CITIZEN SCIENCE:
THEORY AND PRACTICE

METHOD

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The Soundscapes to Landscapes Project: Development of a Bioacoustics-Based Monitoring Workflow with Multiple Citizen Scientist Contributions

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ABSTRACT

Citizen science is an important approach for ecological studies that require county-scale or broader geographic coverage. Here we report on project management, technology, and the variety of roles and levels of engagement of citizen scientists in the Soundscapes to Landscapes project, focused in Sonoma County, California, USA. The project uses low-cost autonomous recording units (ARUs) and bioacoustic analysis to monitor bird diversity and soundscape components at a regional scale. In five years, 259 citizen scientists collectively volunteered 8,390 hours on a range of tasks, with 40% field work and 41% bioacoustic reference data collection, but also including geographic information systems, social media, and data upload. Citizen scientists were a mix of expert collaborators, community volunteers, and undergraduate students. In five distinct field campaigns, 141 citizen scientists deployed recording devices during the breeding bird season at 1,281 sites on public and private lands, and collected 12,431 hours of raw audio recordings. For bioacoustic analysis, we used a custom web-based citizen science interface to produce labeled reference data, through which seven expert citizen scientists and 105 user-level citizen scientists produced 230,066 labeled audio clips. We found that word-of-mouth and personal connections were the best strategies for recruitment and retainment of citizen scientists. Levels of engagement among citizen scientists varied, and community volunteers who participated in more than one task contributed more time to the project overall. Undergraduate students were a valuable citizen scientist group in the project, contributing 48% of the total citizen scientist effort and were particularly important for field work success.

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INTRODUCTION

Citizen science is an important approach for collecting *in situ* biodiversity and ecological information such as species distributions, population abundance, phenology, and ecosystem productivity, with broader spatial and temporal sampling than is economically or logistically feasible with standard research methods (Bonney et al. 2009; Bonney et al. 2014; Dickinson et al. 2012). The growth of web-based informatics and location-enabled mobile technologies has helped simplify, coordinate, and manage surveys by citizen scientists, allowing collection of large amounts of spatially-located ecological data stored in centralized databases (Catlin-Groves 2012; Dickinson et al. 2012). For example, eBird is a well-established global bird monitoring project that uses web- and mobile-based data entry to archive millions of citizen scientist bird sightings per year (Sullivan et al. 2014). However, avian monitoring projects using citizen science, such as eBird or regionally coordinated breeding bird atlas projects, rely on contributors to accurately identify species by sight or vocalization, which limits participation and requires additional verification steps (Catlin-Groves 2012; Dickinson et al. 2010; Robertson et al. 2010). Further, reliance on volunteer birdwatchers can lead to spatial clusters (e.g., in public areas) (Tang et al. 2021; Robertson et al. 2010; Boakes et al. 2010; Tulloch et al. 2013) and temporal sampling bias (e.g., on weekends) (Boakes et al. 2010; Funk and Richardson 2002; Robertson et al. 2010; Szabo et al. 2007), thereby limiting scientific applications (Zhang 2020).

Through online citizen science engagement platforms such as Zooniverse, citizen scientists identify target species (e.g., Snapshot Wisconsin, https://dnr.wisconsin.gov/topic/research/projects/snapshot), space phenomena (e.g., Disk Detective, https://www.zooniverse.org/projects/ssilverberg/disk-detective), or other patterns of interest in large visual, auditory, or audiovisual datasets (Tang et al. 2021). Yet many projects that use crowdsourcing to label and classify data offer a limited level of involvement by providing one or two repetitive tasks, which may decrease long-term citizen scientist engagement and thus require thousands of volunteers to obtain the data necessary for analysis (Raddick et al. 2010; Garbarino and Mason 2016). Citizen science projects that are most successful at sustaining citizen scientist participation are often those in which citizen scientists are involved in project design (Shirk et al. 2012; Bonney et al. 2014), have opportunities for increased responsibility and recognition (Dickinson et al. 2012), and are personally invested in the outcome (e.g., local water quality monitoring) (Capdevila et al. 2020; Shirk et al. 2012).

Passive acoustic monitoring of the environment can provide information on overall ecosystem status and change (Krause and Farina 2016; Pijanowski et al. 2011) as well as on sound-producing wildlife, including birds, amphibians, insects and mammals (Balantic and Donovan 2020; Gibb et al. 2019). Bioacoustic analysis allows automatic detection of bird presence with greater sampling in time and space than with traditional bird observations (Campos-Cerqueira and Aide 2016; Furnas and Callas 2015), removes the influence of human presence on animal vocalization during sampling, and reduces individual observer bias.

Soundscapes to Landscapes (S2L) (Soundscapes to Landscapes 2022) is a distributed, citizen science-based acoustic monitoring project that uses cost-effective mobile- and web-based technologies, autonomous recording units (ARUs), and bioacoustic analysis to monitor bird diversity and broad soundscape components of anthrophony (e.g., cars, airplanes), geophony (e.g., wind, rain), and biophony (e.g., birds, insects, mammals) at a countywide scale. Project citizen scientists are community volunteers and undergraduate interns that participate at varying levels of responsibility depending on skill and interest. Here we discuss project management and the multiple tasks that citizen scientists performed, including deploying and retrieving ARUs, identifying bird vocalizations and other sounds, uploading data, generating field maps, and promoting the project. While the biodiversity results from this project are still in active development, our goal is to provide useful information for developing and managing passive acoustic monitoring projects that seek to engage citizen scientists in multiple roles. We report on successes and challenges with citizen scientist engagement, differences in productivity levels of undergraduate students versus community volunteers, and lessons learned that are broadly applicable to citizen science projects.

