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APPLICATION

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The Australian Acoustic Observatory

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Abstract

1. Fauna surveys are traditionally manual, and hence limited in scale, expensive and labour-intensive. Low-cost hardware and storage mean that acoustic recording now has the potential to efficiently build scale in terrestrial fauna surveys, both spatially and temporally.
2. With this aim, we have constructed the Australian Acoustic Observatory. It provides a direct and permanent record of terrestrial soundscapes through continuous recording across Australian ecoregions, including those periodically subject to fire and flood, when manual surveys are dangerous or impossible.
3. The observatory comprises 360 permanent listening stations deployed across Australia. Groups of four sensors are deployed at each of 90 sites, placed strategically across ecoregions, to provide representative datasets of soundscapes. Each station continuously records sound, resulting in year-round data collection. All data are made freely available under an open access licence.
4. The Australian Acoustic Observatory is the world's first terrestrial acoustic observatory of this size. It provides continental-scale environmental monitoring of unparalleled spatial extent, temporal resolution and archival stability. It enables new approaches to understanding ecosystems, long-term environmental change, data visualization and acoustic science that will only increase in scientific value over time, particularly as others replicate the design in other parts of the world.

KEYWORDS

acoustics, big data, ecological monitoring, sensors

1 | INTRODUCTION

Acoustic recording has the potential to scale terrestrial fauna surveys in the same way that remote sensing drove the scaling of vegetation monitoring. To date, acoustic recording has been used to study and monitor individual species at selected sites, primarily threatened or invasive species (Brodie et al., 2020; Hagens et al., 2018; Law et al., 2018; Taylor et al., 2017). These studies have been short term and designed with particular target species and specific research questions in mind. However, the proliferation of research using remote sensing data has shown the value of long-term generalized data collection that does not target specific species or ecosystems, nor is it driven by pre-determined research questions. Here we describe the design and deployment of the Australian Acoustic Observatory (A2O), which aims to provide an open access database of continuous acoustic recordings from a series of listening stations across the continent (Figure 1), and in so doing provide comparable data at a much broader spatial scale, and much more intensive temporal scale, than could be collected manually.

