

Using Passive Acoustic Monitoring for Understanding and Managing Freshwater Fisheries: A Guide for Non-Acousticians

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Abstract

Effective fisheries science is critical for sustainable management of freshwater and marine fisheries. Recent advances in technology have increased the effectiveness of addressing fisheries data gaps, and streamlined data collection. Passive acoustic monitoring (PAM; also referred to as bioacoustics) has emerged as a central technology in wildlife science and management in many taxa, yet is still not a common data stream in fisheries, despite the fact that many (if not most) fish produce sound in one form or another. Despite conceptual development of PAM for fisheries applications, managers often lack sufficient guidance or experience to effectively bring passive acoustics to their survey approaches. Building on these earlier conceptual foundations, here we provide more mechanistic and procedural guidance directed towards fisheries practitioners on evaluating suitability and implementation for using passive acoustics for fisheries science and management. PAM offers opportunities for numerous fish stocks in freshwater, marine, and estuarine systems and we demonstrate here how it can be applied to needs identified by fisheries practitioners. Most of the marine work using PAM for fisheries has been conducted with the

United States and European coastal waters, we summarize these case studies as well as highlight recent applications in freshwater systems as well. Our hope is that by providing guidance on if and how PAM can be used in fisheries applications will make this survey method more approachable for the broad audience of stakeholders involved in studying, managing, and sustaining fish populations.

Introduction

Scientists and managers have been increasingly using passive acoustic monitoring (PAM) to understand the behavior and ecology species of interest and their habitats (e.g., Browning et al. 2017, Sugai et al. 2018, Gibb et al. 2019, Sugai et al. 2020). While PAM has been embraced as a valuable survey method for terrestrial wildlife and cetaceans (Mellinger et al. 2007, Sugai et al. 2018), it is still in emerging applications for fisheries management (Rountree et al. 2006, Gannon 2008, Luczkovich et al. 2008, Hawkins et al. 2025). PAM has significant appeal as a survey method due to its non-invasive nature and ability to collect continuous data for long durations (Van Parijs et al. 2009), but becomes even more complicated with the rate of rapid change of both hardware, software, and AI technologies (Browning et al. 2017, Rasmussen et al. 2024) as well as the urgencies of changing fish populations and their habitats (Brander 2010, Cinner et al. 2020). Here, we highlight how PAM can be used as part of ongoing management and conservation efforts to help understand and sustain fisheries.

Several excellent reviews have provided an overview of the use of bioacoustics for fisheries research (Rountree et al. 2006, Gannon 2008, Luczkovich et al. 2008). Multiple studies have used PAM to describe the use of animal communication sounds associated with behaviors (Fine

and Thorson 2008, Banse et al. 2024, Oestreich et al. 2024), but what is not always clear is how non-academic fisheries managers can apply this approach to their work at a conservation agency level (Secor et al. 2000, Cowx and Portocarrero Aya 2011, Fenner 2012, Grüss et al. 2014, Cinner et al. 2020). This paper emphasizes the fisheries management uses of passive bioacoustic monitoring including the challenges and opportunities of PAM, as well as short case studies for various ecological questions and management scenarios. We hope that this paper can serve as an entry-level guide for ecological managers as well as traditional researchers who are looking to utilize PAM in their work.

Context and Need for Incorporating PAM into Fisheries

There is ongoing need for cost-effective and efficient means of collecting data to better understand fisheries trends and carry out assessments. Fish populations and their habitats are under increasingly intensive anthropogenic pressures, arising both from direct fishing pressure and the indirect effects of habitat change/loss, climate change, introduced species, etc.

Historically, data gaps have impeded effective data-driven fisheries management for many species due to the costs and logistical challenges of data collection and the limited insights which can be drawn from episodic sampling. In recent years, improvements in sampling technology and the increasing accessibility of such technologies (e.g. optical approaches, genetic approaches like eDNA, telemetry, side scan sonar) have created opportunities to complement traditional fisheries assessment methods (Flowers and Hightower 2013, Hussey et al. 2015, Pflieger et al. 2016, Beng and Corlett 2020, Kazyak et al. 2020). Many new and innovative techniques are developing in these fields at a fast pace, creating an equally rapid growth in opportunity to test and incorporate these techniques into management practices. One such method, which has gained traction and is

now commonly used for ecological studies and the management of a variety of aquatic and terrestrial species, is passive acoustic monitoring. It is equally a technique that has growing potential across diverse fisheries.

