# Citizen Science as an Ecosystem of Engagement: Implications for Learning and Broadening Participation

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*The bulk of research on citizen science participants is project centric, based on an assumption that volunteers experience a single project. Contrary to this assumption, survey responses (n = 3894) and digital trace data (n = 3649) from volunteers, who collectively engaged in 1126 unique projects, revealed that multiproject participation was the norm. Only 23% of volunteers were singletons (who participated in only one project). The remaining multiproject participants were split evenly between discipline specialists (39%) and discipline spanners (38% joined projects with different disciplinary topics) and unevenly between mode specialists (52%) and mode spanners (25% participated in online and offline projects). Public engagement was narrow: The multiproject participants were eight times more likely to be White and five times more likely to hold advanced degrees than the general population. We propose a volunteer-centric framework that explores how the dynamic accumulation of experiences in a project ecosystem can support broad learning objectives and inclusive citizen science.*

*Keywords: public science, conservation, volunteer management, crowdsourcing, education*

**Citizen science is a rapidly growing practice** (Theobald et al. 2015, Parrish et al. 2019) through which nonscientists engage in scientific research (NASEM 2018). The practice has contested terminology, and some have begun to refer to it as *community science* or by other names (see Cooper et al. 2021 for a broader discussion). Over the last century, citizen science has played a major role in advancing scientific discovery (Cooper 2016). The resulting discoveries have been relevant to many fields, from biochemistry to astronomy, and particularly significant in ecology. For instance, over more than five decades, 17% of the research publications on the monarch butterfly (*Danaus plexippus*; Ries and Oberhauser 2015) and 50% of the studies about migratory birds and climate change have leveraged citizen science (Cooper et al. 2014).

Research also suggests that citizen science can have broader benefits beyond its scientific value, including benefits for environmental protection (McKinley et al. 2017), policymaking (Garzón et al. 2013), community building (Newman et al. 2017), recreation (Larson et al. 2020), and volunteer learning (Phillips et al. 2018), with different projects facilitating these broader benefits to different extents. Examination of learning associated with citizen science participation, in particular, is emerging as a distinct field of inquiry (Jordan et al. 2012). As was summarized by a consensus report of the National Academies of Science, Engineering, and Medicine (NASEM 2018), citizen science can help participants learn scientific practices, scientific reasoning, and content and can support the participants' self-efficacy for science, science identity, and data interpretation skills.

In most cases, researchers study volunteers and participation outcomes within the context of a single, stand-alone project. With this project-centric approach, researchers are often interested in the potential impact of volunteer participation and learning linked to experiences with a focal project. All 27 studies cited in two recent reviews of citizen science learning outcomes (Bonney et al. 2016, Peter et al. 2019) were project centric. We identified only four studies of learning outcomes cited in these reviews that acknowledged that the volunteers sometimes contributed to multiple projects (Fortson et al. 2012, Toomey and Domroese 2013,

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Lewandowski and Oberhauser 2017, Chase and Levine 2018). For instance, Toomey and Domroese (2013) mentioned that 6 out of 19 volunteers in the Earthwatch Coyote Project had joined other projects.

Researchers studying volunteers using digital platforms with multiple citizen science projects, rather than stand-alone projects, have begun to quantify the occurrence of multiproject participation. Herodotou and colleagues (2020) evaluated digital trace data (i.e., digital records of activity of users of an online system) from 104 volunteers on the Zooniverse platform and found that 86 had joined multiple online Zooniverse projects and that some had contributed to as many as 42 different projects. Also using digital trace data, Ponciano and Pereira (2019) found that 16%–32% of the volunteers on three platforms (Crowdcrafting, Socientize, and GeoTag-X) had joined multiple projects within a given platform. In a social network analysis examining digital trace data for 3651 SciStarter users, Futch (2020) discovered that 73% of the volunteers had joined multiple projects. Therefore, multiproject participation, particularly for online projects, is potentially a common but largely ignored phenomenon that could influence broader outcomes, such as volunteer learning, that are associated with citizen science participation.

Better understanding the participatory landscape might yield new insight into the value of citizen science and its capacity to influence behavior. For example, environmental education and public health advocates search for approaches to spur public connections with nature and engagement in outdoor recreation, respectively (Holland et al. 2018). Online modes of citizen science projects might serve as gateways to eventual deeper engagement in active outdoor projects. Conversely, offline projects might lead volunteers to try online projects that build technological efficacy or increase their multidisciplinary breadth of understanding. Understanding multiproject participation could also provide new perspectives on the extent to which citizen science projects, collectively, have failed to engage diverse segments of society (Cooper et al. 2021). Many studies reveal high proportions of White, affluent, and highly educated people among citizen scientists in the United States (NASEM 2018) and the United Kingdom (Pateman et al. 2021). If the same individuals tend to participate across multiple projects, it's possible that citizen science engages an even narrower range of the population than previously thought.

The primary purpose of the present article is to improve our understanding of the dynamics of volunteer engagement across the ecosystem of citizen science projects. First, we quantified the prevalence of multiproject participation among a platform-based cohort of volunteers and cohorts derived from two stand-alone projects (objective 1). Second, we characterized volunteers on the basis of their participation dynamics across project disciplines and modes (i.e., online versus field-based offline projects; objective 2). Third, we examined associations between participant characteristics (e.g., demographics, participation frequency) and their multiproject participation patterns (objective 3). We conclude by proposing a volunteer-centric research agenda focused on the significance of and opportunities associated with multiproject participation in citizen science.

## Data sources

We examined multiproject participation using four data sources: online digital trace data from SciStarter.org, a survey of account holders on the SciStarter platform, a survey of participants in the stand-alone citizen science project the Christmas Bird Count, and a survey of participants in the stand-alone project Candid Critters. We chose these data sources in order to sample participation patterns from a diverse cross-section of volunteers, including volunteers from different stand-alone projects and volunteers from a multiproject platform. Each data source is described in more detail below.