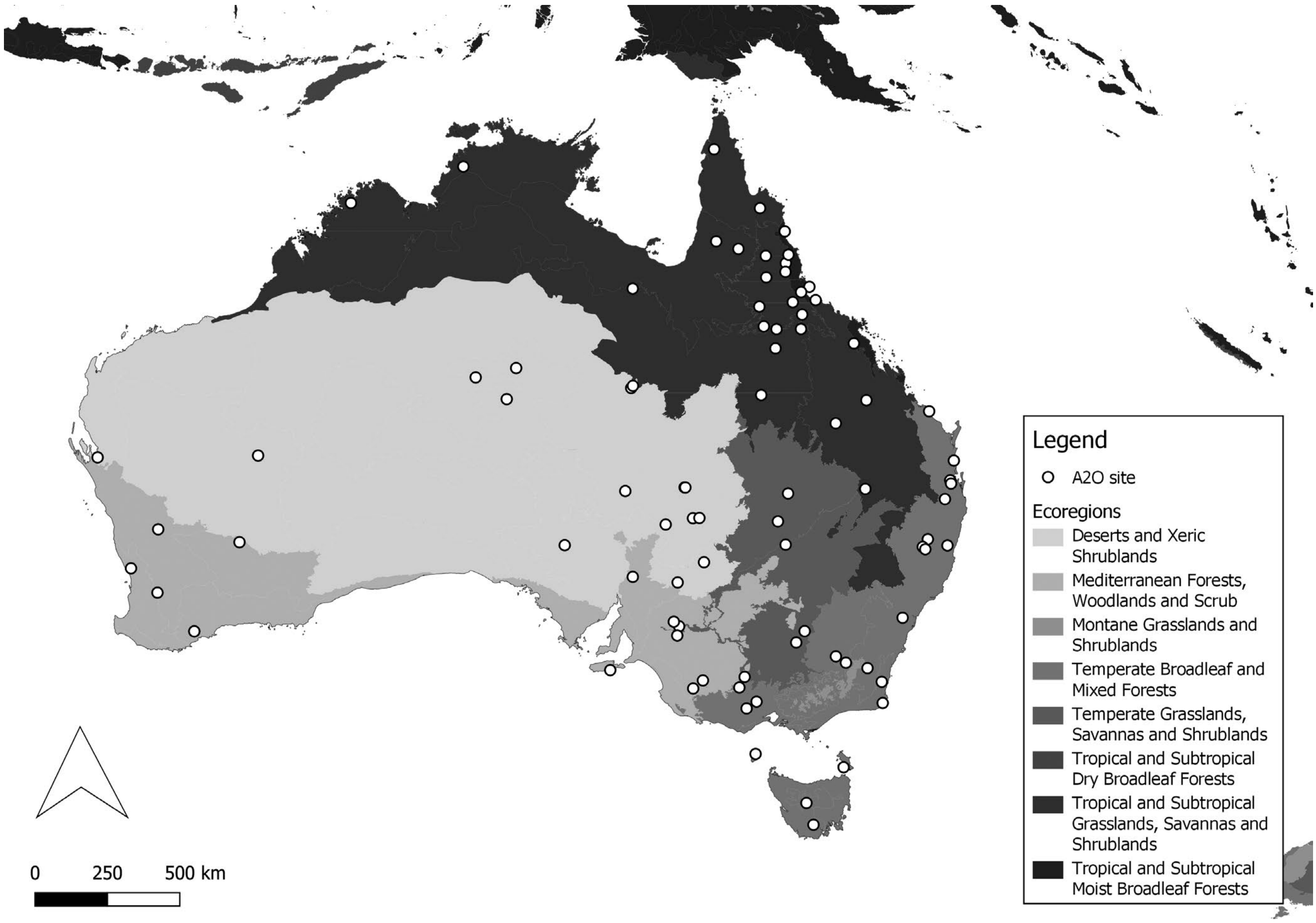

FIGURE 1 Map of Australian Acoustic Observatory sites and ecoregions

Australia is a megadiverse and sparsely populated continent with an unenviable extinction rate (Fusco et al., 2016; Woinarski et al., 2015). The observatory samples a range of habitats that include some of Australia's most remote areas, where little is known about species distributions and survey effort is typically limited. Environmental factors, such as fires and floods, can make whole regions dangerous or impossible to access, whereas deployed sensors can continue to collect data if not directly impacted. The A2O database could be used to answer a broad range of questions about biodiversity dynamics and the processes influencing them. Unlike much traditional biodiversity monitoring (Lindenmayer & Likens, 2018), the A2O is unashamedly a data-first approach, and all data are archived and open access under a Creative Commons Licence. To preserve broad-scale applicability, the data collection strategy must itself be designed for reuse, rather than tailored to a specific research question. A further important use of the A2O is to support research in ecoacoustics (Farina & Gage, 2017). There is a dearth of large, curated datasets of long duration from different environments. These datasets are needed for developing robust analytical tools and citizen science platforms.

In the following sections, we outline the key design features of the A2O, including hardware, sampling design and data management, followed by a discussion of the challenges encountered.

2 | HARDWARE

The A2O was made possible by the falling price of sound recording and storage technology. Nevertheless, the design still entailed trading-off cost, spatial coverage and recording quality of different hardware options.

The acoustic sensors are a proprietary design (Frontier Labs, 2020). Although open-source technology such as AudioMoth (Hill et al., 2017) was preferable, the need to deploy devices for up to a year between service cycles required hardware robust to extreme temperatures, humidity and moderate interactions with flora and fauna. Each 5 kg shoebox-sized sensor incorporates a solar panel, battery, charge controller and recorder in a sealed unit with no external cables (Figures 2 and 3). The sensor can be inexpensively mounted on a single or double star picket (metal fence post) giving up to 2.1 m clearance to protect against wildlife and livestock and may be fitted with a microphone guard for further protection.

The sensors record in mono at 16-bit 22,050 Hz with FLAC lossless compression in 2-hr file blocks stored on PNY Elite-X SDXC 512 GB SD cards, permitting a maximum continuous recording time of 1 year, with two cards. The sensors have four SD card slots, permitting a later upgrade if required. The 22 KHz sample rate enables representation of signals up to 11 KHz, capturing most bird, mammal and insect sounds, although not the ultrasonic calls of bats, since this would rapidly increase storage requirements beyond a reasonable capacity. Each acoustic sensor incorporates a Primo EM172 omnidirectional, low noise and a highly sensitive microphone (80 dB S/N ratio, 14 dBA self-noise, −28 dB sensitivity). Microphones have a flat and wide frequency response of +2 dB ranging from 80 Hz to 20 kHz. The electronics provide a gain of 50 dB yielding an upper sound threshold of 75 dB SPL (20 uPA) before clipping. The recorder is based on a 16 bit 92 dBA signal-to-noise ratio sigma delta ADC that can sample up to 96 kHz and an ARM Cortex M4 CPU (maximum 100 Mhz clock).