Passive acoustic surveys yield rich data sets that can be used to address diverse research needs—investigating species of management interest, quantifying anthropogenic impacts, characterizing environmental factors, and beyond. It is typical for researchers to collect a passive acoustic data set targeted at capturing a particular phenomenon of interest, and then subsequently re-analyze the data for various other purposes down the line. There are a few characteristics of acoustic data which will determine what kinds of research questions they are adequate to address (discussed in detail below), but with a little forethought it is possible to collect acoustic data which can be mined for abundant insights into the systems they arose from. With fisheries management applications in mind, we have structured this document as a guide to navigating some of the considerations that go into collecting and analyzing acoustic data, with case studies illustrating a few of the more common applications of passive acoustic monitoring and detailed discussions of the bioacoustics pipeline from data collection to high-level ecological inference.

Different Types of “Acoustics” Used in Aquatic Research

An important distinction to make at the outset of this guidance document is the difference between passive acoustics, active acoustics, and acoustic telemetry. All three of these methods are commonly referred to as simply “acoustic surveys”, an ambiguous and imprecise term that contributes to ongoing confusion for scientists or managers. Passive acoustic data collection entails deploying sensors to passively record ambient sound, including sounds arising from

living organisms (biophony), natural environmental processes (geophony), and human activity (anthropophony). Collected data capture acoustic pressure through time, and are most often archived on the device and available for analysis after recovery, though real-time or near-real-time data transmission systems also exist. Active acoustics, also commonly referred to as hydroacoustics or echosounder surveys, is the use of sonar to characterize organisms, structures, and sediments in the water column and on the bottom (Martignac et al. 2015, Munnely et al. 2023, White et al. 2023). This is carried out by means of a transducer which emits acoustic pulses or sweeps and then detects the return echoes of these signals after they bounce off surfaces (“backscatter”). Active acoustic surveys are typically carried out by a vessel transiting along survey lines in the study area; collected data capture backscatter versus depth along the trackline. Acoustic telemetry refers to the use of animal-borne transmitter tags to acoustically detect the presence of individual animals and infer their behavior (Hussey et al. 2015, Jacoby and Piper 2025, Welch et al. 2025). Tags may be internally implanted or externally mounted and transmit high frequency acoustic signals at manufacturer- or user-defined intervals. Telemetry receivers are deployed in the study area, often in an array with some spatial coverage, to detect these signals as tagged animals come within range. Each receiver collects time stamps of signal detection, which may include individual identity of the detected tag; some tag models have additional sensors to collect information on, e.g. animal depth, acceleration, water temperature, etc. These three methodologies are not mutually exclusive, and powerful insights can be gained by combining data streams from two or more approaches (Rowell et al. 2015, Lowerre-Barbieri et al. 2018, Kazyak et al. 2020). Passive acoustic monitoring is unique among these approaches for being non-invasive, unobtrusive, and largely autonomous, enabling continuous data collection over long time periods with minimal field effort and disruption to the study species.

Under the umbrella of passive acoustic monitoring, two distinct approaches have emerged: bioacoustics and ecoacoustics. Bioacoustics is the study of sound production, transmission, and reception by living organisms, including temporal and spatial patterns in sound production and ecological interactions (Fletcher 2007, Au and Hastings 2008, Erbe 2018, Odom et al. 2021). Ecoacoustics (also referred to as “soundscape ecology”) involves interpreting soundscape data to investigate ecological processes, often without species identification (Pijanowski et al. 2011, Linke et al. 2018, Stowell and Sueur 2020, Farina et al. 2024).

Sound production has been recognized in fish for many decades (Galton 1874, Abbott 1877, Fish and Mowbray 1970, Myrberg 1980), but only recently have there been efforts to better understand the prevalence and importance of acoustic signaling among fishes (Rountree et al. 2019, Looby et al. 2022, Rice et al. 2022). Recent reviews and phylogenetic work suggest that many fish species make sounds (Looby et al. 2022, Rice et al. 2022), which can convey information on behavior, demographics, important life history events, and ecological interactions (Looby et al. 2022, Looby et al. 2023a, Looby et al. 2023b). For important fisheries stocks, insights from these acoustic cues can address data gaps as well as complement other traditional fisheries monitoring approaches (Van Hoeck et al. 2021). There are a few notable examples of how bioacoustics has been applied to advance fisheries management practices or understanding, mostly in the marine realm, and only more recently for freshwater and estuarine species (Casaretto et al. 2014, Caiger et al. 2020, Fournet et al. 2022, Souza et al. 2023). The current challenges to the uptake of passive acoustic monitoring for fisheries management are the need for further acoustic characterization work (“Who makes sound? What do they sound like?”) (Rountree et al. 2019, Jarriel et al. 2024), and practical questions as to implementation of this new approach in the fisheries field (“How do we use these sounds to manage fisheries?”).