SciStarter.org hosts one of the largest online, searchable catalogues of citizen science projects. Project leaders share their projects on SciStarter in order to recruit participants, and prospective participants use the website in order to find projects of interest. Unlike other citizen science platforms that have been studied, SciStarter includes both field-based offline projects and many online projects. We examined the records of online activity (hereafter, digital trace data) of those with accounts on SciStarter.org to identify the projects they joined. The digital trace data we included were derived from all SciStarter account holders who visited SciStarter and clicked a "join" button for a citizen science project between September 2017 and December 2018. This timeframe corresponds to approximately the first 16 months after the launch of SciStarter 2.0 technology, which allows for more comprehensive tracking of volunteer behavior on the website (Hoffman et al. 2017). We interpreted clicking "join" on a project on SciStarter as a proxy for project engagement and an indication of volunteers' behavioral intention to participate. In the present article, we use the terms *join* and *participate* interchangeably as a general estimate of engagement but note that, for the digital trace data, clicking "join" on a project doesn't necessarily mean a volunteer actually participated in that project.

We distributed surveys (supplemental table S3) to obtain self-reported information about projects joined by SciStarter account holders, as well as volunteers contributing to the Christmas Bird Count and North Carolina's Candid Critters. Although Candid Critters and the Christmas Bird Count involve the same mode (offline) and disciplinary area (ecology and environment), they differ in size, age of project, and subtopic. The Christmas Bird Count is a field-based, bird-focused project that spans across the United States and some other countries and has been around for more than 100 years; engagement typically occurs for 1 day per year during a window of time between Christmas and New Year's Day (LeBaron 2016). Candid Critters is a field-based, mammal-focused project initiated in 2016 that spans North Carolina; engagement typically involves the deployment and later

retrieval of motion-sensitive cameras in forests to collect digital images of wild mammals (Lasky et al. 2021). Candid Critters engages in targeted recruitment of groups such as hunters and library patrons (Lasky et al. 2021). Following human subjects research approval, we initiated survey implementation. We distributed the survey to participants of the Christmas Bird Count in February 2016 with responses from an estimated 12% of volunteers (Shipley et al. 2019). We distributed the survey to participants in Candid Critters three times between 2017 and 2019 with responses from 47% of volunteers. We distributed the survey to SciStarter account holders twice, in October 2018 and May 2019, with responses from an estimated 10% of account holders active on the website between September 2017 and December 2018 (Futch 2020). The SciStarter survey may have included some individuals whose citizen science engagement was also captured in the digital trace data. We view the SciStarter survey and SciStarter digital trace data as two samples (that may not be fully independent) of a population of participants. See supplemental table S1 for more details about each survey data source. Inclusion of the digital trace data from SciStarter enabled us to control for possible sampling response bias in the survey of SciStarter account holders because digital trace data includes the entire population of account holders. All human subjects research was approved by the Institutional Review Board at North Carolina State University with protocols no. 12200 (SciStarter digital trace data), no. 14278 (SciStarter survey), no. 6638 (Christmas Bird Count), and no. 12419 (Candid Critters).

**Project and participant coding.** Each survey asked its respondents what citizen science projects they had participated in (table S3). Each survey also asked the respondents for their race or ethnicity, gender, age, education and occupation. Some of the surveys also asked the respondents about their income, political leaning, and whether they had children. The surveys also assessed the volunteers' years of experience doing citizen science, frequency of participation, and a variety of other questions unrelated to this study (e.g., satisfaction with various aspects of citizen science projects).

We compiled a list of citizen science projects on the basis of survey responses and digital trace data. Using consensus methods (Olson et al. 2016), a group of four researchers (see the acknowledgments) worked together to develop 14 discipline categories for all projects in this list (supplemental table S2). These categories were initially based on an existing project typology used by SciStarter but were iteratively revised during coding on the basis of the hundreds of projects our team reviewed. The researchers initially worked independently to code the projects by discipline and mode and then met to resolve any discrepancies. Once interrater reliability reached 80%, each researcher coded the projects independently using the developed categories with three levels of hierarchy. The highest classification level was disciplinary topic (e.g., astronomy and space, ecology and environment). The next level was subtopic (e.g., birds, mammals). The foundational level was project names, standardized in order to not double count a project. The group of four researchers also classified each project by mode of participation (e.g., entirely online, offline). For details, see table S2.

Next, we categorized each volunteer from our four data sources into one of three groups according to whether they participated in a single project (singleton), participated in multiple projects within a single disciplinary topic (discipline specialist), or participated in multiple projects from more than one disciplinary topic (discipline spanner). We also categorized each volunteer into one of three groups according to their mode of participation: singleton (participated in one project), mode specialist (participated in at least two online projects or at least two offline projects), and mode spanner (participated in at least one online project and at least one offline project).

**Data analysis.** For objective 1, we tallied the total number of projects joined by each volunteer from the four data sources. For objective 2, we counted the number of volunteers from each data source that were singletons, specialists, and spanners across disciplines and modes. For objective 3, we compared the characteristics of the participants in our sample with the characteristics of the US population (both Candid Critters and the Christmas Bird Count are United States–based projects, and the majority of SciStarter participants are from the United States). For objective 3, we used multinominal logistic regression for each data set independently (Stata Corp, version 16.1) to test whether volunteer characteristics were associated with patterns of disciplinary singletons, discipline specialists, or discipline spanners, as well as mode specialization versus spanning. In each regression, type of project participation was the outcome variable (with singletons serving as the reference group) and potential predictors included age, years of experience in citizen science, race, gender, education, occupation, political views, income, having dependent children, and participation frequency. There were too few mode spanners in the Candid Critters survey to include these data source in the regression analysis.

## Objective 1: Prevalence of multiproject participation

Overall, the respondents participated in an extraordinary diversity of citizen science projects. We collected 3894 survey responses and digital trace data from 3649 SciStarter volunteers. The variable sample pool and response rates across the three survey cohorts resulted in an uneven distribution of responses: 3191 were from participants in the Christmas Bird Count, 280 were from participants in Candid Critters, and 423 were from SciStarter account holders. The combined samples of volunteers collectively joined 1126 unique citizen science projects. The volunteers' multiproject participation spanned a remarkably wide range from one to 50 projects. Approximately 77% of all volunteers across all four data sources had joined multiple projects, whereas 23% volunteers were singletons (participated in only one project). The respondents to the Christmas Bird Count survey

