Deciphering Coral Reef Soundscapes Utilizing 360° Video and Spatial Audio

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Abstract

Coral reef soundscapes hold an untapped wealth of biodiversity information. The identity of species for marine biological sounds is largely unknown. Given a scalable ability to identify sound sources, acoustic monitoring could begin to reveal biological distribution, key/invasive species, behavior, and abundances at an unprecedented temporal and spatial scale. We have developed and implemented 360° video and spatial audio visualizations to address this fundamental knowledge gap. By verifying the identity and behavioral context of acoustic events, we demonstrate the collection of species-specific acoustic diversity, encompassing a growing library of 34 species previously unrecorded in their natural habitat. By continuing to focus on biodiversity hotspots, we envision a transformative role for acoustic monitoring as a novel tool in actionable conservation strategies.

Introduction

Animal sounds contain extensive information about community assemblage and ecosystem function across time and space (Burivalova et al. 2019, Mooney et al. 2020, Rasmussen et al. 2024), and this is particularly true for high-biodiversity environments such as tropical coral reefs, where most inhabitants produce and respond to sounds (Lobel et al. 2010, Tricas and Boyle 2014, Parmentier et al. 2021, Rice et al. 2022). In fact, the majority of fish species likely make sounds (Lobel et al. 2010, Tricas and Boyle 2014, Parmentier et al. 2021, Rice et al. 2022). In reef environments, high fish biodiversity and the presence of taxa within core functional groups play critical roles in reef health, resilience, and recovery (Burkepile and Hay 2008, Duffy et al. 2016, Duarte et al. 2020, Honeycutt et al. 2023). Previous studies suggest that the abundance and behavior of these species could be detected by listening for species-specific sounds (Myrberg et al. 1993, Tricas and Boyle 2021), which could serve as key indicators of community integrity or recovery processes (Fournet et al. 2019, Lamont et al. 2022). One barrier has stood in the way – we have been unable to decode the coral reefs' complex soundscapes.

Globally, coral reefs and reef-based fisheries are in decline (Eddy et al. 2021). Improving long-term passive acoustic monitoring (PAM) capabilities for coral reefs can enable PAM to become an important complement to other technologies supporting conservation decision making. For example, PAM provides finer spatial and temporal resolution than other approaches (e.g., eDNA, telemetry). PAM data can deliver valuable insights within ongoing monitoring efforts (Madin et al. 2019, Waterhouse et al. 2020, Lamont et al. 2022, Edmunds 2024) and can inform actionable measures for adaptive management. PAM studies can target important protected or imperiled soniferous species (Schärer et al. 2012, Pyć et al. 2021), document ecosystem regime shifts, and

examine soundscape composition patterns at the community level (Bertucci et al. 2016, Lin et al. 2021, Puebla-Aparicio et al. 2024). In fact, PAM may be better suited than other technologies to gather measurable, verifiable data on Key Performance Indicators (KPI) relevant to innovative financing mechanisms for ocean conservation (Sumaila et al. 2022, International Capital Market Association 2024).

The fundamental challenge in realizing the utility of PAM for *in situ* fish assessments is that sounds from relatively few fish species have been identified (Looby et al. 2022, Rice et al. 2022), and the vast majority of recorded underwater biological sounds through PAM surveys cannot be attributed to a particular taxonomic group beyond "biological" or "fish" (Knudsen et al. 1948, Wenz 1960, Jarriel et al. 2024). Without taxonomic specificity (ideally to species level), PAM analysis can only yield measures of coarse spectral and temporal patterns. These measures have been used to derive indices that are *proxy* measures for biodiversity (Harris et al. 2016, Bradfer-Lawrence et al. 2019, Bradfer-Lawrence et al. 2023). While acoustic proxies have shown some correlation with on-the-ground diversity in some terrestrial ecosystems, they are not yet proving to reflect actual patterns of diversity in marine systems (Kaplan et al. 2015, Staaterman et al. 2017, Dimoff et al. 2021, Raick et al. 2023). Even when acoustic indices do reflect patterns of biodiversity, they remain computational abstractions of complex soundscapes and do not provide sufficient detail, such as direct species-level information, to drive conservation action through regulatory frameworks; conservation decision-making requires taxon-specific data (McNeely 2002, Godfray et al. 2004).

When species-specific sounds are known and available for comparison, we can directly measure species presence/absence, call type, and detection rates. Using presence/absence, we can decode the soundscape and implement species-informed biodiversity metrics, map species distributions, and detect indicator species (Fournet et al. 2019) and invasive species (Amorim et al. 2023). When we know the sound types, we can map crucial behaviors such as spawning, territoriality, or feeding in space and time (Oestreich et al. 2024). To infer density and abundance requires knowledge of species identity and other information, such as detection probability (Marques et al. 2013). Therefore, species IDs enable the development of actionable metrics on which evidence-based adaptive management and policy decisions can be made (Fig. 1).