Several reviews have noted possible applications of PAM to fisheries needs , but while these papers provide a conceptual foundation, they do not explicitly provide guidance on *how* to do it; guides on how to implement PAM for other taxa (Browning et al. 2017, Sugai et al. 2018, Gibb et al. 2019, Sugai et al. 2020) may not be directly applicable to fisheries management needs due to the differing environmental contexts that drive changes in phenology, habitat and abundance. Importantly, there have also been significant advances in the field of bioacoustics since these reviews were published, reflecting the fast pace of development of both hardware and analytic algorithms which the bioacoustics practitioner can benefit from to improve the quality of data collected and streamline data management, analysis, and sharing. It is also worth noting that passive acoustic data makes for particularly captivating material with which to engage a broad audience of fisheries stakeholders with the excitement and utility of fish sound (Spriel et al. 2024).

In taxonomic groups where libraries of identifiable sounds have grown and matured, the application of PAM has expanded to use those sounds in applied ecology and population management (Browning et al. 2017, Gibb et al. 2019). These sounds may be associated with key behaviors of management interest (e.g., migration, spawning, courtship, predation), may provide demographic insights (e.g. sex, age), and are often useful for tracking and quantifying populations in time and space. In recent years, PAM has become widely adopted for studying and assessing cetaceans (Mellinger et al. 2007, Zimmer 2011), birds (Sebastián-González et al. 2015), anurans (Barnes and Quinn 2023), bats (Stahlschmidt and Brühl 2012, Froidevaux et al. 2014, van Merriënboer et al. 2024), and other wildlife (Gibb et al. 2019, Wijers et al. 2021).

PAM is continually and rapidly increasing in sophistication with ongoing advances in hardware, software, and analytical approaches. In recent years we have seen improvements in

recording technology that have increased portability, durability, and extended potential recording time through longer battery life and larger memory storage. These very improvements are simultaneously decreasing costs and increasing the accessibility of this methodology and expanding its adoption beyond the Global North. Over the last 5 years, advances in the field of machine learning (ML) have revolutionized the analysis of passive acoustic data, automating tasks which had hitherto relied upon tedious manual analysis, including signal detection and classification, dimensionality reduction, and anomaly detection (Tuia et al. 2022, Rasmussen et al. 2024, van Merriënboer et al. 2024). The increasing trend towards open-source software and the sharing of pre-trained models has spurred the uptake of ML methodologies, historically reserved for computer programmers, by biologists and ecologists, and significantly truncated the data analysis pipeline (Bohnenstiehl 2023b, a, Ibrahim et al. 2024).

Efforts to create sound libraries have increased the accessibility of reference examples and addressed some of the challenges of obtaining training data for data-hungry ML algorithms (Kettle 1989, Ranft 1997, Rountree et al. 2002, Kahl et al. 2021, Parsons et al. 2022, Looby et al. 2023b). Ongoing development of approaches for acoustic localization (Locascio and Mann 2011, Parsons et al. 2012, Yamato et al. 2018, Wilson et al. 2019), density/abundance estimation (Rowell et al. 2012, Marques et al. 2013, Rowell et al. 2017), and evaluation of anthropogenic impacts (Slabbekoorn et al. 2010, Putland et al. 2018, González Correa et al. 2019, Mackiewicz et al. 2021, Siddagangaiah et al. 2022) continue to improve their efficiency and accuracy. While limitations do remain, primarily in the breadth of known species-specific acoustic cues, and the availability of labeled training data (Ghani et al. 2023, van Merriënboer et al. 2024). These advances have promoted technology transfer from basic science to practical applications.

Increasingly, PAM is integrated as a complementary approach to traditional survey methods where the acoustic data can add informational value, often at lower costs.

“Is PAM right for me? How do I use it to answer my questions?”: Methodology and Decision Making

As PAM has not been widely adopted for freshwater and estuarine fisheries management, it may not be obvious how exactly this approach can be incorporated into ongoing monitoring and assessment efforts and used to complement other data streams. As with any methodology, there are several levels of consideration when exploring new applications of PAM. Here, we outline some thought processes one might use to evaluate the suitability of PAM for a particular fisheries-related research or management need, and determine how best to implement a PAM study, and provide graphical representations of the decision-making processes for ease of reference. Consulting with end-users and stakeholders in fisheries management, we consolidate the breadth of fisheries management needs into different relevant topic areas and provide guidance of how passive acoustic monitoring could be used to reach these fisheries goals in the form of topic-specific decision trees. Readers may notice some key considerations and decisions which arise across topic areas, reflecting stakeholder needs and uses for the collected data and analytic outputs which will have important implications. While the topic areas presented here are not comprehensive, we believe they illustrate important common considerations for applying PAM to diverse needs and can be adapted and extended to readers' particular needs.