METHODS

STUDY AREA

Sound data collection for S2L was focused in Sonoma County, California, USA. Spanning 4,118 km^2, the county has a variety of habitat types, including forest, shrubland, grassland, agricultural, and urban (Figure 1). Sonoma hosts a broad network of birdwatchers, college students, and conservation-minded organizations and stakeholders. The county is largely (~90%) privately owned, which allowed property owners to participate as citizen scientists by providing access to their land and optionally by deploying ARUs.

PROJECT OVERVIEW

The S2L project involved citizen scientists, staff, and a science team distributed across academic and non-profit institutions. It required a variety of strategies for project

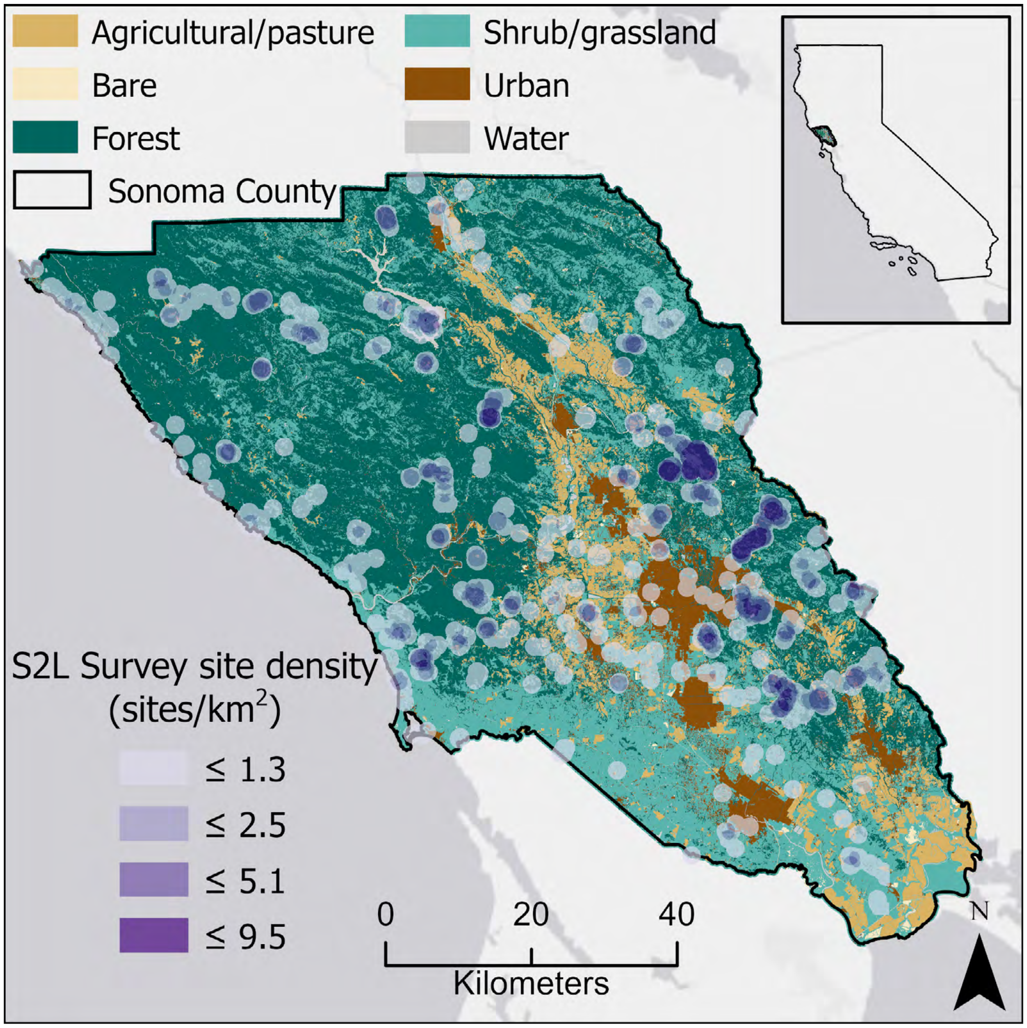


Figure 1 Study area and sampling density. Study area and sound recorder sampling density (number of sites per km^2) in Sonoma County (n = 1,281). Land cover layer from Sonoma County Agricultural Preservation and Open Space District.

management and for citizen scientist recruitment and engagement (Figure 2). We thus sought technological solutions to provide efficient, low-cost, secure, and collaborative tools for implementing and managing project components and data streams (Figure 3). We provide technology website links in Supplemental Table 1.

STEP 1. ESTABLISH WORKFLOW AND PROJECT COORDINATION STRUCTURE

Overall project management was led by a core team of science investigators and a paid full-time project coordinator. We used Slack for communication between the science team and highly involved citizen scientists, and we stored sound recordings, meeting notes, code, reference data, and geospatial data in Google Drive (Figure 3).

This project required coordination of hundreds of citizen scientists, properties, landowners, deployments, and sample sites. To organize and track each workflow component, we used Airtable, a cloud-based interface that combines the features of spreadsheets with those of a simplified database (Figures 2 and 3). Additional information on Airtable is provided in Supplemental Text 1. The project coordinator facilitated data collection and tracking using built-in Airtable features such as web-based forms (e.g., for volunteers to provide contact information) and calendar views (e.g., for scheduling deployments).

We created a website (Soundscapes to Landscapes 2022) as an information base. The site includes general project information, science outcomes (e.g., presentations, publications), monthly newsletters, social media links, and a volunteer portal. All citizen scientists reported their hours via a form in the portal, and these self-reported hours data are used in the results. More details about the project website are provided in Supplemental Text 4.