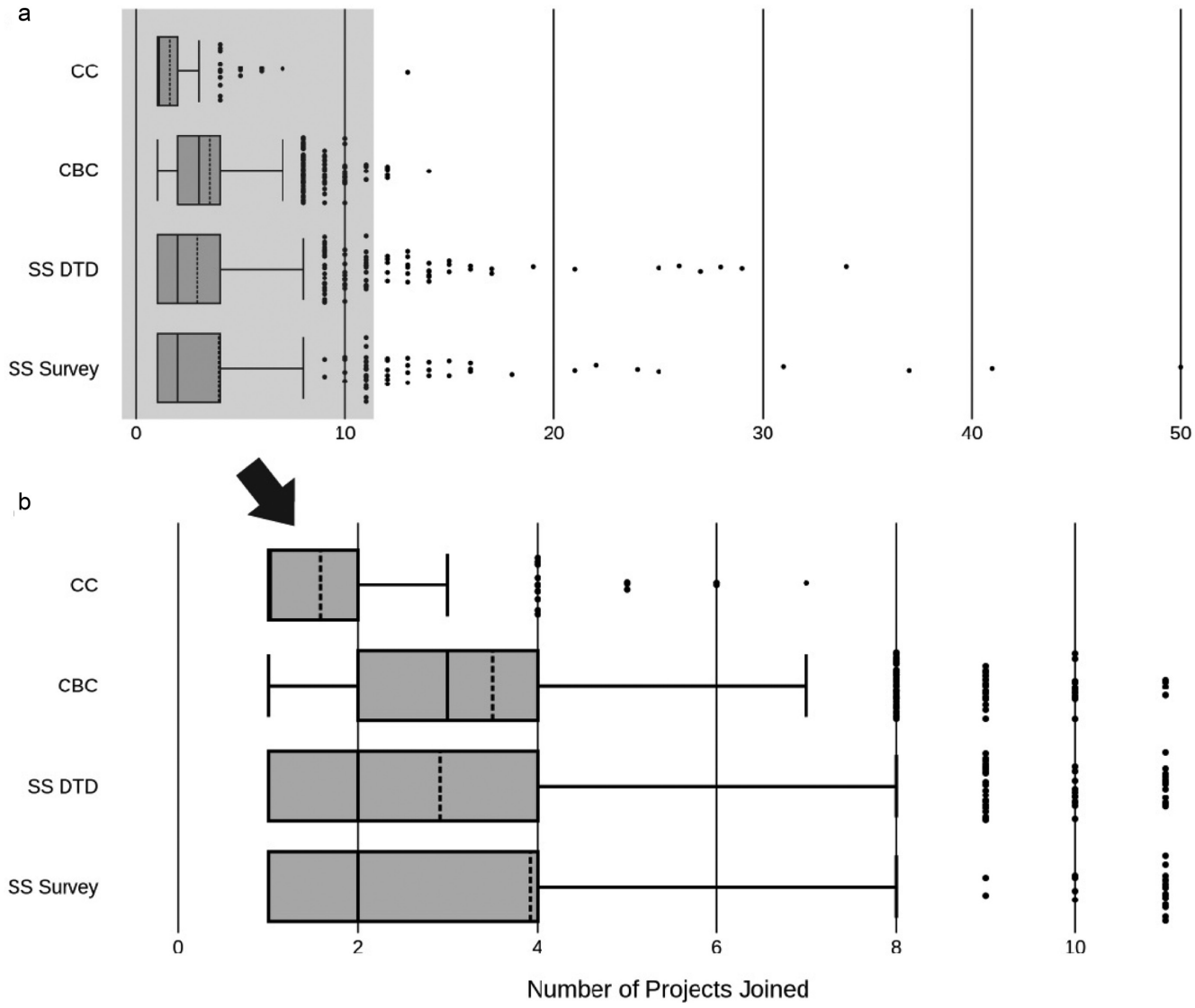


***Figure 1. Number of projects joined by citizen science volunteers from four different data sources. Dotted lines denote average, boxes indicate quartiles, dots indicate outliers. (a) Highlights wide range of project joins, particularly among SciStarter volunteers. (b) Enlarged view of the area in gray. Abbreviations: CBC, Christmas Bird Count survey; CC, Candid Critters survey; SS DTD, SciStarter digital trace data; SS survey, SciStarter survey.***

participated in significantly (*t*-test, $p < .001$) more projects (mean [*M*] = 3.5 projects, median = 3 projects) than those to the Candid Critters survey (*M* = 1.6, median = 1; figure 1). The estimates based on the respondents of the SciStarter survey (*M* = 3.9 projects, *median* = 2 projects) approximated the estimates from the SciStarter digital trace data (*M* = 2.9, *median* = 2; figure 1).

### Objective 2: Characterization of volunteer discipline and mode spanning

Of the 77% of the participants in our cohort samples engaged in multiple projects, they were roughly split evenly between discipline specialists (39% participated in multiple projects within a single disciplinary topic) and discipline spanners (38% participated in multiple projects from more than one disciplinary topic). Most (82%) discipline spanning in our sample was across four disciplinary topics: ecology and environment (62%), pollution (9%), geology and Earth science (6%), and astronomy and space (5%).

We detected little discipline and mode spanning among the Candid Critter respondents, because 75% of these respondents were singletons (figure 2a). Of those Candid Critter respondents who joined multiple projects, most (75%) were discipline specialists, staying in the ecology and environment disciplinary category. Many (24%) of

