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Designing Cyberinfrastructure for Knowledge Sharing: A Bioacoustics Case Study

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Abstract

FishSounds is an online portal that provides open and user-friendly access to academic scholarship regarding the sounds made by fish species. It is the result of an international collaboration between students, scientists, and information professionals, and has become a resource used around the globe for research, education, journalism, and general interest. This website is just the first instance of a new approach to sharing knowledge and an emerging cyberinfrastructure for open scholarship. The codebase behind FishSounds was designed to be reusable with other datasets, and in the coming years, additional portals will connect users to knowledge from varied subject areas across academic disciplines. This discussion examines the development and reception of FishSounds as a case study for the creation of these websites, called searchable online catalogues of knowledge or SOCKs. As it is publicly released, the SOCK platform will continue to evolve and develop new strategies based on the lessons learned from different audiences accessing FishSounds.

Keywords: open scholarship, citizen science, platform development, reusability principle, data-first approach

Introduction

Over the past 5 years, an international team of students, scientists, and information professionals have collaborated to transform the subdiscipline of fish bioacoustics from one considered understudied and poorly catalogued to a leader in ecological science that other efforts may look to as a model (Looby, Vela, et al., 2023; Parsons et al., 2022; Rountree et al., 2006, 2019). At the core of this change were systematized reviews of scholarship in the field (Looby et al., 2022; Looby, Bravo, et al., 2023; Looby, Cox, et al., 2023) and the development of a new website, FishSounds, that presents the collected data in an easy-to-find and intellectually accessible way (Looby, Vela, et al., 2023). The methodology and technology behind FishSounds were designed to be reusable for other subject areas, and an upcoming project will further develop the codebase into a robust cyberinfrastructure that will be used to create additional websites from a variety of academic disciplines, such as medicine, law, and fine arts. These websites, known as searchable online catalogues of knowledge (SOCKs), have the potential to revolutionize open scholarship by making the key information freely available and by expanding the scope of who can contribute to academic inquiry. This discussion summarizes the project to-date and reflects on the lessons learned from the reception of FishSounds as we prepare for the wider release of the SOCK platform.

Literature

Fish bioacoustics—the study of the sounds produced by or affecting fishes—is a field with ancient origins that became a formalized science in the late 19th century (Looby, Cox, et al., 2023). To date, over 1,061 fish species have been documented to produce sound (Looby et al., 2022), but the mechanisms and reasons for sound production in fish are diverse. For example, the plainfin midshipman (*Porichthys notatus*) produces three distinct vocalizations: a hum, a growl, and a grunt, through specialized muscles around their swim bladder (McIver et al., 2014), while Pacific salmon (*Oncorhynchus* spp.) produce a variety of air movement sounds by releasing moving air into and out of their swim bladder (Kuznetsov, 2009; Murchy et al., 2023; Neproshin, 1972; Neproshin & Kulikova, 1975). For the midshipman, we know the reason these calls are produced, namely mating and antagonist calls (Mohr et al., 2017), but for salmon, the exact reason is unknown (Neproshin & Kulikova, 1975). Other species that produce similar air movement sounds have been documented to use these types of sounds for communication (Kaartvedt et al., 2021; Wilson et al., 2003), so that is also possible for salmon.

Fish sounds serve many ecological and monitoring functions that have made them of increasing research interest in recent decades (Looby et al., 2022; Looby, Cox, et al., 2023), with passive acoustic monitoring (PAM) now a common tool used to monitor and protect aquatic ecosystems. One example comes from invasive species management: the freshwater drum (*Aplodinotus grunniens*), which are invasive in the northeast portion of the United States, produce knock sounds that have been used to confirm establishment of spawning populations (Rountree & Juanes, 2017). Using PAM to monitor for invasive species that produce sound represents a low-cost tool to protect native ecosystems from invasion, but many invasives have not been examined for the possibility of sound production. Despite an extensive history and ever-growing interest, the study of fish sound production has faced limitations due to the sheer diversity of fish species (~35,000) and their wide range of acoustic behaviours (Looby, Cox, et al., 2023; Parsons et al., 2022).