STEP 2. RECRUIT CITIZEN SCIENTISTS

We used several approaches to recruit citizen scientists to participate in S2L. We divide citizen scientists into two

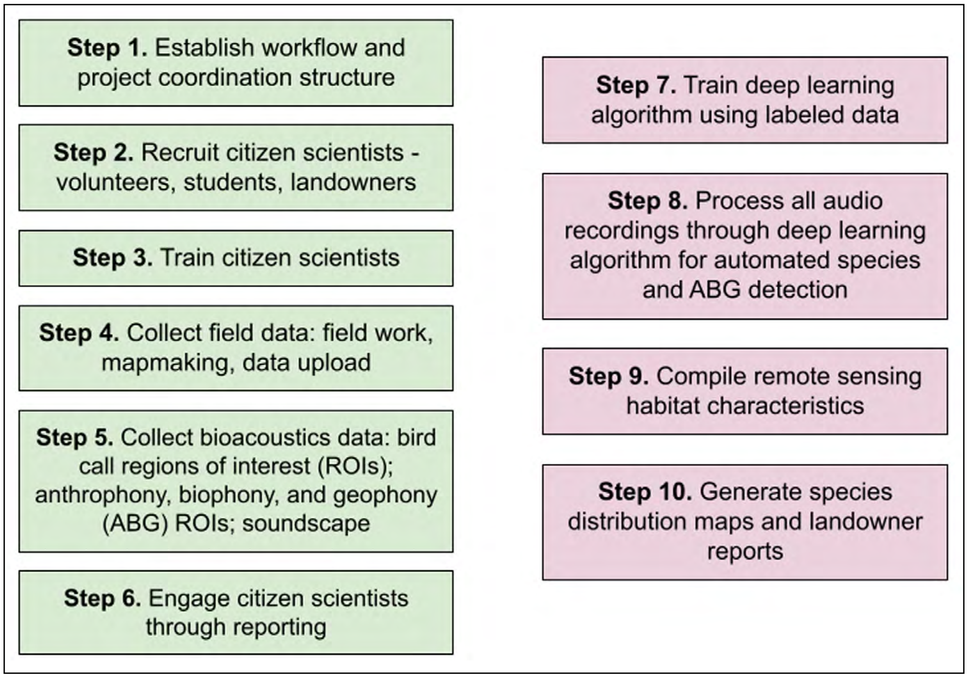


Figure 2 Overall workflow for the Soundscapes to Landscapes project. This paper addresses Steps 1–6 (*green*). Steps 7–10 will be addressed in subsequent papers.

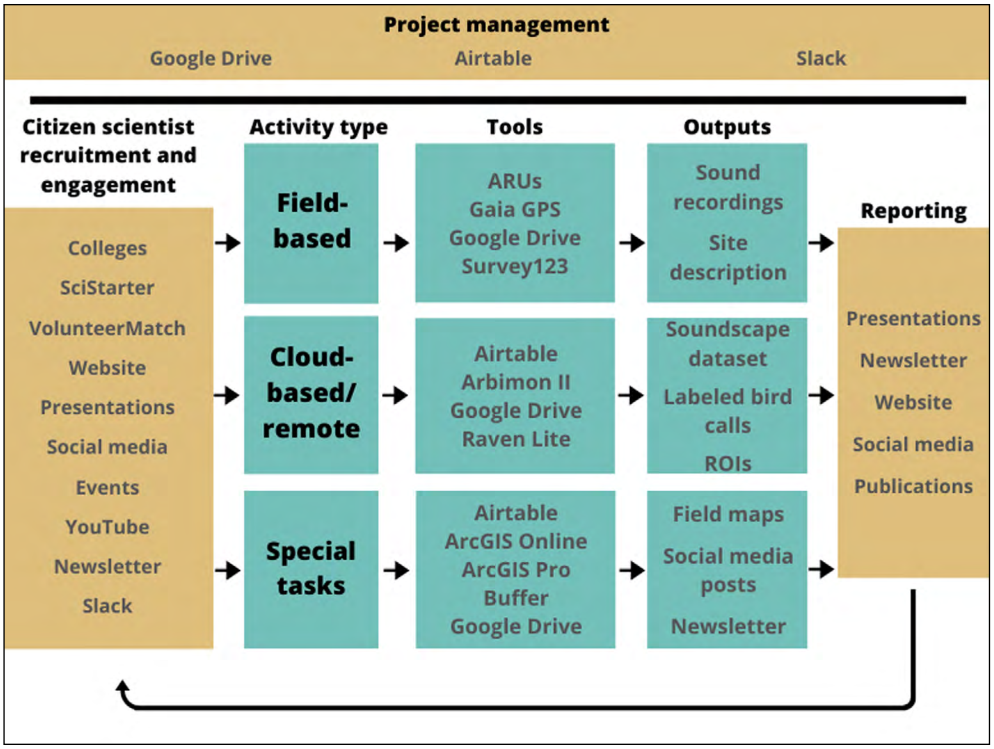


Figure 3 Project management components and the tools used by citizen scientists to engage in multiple project activities. Boxes shaded teal indicate activities that were primarily completed by citizen scientists, managed by the project coordinator.

categories: 1) community volunteers, including property owners, and 2) student interns who received academic credit. We initially recruited three community volunteers with extensive knowledge of bird vocalizations to participate as official collaborators. This ensured that we had the expertise needed to successfully accomplish the project, and these collaborators also assisted with citizen scientist recruitment.

To recruit community volunteers, we used word-of-mouth, presentations to local birding groups (e.g., local Audubon chapter), the project website, and social media. To recruit undergraduate students, we gave presentations in college classrooms, advertised on college career boards, and sent announcements to targeted email lists. All citizen scientists signed up on our website using a simple Airtable form, which allowed them to choose desired activities. For online bioacoustics activities, we also used volunteer recruitment websites SciStarter and VolunteerMatch, which had a global reach.