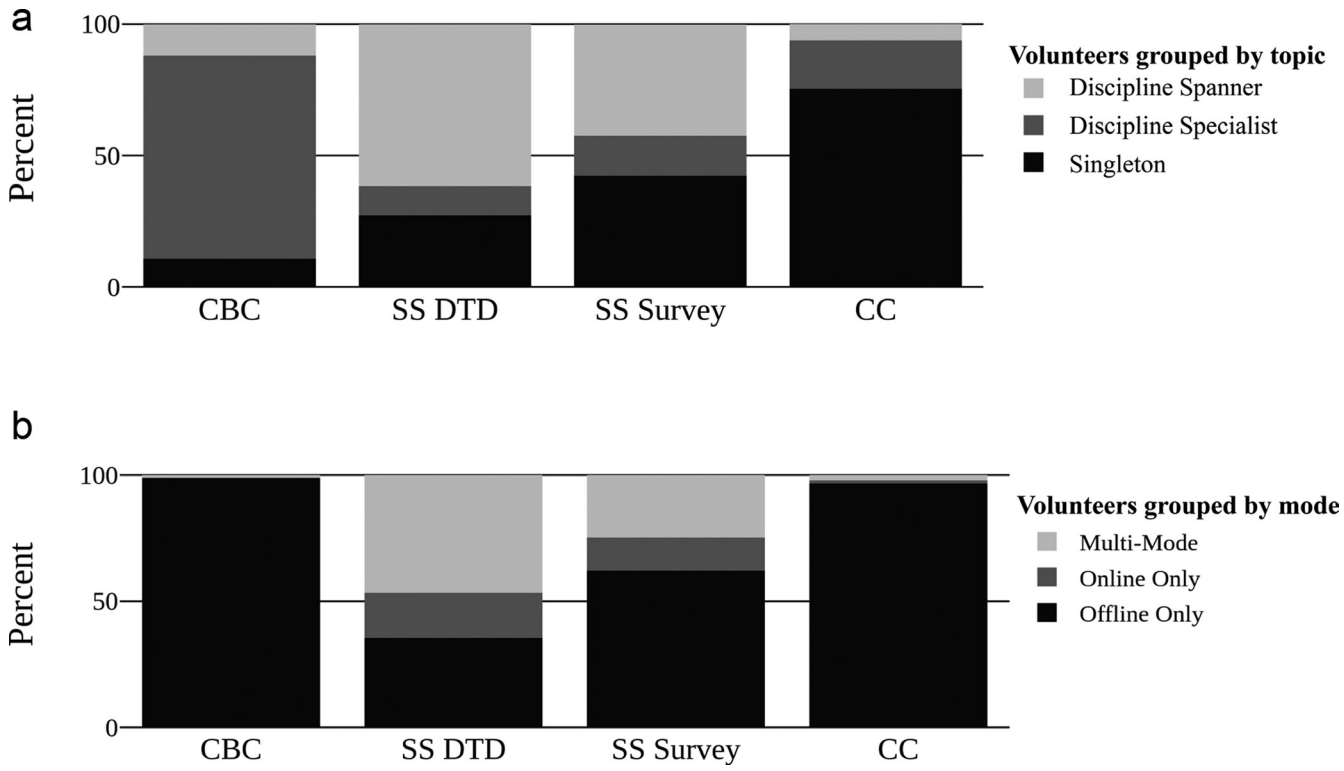


***Figure 2. Participation patterns among citizen science volunteers from four data sources. (a) Percentage of volunteers from each data source that participated in one project (singleton), multiple projects within only one disciplinary topic (discipline specialist) or multiple projects and multiple project topics (discipline spanner). (b) Percentage of volunteers from each data source that only joined online project(s), only joined offline project(s), or joined at least one project from both modes. This figure excludes volunteers whose participation patterns we were unable to code (3% of participants in panel (a), 4% of participants in panel (b)). Abbreviations: CBC, Christmas Bird Count; CC, Candid Critters SS DTD, SciStarter digital trace data; SS survey, SciStarter survey.***

the projects joined by Candid Critters volunteers (outside of Candid Critters) were bird projects, even though Candid Critters is focused on mammals. Discipline specialists were most prevalent among the respondents to the Christmas Bird Count survey (77% of respondents), with most participation in ecology and environment, within the subtopic birds (figure 3). This included participation in related projects such as eBird and The Great Backyard Bird Count. Discipline spanners were more common among account holders on the SciStarter platform (62% of the volunteers in the digital trace data, 42% of the respondents to the SciStarter survey) than among the respondents from the stand-alone projects (Christmas Bird Count survey, 12%; Candid Critters survey, 6%; figure 2a). Among volunteers in the digital trace data, the most popular disciplinary topics were ecology and environment (45% of projects joined), health and medicine (14% of projects joined), and geology and Earth science (10% of projects joined). Among the respondents to the SciStarter survey, the most popular disciplinary topics were ecology and environment (52% of projects joined), pollution (7% of projects joined), and geology and Earth science (6% of projects joined; figure 3).

In regards to the mode of participation, the majority (52%) of the volunteers joined multiple projects within a single mode (either online or offline), whereas 25% of the volunteers were mode spanners, joining at least one online project and at least one offline project. As was noted above, the remaining 23% of the volunteers were singletons, participating in just a single project. Among these singletons, 77% participated in an offline project, and 23% participated in an online project. Among the multiproject volunteers, 62% only joined offline projects, 6% only joined online projects, and 33% joined projects from multiple modes.

The participation patterns by mode were strongly divergent across the different data sources. The respondents to the Christmas Bird Count and Candid Critters surveys, both offline projects, participated almost entirely in other offline projects. Among the multiproject participants, 99% of the Christmas Bird Count volunteers and 93% of the Candid Critters volunteers only participated in other offline projects. In contrast, participation in projects from multiple modes (both online and offline projects) was more common among SciStarter users (figure 2b). Among the multiproject participants that took the SciStarter survey, 48% participated only in offline projects, 8% participated only