The first step for any application is to evaluate the suitability of acoustic data for study of the species and/or processes of interest. When a species or ecological process is known to

produce sound, the use of acoustic data is a natural choice for low-effort continuous monitoring and quantification of that species/process. In such cases, subsequent topic-specific decisions concern ensuring that acoustic data collected are adequate to capture the signal(s) of interest with the appropriate temporal and spatial scales to address the desired research questions and identifying analyses that will yield actionable insights. When it is not known if a species/ecological process of interest produces sound, the first line of inquiry often concerns pairing acoustic recordings with other data types to identify and subsequently validate potentially informative acoustic cues. Another approach might involve identifying relevant co-occurring species that are acoustically detectable that can be a proxy for the presence of the species of management interest. In this way PAM and bioacoustics may still be relevant for fisheries management even when the focal species is not demonstrated to be acoustically active.

Technical Guidance and Survey Design

As discussed above, passive acoustic data are rich and complex, lending themselves to diverse lines of inquiry and successive rounds of utilization. Some careful forethought at the outset will ensure that data collected are suitable to address the various research questions of interest, while balancing data collection, management, and analysis effort against needs. Considerations when designing a passive acoustic survey or monitoring program range from the research questions and hypotheses which can effectively be addressed with passive acoustic data to the technical details of the data acquisition system and the data analysis pipeline. While engineering and digital signal processing expertise are always advantageous to the bioacoustics practitioner, off-the-shelf options for recording devices and acoustic data analysis software are increasingly available, making the methodology accessible to practitioners at all levels of

experience. Here we discuss some of the key factors to be weighed in designing a passive acoustic survey, from hardware selection and survey design to data analysis strategies and skill building resources.

Hardware selection and survey design

Hardware selection and survey design are inextricably linked and must be considered simultaneously when planning a passive acoustic survey (Sugai et al. 2020, Teixeira et al. 2024). When selecting underwater recording equipment, factors such as hydrophone sensitivity, noise floor, depth rating, and battery life, amongst others, all impact the suitability of a device for capturing a desired signal in its environment. Not surprisingly, the quality of underwater recording devices scales with their cost, which can range over 3 orders of magnitude, and the choice of recording device may often come down to price point. Much of the initial development of underwater acoustic recording systems was driven by naval research and funding, which yielded sophisticated and expensive systems which required considerable expertise to operate. Only recently have more affordable off-the-shelf options come on the market, increasing the accessibility of this methodology for broader adoption, including by those who do not have the engineering expertise to assemble and operate some of the more complex devices. The high-cost end of the spectrum consists of devices which cost tens of thousands of dollars and are equipped with high quality omni-directional calibrated piezoelectric hydrophones, low-drift clocks (essential for accurate acoustic sampling), low self-noise, large capacity data storage, and large battery capacity. These models are typically designed for long-duration deployments (6 months - >1 year) at depths up to several thousand meters and collect very high-quality data. The low-cost end of the spectrum includes devices which cost on the order of \$100. These options use the

most inexpensive sensors and electronic components, have limited data storage capacity and battery life supporting deployments of hours to weeks, are only rated for depths up to a few 10s of meters, deliver much lower-quality data (poor signal to noise ratio), and may not perform reliably. When deciding how to allocate project funding it may be tempting to opt for the least expensive devices. In this case it would be prudent to build redundancy into the survey design to provide a contingency in case of low-cost device failures, which are commonplace. If absolute sound levels are desired—for example, to characterize noise regimes, or estimate source levels of sounds of interest—then a device equipped with a calibrated hydrophone with a known frequency response is necessary.