The sensors capture as much metadata (provenance) as possible. Each recording contains GPS-provided time and location metadata, as well as recorder, microphone and SD card serial numbers, so that we know when, where and how data have been collected.

FIGURE 2 A deployed acoustic sensor, showing solar panel and microphone orientation

Sensors are solar powered for long-duration deployment: each one uses a 10 W 12 V solar panel and a 2.5 kg LANplus Australia ML-127 12 V 7 Ah AGM battery. At subtropical latitudes, the sensors can operate on as little as 1 hr of direct sunlight per day; a discharged battery can be recharged in 2 days of normal operation (10 hr of direct sunlight), and the sensors can run for 39 days on a fully charged battery with no sunlight. This permits continuous recording during important phenological changes associated with rain and high cloud cover, such as recording the emergence of elusive burrowing frogs that call only with desert rain. In some low-light environments, for example, rainforests, our preferred approach is to simply swap out the batteries every month for recharging, given that these sites are readily accessible in our design.

The A2O relies on the goodwill of third parties to deploy, maintain and service sensors (annual SD card and battery changes) during already scheduled field trips, ranger patrols or site visits. Simple logistics are vital for both sensor deployment and servicing. A plastic box containing SD cards, deployment and service instructions, a USB key for ancillary site data, and sensor identification tags, is initially sent with four acoustic sensors and microphones, to each site prior to deployment. New SD cards, microphones, ancillary datasheets and silica gel are sent to A2O sites at each annual service. Full SD cards are replaced with empty SD cards, and then posted to QUT in the plastic box for data upload.

While a networked system with real-time data feeds is appealing (Sethi et al., 2018), many deployments are in areas with no networking other than by satellite connectivity, which has high running costs and power consumption. Narrow-band networking technologies such as LoraWAN and onboard processing (edge computing) are suitable for a system targeting particular species (Roe et al., 2018), but for an observatory, there is no a priori list of targeted species. Note that even a networked system would still require annual maintenance and site surveys, so this approach balances ease of

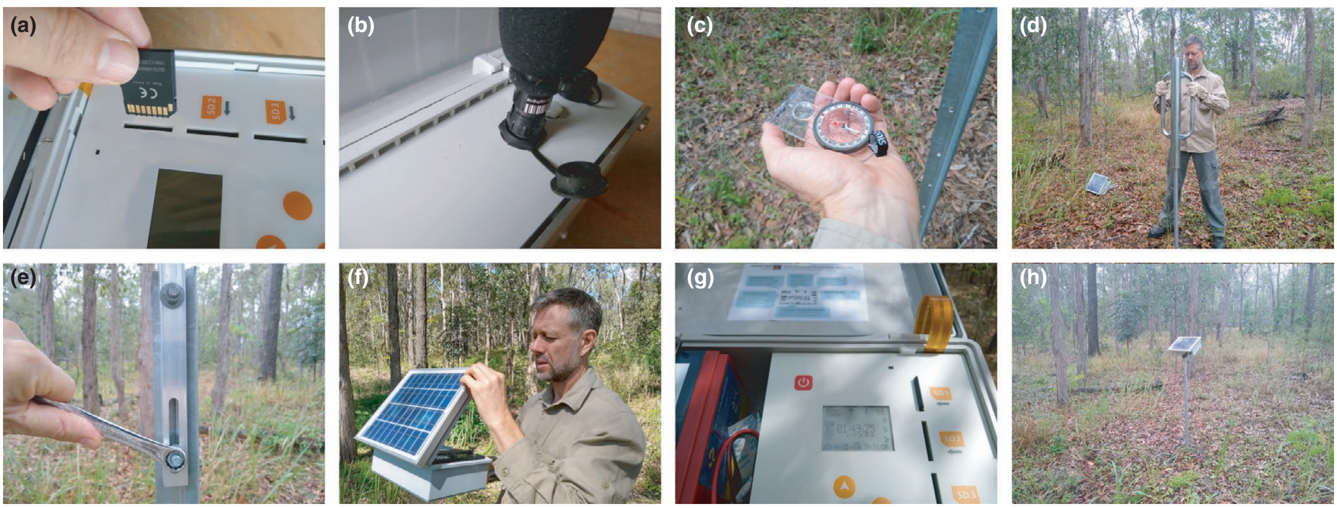

FIGURE 3 Acoustic sensor equipment and deployment: (a) Two 512 GB SD cards are inserted. (b) The microphone is attached. (c) The star picket is positioned to ensure sensor is north-facing. (d) The star picket is driven into the ground. (e) The sensor is attached to the star picket. (f) The acoustic sensor box is opened. (g) The sensor is turned on and checked to ensure that it is operating correctly. (h) The sensor is left to record for 12 months

data collection while ensuring the maximum number of sensors are deployed.

