Received: 27 February 2020 | Accepted: 2 June 2020
DOI: 10.1111/2041-210X.13438

APPLICATION

Methods in Ecology and Evolution | BRITISH ECOLOGICAL SOCIETY

SAFE Acoustics: An open-source, real-time eco-acoustic monitoring network in the tropical rainforests of Borneo

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Funding information
Sime Darby Plantation Bhd; Engineering and Physical Sciences Research Council, Grant/Award Number: EP/R511547/1; Natural Environment Research Council, Grant/Award Number: NE/K007270/1 and SSCP DTP; World Wildlife Fund

Handling Editor: Veronica Zamora-Gutierrez

Abstract

1. Automated monitoring approaches offer an avenue to unlocking large-scale insight into how ecosystems respond to human pressures. However, since data collection and data analyses are often treated independently, there are currently no open-source examples of end-to-end, real-time ecological monitoring networks.
2. Here, we present the complete implementation of an autonomous acoustic monitoring network deployed in the tropical rainforests of Borneo. Real-time audio is uploaded remotely from the field, indexed by a central database, and delivered via an API to a public-facing website.
3. We provide the open-source code and design of our monitoring devices, the central web2py database, and the ReactJS website. Furthermore, we demonstrate an extension of this infrastructure to deliver real-time analyses of the eco-acoustic data.
4. By detailing a fully functional, open source, and extensively tested design, our work will accelerate the rate at which fully autonomous monitoring networks mature from technological curiosities, and towards genuinely impactful tools in ecology.

KEYWORDS
applied ecology, bioinformatics, community ecology, conservation, monitoring (community ecology), monitoring (population ecology), software, surveys

1 | INTRODUCTION

Natural ecosystems around the world are undergoing rapid changes due to increasing human pressures (Lambin & Meyfroidt, 2011; Walther et al., 2002). Monitoring these changes in real time is essential for deploying interventions where and when they are most urgently needed, and for furthering our understanding of complex ecological responses to habitat quality degradation (Edwards, Beaugrand, Hays, Koslow, & Richardson, 2010).

While traditional survey methods tend to be slow and laborious (Fitzpatrick, Preisser, Ellison, & Elkinton, 2009), automated recording and analysis of the sounds of an environment—its soundscape—has shown great promise as a tractable route to scalable ecological monitoring (Pijanowski et al., 2011; Sethi, Ewers, Jones, Orme, & Picinali, 2018; Sethi, Jones, et al., 2019). Here, we detail the design and implementation of SAFE Acoustics, a fully automated, real-time, eco-acoustic monitoring network. The network is deployed across a tropical rainforest fragmentation experiment in Sabah, Malaysia (Ewers et al., 2011), and will be used to probe the effects of logging intensity and agricultural land conversion on biodiversity and ecosystem stability.

The SAFE Acoustics monitoring network can be broadly split into three key components: (a) an array of real-time acoustic monitoring