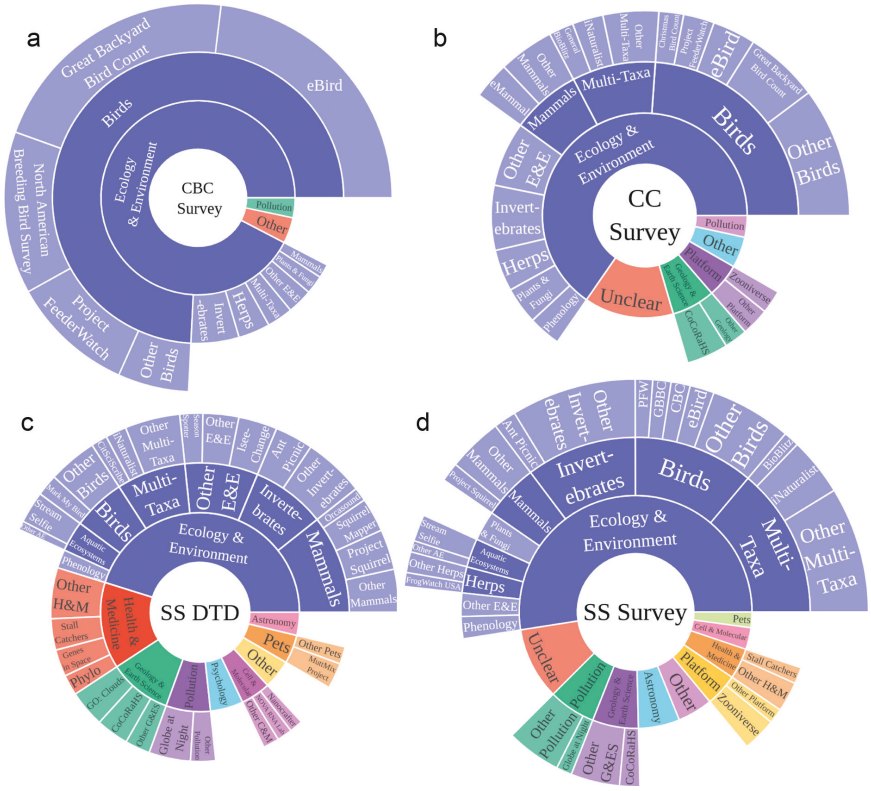


***Figure 3. Projects joined by citizen science volunteers from four data sources, binned by disciplinary topic and (for the ecology and environment topic) by subtopic. Individual project names are also provided for popular projects within each data source, for a maximum of three levels of hierarchy (topic, subtopic, and project name). In each figure, the size of an arc indicates the fraction of total project joins within that arc's category. (a) The respondents to the Christmas Bird Count survey joined a citizen science project besides the Christmas Bird Count 7999 times. Most of these project joins were to other bird projects. (b) The respondents to the Candid Critters survey joined a citizen science project besides Candid Critters 205 times. Most of these project joins were to other ecology and environment projects. (c) The SciStarter digital trace data collected 10,659 instances of a volunteer joining a project on the platform. Approximately half of these were ecology and environment projects. (d) The respondents to the SciStarter survey joined a citizen science project 1658 times. As with the digital trace data, about half of these projects were ecology and environment projects. Unpopular project topics and subtopics were pooled for each figure into a category labeled other (followed by the appropriate topic or subtopic) to increase readability. Some names were shortened in the figures to increase readability. Abbreviations: CBC, Christmas Bird Count; GBBC, Great Backyard Bird Count; other AE, other aquatic ecosystems; other E&E, other ecology and environment; other G&ES, other geology and earth science; other H&M, other health and medicine; PFW, Project FeederWatch.***

in online projects, and the remaining 43% participated in projects from multiple modes. Among the multiproject participants in the SciStarter digital trace data, 25% participated only in offline projects, 11% participated only in online projects, and the remaining 64% participated in projects from multiple modes. The majority of singletons from the SciStarter survey (79%) and digital trace data (65%) participated in an offline project as opposed to an online project.

### Objective 3: Characteristics of the multiproject participants

The survey respondents from each sample were overwhelmingly more likely to be White, highly educated, and to work in science and science-related fields than the general US population (table 1). The survey respondents were three (SciStarter) to 10 times (Candid Critters, Christmas Bird Count) less likely to be people of color than the general US population. Across all projects, the participants were roughly five times more likely to have advanced degrees than the general population and six to seven times more likely to work in STEM fields. The age of the SciStarter respondents was fairly representative of the US adult population, whereas the survey respondents in the Christmas Bird Count and Candid Critters tended to be older (e.g., 30%–48% of the participants were over 65, compared with 16% of the general population). Conversely, the gender of the Christmas Bird Count and the Candid Critters respondents was representative of the US population, whereas the SciStarter respondents were more likely to identify as female. The Christmas Bird Count respondents were roughly three times more likely to have liberal political views compared with the general US population and had a slightly higher income than the US median. The Christmas Bird Count was the only survey that collected data about political views or income. Demographic data were not available in SciStarter digital trace data.

When controlling for other volunteer characteristics across all three surveys, the multiproject participants—in some cases, discipline specialists and, in other cases, discipline spanners—were more likely to work in STEM fields relative to singletons (indicated by $p < .05$; table 2). For instance, among the Candid Critters volunteers, discipline specialists were 4.26 times more likely to work in STEM fields than singletons. Among the Christmas Bird Count and SciStarter volunteers, discipline spanners were 1.74 and 1.90 times more likely to work in STEM than singletons, respectively. SciStarter and Christmas Bird Count

***Table 1. Proportional demographic characteristics of citizen scientists in samples collected from 2016 to 2019 compared with the general US population.***

| | Christmas Bird Count ($n$ = 3191) | Candid Critters ($n$ = 280) | SciStarter survey ($n$ = 423) | US population[a] |
|---|---|---|---|---|
| Female | .46* | .51 | .69* | .51[b] |
| White and not Latinx | .96* | .96* | .88* | .60[b] |
| 65 years old and over | .48* | .30* | .18 | .16[b] |
| Graduate or professional degree | .49* | .43* | .53* | .12[b] |
| Liberal political views | .68* | | | .24[c] |
| Median household income | $65,000–$80,000* | | | $63,000[b] |
| Work in STEM occupations | .46* | .33* | .48* | .06[d] |

*Note:* The percentages do not include nonrespondents (1%–12% for all questions except household income, which was 18% nonresponse). The CBC and CC surveys' occupation questions asked about work in the life sciences, natural resources, and conservation fields, rather than STEM fields.
[a]Christmas Bird Count and SciStarter are open to international volunteers but the majority of participants are from the United States.
[b]These data are from a US Census Bureau American community survey 2019 (www.census.gov/acs/www/data/data-tables-and-tools/data-profiles).
[c]These data are from the Gallup Poll social survey 2019 (https://news.gallup.com/poll/275792/remained-center-right-ideologically 2019.aspx).
[d]These data are from the US Bureau of Labor Statistics' Employment Projections 2019 (www.bls.gov/emp/tables/stem-employment.htm).
*$p < .05$.

***Table 2. Relative risk ratios in multinomial logistic regression examining participant characteristics associated with multiproject discipline specialization and spanning (relative to single-project participation) from surveys of volunteers of the Christmas Bird Count ($N$ = 2324, pseudo $R^2$ = .03), SciStarter ($N$ = 309, pseudo $R^2$ = .14), and Candid Critters ($N$ = 117, pseudo $R^2$ = .08).***

| | Discipline specialist | | | Discipline spanner | | |
|---|---|---|---|---|---|---|
| | Christmas Bird Count | SciStarter survey | Candid Critters survey | Christmas Bird Count | SciStarter survey | Candid Critters survey |
| Age | 0.97*** | 0.99 | 0.99 | 0.97*** | 0.99 | 1.01 |
| Time participating[a] | 1.03*** | 1.20*** | 0.97 | 1.03** | 1.17** | 1.04 |
| Race (binary; 1, White) | 1.55 | 3.68 | | 1.22 | 2.58 | |
| Gender (binary; 1, male) | 1.02 | 0.37* | 0.95 | 1.11 | 0.49* | 0.92 |
| Education (binary; 1, holds graduate degree) | 0.82 | 1.05 | 1.10 | 0.87 | 1.14 | 0.92 |
| Occupation (binary; 1, works in science) | 1.08 | 1.05 | 4.26** | 1.74** | 1.90* | 3.70 |
| Political views (binary; 1,= liberal) | 1.36* | | | 1.72** | | |
| Income[b] | 1.00 | | | 0.94 | | |
| Children (binary; 1, parent) | | 0.45 | 0.51 | | 0.45* | 1.15 |
| Participation frequency[c] | | 1.21* | | | 1.28*** | |