Choice of recording platform, be it static or mobile, should be informed by the nature of the sampling to be carried out, and will determine which recording devices are compatible. For point sampling, midwater or bottom-mounted moorings are commonly employed when long-term data collection (days to months) is desired at a given site, while a small recorder or dip hydrophone lowered from a vessel or other stationary platform may be sufficient for an acoustic snapshot (minutes or hours). Moorings can be designed to accommodate large, unwieldy recording packages which it would be impractical to repeatedly lower from a stationary platform, but deployment and recovery of large moorings may require a vessel equipped with a crane, A-frame, winch, or other heavy machinery. If spatial coverage is also a priority, multiple sensors may be deployed on an array of moorings. Line transect surveys are another approach used to cover large geographic areas by towing an acoustic recorder or array while underway. Line transect data is similar to dip hydrophone data in that it typically represents an acoustic snapshot at every position along the transects, rather than a long acoustic record. Line transect surveys can be carried out by a research vessel manned with a scientific crew, or by an autonomous vehicle.

In addition to the type of acoustic record desired, other factors which interact to determine deployment durations include deployment/recovery logistics and data characteristics. For sites which are readily accessible it may be feasible to recover and redeploy devices frequently, potentially allowing a long data record to be constructed from consecutive short deployments. For field sites which are difficult or costly to access, it may be worthwhile to invest in a device which can remain in place and actively recording for a long period of time.

The recording regime and the sampling rate are primary determinants of recording duration for any device, as these dictate how quickly batteries are drained and onboard data storage is filled. Implementing a duty cycle is one way to extend battery life and reduce data size. Practically speaking, this may look like programming the device to record for 10 minutes at the top of each half hour, followed by 20 minutes in stand-by (a 33% duty cycle). All else held equal, such a recording regime would increase battery life and decrease (uncompressed) data size by a factor of about three compared to continuous recording.

Sampling rate (F_s) describes how frequently the sound pressure is sampled, which determines the rate of power usage and data accumulation. Additionally, the sampling rate is twice the highest frequency available for analysis according (for example, a sample rate of 10,000 Hz yields acoustic information from 0-5000 Hz). In bioacoustics studies F_s values commonly range from tens to hundreds of thousand Hz (or 0.1-100 kHz), dependent upon the frequency range of the target signals. Setting the sampling rate at slightly more than twice the maximum frequency of the target signals will avoid excessive power use and needlessly large data sets, though this will also preclude future analysis of the data for higher frequency signals. Some devices offer data compression as part of their onboard data acquisition and storage

pipeline, which can substantially increase data storage capacity; for research purposes only lossless compression formats should be used.

Data management

Passive acoustic surveys quickly produce large data sets on the order of hundreds or thousands of gigabytes, the management and storage of which becomes a nontrivial task (Roch et al. 2016, Wall et al. 2021). We present here a few best practices that can help to reduce confusion relating to data provenance, streamline data storage and sharing, head off data loss, and improve comparability across data sets. In addition to these best practices, it is always a good idea to budget for data management resources relating to data housing, quality control, back-ups, and archiving, such as computers/servers, hard drives, and labor. A plan for data management should be laid out at the beginning of each new bioacoustics project in order to standardize and streamline the data pre-processing workflow. No analysis should be undertaken until data have been pre-processed, and a secure copy of the original data, untouched by analysis, should always be maintained to avoid data loss due to accidental corruption of files by a faulty analytic workflow. We have included an example pre-processing workflow below.

Metadata: When collecting acoustic data, many aspects of the data collection scheme will inform interpretation of the resulting data. However, audio files typically do not contain such information about the survey design, and a naïve comparison of sound files collected with fundamentally different schemes can lead to spurious conclusions. Therefore, it is important to record key pieces of information about each deployment, referred to as the metadata, and keep that information collocated with the audio data for future reference (Roch et al. 2016). While no universally accepted standard for passive acoustic metadata exists, there have recently been some efforts to develop such a standard in response to the proliferation of passive acoustic surveys and

movements towards open data sharing. Table XX lists some key pieces of metadata pertaining to the project, deployment platform, and recording device.

Table 1 Common passive acoustic metadata describing important aspects of the project, deployment platform, and recording device.

Project	Platform	Recording Equipment
Project name	Platform type	Device type
Principal Investigator	Latitude	Device serial number
Deployment #	Longitude	Sampling rate
Deployment Date	Sensor Depth	Bit depth
Data Start Date		
Data End Date		
Recovery Date		

File naming: Many recording devices output sound files named according to the timestamp of the first sound pressure sample in the file. Such timestamps are essential for interpreting acoustic data which were collected through time, but files named only by timestamp are prone to confusion across devices/sites. It is important to ensure that the audio file names convey sufficient metadata so data provenance is clear, even if an audio file is removed from its parent folder. A good practice is to include metadata describing the project, site, deployment, and device ID in file names, in addition to the time stamp. The time zone of the time stamps should be included as well.