In addition to the limited research on fish sound production, the impact of elevated underwater noise on fish is similarly lagging to other acoustic species (e.g., marine mammals; Castellote et al., 2012; Dahlheim & Castellote, 2016; Holt et al., 2009). Some fish species have been shown to alter the amplitude and frequency of their vocalizations (Holt & Johnston, 2014; Luczkovich et al., 2016), but gathering information on sound production in the absence of noise is required first to understand the potential changes. Currently only around 4% of fish species have been examined for sound production; even fewer are soniferous (Looby et al., 2022). Understanding the extent and breadth of sound production is needed to understand the continued changes to the underwater environment and conservation challenges faced by fish species, highlighting the need for a cohesive catalogue of fish sound production and the continued examination of fish bioacoustics.

To accomplish this task of developing a catalogue of fish sounds, the cyberinfrastructure needed to consolidate this information and support the field would have to incorporate multiple forms and levels of data (e.g., fish taxonomy, recording metadata) and media (e.g., audio files, text files, image files); organize information described and compiled largely without standardized terminology or methodology; and be scalable to the diversity of fishes and sounds as well as the potentially terabytes of data that could be generated by a single study (Barroso et al., 2023; Looby, Cox, et al., 2023; Looby, Vela, et al., 2023; Parsons et al., 2022). These cumulative challenges have led the field of fish bioacoustics to lag behind comparable subdisciplines that focus on other taxa, such as marine mammals and birds (Mercado & Perazio, 2022; Parsons et al., 2022), when it comes to assembling recording libraries or standardizing sound naming conventions (Looby, Cox, et al., 2023). An example of the difference in volume of research can be seen in comparison of bird and fish species included in Cornell University's online Macaulay Library (https://www.macaulaylibrary.org/). Overcoming this disparity in advancement presents an opportunity to develop a model that is robust to the various challenges associated with data consolidation and is applicable beyond the study of fish ecology.

Development

To address these challenges and facilitate future research, marine biologist Audrey Looby undertook a systematized review of academic literature related to sound production by fishes as part of her graduate research in 2018 (Looby et al., 2022). In partnership with the research group MERIDIAN, the resulting dataset was then used as the basis for the website FishSounds (https://fishsounds.net), which launched in October 2021 (Looby, Vela, et al., 2023). The initial website allowed users to search through a comprehensive corpus of scholarship via three search forms that accessed the collection from one of three points of view: fish-centric, research-centric, or recording-centric (Looby, Vela, et al., 2023). A version 1.1 release expanded the materials included and provided additional resources (Cox et al., 2023), while updates under version 2 added data visualizations and numerous features and revisions in response to user feedback. FishSounds is now the largest public repository of fish sound production information and recordings, with information on more than 1,200 species and with more than 1,200 representative recordings.

This website is only the beginning, however, as the codebase behind FishSounds was developed with re-use in mind and is intended to be the foundation of a new cyberinfrastructure for open scholarship across disciplines. FishSounds itself already re-uses the code in its three views (fish, research summary, and recording), with different data schemas and search form settings in each. The pilot version of the codebase is available now under the MIT license (https://tlo.mit.edu/understand-ip/exploring-mit-open-source-license-comprehensive-guide) and updates, including a graphical interface for implementing a SOCK, will be made as stable releases are developed.

Design

There were two key design concepts used in the development of FishSounds and the SOCKs codebase: a data-first approach (Bermes, Fauduet, & Peyrard, 2010; Fauduet & Peyrard, 2010; Oppermann & Munzner, 2020) and the reusability principle (Anguswamy & Frakes, 2012; Pirta & Grabis, 2017; Yin & Tanik, 1991). In technical terms, a data-first approach means that the system was designed based on a real-world dataset that reflected the quantity, diversity, (in)completeness, and (un)certainty of actual scientific analyses and results. The alternative would be to use a constructed dataset based on a subject-matter expert's conception of the data in their domain, but this approach would incorporate any biases or inaccuracies in their understanding and would risk the system's processes, functions, and visualizations not working as intended when real data was introduced into the system.