STEP 3. TRAIN CITIZEN SCIENTISTS

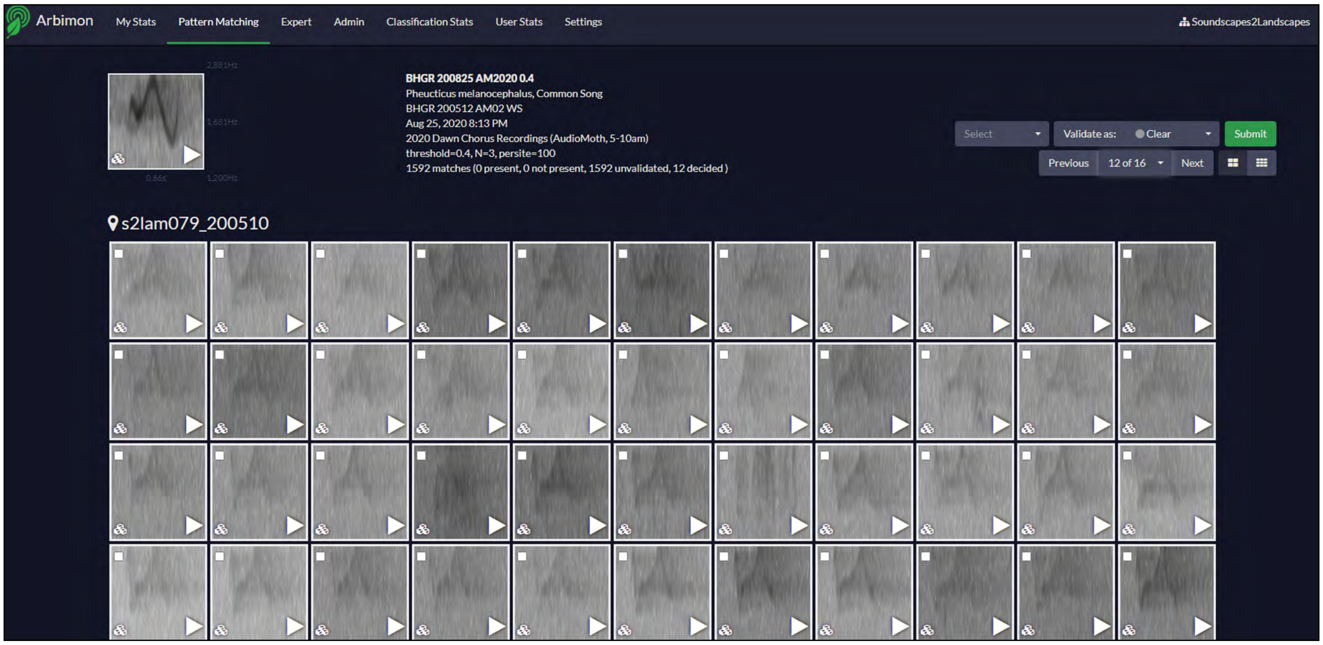
Staff provided training days for ARU deployments prior to each annual field campaign. We engaged local citizen scientists in bioacoustics activities by hosting a series of in-person training events in which we presented a project overview, provided dinner, and assisted citizen scientists with bird call validations (Figure 4). During the COVID-19 pandemic when in-person gatherings were not possible, we provided a series of short training videos on YouTube to enable remote participation in the project.

STEP 4. COLLECT FIELD DATA

Autonomous recording units and auxiliary applications and equipment

We used two types of ARUs to collect sound recordings at sample sites (Figure 3: Field-based). In 2017 and 2018, we used ten Android-based smartphones (US$300/unit) with attached microphones and waterproof cases, using the Arbimon Touch app developed by Sieve Analytics. In 2019, we transitioned to the AudioMoth (Hill et al. 2019), which has been used in bird, amphibian, insect, and mammal research applications (Barber-Meyer et al. 2020; LeBien et al. 2020; Zhong et al. 2020). The AudioMoth costs about US$85 per unit with batteries and SD memory card, is easy to program, and has a simple data upload from the SD card. We programmed ARUs to sample 1 of every 10 minutes, thus providing temporal sampling through day and night. We chose not to record continuously as this would require our project to archive and process large amounts of data, would incur higher data storage costs, and our project goal was to capture species at a site level, not every instance of vocalization. Further, recordings typically spanned 3 to 4 days, with the goal of capturing more spatial than temporal variation in a field season.

We developed a stratified random sampling design based on land use, distance-based variables, and forest structure and chemical properties (Supplemental Text 2). Using ArcGIS Pro geographic information system (GIS) software, trained citizen scientists created property-scale maps for citizen scientists to use in the field (Figure 3: Special tasks). Field teams used the free smartphone application Gaia GPS to navigate to site locations and the ArcGIS Survey123 application to collect auxiliary site data, including location coordinates, date and time of deployment, property information, and photographs of the survey site (Figure 3: Field-based). We chose Survey123 because it was easy



BHGR 200825 AM2020 0.4
Pheucticus melanocephalus, Common Song
BHGR 200512 AM02 WS
Aug 25, 2020 8:13 PM
2020 Dawn Chorus Recordings (AudioMoth, 5-10am)
threshold=0.4, N=3, persite=100
1592 matches (0 present, 0 not present, 1592 unvalidated, 12 decided)

s2lam079_200510

Figure 4 Example pattern matching output for review by citizen scientists in Arbimon.

to configure and update with a web-based form, was available on both Apple iOS and Android mobile devices, and allows citizen scientists to transfer the data to ArcGIS Online where a service automatically updates a vector point GIS layer.

Deployment campaigns

From 2017 to 2021, the S2L project deployed ARUs annually in field campaigns spanning late March to early July, capturing most of the breeding season when birds vocalize for mating and for defending their territory. We used two approaches to deploy ARUs to sampling locations: volunteer deploy and mail deploy. For the volunteer approach, a team of at least two citizen scientists traveled to public and private properties to deploy ARUs. The mail approach involved sending the ARUs, instructions, and a prepaid return box to private property owners to deploy on their own properties.

