although the magnitude of citizen science effort focused on a single species like monarchs may be unlikely to be duplicated in other species, that is precisely what makes monarch-focused efforts uniquely positioned to help us understand the dynamics and contributions of these programs. Future research on this model system should be focused on the motivations of individuals for participation and the effects on the participants themselves, in terms of their knowledge of monarch biology, the process of science, and their motivation to carry out conservation actions. This "citizen army for science," which has contributed to nearly 20% of all monarch research, can also be considered a "citizen army for conservation" (Oberhauser and Prysby 2008), not only because of the conservation implications of their data, but also as a result of the actions that are inspired by their involvement. In this age of digital information and crowdsourcing, the potential for involving citizens in science and action has only begun to be tapped.

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Supplemental material

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