The reusability principle, meanwhile, means that wherever possible the system was designed using processes and functions that can be re-used to perform similar tasks with different pieces of data. This is accomplished by abstracting the data based on their types (string, number, date, etc.), relationships (one-to-one, one-to-many, many-to-many, etc.), and other considerations into sets of patterns, such as a single string or an array of numbers. A function can then be given any data that matches a known pattern, along with other variabilized options, and the system will process, analyze, and/or display the data, whatever it may be, in the same way. This allows components of the system to be re-used rather than needing to repeat the same code every time data is accessed. In FishSounds, for example, the same functions are used with three datasets—metadata on fish species, reference materials, and audio recordings—to produce three search pages with different search fields and result cards.

To explain these design concepts in a more accessible way, we offer the following metaphoric description, as originally presented by the authors at the Global Library of Underwater Biological Sounds (GLUBS) workshop at Woods Hole, Massachusetts, USA, in 2023.

Think of the system as a bedroom closet organizer, and the data as the various clothing and accessories that it needs to hold. If you determine that your current organizer is no longer suiting your needs, there are several ways you could approach replacing it. You could hire a contractor to design a custom organizer to precisely match your vision for the space, but this would have several implications: there would be a high upfront cost for the required labour; as pieces needed to be replaced or repaired, there could be additional expenses and delays; and the organizer would likely be inextricable from that closet, so if you were to move, it would be difficult to take with you. Alternatively, you could use a pre-made organizer solution consisting of flexible components (e.g., extendable rods) designed to fit together that only need to be architected once and are then mass-produced and sold to many customers. You would still be able to select and configure these components to make something that would suit your space and needs, and while the result may not be as aesthetic or cohesive as custom construction would be, it would likely be cheaper, easier to maintain, and could be reinstalled in a different location if required. This is the reusability principle.

To select the components you need to purchase, meanwhile, you might consider different factors and priorities. As the subject-matter expert of your own wardrobe preferences and sense of style, you could provide insight into what types of clothing you wear most often to ensure these are kept accessible, or into the purpose of articles of clothing that, for example, should not be folded or overcrowded to prevent wrinkling. You would likely struggle, however, to list every piece of clothing you own and would need to make an educated guess of the total volume of space that your pants, for example, would take up. To be more accurate, you could instead go through all your clothing to count and measure what you have, remove what is no longer needed, and assess how you are likely to expand your wardrobe over time, so that you could make an informed decision about what to buy. This is a data-first approach.

Together, these two concepts resulted in a system that was designed to handle a real-world dataset, but not to handle *exclusively* that dataset. By switching out the data and variable settings, the SOCKs codebase could be used to easily make additional websites in the style of FishSounds but for other subject areas. As new data types and patterns are encountered, functions can be amended or added to expand the capacity of the entire system. The codebase thereby constitutes a new cyberinfrastructure for open scholarship for which FishSounds is the first implementation. An upcoming project will create additional implementations to thoroughly test and improve the system, and the results will be released as an open-source platform for use by academia and the public more widely.

Program Evaluation

Reception of FishSounds has been positive, and it has a steadily growing userbase from various backgrounds (Google Analytics, 2023). Academic researchers who study fish and/or bioacoustics contribute to a baseline usership of approximately 350 visitors per week as of spring 2024. There are also frequent peaks in traffic when the site is referenced in media reports or shared on social media, resulting in a total of more than 15,000 users and almost 100,000 pageviews in 2023, with a true global spread (see Figure 1). The project FishSounds Educate, funded by Fisheries and Oceans Canada, used the website to bring the science of underwater sound into classrooms across Canada and the United States (Spriel et al., 2024). The upcoming FishSounds Fisheries expansion will address government and industry stakeholders' interest in using acoustics to passively monitor sound-producing fish populations, which is an emerging topic in ocean conservation that has been constrained by a lack of consolidated fish sound recordings. All in all, FishSounds has taken scholarship regarding fish bioacoustics from an inaccessible and underappreciated niche to a freely available and widely referenced topic.