STEP 5. COLLECT BIOACOUSTIC REFERENCE AND VALIDATION DATA

Bird vocalizations

The citizen scientists found sample clips of bird vocalizations from 8,083 hours of audio recording data we collected in the first four years of the project (Figure 3: Cloud-based/Remote). We used the web-based Arbimon platform, which allows users to sort, visualize, listen to, and identify bird vocalizations (Aide et al. 2013). We partnered with Sieve Analytics (the platform creator) to design a citizen science interface for collecting the representative bird vocalizations needed for developing automated detection approaches with deep learning.

In the Arbimon citizen science interface, a volunteer with bird vocalization knowledge (hereafter, "expert") delineates a bounding box representing a distinct bird vocalization within a 1-minute spectrogram, that is, a time versus frequency graphic depiction of a recording (Figure 4). The system then uses this template region of interest (ROI) and a pattern matching algorithm (LeBien et al. 2020) to find similar ROIs above a specified correlation threshold in our sound recordings. This results in hundreds to thousands of potential matches.

The Arbimon citizen science interface allows user- (citizen scientists with minimal or no bird vocalization knowledge) and expert-level citizen scientists to validate if matched ROIs include the bird vocalization in the template ROI by assessing the spectrogram or by listening to the sound clip (Figure 4). The system records validations of the same ROI among multiple user-level citizen scientists and provides a consensus vote. We chose a threshold of three user-level citizen scientist votes for either present or absent to reach a consensus, at which point the ROI was removed from further review. The expert citizen scientist can provide sole votes on ROIs to quickly boost the number of present ROIs, and can also review consensus validations to reduce false positives. This approach allowed our citizen scientists to develop ROI data for 54 bird species (Figure 3: Outputs).

Our goal was to collect ROI data to train a deep learning algorithm that would detect bird vocalizations and could be applied to recordings at the second level. To gain a realistic sense of model accuracy, we sought a per-second assessment of bird species within a sample of recordings, independent of ROIs. We selected a total of 905 1-minute recordings using a stratified random design (see Supplemental Text 3). Expert citizen scientists used Arbimon to visualize spectrograms and listen to each recording, and noted the start times of bird vocalizations in an Airtable base, creating a soundscape dataset (Figure 3: Outputs).

Soundscape components

The project also sought to detect broad soundscape components of anthrophony, biophony, and geophony (ABG) in our recordings. User-level citizen scientists manually collected ROI data for ABG using two tools: Arbimon and Raven Lite from Cornell Lab of Ornithology. The Raven Lite software was not web-based, but was better suited for delineating ROIs around ABG than Arbimon, which was designed for biodiversity applications. Additionally, user-level citizen scientists noted start and stop times of ABG in a subset of 682 1-minute recordings from the soundscape dataset.

STEP 6. ENGAGE CITIZEN SCIENTISTS THROUGH REPORTING

We used several approaches to report on project progress to help keep citizen scientists motivated and engaged (Figure 3: Reporting). First, we showed citizen scientist hours in a leaderboard on our project website (see Supplemental Text 4; Supplemental Figure 1). Further, we used Mailchimp to send a monthly email newsletter that included project updates and opportunities for citizen scientist participation, a featured bird-of-the-month with an example bird vocalization, a highlight of a citizen scientist, and a spotlight on a partner organization. We used the website to highlight publications or media content about our project, and we used Buffer to post regularly on social media with project updates, images, and announcements. Throughout the project, two citizen scientists (one community volunteer and one student intern) helped manage our social media accounts (Figure 3: Special tasks).

RESULTS

OVERVIEW OF CITIZEN SCIENTIST PARTICIPATION

A total of 259 citizen scientists collectively contributed 8,390 hours over the duration of the study, primarily on 40% field work and 41% bioacoustic data collection. Student interns and citizen scientist collaborators were a driving force in accomplishing much of the citizen science tasks and contributed to 68% of total citizen scientist hours. Community volunteers contributed more time to the project if they participated in multiple tasks (Figure 5). Conversely, student contributions did not vary based on the number of tasks that they participated in (Figure 5). Student interns contributed more time to data upload, field work, and ABG ROI collection, while community volunteers contributed more time to all other tasks (Figure 6). The greatest number of citizen scientists participated in cloud-based/remote activities, resulting in the greatest amount of volunteer time dedicated to these activities.

FIELD DATA COLLECTION

In total, 141 citizen scientists contributed 3,687 hours to field work activities. Over five field campaigns, citizen scientists used 125 ARUs to collect sound recordings from 1,281 sites (Table 1). With volunteer deployments, ARU turnaround was 4 to 5 days, whereas mail deployment ARU turnaround was 2 to 3 weeks. During the study, we visited 192 properties (35% public versus 65% private land).

BIOACOUSTIC REFERENCE DATA COLLECTION

Citizen scientists volunteered 3,448 hours on cloud-based/remote activities over the four years that the project was focused on collecting bioacoustic reference data. Seven expert citizen scientists with knowledge of bird vocalizations were critical to this phase and volunteered 1,715 hours to work on the following tasks: initial experimentation and testing of bird call modeling, finding representative bird vocalizations for pattern matching and reviewing ROI validations, and creating the soundscape dataset (Supplemental Text 3).

User-level citizen scientists volunteered 1,733 hours to: identify ABG soundscape components, validate ROIs in Arbimon, and manually collect a total of 5,396 ABG ROIs in Raven Lite. Hours came primarily from local citizen scientists, with ~9% from SciStarter and VolunteerMatch. Of 105 user-level citizen scientists, the top numbers of citizen scientists and validations were from citizen scientists recruited through colleges, word-of-mouth, and VolunteerMatch.