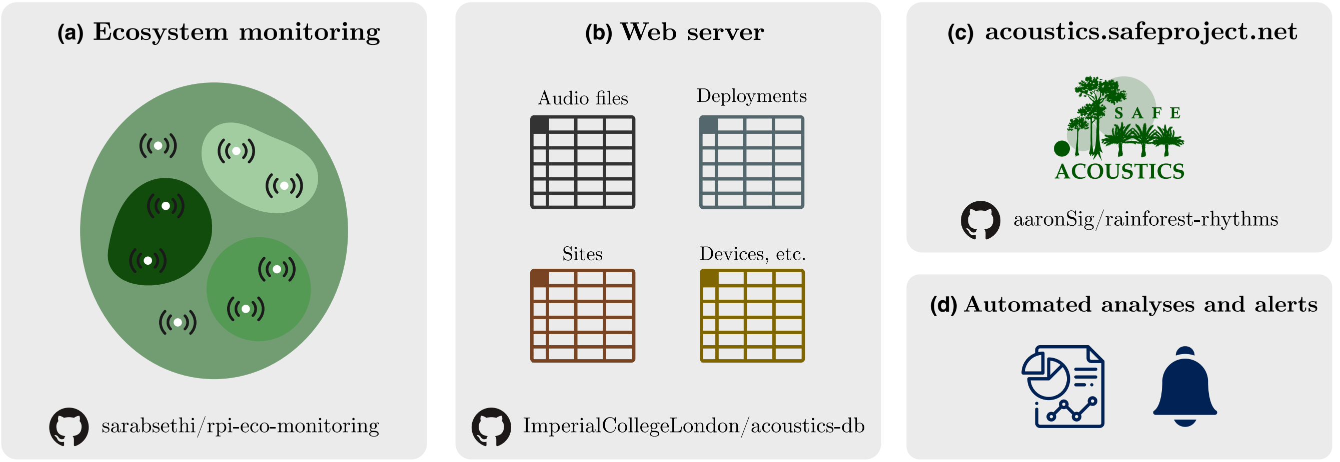

FIGURE 1 A pipeline for a continuous, real-time acoustic monitoring network. (a) Real-time acoustic monitoring devices record audio from the field and upload files to a remote FTP server. (b) A web server continuously scans and indexes the incoming audio and provides a standardized interface to access it. This interface is used by (c) a website, which allows the public to browse and listen to the latest audio data, and (d) real-time analyses, which automatically extract ecological information from the soundscapes. Open-source code and documentation is available for each component of the system at: (a) github.com/sarabsethi/rpi-eco-monitoring, (b) github.com/ImperialCollegeLondon/acoustics-db and (c) github.com/aaronSig/rainforest-rhythms

devices deployed in the field (Figure 1a); (b) a web server that indexes the incoming audio and provides a standardized machine-readable interface to the data (Figure 1b); and (c) a website which allows the public to browse and listen to the latest audio from the network (Figure 1c). Additionally, we demonstrate how this infrastructure can be extended to deliver real-time estimates of habitat quality using a fully automated analysis pipeline (Figure 1d).

Every ecological monitoring effort has its own unique challenges and goals, and developing a one-size-fits-all solution is not possible (Sugai, Desjonquères, Silva, & Llusia, 2020). Therefore, we have open sourced all the technology developed during our study, including the hardware design and firmware, and complete source code for the web server and public-facing website. Our system provides a fully functional template for a robust and reliable autonomous ecological monitoring network, which others can adjust and build upon to fit the particular needs of their own projects.

2 | REAL-TIME MONITORING DEVICES AND SERVER INFRASTRUCTURE

The SAFE Project is a forest fragmentation experiment in Malaysian Borneo, with study sites across old growth, selectively logged and salvage logged forest, and within nearby palm oil plantations. We deployed 11 Raspberry Pi based autonomous acoustic monitoring devices (Sethi et al., 2018) across this gradient of land-use intensity in February 2018. Each solar-powered device continuously transmits compressed audio files to a remote FTP server using a 3G mobile internet connection. Data is uploaded within a folder structure specifying the unique device ID, date and time of each recording. FTP servers can be of arbitrarily large size, and handle hundreds of concurrent connections, making them suitable for our purposes (although commercial hosting services may enforce stricter limits). The monitoring devices used are fully open source, and further information can be found at https://github.com/sarabsethi/rpi-eco-monitoring for the firmware, and http://rpi-eco-monitoring.com for step-by-step assembly instructions.

To enable efficient searching and retrieval of the acoustic data, a web2py-based (Di Pierro, 2011) web app performs a daily scan of the FTP server, and automatically indexes new audio files in an SQL database. An 'Audio' table contains an entry for each recording, along with its date, time, and the unique device ID it was uploaded from. A 'Deployments' table links device IDs to geographical monitoring sites, and a 'Sites' table contains metadata such as habitat quality for each location. The web app is also able to index audio from semi-autonomous recording devices (e.g. AudioMoths; Hill et al., 2018) using the same database structure. We integrated independent avifaunal and herpetofaunal point-count datasets within our database to provide a list of expected species at each site (Sethi, Ewers, et al., 2019). A full inventory of animals present in this dataset is stored in a 'Taxa' table, and associated metadata and media is linked from the Global Biodiversity Information Facility (GBIF).

The web app additionally provides an application programming interface (acoustics-db API) to provide access to the audio data in a machine-readable format. This allows external applications to retrieve data from the monitoring network in a standardized manner, without needing direct access to the raw data or any prior knowledge of back-end implementation details. The API forms the backbone of both the public-facing website, and the real-time analysis pipeline presented in the following sections. The SAFE Project currently has this server deployed at https://acoustics-db.safeproject.net. Full source code for the web app, and detailed documentation (including a step-by-step deployment guide) is available at https://github.com/ImperialCollegeLondon/acoustics-db.