3 | Aims of the A2O

The A2O aims to generate a long-term, continuous acoustic dataset spanning Australia's ecoregions, enabling broad research questions that can be studied at scales from local to continental including:

1. **Biodiversity inventory:** Data may be used as a biodiversity survey tool at a given sensor location, including single and multiple species studies (e.g. koala distribution), phenological questions (e.g. when does a certain species call?) or to conduct assessments of biodiversity (e.g. using acoustic indices; Bradfer-Lawrence et al., 2019; Sueur et al., 2014). Recordings capture a wide variety of taxa and 'noisy' events (e.g. rain, wind, thunder).
2. **Biodiversity monitoring:** Longitudinal changes in data recorded from a given sensor over time may be used to detect seasonal changes, annual changes and associated environmental correlates. For example, the arrival and departure of migratory or nomadic species can be documented (Smith et al., 2020).
3. **Response to environmental events:** Questions include the impact of rainfall, flood or fire, and encompass both short- and long-term responses.

4 | SAMPLING DESIGN

Acoustic sensors are deployed in groups of four sensors comprising a **site**, spanning a range of ecoregions (Figure 4). The number of sites within an ecoregion reflects the relative cover of that ecoregion and its constituent habitats. For example, montane grasslands and shrublands occupy a small percentage of land area in Australia and are, therefore, represented by fewer sites when compared to a more extensive ecoregion (e.g. tropical savanna). The location of four sensors within each site provides replication and protection against sensor failure.

Sensors are deployed in pairs, one pair in a wet area and one in a dry area, and each site has two sensor pairs (four sensors). Sensors are positioned between 500 and 5,000 m apart, close enough to effectively monitor the same broad area, but far enough apart that they can be treated as independent samples. However, sensors from different pairs can be up to 20 km apart where necessary, due to spatial constraints of a site, to ensure both pairs of sensors monitor similar vegetation types.

The two wet sensors are deployed within 50 m of a waterbody (e.g. drainage channel, ephemeral creek, permanent river, dam, etc.) to capture water-reliant taxa such as amphibians and waterbirds. The two dry sensors are established at least 500 m from a waterbody. The combination of wet and dry sensors at each site enables their comparison. Although riparian habitat is generally more biodiverse than other areas, not all taxa and acoustic activity is centred on wetter areas. We considered that 500 m was sufficiently distant that an animal making sound that is detected by a dry sensor is likely occupying habitat that is not directly linked to the water itself (Figure 5).

At each sensor, a range of data are recorded to provide context for the sound, allowing users to model site variables in fine detail. These include the GPS coordinates, dominant vegetation structure and composition in tree, shrub and ground layers, landform, disturbance processes and photographs of the sensor point in each cardinal direction. Weather conditions for each site are recorded through a dedicated weather station, or via a Bureau of Meteorology station that is deemed sufficiently close to provide usable data. Other data, collected by other remote sensing systems, such as LiDAR, can, at least in theory, be combined with the sound data and aligned in time and space to look for correlates with patterns in the biotic sounds.

5 | DATA MANAGEMENT AND ANALYSIS

All A2O data are preserved and stored in a cloud-based system. Over its initial 5-year lifetime, the A2O will collect almost 2 millennia of sound (2 Petabytes of data). The system has a WordPress front end for blogs, site overviews and ad hoc unstructured data, and a custom data portal for all acoustic data and metadata, including photos. The portal is written in Ruby and Angular, and the code is opensource.