Our work with the Arbimon citizen science interface spanned 16 months and included 686,858 individual votes on pattern match results (average 400 votes per citizen scientist hour). There were 230,066 final bird vocalization ROIs validated by citizen scientists through consensus-based (76%) or expert (24%) methods (Figure 7; Supplemental Table 2). These ROIs included 54 species with a collective 51,906 clips indicating a species presence,

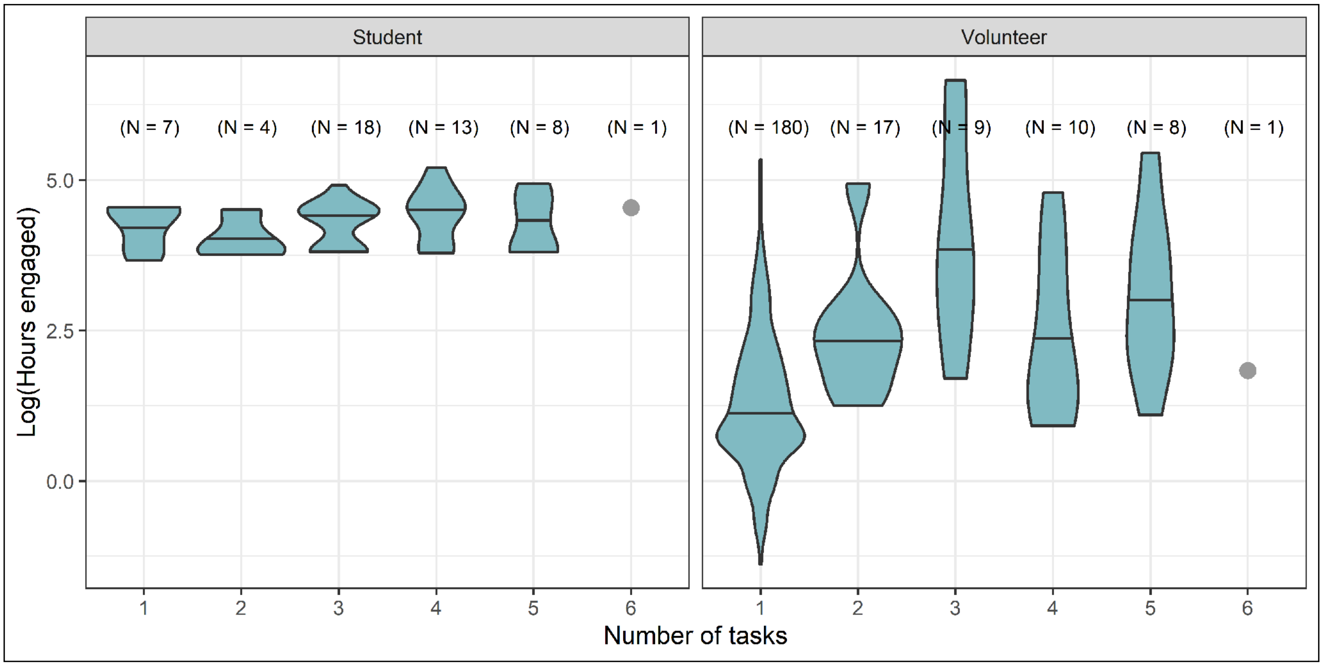


Figure 5 Number of tasks each citizen scientist engaged in by hours engaged (note log scale). Volunteer participation in more than one task is correlated with a greater number of hours contributed overall.

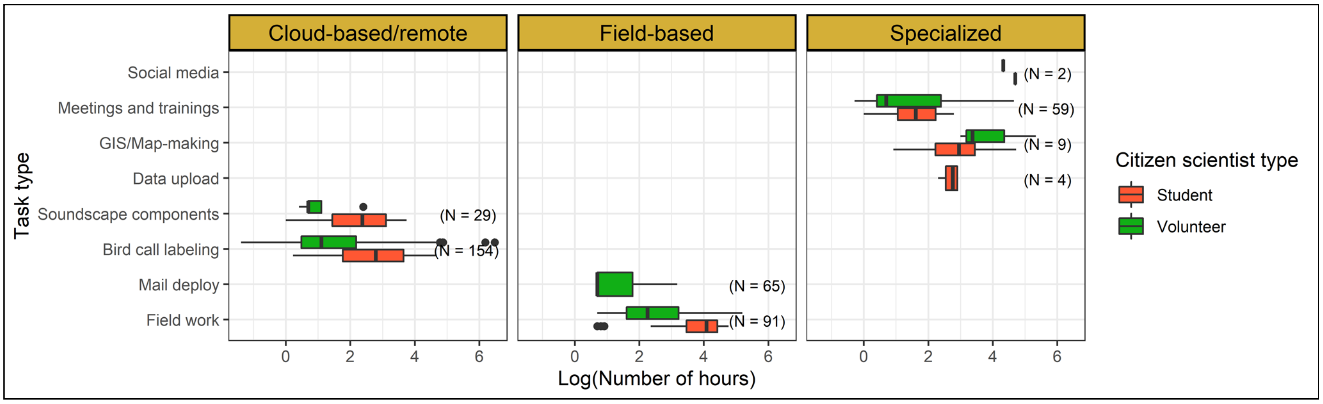


Figure 6 Citizen scientist participation (log of hours) by activity type.

	VOLUNTEER DEPLOY	MAIL DEPLOY	ALL
Number of sites surveyed	1,130	151	1,281
Sites per volunteer hour	0.33	0.55	0.34
Sites per deployment (avg)	5.8	1.6	4.4
Hours of recordings	10,353	2,078	12,431
Hours of recordings per site (avg)	9.2	13.8	9.7
Number of days deployed per site (avg)	3.8	5.8	4
Number of deployment events	195	93	288

Table 1 Key statistics for field work.

ranging from 496 to 3,049 ROIs per species (average = 961). Since acquiring enough consensus-based present ROIs for a given bird species could be slow, citizen scientist experts helped move all species to completion faster; including 20 exclusively expert-validated species (Supplemental Table 2). In the end, 75% of our ROIs with species present were validated by experts (Figure 7).