[a]Candid Critters survey uses months of participation, the other surveys use years of participation.
[b]Income binned into 10 levels of approximately $20,000 at each level.
[c]Participation frequency binned into eight levels from less than once per year to multiple times per week.
*$p < .05$. **$p < .01$. ***$p < .001$.

respondents with more experience doing citizen science (more years and engaging more frequently) were more likely to do multiple citizen science projects and to cross disciplinary boundaries. Being younger, female, liberal, and not having child dependents were also positively associated with multiproject participation or discipline spanning among respondents in at least one data source (table 2).

Holding all other variables constant, the younger respondents within both the Christmas Bird Count and SciStarter samples were more likely to be mode spanners than singletons. For instance, for every 1-year increase in age among Christmas Bird Count volunteers, the likelihood of being a mode spanner decreased by 6%. The mode spanners from the Christmas Bird Count also had significantly higher income, whereas the mode-spanning SciStarter volunteers were significantly less likely to have dependent children and significantly more likely to be female and to have high levels of citizen science experience (more years and more frequent

***Table 3. Relative risk ratios in multinomial logistic regression examining demographic correlates of mode specialization and spanning in citizen science (relative to singletons) from surveys of volunteers of the Christmas Bird Count (N = 2286, pseudo $R^2$ = .05), SciStarter (N = 282, pseudo $R^2$ = .15).***

| | Mode specialist | | Mode spanner | |
|---|---|---|---|---|
| | Christmas Bird Count | SciStarter survey | Christmas Bird Count | SciStarter survey |
| Age | 0.97*** | 0.99 | 0.94*** | 0.96** |
| Years participating | 1.03*** | 1.18** | 0.98 | 1.16** |
| Race (binary; 1, White) | 1.56 | 2.87 | 1.10 | 1.53 |
| Gender (binary; 1, male) | 1.01 | 0.53 | 2.17 | 0.38* |
| Education (binary; 1, graduate degree) | 0.82 | 1.20 | 1.31 | 1.10 |
| Occupation (binary; 1, works in science or conservation) | 1.17 | 1.68 | 0.80 | 2.02 |
| Political views (binary; 1, liberal) | 1.37* | | 1.88 | |
| Income[a] | 0.99 | | 1.20* | |
| Children (binary; 1, parent) | | 0.61 | | 0.37* |
| Participation frequency[b] | | 1.27** | | 1.38*** |

[a]Income was binned into 10 levels of approximately $20,000 at each level.
[b]Participation frequency binned into eight levels from less than once per year to multiple times per week. *$p < .05$. **$p < .01$. ***$p < .001$.

contributions). Relative to singletons, the mode specialists with both the Christmas Bird Count and SciStarter had more years of citizen science experience. In addition, among the Christmas Bird Count volunteers, the mode specialists were significantly more likely to have liberal political views. Among the SciStarter volunteers, the mode specialists participated significantly more frequently in projects (table 3). In summary, considering both discipline and mode, having a greater breadth of engagement in citizen science was generally linked to a variety of volunteer characteristics, particularly having more citizen science experience (participating more frequently and for a longer amount of time), working in fields related to science, being younger, identifying as liberal, and not having children. The differences both between the specialists and the singletons and between the spanners and the singletons were always in the same direction: The specialists and the spanners appeared to have similar characteristics.

## Key findings regarding multiproject participation

Our analysis provides evidence that multiproject participation is widespread among citizen science volunteers, suggesting that volunteers are finding access to an array of inroads into citizen science. Remarkably, some volunteers have engaged in dozens of different projects over the course of their involvement in citizen science. Given that disciplinary specialization and spanning were linked to having more frequent and more sustained experiences with citizen science, participation breadth (i.e., spanning) may not hamper participation depth (i.e., specialization). Contrary to what some project managers have suggested (Sharova 2020), sharing volunteers across multiple projects may not lead to a decrease in data generation, because the volunteers that join multiple projects reported engaging in projects more frequently and for a longer amount of time. Instead, perhaps initial experience with a single citizen science project amplifies interest within volunteers that cascades to sustained and heightened engagement over time. This reflects the significant life experiences framework, which shows how formative experiences in environmental education can increase engagement with environmental topics later in life (Tanner 1980, Wells 2012). Participation breadth and depth may work in concert rather than in conflict. Rather than dabbling in a variety of projects, multiproject participants may be deeply engaged in a variety of citizen science projects as they explore the ecosystem of projects.

We found important differences in the patterns of multiproject participation between the participants in stand-alone projects and those in the SciStarter platform. Although nearly 90% of the volunteers sampled from the Christmas Bird Count participated in projects other than the Christmas Bird Count, the vast majority of these projects were other offline bird projects. This suggests that the Christmas Bird Count volunteers take a cloistered approach to citizen science, only joining projects similar to the Christmas Bird Count. Their experience with citizen science may deepen engagement with their favorite taxa, but it does not appear to lead to engagement in other areas of science. Similarly, the volunteers we sampled from Candid Critters also tended to stick to other offline ecology projects. In contrast, disciplinary boundary spanning was widespread among SciStarter volunteers. Although approximately half the projects joined by SciStarter volunteers were focused on ecology—according to both the digital trace data and the survey—the other half of projects were split among a diverse array of topics including geology, astronomy, health, and pollution. In addition, the SciStarter volunteers were much more likely to join online projects or to join both online and offline projects

than were the participants in the stand-alone projects we surveyed. This suggests that, relative to stand-alone projects that rely on a single mode of participation, platforms such as SciStarter.org offer a diverse landscape of projects that may foster broader and deeper engagement and serve as gateways to new projects.