File formats and compression: A few audio file formats are commonly used for bioacoustics applications, which can be categorized as uncompressed or compressed. Uncompressed file formats (e.g. WAV, AIFF) offer high data fidelity at the cost of large file sizes. Compressed file formats can be further subdivided into lossless (e.g. FLAC) and lossy (e.g. MP3) formats; to avoid loss of important information, only lossless compression should be used for scientific bioacoustics applications. Some acoustic devices record data to uncompressed sound files, while others carry out compression as the files are written, reducing file sizes, increasing the amount of data which can be stored in onboard memory, and extending deployment durations. Uncompressed files can also be compressed later in the workflow for ease of storage and sharing. Free software (e.g. Raven Compass) is available for converting between audio file formats.

Data backups: Audio data capture a particular moment or period at a recording site, and, barring time travel, cannot be replaced or replicated if lost. External hard drives are commonly used to store large acoustic data sets, but such equipment is notoriously susceptible to failure and catastrophic data loss. It is highly advisable to replicate acoustic data sets in duplicate or triplicate; magnetic tape or cloud-based back-ups are more reliable than spinning hard drives. At least one copy of the data should be stored in a different location, preferably in a separate building.

Example Data Pre-Processing Workflow:

- 1) Offload sound files from device.

- 2) Perform a quality check on sound files. Did the device record according to the programmed schedule and expected duration? Are the file sizes as expected? Do the data look/sound good? Make note of any data issues, as these notes can be useful for improving future survey designs and tracking the performance of recording devices.
- 3) Re-name sound files to include desired metadata in the file names, with an eye to avoiding future confusion over data provenance (which site/deployment/device).
- 4) Back up the sound files at least in duplicate, preferably in triplicate, and relocate a copy to a secure offsite location. Optionally, convert file formats as part of this step. This may be done to reduce data size (compression) or to obtain a copy of the data in a file format necessary for a particular analysis (i.e. the desired analytic software may not be compatible with the file format written by a particular recording device).

Analysis strategy

At the most basic level, PAM data analysis often starts with the detection/classification of species-specific acoustic cues, and/or quantification of noise in particular frequency bands. One or both of these tasks, which have traditionally been accomplished through some combination of manual data review and digital signal processing (DSP) techniques, are necessary to address most bioacoustics research questions. Higher-level analyses use the outputs of these basic tasks, sometimes in combination with other data types, to address more complex behavioral and ecological questions. These tasks may sound straightforward to the uninitiated, but any experienced bioacoustics practitioner will tell you that they often account for a disproportionate amount of analytic time and effort. Luckily there are many resources and tools available to help address these needs, suitable for analysts spanning a range of skill levels, from Python packages

for skilled coders to code-free graphical user interfaces for those who are not prepared to write their own DSP scripts.

In recent years the field of bioacoustics has become synonymous with big data, necessitating the adoption of high throughput analytic approaches, such as automated detection and classification algorithms, dimensionality reduction, and unsupervised clustering and anomaly detection. Machine learning algorithms have gained traction for many of these analytic needs thanks to their ability to handle large, high dimensional data and the high levels of accuracy they have been shown to achieve on many tasks. Many of these tools are becoming increasingly accessible to those who do not have a computer science background, but there is still a learning curve to properly apply them and interpret their outputs. Those who are new to such analyses would benefit from availing themselves of freely available tutorials and training materials, and/or consulting with more advanced practitioners (e.g. the creators and power users of these tools) to ensure their correct application.

At the outset of a PAM study, the targeted outputs and analytic strategy should be informed by consideration of the analytic skill levels of the researchers involved, as well as the availability of existing software packages and applications. Three-dimensional animal movement tracks and animal density estimates may be attainable for a skilled practitioner focusing on tractable species, while simpler time series of acoustic activity or noise levels will be more realistic for a novice. For species-level analyses, an important consideration is whether there exist publicly available detection/classification models which attain a level of performance acceptable for the research needs, or whether a custom model will need to be created. Coding and training new models from scratch has traditionally been a labor-intensive undertaking, though recent advances in bioacoustics transfer learning, and the trend towards open-source code

and models, are beginning to expedite the process. The pre-requisite for species-level analyses is knowledge of species-specific acoustic cues (see Note below); more progress has been made on this front for marine taxa than for freshwater taxa, but this is an area of active research.

Timestamped detection events are the basic output from species detection/classification algorithms; metrics of the detected signals may also be of interest (e.g. peak frequency, duration, signal-to-noise ratio (SNR), etc.).