A pipeline of processes checks files, extracts metadata and uploads data by reading files from SD cards in parallel from four high-speed USB 3.0 SD card readers to a PC and then into the cloud (Figure 6). USB keys containing site data are uploaded separately. This is all done from a central location; first, because the ingest

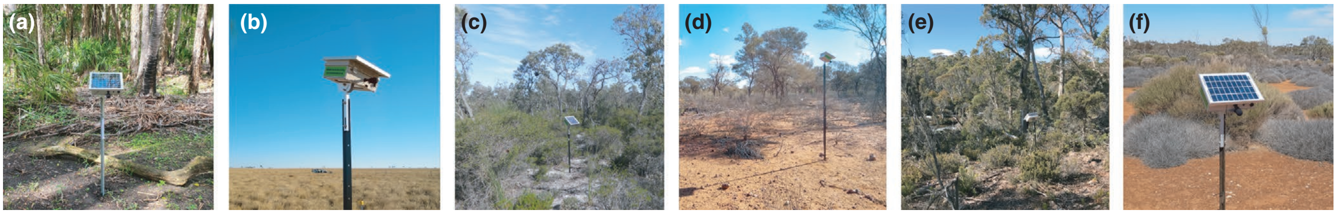

FIGURE 4 Examples of Australian Acoustic Observatory sites: (a) Reedy Creek (Temperate Broadleaf and Mixed Forests); (b) Mitchell Grass Rangelands (Tropical and Subtropical Grasslands, Savannas and Shrublands); (c) Gingin (Mediterranean Forests, Woodlands and Scrub); (d) Bowra (Temperate Grasslands, Savannas and Shrublands); (e) Five Rivers (Temperate Broadleaf and Mixed Forests); (f) Gluepot Reserve (Mediterranean Forests, Woodlands and Scrub)