DISCUSSION

The S2L project was successful at harnessing low-cost technology and the energy of citizen scientists interested in biodiversity conservation to acquire a large volume of acoustic recordings at a regional scale. Further, citizen scientists participated directly in the scientific process by collecting bird vocalization and soundscape component reference data for training and testing of deep learning algorithms for subsequent scientific analyses.

ENGAGING CITIZEN SCIENTISTS IN AN ACOUSTICS-BASED MONITORING PROJECT

Of all outreach methods used to engage citizen scientists, word-of-mouth and local connections were the most successful in recruiting and maintaining participation. Targeted emails to local colleges attracted a large pool of students desiring field experience, and who ultimately completed the majority of volunteer deployments. Presenting to community groups was also effective in recruiting citizen scientists, particularly for bioacoustics-based activities. We had less success with online platforms VolunteerMatch, SciStarter, and social media, and citizen scientists recruited through these methods tended to be one-time participants.

Community volunteers were more likely to stay engaged in the project if they participated in more than one task. For example, several volunteers who started by doing field work also became interested in working with the collected audio data as they learned more about the project. Additionally, volunteers could utilize existing skills to participate in activities they were most interested in, like social media, bird identification, GIS, and programming. Because of this variety, many volunteers stayed engaged with the project even after their participation in a specific task declined. By engaging citizen scientists in multiple components of the project, it may help them develop a deeper sense of commitment by feeling co-ownership of the project and its outcomes (Pandya 2012).

It worked well to engage citizen scientists in the bioacoustics work using remote participation and in-person

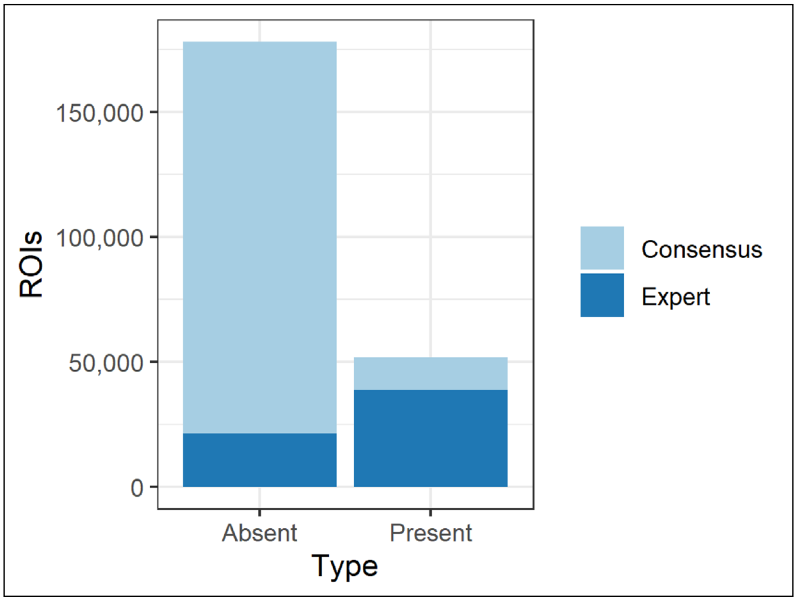


Figure 7 Regions of interest (ROIs) in Arbimon where a bird vocalization was deemed present or absent based on consensus-based voting or expert review.

bird blitzes. Bird blitzes gave participants the advantage of meeting the project team, learning more about the science, and obtaining one-on-one training. Conversely, using a web-based interface enabled broader geographic citizen scientist recruitment as well as remote participation by locals who were unable to attend in-person events. Remote participation became a significant advantage during the COVID-19 pandemic and associated stay-at-home restrictions.

INTEGRATING UNDERGRADUATE STUDENTS INTO CITIZEN SCIENCE

Roughly half of all citizen scientist hours in the project were from undergraduate students who received academic credit through internships with collaborator Point Blue Conservation Science. Engaging this citizen scientist group annually provided a cohort of students desiring field experience that could be expected to participate for the duration of the semester. Many students participated in only one annual field campaign, requiring us to provide training before each campaign. Notably, community volunteers ultimately required roughly the same amount of training hours as students (Figure 6: Meetings and trainings). The number of tasks that students participated in were not correlated with an increase in hours (Figure 5) because we assigned a range of tasks to give students a robust educational experience.

Besides these utilitarian benefits, a growing body of research links undergraduate involvement in citizen science projects and improved student learning outcomes, such as a better understanding of the scientific process, better connection to the natural world, and data literacy (see Hitchcock et al. 2021 in the special collection “Citizen Science in Higher Education” in *Citizen Science: Theory and Practice*). In S2L, we were able to engage students in multiple tasks, leveraging their existing knowledge in topics of social media, bird identification, and GIS. We did not set out to measure student learning outcomes, and thus have no quantitative data to assess how students were impacted by their experience—a limitation of many citizen science projects (NASEM 2018). However, ancillary evidence from students featured in our newsletter spotlight indicates that they were particularly motivated by the ability to explore the natural world, and they gained a sense of scientific discovery.

DEPLOYING ARUS ON PUBLIC AND PRIVATE LANDS

We sought a range of citizen scientist engagement in deploying ARUs with a driving goal to sample as much private land in the county as possible. We succeeded at reaching this goal; two thirds of sampled sites were located on private lands.