The reception of FishSounds reinforces the importance of the development of products beyond peer-reviewed publications within academic endeavours. Many disciplines, including bioacoustics, have called for data-sharing platforms for decades (Binley et al., 2023; Parsons et al., 2022). Numerous barriers restrain the creation and maintenance of these searchable catalogues of knowledge. Most notably, institutional recognition of the value of these products has lagged in the hiring and tenure processes, and routes for funding long-term data management are scarce. Fortunately, this is changing as research data is increasingly recognized as its own valuable output through the rise of data papers, journals requiring data repositories, and funders mandating data management plans. This creates a research landscape where developing a data catalogue can be academically productive for those leading the effort and benefit the broader community (Costello et al., 2013; Edgar et al., 2014; Froese &

Pauly, 2010). It also, inadvertently, addresses a longstanding challenge in the sciences—publicizing insignificant results. The requirement for findings to be statistically significant causes researchers to be reluctant to publish non-significant results, creating publication biases (Echevarría et al., 2021; Nimpf & Keays, 2020; Salvador et al., 2022). A more equitable assessment of the value of data created by any robust scientific effort allows this information to inform future research and educate society. For example, the summaries of methodologies and key findings currently included in the Research Summary view on the FishSounds website are derived from publications. The platform could also integrate unpublished research, making that information available and citable with less delay, effort, and expense. There is an evident appetite for easy-to-search activity summaries, but a cultural shift on the part of researchers, institutions, and funding agencies would be required to normalize the contribution of such data.

Figure 1

Charts from Google Analytics (2023) for FishSounds Website

Note. This figure shows the annual total visitors and pageviews, a line chart of week-by-week visitor counts, and a world map indicating the country of origin of visits for 2023. It was generated on May 8, 2024, for this specific website, using tools provided by Google Analytics (https://analytics.google.com).

Findings and Limitations

As we prepare to launch the next phase of our research and move from a single pilot website to a suite of SOCKs, the lessons learned from the original effort will be key to continued success.

The initial audience for FishSounds was researchers studying fish bioacoustics, who quickly recognized the potential of the application. The version 1 launch was promoted primarily to the professional and social networks of bioacousticians involved in the project as we sought early feedback. The response from the research community was overwhelmingly positive, with scientists eager to contribute recordings from their own research and provide citations for materials missed in the initial data collection. It also caught the attention of an international working group of bioacousticians attempting to develop standards for acoustic data and envision cyberinfrastructure to facilitate their use (Parsons et al., 2022). In our conversations with members of the Global Library of Underwater Biological Sounds (GLUBS) working group, one risk for SOCKs that became clear was the potential for over-proliferation of the sites if separate instances are established for very similar topics. Having more information collected in one place makes it more accessible for users, but academic funding and advancement models tend to incentivize the creation of many smaller products, each controlled by a different principal investigator. We intend to address this risk by demonstrating the advantages of contributing to an existing SOCK rather than starting a new one, supporting attribution of data contributors to the sites, and adding functionality that will allow a single database to provide the backend for multiple SOCKs so that both larger general sites and smaller more specific ones can exist simultaneously.

To reach a broader audience, in January 2023, FishSounds Educate brought the website into classrooms of all sorts, including K–12 public schools, postsecondary institutions, virtual spaces, and nature clubs (Spriel et al., 2024). The commentary we received from student and teacher audiences was invaluable in revising the interface and functionality in the version 2 releases. Search forms were modified so users could search by fish species on all pages, and the common-name field, which is more familiar to a public audience, was highlighted over taxonomic names. The need for interactivity was also a key takeaway, as games and activities proved to be an effective pedagogical tool for helping students understand the science of sound. To date, three interactive visualizations have been added to the website: a map demonstrating geographical spread of data, a dendrogram or tree chart showing a taxonomic breakdown of data, and a list view presenting an alphabetized inventory of data. While the inclusion of such visualizations in future SOCKs will require custom coding, a growing library of supported plug-ins will make additions relatively simple.