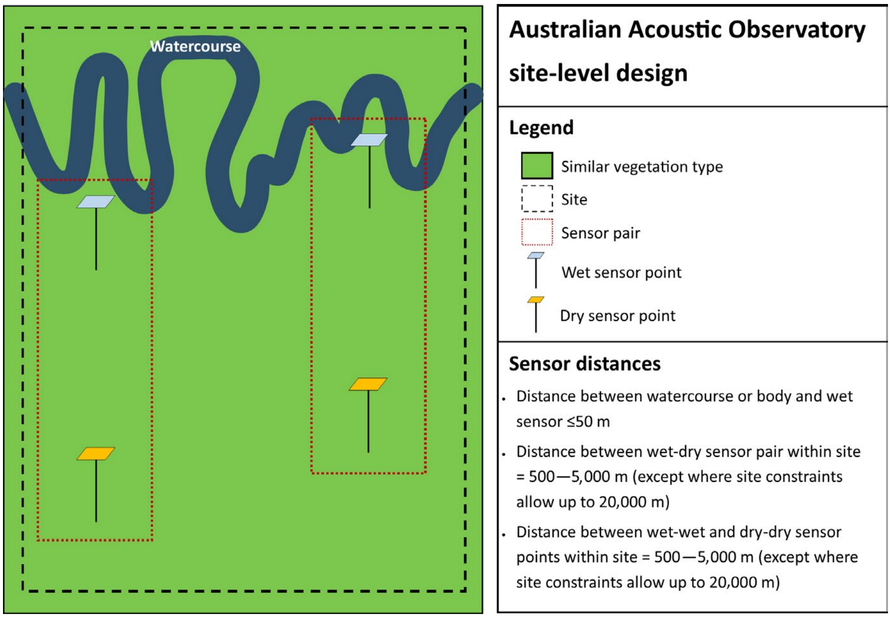

FIGURE 5 Site layout for Australian Acoustic Observatory sensors

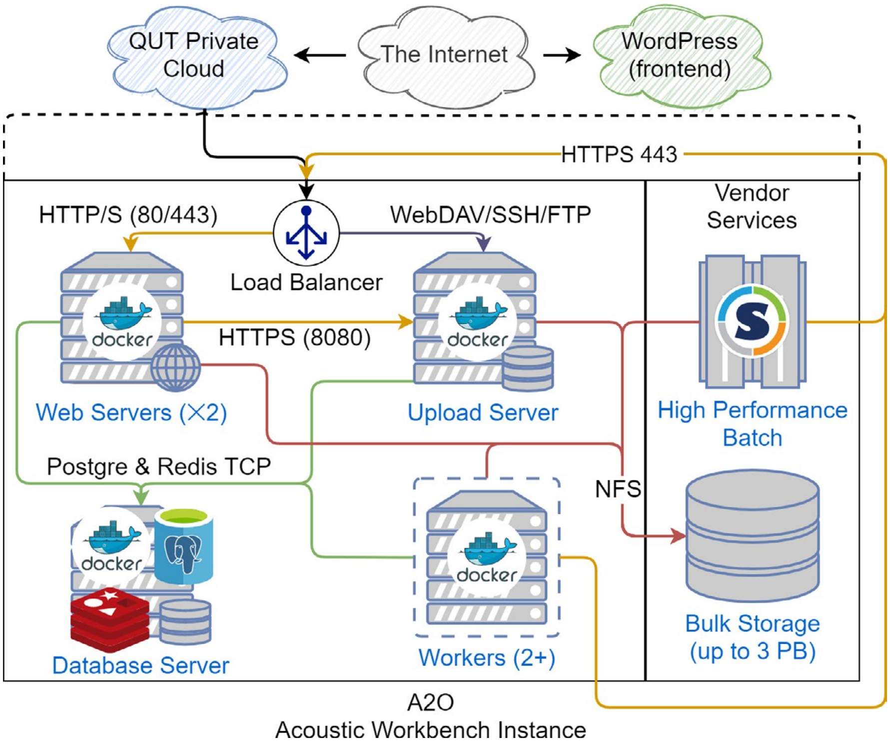

FIGURE 6 Australian Acoustic Observatory systems architecture

pipeline requires a reliable high bandwidth connection to the cloud system, and second, if data or hardware become corrupted or damaged, this is easiest to manage centrally.

Data are made freely available and can be visualized, browsed, shared, analysed and downloaded through a web frontend (Figure 6). Currently, data can be analysed in three main ways; however, the raw data archive enables reanalysis in the future as new techniques are developed.

Recognizers: call recognizers can be run across the data. As this is computationally intensive, recognition jobs are queued for execution on a high-performance computing system, in parallel if needed, and asynchronously so the user can continue to use the portal while they wait.

Indices and browsing: acoustic indices summarize audio at different time scales. A time series of three overlaid spectral indices visualized as a false colour spectrogram produces a map of audio that can be zoomed to different resolutions and panned through time. This interactive interface allows rapid navigation through days or years of sound, and in some cases visual recognition of long-duration patterns and specific events such as frogs chorusing (Figure 7).

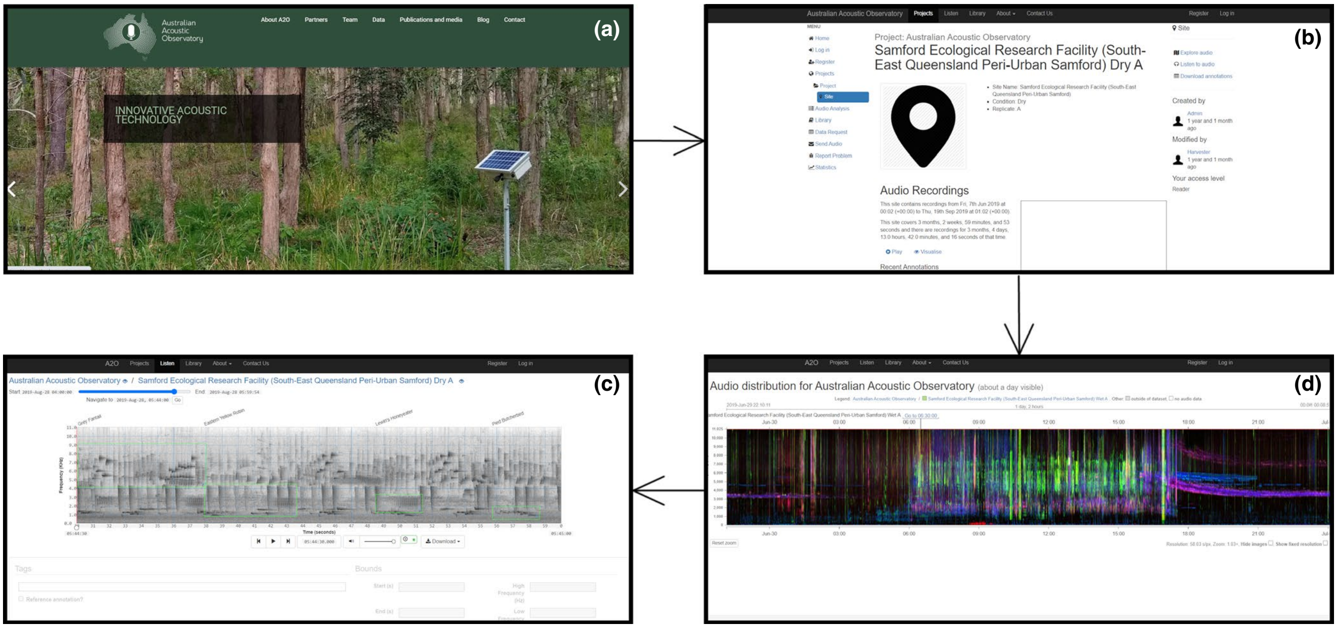

FIGURE 7 Screenshots of user interface. (a) General information is accessed through a front-end website. (b) Recordings and metadata are available for each sensor. (c) Zooming long-duration false-colour spectrograms are generated using the 'Visualize' function. (d) Grey-scale spectrograms representing 30 s of sound data may be accessed by selecting a given point on any zooming long-duration false-colour spectrogram, with the capacity to annotate sounds