FIGURE 2 A public-facing website provides a user-friendly interface to engage with audio from our acoustic monitoring network. We developed a ReactJS web app (http://acoustics.safeproject.net) which allows the public to browse a map of our monitoring network (left), listen to audio across the day from each of the recorders (bottom) and explore the species communities present at each location (right)

3 | PUBLIC-FACING SAFE ACOUSTICS WEBSITE

To expose the audio collected from our acoustic monitoring network in a user-friendly interface, we developed a public-facing website (http://acoustics.safeproject.net/, Figure 2). The website is implemented using the ReactJS framework and is rendered entirely on the client side to reduce server-side load and associated costs. Audio file links and their associated metadata are acquired from the acoustic monitoring network through the acoustics-db API. Users of the website are able to browse a map of the recorder locations, listen to audio across the different hours of the day, and explore the species communities at each site. Exploring qualitatively how the soundscape changes across different levels of landscape degradation, and throughout the stages of the diurnal cycle serves as an impactful scientific communication tool. Full implementation details of the website can be found together with the open-source code at https://github.com/aaronSig/rainforest-rhythms.

4 | SCOPE FOR REAL-TIME AUTOMATED ANALYSES AND ALERTS

While the website encourages visitors to explore soundscape variation across the landscape qualitatively, our server infrastructure can be built upon to provide quantitative insights into ecological health (Sethi, Jones, et al., 2019). We plan on developing continuous analysis methods which monitor habitat quality, autonomously detect environmental 'anomalies', and record the presence of certain species in real time (Sethi, Jones, et al., 2019; Shiarella, 2018).

An example extension we developed to perform real-time analysis of the incoming audio is as follows. A virtual machine (VM) hosted on Amazon Web Services contacts the acoustics-db API once per day to access the latest audio uploaded from the SAFE Acoustics network. The audio is then processed by an automated audio analysis algorithm on the VM (in this demonstration, a speech to text conversion is performed), and the results are published on Twitter (https://twitter.com/BotJungle). A similar approach—employing a more ecologically focussed analysis—could be taken to update a web-based dashboard, or send email alerts to communicate analysis results to land managers or scientists in real time.

5 | CONCLUSIONS

Over 16,500 hr of audio (49,468 files) have been uploaded from the SAFE Acoustics monitoring network, and the public-facing website has hosted over 14,000 unique visitors. Each stage of the pipeline, from autonomous monitoring hardware to the website user-interface, has been made fully open source, along with detailed documentation available online. We believe that our scalable, robust design will provide an exemplar of a successful ecological monitoring network for other scientists to build upon. Our work will contribute towards the accelerating rate at which wide scale, fully autonomous monitoring is moving from a long-held aspiration to a genuinely impactful tool in ecology.

ACKNOWLEDGEMENTS

We thank the research assistants and staff at the SAFE project camp, in particular Ryan Gray, Jani Sleutel, Adi Shabrani, Nursyamin Zulkifli, Unding Jami and the canopy access team. We thank Henry Bernard for his collaboration. We acknowledge the support of the Imperial College Advanced Hackspace. This project was supported by funding from WWF UK (Biome Health Project), the Sime Darby Foundation, the Engineering and Physical Sciences Research Council [EP/R511547/1] and the Natural Environment Research Council [NE/K007270/1]. S.S.S. is also supported by Natural Environment Research Council through the Science and Solutions for a Changing Planet DTP.

AUTHORS' CONTRIBUTIONS

S.S.S., R.M.E., N.S.J., A.S., L.P. and C.D.L.O. contributed to the conceptualization and final implementation of the study; C.D.L.O., A.S. and S.S.S. developed the open-source software for the monitoring hardware, acoustics-db server and SAFE Acoustics website; S.S.S. and R.M.E. led the field deployments of the monitoring devices; S.S.S. led the manuscript writing process with revisions provided by all authors.

PEER REVIEW

The peer review history for this article is available at https://publons.com/publon/10.1111/2041-210X.13438.

DATA AVAILABILITY STATEMENT

Source code, documentation and deployment instructions are available for each component of our system at http://doi.org/10.5281/zenodo.3885148 (Sethi & Orme, 2020; real-time monitoring devices), http://doi.org/10.5281/zenodo.3885205 (Orme & Sethi, 2020; acoustics-db server) and https://doi.org/10.5281/zenodo.3897488 (Signorelli, Sethi, & Orme, 2020; public-facing website).

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How to cite this article: Sethi SS, Ewers RM, Jones NS, Signorelli A, Picinali L, Orme CDL. SAFE Acoustics: An open-source, real-time eco-acoustic monitoring network in the tropical rainforests of Borneo. *Methods Ecol Evol*. 2020;11:1182–1185. https://doi.org/10.1111/2041-210X.13438