A third source of traffic and feedback on the site has been the result of exposure to the public via journalistic media and social media (Looby, Vela, et al., 2023). While the project has been included in a few formal press releases, increasingly, journalists will cite the website as an authority in articles reporting on fishes in various capacities (e.g., Adkins, 2024). Users visiting after having seen these reports are visible in the Google Analytics referral tracking, as are links from artificial intelligence (AI) products such as ChatGPT (https://openai.com/) that have included FishSounds' data as part of their training material. Our experience with this audience has introduced two main challenges. First, while researchers are accustomed to, and indeed often prefer, the idea of "grey" truth in information—where what is true can be nuanced or contested and may change over time—the public has been conditioned to expect a simple binary answer to most questions, like what search engines can display in a result snippet or an AI tool can provide in a response. Second, though members of the public are enthusiastic about sharing knowledge and want to contribute as citizen scientists, academic scholars remain protective of their expertise and are reluctant to treat data collected by citizen scientists as equivalently reliable. We have attempted to address the former by frequently engaging with the media ourselves directly, while we are addressing the latter through a collaborative open call for freshwater sound recordings, which will first be validated through a peer-reviewed data publication before being added to the website. Additional solutions to these issues, however, may require further investigation.

Conclusion

Development of FishSounds as a pilot SOCK will continue over the coming years. An administrative portal is entering alpha testing and will enable more frequent data updates, starting with recent publications and a backlog of donated recordings. The collection will also be significantly expanded by adding the results of a new systematized review of underwater invertebrate sound production, as the test case for having multiple SOCK search interfaces connected to the same database. Several of the most effective activities developed for FishSounds Educate will also be reproduced digitally, to create an interactive lab for student visitors. Finally, the FishSounds Fisheries project will allow us to work with new audiences from industry and government perspectives and determine what data and functionality are required to support their information needs.

Meanwhile, the SOCK cyberinfrastructure project is currently seeking partners as we prepare a funding application to support the creation of additional websites. We hope to include use cases from varied disciplines to test how well the system can adapt to data from diverse domains such as science, social science, humanities, medicine, and law. Each SOCK instance will be overseen by a team consisting of a subject matter expert in the field, a librarian or information professional to help define the scope of the topic area, and a research assistant who will perform the required systematized review. Development staff on the project will then work with these teams to convert each dataset into a new SOCK. The feedback from this development will inform the public release of a cyberinfrastructure software package.

FishSounds has been a successful pilot project in the development of a new cyberinfrastructure for SOCKs. The reusability of the system will be thoroughly tested and improved in an upcoming expansion project, and the resulting codebase has the potential to advance open scholarship by making important information more available and incorporating more viewpoints into our understanding of the world. Many of the challenges we face in this regard are not technological but sociocultural, as academia continues to struggle with altering conventional notions of authority and trustworthiness. However, we believe that SOCKs are well-placed to demonstrate to researchers that there are more benefits than threats to involving the public in knowledge creation and sharing, and that establishing this value will be key to initiating meaningful change.

Authors' Contributions

Sarah Vela was the data manager and developer for FishSounds and the SOCK codebase and was the primary author of this paper.

Audrey Looby completed the original systematized review to collect data for the FishSounds website and was an editing author of this paper.

Brittnie Spriel was Project Coordinator of FishSounds Educate and was an editing author of this paper.

Hailey L. Davies was Lead Researcher and Coordinator of FishSounds Educate and was an editing author of this paper.

Kelsie A. Murchy was an Acoustic Data Supervisor of FishSounds and was an editing author of this paper.

Kieran Cox provided subject matter expertise in the design of FishSounds and was an editing author of this paper.

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Ethics Statement

Ethics review was not applicable.

Conflict of Interest

The authors do not declare any conflict of interest.

Data Availability Statement

All data associated with the website are openly available both on the FishSounds website itself at FishSounds.net (https://fishsounds.net) as well as in a Borealis permanent data repository at https://doi.org/10.5683/SP2/TACOUX (Looby et al., 2021).

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