Citizen science and listening: users can listen to and annotate sounds with a regular spectrogram interface. Annotations, either created by users or automated analyses, can be verified by other users. Annotations, and acoustic indices, can also be downloaded in CSV format (Figure 7).

6 | DISCUSSION

The A2O has been operational since June 2019. As of June 2020, over 300 of the 360 sensors have been deployed. Data are currently being collected and uploaded into the portal (https://acousticobservatory.org/), and to date there have been over 1,140 users of the observatory.

Sensor deployment was hampered by severe bushfires in 2019 and 2020, the COVID-19 pandemic, and logistical complexities of managing multiple permits required for deployment across Australia. The requirement for open access data simplified discussions with landholders, and most were supportive of this arrangement. The most significant technical challenge for the A2O project was ensuring that the sensors were operationally reliable for long-term deployments. Much of the testing was conducted at a local field site prior to and following initial deployment, including experimentation with solar panel response to variable amounts of sunlight and shade, field testing firmware, documenting service protocols and demonstrating sensor operation to users. A sensor deployment manual and instructional video were produced as part of this process. If the A2O model was to be replicated, it would be advisable to establish formal agreements with as many participant groups and landholders as early as possible.

The A2O entails trade-offs among various design parameters including numbers of sensors, storage, data quality and sensor coverage versus density. Data storage has been one of the biggest project costs. In June 2020, each sensor cost approximately $1,000 AUD, with 5 years of data storage per sensor, approximately 5 TB, costing a similar figure. Having sites serviced either every 6 or 12 months requires three 512 GB SD cards, totalling roughly $500, per sensor. At any one time, two-thirds of the cards are recording, and the others are in transit for data upload or in reserve.

Recording at a higher sample rate, for example, 44 KHz, would double the storage cost and reduce the total number of sensors by more than one-third. The sensors have four SD card slots, of which we use two; therefore, we could add SD cards and record at a higher rate when storage costs fall sufficiently. Lossless FLAC compression is also an important cost-saving, as using a lossy format (Sethi et al., 2018, Wildlife Acoustics) might cause problems with some analyses.

The A2O project grew out of several of our smaller, long-term acoustic sensing projects, particularly the deployment of four recorders in the Sturt Desert which have been operating since 2015. We hope that the A2O provides a useful resource for scientists studying the Australian environment that it promotes further research into ecoacoustics, and that others will take inspiration from the project and replicate the A2O design across other continents.

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AUTHORS' CONTRIBUTIONS

P.R., R.A.F., P.G.M., L.S., D.T. and D.M.W. wrote the paper and conceived the A2O concept. P.R., P.E., M.T. and A.T. designed and implemented the A2O system.

PEER REVIEW

The peer review history for this article is available at https://publons.com/publon/10.1111/2041-210X.13660.

DATA AVAILABILITY STATEMENT

All data are freely available from www.acousticobservatory.org; all code is freely available from Zenodo at https://zenodo.org/record/4274299 (Towsey et al., 2020), https://zenodo.org/record/4748041 (Truskinger et al., 2021) and https://zenodo.org/record/4748030 (Alleman et al., 2021).

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REFERENCES

Alleman, C., Truskinger, A., Cottman-Fields, M., Eichinski, P., & Roe, P. (2021). QutEcoacoustics/workbench-client: Initial release (Version 4.0.2). *Zenodo*. https://doi.org/10.5281/zenodo.4748030

Bradfer-Lawrence, T., Gardner, N., Bunnefeld, L., Bunnefeld, N., Willis, S. G., & Dent, D. H. (2019). Guidelines for the use of acoustic indices in environmental research. *Methods in Ecology and Evolution*, *10*(10). https://doi.org/10.1111/2041-210x.13254

Brodie, S., Yasumiba, K., Towsey, M., Roe, P., & Schwarzkopf, L. (2020). Acoustic monitoring reveals year-round calling by invasive toads in tropical Australia. *Bioacoustics: the International Journal of Animal Sound and Its Recording*, *17*. https://doi.org/10.1080/09524622.2019.1705183

Farina, A., & Gage, S. H. (2017). *Ecoacoustics: The ecological role of sounds*. John Wiley & Sons.