Quantification of noise in particular frequency bands is a much more straightforward task than detection/classification of specific cues, though the insights to be gained are correspondingly coarser. This approach can be useful for characterizing broad patterns in noise, such as the occurrence of chorusing events, quantification of anthropogenic noise contributions, comparing soundscape characteristics across sites, etc. An important note is that the computation of absolute noise levels (dB re: μPa) requires calibrated recordings—that is, recordings made with a device for which the relationship between received sound pressure and system response is known. Noise levels computed from uncalibrated devices cannot be compared across devices, as variability in sensitivity between devices cannot be accounted for and may be significant. Therefore, calibrated devices must be used if noise analysis is a research objective.

It is worth pointing out that advancements in the field of bioacoustics often arise from interdisciplinary collaborations between researchers with biological/ecological expertise and those with technical expertise (Rountree et al. 2006, Kahl et al. 2021, Wood et al. 2021, Tuia et al. 2022, Fleishman et al. 2023, Ross et al. 2023). For fisheries management research questions which necessitate analyses that are beyond the reach of the novice bioacoustics practitioner, partnerships with data scientists, engineers, and computer scientists can expand the scope and

complexity of potential analyses, enabling higher level behavioral and ecological questions to be addressed.

Box 1. Species sound signatures: The characterization of species-specific acoustic cues is often not straightforward, and different observations provide varying levels of certainty that a given cue can reliably be used to infer presence of a particular species. Combined insights from more than one of the approaches outlined below can build confidence in a species-sound assignment.

For animals which can be held in captivity, recordings made in tanks containing a single species may be a good starting point for acoustic characterization (Lin et al. 2007, Rice and Bass 2009, Širović and Demer 2009, Vasconcelos et al. 2024). Captive recordings are particularly useful for characterizing the mechanism of sound production, as they permit observation of calling animals at close range (Clark and Dunn 2022). The question is whether the behaviors exhibited in the tank setting are representative of those exhibited in the wild, including acoustic behaviors. Differences may arise from stress responses to the tank environment, different presence/absence of conspecifics or other species, or captive recording effort which does not coincide with behaviors that are only exhibited during certain life history events (e.g. reproductive behaviors). Tanks also tend to be noisy recording environments due to the operation of water pumps, aerators, and filters, and the reverberation of sounds within a confined space with reflective walls; this may result in some distortion of the calls (Akamatsu et al. 2002). While tank recordings may answer the question of whether, and how, a given species produces sound, the utility of those sounds for use in a PAM framework is not guaranteed.

Field recordings obtained via PAM are more likely to capture animals during natural behavioral states, but entail uncertainty as to which species are present and typically lack contextual insights into behavioral state during calling. One way to remedy these challenges is to pair PAM recording with concurrent visual observation, either in person or using video or still cameras. This approach has been employed with good success in high visibility environments (Tricas and Boyle 2014, Mouy et al. 2023, Dantzker et al. 2024), though it may not be feasible in turbid systems (Fournet et al. 2022, Souza et al. 2023). Other approaches to observing focal species' presence, such as telemetry tags, netting, and sidescan sonar, can all help to associate a particular sound with a given species, but they cannot rule out the simultaneous presence of other soniferous species or provide direct insights into behavioral states during calling.

Another approach for acoustically characterizing animals in the field is through the use of body-mounted acoustic sensor tags, a methodology that has been very successful for marine mammals (Wright et al. 2024, Zeh et al. 2025). Data arising from such devices has undisputed species assignment and, after a period of tag acclimation, has a good chance of reflecting naturalistic behaviors. However, this approach requires either capture of animals or significant expertise in deploying tags on free swimming individuals, is very costly, requires the recovery of devices after detachment, and is not well suited to smaller species due to the size of the tags themselves.

Table 2: A selection of popular tools for bioacoustic data analysis.

Name	Coding required	Description	Reference
Avisoft Pro	No	Signal measurement and annotation	https://avisoft.com/
Raven Pro	No	Signal measurement and annotation, ability to run automated detection algorithms	(K. Lisa Yang Center for Conservation Bioacoustics 2024)
BirdNET Analyzer	No	AI toolbox for developing automated recognition models	https://birdnet-team.github.io/BirdNET-Analyzer/
seewave	Yes	Signal measurement	(Sueur et al. 2008)
tuneR	Yes	Signal measurement	(Ligges et al. 2024)
PAMGuard	No	Signal measurement, automated detection, annotation	https://www.pamguard.org/
PAMGuide	No	Signal measurement,	(Merchant et al. 2015)
PyPAM	Yes	Signal measurement, automated detection, annotation	https://github.com/lifewatch/pybam
MANTA	No	Signal measurement, generation of long term spectrograms	(Miksis-Olds et al. 2021)
Triton	No	Signal measurement, generation of long term spectrograms, automated detection	(Wiggins et al. 2010)