All types of multiproject participants (discipline specialists, mode specialists, boundary spanners, and mode spanners) tended to have more experience with science, both professionally and through citizen science. A core goal of citizen science is to engage the public more inclusively than does the professional scientific enterprise. If citizen science were succeeding in this regard, we would expect to see high proportions of participants from underrepresented groups and those employed in non-STEM fields engaging with citizen science. Unfortunately, we found the opposite. Out of the nearly 3600 volunteers whose demographics we collected, fewer than 200 (5%) identified as Black, Asian-American, Pacific Islander, Native American, Latinx, or any other minority racial or ethnic group in the United States. By comparison, 40% of the US population identifies with one or more of these minority racial or ethnic groups (see table 1). Nearly half of the volunteers we sampled worked in science-related fields, and half held PhDs, MDs, or other advanced degrees. In short, citizen science participants are nearly exclusively individuals who, relatively speaking, already have access to science. Therefore, citizen science may not be effectively broadening public participation in science. These trends held across all three of our survey data sets. Although acknowledging the caveat that our surveys might have oversampled highly engaged volunteers, the possibility that the most committed citizen science participants are up to 10 times more likely to be White, and seven times more likely to hold advanced degrees, than the general population suggests that citizen science has a strikingly narrow reach in terms of public engagement. A better understanding of multiproject participation and the ways that participants navigate a landscape of citizen science options could help meet the immediate need to address diversity, inclusion, and equity in citizen science (Cooper et al. 2021).

It is impossible to know whether our sample is representative of all citizen scientists, given the quantity and diversity of projects that exist. SciStarter members and participants in the Christmas Bird Count may be representative of high-engagement types of volunteers. Furthermore, participation in each of the surveys was voluntary, which may have biased the sample further toward citizen science volunteers who were more engaged than the general population of volunteers. This caveat is tempered somewhat by the digital trace data, which collected data from the full population of SciStarter account holders from (although, there is bias here too, given the fact that not all SciStarter users create an account on the platform). In addition, our findings should be interpreted as a snapshot in time, and they may not necessarily demonstrate the current demographic characteristics of citizen science volunteers across a wider range of projects. Recent campaigns to increase diversity among citizen science volunteers such as Black Birders Week (Langin 2020) and partnerships between SciStarter and community organizations may have altered the demographic composition of volunteers after we gathered the data for this study. It is also important to note that the two stand-alone projects that we sampled for this study were offline ecology projects. Future research should explore the prevalence and dynamics of multiproject participation among volunteers with stand-alone projects from other disciplines and modes, as well as from citizen science platforms besides SciStarter.org. Despite any potential shifts, our data mirror previous research highlighting a lack of racial, ethnic, income, and education-based diversity among citizen science volunteers (NASEM 2018, Pateman et al. 2021).

**Recommendations for volunteer-centric management to maximize broader outcomes.** Our results demonstrate that a key dynamic of contemporary citizen science is participation in multiple projects. We therefore propose a volunteer-centric agenda for researchers interested in the phenomenon of citizen science that foregrounds multiproject participation when exploring fundamental questions about the scientific, environmental, and societal value of citizen science (table 4). Below, we outline five themes of particular importance for such an agenda.

First, studies of citizen science learning outcomes may benefit from evaluating volunteer learning holistically across the diverse landscape of projects in which volunteers engage. We found that 77% of the thousands of citizen scientists we sampled participated in multiple citizen science projects. Therefore, researchers examining learning outcomes solely with reference to a single focal project may be missing a significant portion of most volunteers' experiences. This may be particularly true for volunteers who have the potential to learn the most from their citizen science experiences—those participating frequently—given that we found that more frequent engagement is linked to more multiproject participation. In addition, there is some evidence from other settings to suggest additive and synergistic effects of volunteer learning through engaging with more than one project. For example, participation in two forms of outdoor recreation (birdwatching and hunting) was associated with higher levels of conservation behaviors than participation in either recreational pursuit in isolation (Cooper et al. 2015). Also, a greater breadth of youth participation across extracurricular activities was associated with higher scores in a variety of outcomes such as academic performance and well-being when compared with deep engagement in fewer activities (Rose-Krasnor et al. 2006). The few studies that mention multiproject citizen science participation in the context of learning outcomes find that multiproject volunteers exhibit higher retention (Parrish et al. 2019) and contribute more frequently (Ponciano and Pereira 2019) to projects than volunteers that participate in just one project do, and this is in line with our results. Participating in multiple citizen

***Table 4. A volunteer-centric framework opens new research directions addressing broader themes in the field of citizen science relevant to theory and practice.***

| Theme | Examples of volunteer-centric research questions |
|---|---|
| Volunteer learning | • How can multiproject participation support learning outcomes?<br>• In what ways are motivations linked to discipline spanning and mode spanning?<br>• What other forms of spanning (e.g., skills) occur among multiproject volunteers?<br>• To what extent does specialization and spanning influence learning?<br>• To what extent does data quality vary with specialization and spanning? |
| Guided learning trajectories | • What learning outcomes of initial citizen science experiences lead to specialization and spanning?<br>• How can citizen science platforms (e.g., Zooniverse, SciStarter) cultivate learning trajectories?<br>• What learning outcome of online projects lead to mode spanning?<br>• How do science skills and literacy translate across (or become reinforced by) specialization and spanning?<br>• To what extent are specialization and spanning linked to motivations, such as social orientation to conservation orientation? |
| Participation skew | • How does unequal participation manifest across projects?<br>• How often are high-contributing volunteers in one project also high-contributing volunteers in other projects?<br>• What participant characteristics lead to simultaneous participation (i.e., engaging in multiple projects at the same time) and sequential participation (i.e., engaging in one project before shifting to a different one)?<br>• How do project characteristics affect simultaneous versus sequential participation? Are specialization and spanning linked to simultaneous or sequential participation? |
| Demographic diversity | • What is the degree of skew in demographic patterns across the ecosystem of projects?<br>• What are the causes of demographic bias in participation, specialization, and spanning?<br>• Can learning brokers or facilitator organizations (e.g., corporate volunteer groups) engage non-STEM professionals?<br>• How does demographic bias across projects affect learning outcomes? |
| Project leaders and platforms | • How does multiproject participation enable new gateways and recruitment to citizen science?<br>• Can specialization and spanning alter project manager concepts of sharing volunteers?<br>• How can projects position themselves within a volunteer-centric framework as beginner or advanced projects to engage volunteers at the appropriate level?<br>• How can scaffolding within and across projects foster learning trajectories?<br>• What role do platforms, learning brokers, and facilitator organizations play in guiding volunteer trajectories? |

science projects could also lead to synergistic effects in the achievement of learning outcomes such as trust in science or science literacy (Bonney et al. 2016) if different projects reinforce one another or if participating across projects leads to deeper curiosity about unfamiliar epistemologies. For instance, positive interactions with scientists leading different projects might reinforce a volunteer's favorable impression of scientists and science as a whole. A volunteer-centric research agenda could also go beyond participation in citizen science and extend to other forms of public engagement in science and environmental learning, such as visits to museums and engagement in outdoor recreation (Bell et al. 2009). Therefore, a volunteer-centric perspective urges researchers to consider more fully the aggregation of experiences that might serve as antecedents that influence learning and behavior.