Although we envisioned mail deployment as a means to access more private lands than may be otherwise possible, we found that volunteer deployments were more efficient and provided the majority of our sound recordings. Although volunteer deployments required extensive coordination, citizen scientists were trained prior to conducting field work and generally needed little technical support once in the field. Further, the rapid ARU turnaround with volunteer deployments enabled us to redeploy the same devices to other sites quickly, whereas slow ARU turnaround with mail deployments limited redeployment. Although we provided detailed written instructions, as well as training videos in the fifth year, some property owners still found using the ARUs and smartphone applications challenging; they needed technical coaching or gave up entirely. Other citizen science projects have also found the technical design of applications and web-based interfaces to be a barrier for citizen scientist participation, and suggest that applications should be easy to learn and use (Benyei et al. 2020; Hobbs and White 2012; Martin et al. 2016).

TECHNOLOGICAL SOLUTIONS FOR CITIZEN SCIENCE DATA ACQUISITION AND MANAGEMENT

We found AudioMoths to be low-cost and easy to program and deploy, and they replaced smartphones as the preferred ARUs in our project. One disadvantage was that AudioMoths lost their programming when the batteries were dislodged. It also may have been more efficient if there was an integrated smartphone application that could bundle functions of navigating to the sample site (e.g., Gaia GPS), logging location and auxiliary information (e.g., Survey 123), connecting to the AudioMoth via bluetooth to turn it on/off (e.g., currently a manual switch), and uploading recordings to our data repository via WiFi.

We used a custom citizen science interface in Arbimon for collecting our bird vocalization reference data. This is in contrast to many citizen science projects that use the Zooniverse platform for crowd-sourced, consensus-based voting, particularly within the domain of image interpretation (Cox et al. 2015; Willi et al. 2019). Arbimon allowed us to leverage web-based soundscape infrastructure and domain expertise at Sieve Analytics, and allowed integration with the system's cloud-based pattern matching algorithm. Arbimon tools were easy for expert citizen scientists to use to identify representative ROI templates and run pattern matching jobs in a web-based environment that had access to all project recordings. The citizen science interface had an advantage in showing both site and temporal information for multiple matched ROIs on one page, making review more accurate and efficient.

Despite these benefits, Arbimon's pattern matching algorithm results revealed that it can be inefficient for many species, producing many matches where the bird is absent, which ultimately wastes citizen scientist time. Therefore, we relied on experts to validate enough ROIs with birds present in order to proceed with deep learning development, which will be presented in a forthcoming paper.

As a start-up, science-based project relying on the academic and non-profit sector, we faced obstacles due to limited time and funding as well as a distributed work environment. We leveraged web-based tools (e.g., Slack, Google Drive, Airtable) for effective, cloud-based, low-cost collaboration and data management. However, owing to the significant time needed to develop our data processing pipeline, we did not reach the final outcomes at the time of completing field campaigns (Figure 2: Steps 7–10). One outcome that is now complete are landowner reports, which include the overall species richness and the number of detections of species and soundscape components through a 24-hr period for each site on a property. Additional project outcomes are regional maps of species distributions and ABG soundscape components using geospatial modeling. These deliverables are in progress and will be described in subsequent papers. The lag time in providing deliverables to citizen scientists and property owners potentially decreased long-term project enthusiasm, as consistent and timely feedback with citizen scientists often increases motivation for longer-term engagement, particularly when that feedback relates individual citizen scientist contributions to scientific outcomes (de Vries et al. 2019).

CONCLUSIONS

The development of low-cost sound ARUs allows passive acoustic sampling over more locations and time periods than previously available with more expensive equipment, and opens exciting opportunities to enlist citizen scientists in environmental monitoring. Further, web-based tools provide a platform for citizen scientists to assist with bioacoustic analysis at scale. In five years, the S2L project engaged 259 citizen scientists to collect 12,431 hours of audio recordings and validate 230,066 samples of bird vocalizations needed for automated species detection algorithms. Although S2L was focused on broad spatial sampling at the county scale, our approach of engaging undergraduate students and community volunteers in citizen science could be scaled to include sampling over larger regions and longer time periods. Offering a variety of tasks for citizen scientists to participate in was a successful engagement approach. However, there is no single platform that will meet all the data management, analysis, and social engagement needs of a citizen science bioacoustics project like S2L. Acoustic surveys are a cost-effective means to monitor biodiversity, thus the development of bioacoustic citizen science platforms is needed.

DATA ACCESSIBILITY STATEMENT

The sound recordings and reference data collected as part of Soundscapes to Landscapes have not yet been published. We intend to publish these data in a public depository upon completion of the project.

SUPPLEMENTARY FILE

The supplementary file for this article can be found as follows:

- **Supplemental Materials.** DOI: https://doi.org/10.5334/cstp.391.s1
    - Supplemental Text 1: Project management Airtable base description.
    - Supplemental Text 2: Field sampling design.
    - Supplemental Text 3: Soundscape sampling design and results.
    - Supplemental Text 4: Project website volunteer portal details.
    - Supplemental Figure 1: Volunteer leaderboard on project website.
    - Supplemental Table 1: Links to products used in Soundscapes to Landscapes.
    - Supplemental Table 2: Bioacoustics reference data.

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COMPETING INTERESTS

The authors have no competing interests to declare.

AUTHOR CONTRIBUTIONS

LS and MC designed and obtained funding for S2L. LS, MC, and RS coordinated project management. LS, MC, and RS performed data processing and analysis. DL, MT, TE, TT, TS, and WS were citizen scientist bird experts in bioacoustics work, and each volunteered more than 100 hours to the project. WS helped coordinate and train citizen scientists in bioacoustics work in years one and two. TS helped with field and citizen scientist coordination during year four in a temporary paid position. KC, a citizen scientist, worked on social media and bird call validations, and volunteered more than 100 hours to the project. LS, MC, and RS wrote the first draft of the paper. All co-authors commented on and approved the final manuscript.

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