When Not to Use Acoustics

While PAM has many strengths and wide-ranging applications, it is by no means a silver bullet, and some circumstances may preclude its use. The most obvious is the case wherein the target species does not produce sound at all, either actively or incidentally, and no other proxy species can be identified. Another case may be when the target species produces low amplitude sounds, and/or the recording environment is noisy in the same frequency range as those sounds, both of which can result in low SNR and poor detectability. Similarly, when the sounds produced

by the target species cannot be readily distinguished from other co-occurring signals due to similarity in the frequency and/or temporal characteristics, a high incidence of false positives becomes likely, and time series of species' acoustic presence become less reliable. A case where PAM may have mixed success is when the target species is rarely encountered due to low numbers of individuals and/or highly patchy and variable distribution over a large region, such as for pelagic species. In the case of very low rates of acoustic encounters, sparse time series of species presence may not be adequate to fully characterize patterns in activity, or estimate density/abundance (Wood et al. 2021). However, provided the calls of the target species are readily detected and distinguished from other sounds, particularly with automated methods, PAM can still be a powerful tool for detecting rare acoustic presence events. This can be quite effective for monitoring for the presence of invasive species (Rountree and Juanes 2017, Schärer-Umpierre et al. 2019).

Combination with other methods (how PAM enhances other methods, or can be enhanced by them)

Traditional Fisheries Gear: PAM is a natural complement to traditional fisheries sampling methods (e.g. trawls, seines, gill nets, electrofishing) as it does not induce behavioral change, may represent species/individuals which evade capture, and can provide insights to spatiotemporal patterns in presence outside of the traditional survey time periods (year round, day and night, in most weather conditions, passive acoustic localization). PAM may be used to provide information on presence, abundance, and/or behavioral state to complement traditional biodiversity assessments, and investigations into demography or habitat use. Conversely, observations of captive animals can be used to validate species sound signatures (see Note above

for some caveats), and to elucidate the behavioral context and physiological mechanisms of sound production. Knowledge of the behavioral context of sound production for a given species makes passive acoustic data informative beyond simple acoustic presence/absence.

Other Observational Methods

Light conditions and water clarity allowing, passive acoustic data can be combined with photography/videography to validate assignment of acoustic cues to particular species and gain insight into the behavioral context of sound production. This kind of work is key to expanding the pool of species that can be effectively monitored using PAM, and gaining insights beyond acoustic presence/absence. PAM data can provide information on spatiotemporal patterns in presence outside of the coverage provided by active acoustics survey (i.e. echosounders, sidescan sonar), which are typically limited in temporal coverage due to their labor intensive nature. Active acoustics can also be used to enumerate individuals, which can then be combined with passive acoustic data to estimate calling rates, an essential step in estimating animal density/abundance from passive acoustic data. PAM can complement weir and optical fish counting methods by simplifying logistics (robust to a wide range of environmental conditions, little servicing required) and providing finer temporal resolution.

Other Non-Observational Methods

Environmental DNA (eDNA) provides coarse presence/absence insights with little effort overhead. PAM surveys and target species can be guided by eDNA findings, and can then provide finer resolution spatial presence insights (including potentially acoustic localizations), in

addition to behavioral context. Similarly, PAM can provide fine scale presence insights and behavioral information to complement telemetry surveys. PAM insights into species presence and habitat use patterns can also be used to guide the placement of telemetry receivers to improve telemetry survey design. Passive acoustic density/abundance estimates can also be used to validate aggregation size estimates obtained through tagging effort and a mark-recapture framework.

Future Directions

The field of bioacoustics is maturing and expanding rapidly, however there is often a steep learning curve which entails mastery (or comfort) in working with hardware, software, and interpretation of audio data. Despite the many benefits that it can offer to fisheries and wildlife surveys, the expertise required makes it appear unapproachable or intimidating to people unfamiliar with it. With the growth in awareness and appreciation of the ubiquity and significance of sounds produced by fishes and the increasing accessibility of the hardware/software tools, we are optimistic that PAM will have uptake and increased usage in the fisheries management community. The focused effort on matching species and their sounds will further increase the opportunities and use cases for which PAM can be implemented.

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