Frontier Labs. (2020). *Solar BAR*. Retrieved from https://frontierlabs.com.au/catalog/product/view/id/2066/s/solar-bar/category/41/

Fusco, D. A., McDowell, M. C., & Prideaux, G. J. (2016). Late-Holocene mammal fauna from southern Australia reveals rapid species declines post-European settlement: Implications for conservation biology. *Holocene*, *26*(5), 699–708. https://doi.org/10.1177/0959683615618261

Hagens, S. V., Rendall, A. R., & Whisson, D. A. (2018). Passive acoustic surveys for predicting species' distributions: Optimising detection probability. *PLoS ONE*, *13*(7), e0199396. https://doi.org/10.1371/journal.pone.0199396

Hill, A. P., Prince, P., Piña-Covarrubias, E., Doncaster, C. P., Snaddon, J. L., & Rogers, A. (2017). AudioMoth: Evaluation of a smart open acoustic device for monitoring biodiversity and the environment. *Methods in Ecology and Evolution*, *9*(5). https://doi.org/10.1111/2041-210X.12955

Law, B. S., Brassil, T., Gonsalves, L., Roe, P., Truskinger, A., & McConville, A. (2018). Passive acoustics and sound recognition provide new insights on status and resilience of an iconic endangered marsupial (koala *Phascolarctos cinereus*) to timber harvesting. *PLoS ONE*, *13*(10), e0205075. https://doi.org/10.1371/journal.pone.0205075

Lindenmayer, D., & Likens, G. E. (2018). *Effective ecological monitoring*. CSIRO Publishing.

Roe, P., Ferroudj, M., Towsey, M., & Schwarzkopf, L. (2018). Catching toad calls in the cloud: Commodity edge computing for flexible analysis of big sound data. *Proceedings of the IEEE 14th International Conference on eScience* (pp. 67–74). From: 2018 IEEE 14th International Conference on e-Science (e-Science), 29 October-1 November 2018, Amsterdam, The Netherlands. https://doi.org/10.1109/eScience.2018.00022

Sethi, S., Ewers, R., Jones, N., Orme, C. D. L., & Picinali, L. (2018). Robust, real-time, and autonomous monitoring of ecosystems with an open, low-cost, networked device. *Methods in Ecology and Evolution*, *9*(12), 2383–2387. https://doi.org/10.1111/2041-210X.13089

Smith, D. G., Truskinger, A., Roe, P., & Watson, D. M. (2020). Do acoustically detectable species reflect overall diversity? A case study from Australia's arid zone. *Remote Sensing in Ecology and Conservation*, *6*(3). https://doi.org/10.1002/rse2.173

Sueur, J., Farina, A., Gasc, A., Pieretti, N., & Pavoine, S. (2014). Acoustic indices for biodiversity assessment and landscape investigation. *Acta Acustica United with Acustica*, *100*(4), 772–781. https://doi.org/10.3813/AAA.918757

Taylor, A., McCallum, H. I., Watson, G., & Grigg, G. C. (2017). Impact of cane toads on a community of Australian native frogs, determined by 10 years of automated identification and logging of calling behaviour. *Journal of Applied Ecology*, *54*(6), 2000–2010. https://doi.org/10.1111/1365-2664.12859

Towsey, M., Truskinger, A., Cottman-Fields, M., & Roe, P. (2020). QutEcoacoustics/audio-analysis: Ecoacoustics Audio Analysis Software v20.11.2.0 (version v20.11.2.0). *Zenodo*. https://doi.org/10.5281/zenodo.4274299

Truskinger, A., Cottman-Fields, M., Eichinski, P., Alleman, C., & Roe, P. (2021). QutEcoacoustics/baw-server: Zenodo chore release (version 3.0.4). *Zenodo*. https://doi.org/10.5281/zenodo.4748041

Woinarski, J. C. Z., Burbidge, A. A., & Harrison, P. L. (2015). Ongoing unraveling of a continental fauna: Decline and extinction of Australian mammals since European settlement. *Proceedings of the National Academy of Sciences of the United States of America*, *112*(15), 4531–4540. https://doi.org/10.1073/pnas.1417301112

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