A second implication for a volunteer-centric framework is the concept of guided learning trajectories. We found that, in examining volunteers' citizen science experiences holistically, volunteers on a multiproject citizen science platform were much more likely to participate in projects from multiple disciplines and modes than volunteers from stand-alone projects. This finding leads to a fascinating possibility: that platforms such as SciStarter might design scaffolds and trajectories that foster learning across projects. For example, some projects could be designed as gateways with entry-level protocols and other projects could plan for data quality standards that require volunteers with prior experiences and skills gained in gateway projects. Some projects could encourage progression from online to offline participation—a potential remedy for the global decline in connection to nature and "extinction of (authentic) experience" (Schuttler et al. 2018). Offline projects could also foster positive, face-to-face social interactions that combat loneliness and encourage other positive health outcomes (Twenge et al. 2019). Characterizing and managing motivations, such as facilitating shifts from socially oriented motives to conservation-oriented motives (Larson et al. 2020), may play an important role in creating trajectories across projects. By scaffolding learning experiences across multiple citizen science projects, citizen science can recreate aspects of formal learning (i.e., universities) in the informal setting, with introductory and advanced level projects that enable gateways to even deeper knowledge.

Third, a volunteer-centric research agenda presents a new opportunity to conceptualize and study participation skew in citizen science. The heuristic rule called the Pareto principle, in which effort tends to be greatly partitioned (e.g., 20% of peapods produced 80% of peas; Pareto 1935), often describes participation within a citizen science project,

whether outdoor (e.g., eBird; Wood et al. 2011) or online (Ponciano et al. 2014). Rather than an immutable rule, the phenomenon of the Pareto Principle in citizen science may arise from the digital divide or concerns about privacy protections, extractive research practices, and other aspects of citizen science that vary with age, race, and culture to produce unequal participation that results in biased and nonrepresentative samples (Foster et al. 2017, Bietz et al. 2019). Although participation inequality can vary over several orders of magnitude within a citizen science project (Haklay 2016), we also found participation inequality across projects: Approximately 11% of citizen science volunteers in our sample participated in between 6 and 50 different projects, but 46% participated in only one or two. New research into the patterns of the Pareto Principle manifesting across multi-project participation could have practical implications for volunteer management. A volunteer-centric research agenda therefore adds a new dimension to studies of unequal participation within each project and simultaneously across projects.

A fourth implication for a volunteer-centric framework centers on the demographic diversity of participants. Despite the promise of citizen science to democratize science (Irwin 2002), as our study and others have demonstrated (e.g., Pateman et al. 2021), citizen science volunteers do not reflect the diversity of the population at large, in gender (Cooper and Smith 2010, Curtis 2018), STEM profession, and race. Indeed, according to our study, working in a STEM field is highly predictive of engaging more broadly across the citizen science landscape. Exploring how multiproject participation or learning trajectories might differ across race, economics and education should be an important goal of a volunteer-centric framework. Furthermore, this framework would allow for a more precise assessment of the extent to which citizen science engages different segments of society across the entire ecosystem of citizen science. Although we found strong demographic homogeneity among all four of the data sources in our sample, it's possible that certain place-based or community-centered projects that we did not sample have more diverse participants. With a project-centric framework, researchers might explore how participants in a given citizen science project navigate issues of inclusivity; with a volunteer-centric framework, researchers can consider more holistically the systemic issues in citizen science design that exclude marginalized groups, perhaps leading to new solutions (Cooper et al. 2021, West et al. 2021). For example, assessing engagement in citizen science supported by intermediaries or facilitators (e.g., schools, Scout groups, or corporate volunteer programs) might reveal new insights into barriers to broadening participation (Salmon et al. 2021). We collected the SciStarter data in this study prior to SciStarter's addition of dozens of organizations that function as facilitators or learning brokers. Future research with a volunteer-centric framework will compare volunteer characteristics and engagement patterns among those associated with facilitator organizations and independent volunteers.

Finally, the fifth theme in a volunteer-centric framework is its implications for project leaders and platforms. Currently, many project managers employ a unitary approach to managing volunteers, where volunteers are viewed as finite resources over which projects compete (Sharova 2020). Given unequal participation within and across projects, alternative volunteer management approaches could build on our designations of spanners and specialists and distinguish supercontributors, dabblers, and other possible categories of volunteers (for instance, see Eveleigh et al. 2014 and Fischer et al. 2021). Project managers could cooperate and coordinate with regard to their volunteer needs and scaffold learning and engagement to jointly foster individual and collective volunteer capacity in citizen science. Citizen science platforms could facilitate such cooperation, particularly through interactions with learning brokers, such as environmental educators. Importantly, however, our results show that multiproject participation is not restricted to third-party platforms, a result with little prior evidence in the literature, and can emerge in many different citizen science contexts.

## Conclusions

Because of the prevalence of multiproject participation in citizen science, we suggest a course for future research and volunteer management that addresses enduring questions about participation, contributions, and learning across the ecosystem of projects. We proposed a volunteer-centric framework of participation that recognizes volunteers engaging across multiple projects, topics, and modes, and centers questions about how to make the ecosystem of projects relevant and inclusive to diverse cultures. We recommend that citizen science researchers consider learning outcomes and volunteers' broader contributions to science within a volunteer-centric, project-agnostic framework. At a practical level, this focus will lead to the inclusion of an important variable in studying volunteer learning through citizen science: multiproject participation. More broadly, such a holistic focus will be an important step forward for the field of citizen science, and a critical step toward engaging diverse populations and better understanding the millions of people that volunteer their time every year to contribute to scientific and environmental progress.

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## Supplemental material

Supplemental data are available at *BIOSCI* online.

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