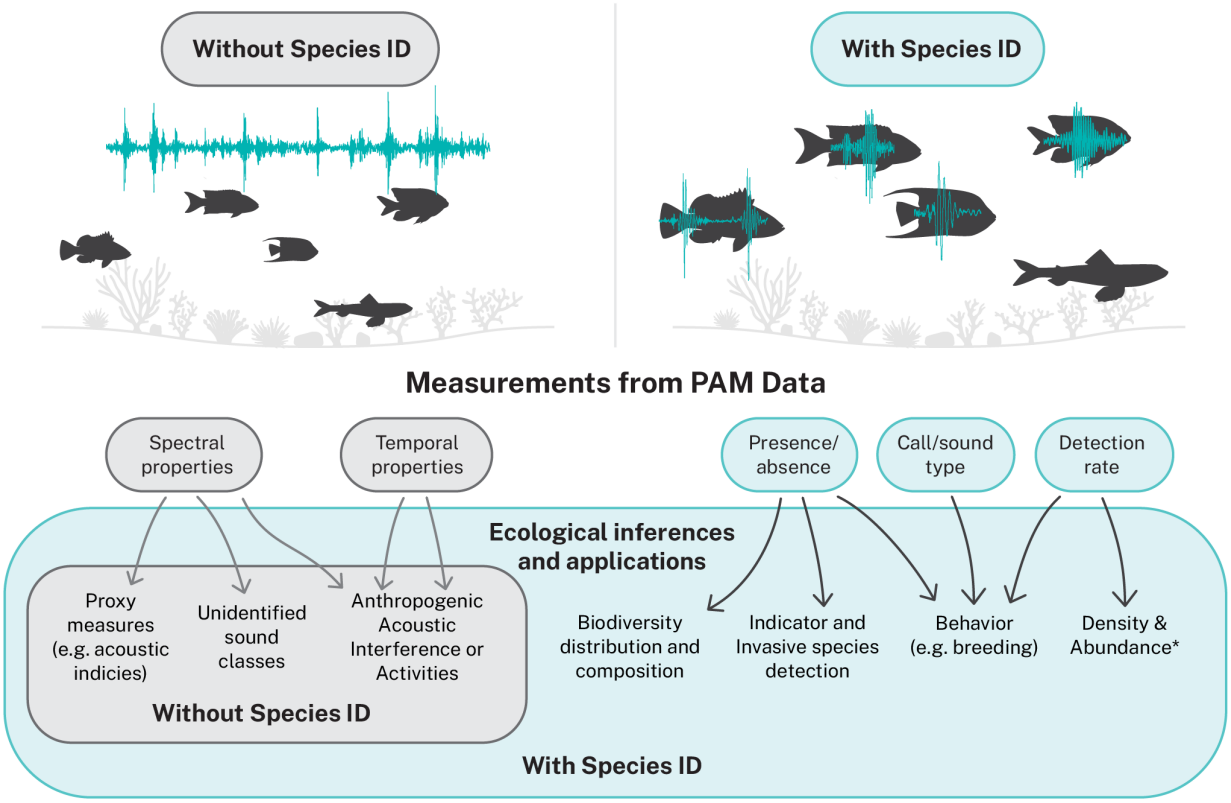

Fig. 1. Conservation inferences from bioacoustics, both without and with species identities from sound. Without known species IDs, we can only measure the spectral and temporal properties of ambient sound. These can be processed into acoustic indices, examined for noise analysis, or clustered into sound types, limiting PAM studies to generalized categories such as biophony and anthrophony. Given species-specific sounds, we can directly create meaningful measures of biodiversity, detect indicator and invasive species, and monitor for behaviors. *When combined with source levels, propagation measures, detection probability, and call rate, estimations of density and abundance can be made (Marques et al. 2013).

A lack of basic knowledge of species-specific fish sounds has severely limited opportunities for PAM in scalable and effective conservation approaches on coral reefs. For other taxonomic groups where species IDs are known– such as those of most species of birds, bats, cetaceans, and frogs– a long history of focal recordings has enabled the collection of a sufficient number of validated sounds (Kellogg 1960) to be used for the development of feature-based detection algorithms and ML methods (Kahl et al. 2021, Tuia et al. 2022). In systems where IDs are known (e.g., terrestrial, cetacean), these techniques are rapidly developing to enable long-term PAM monitoring systems supporting biodiversity conservation to function at large spatial and temporal scales (Gibb et al. 2019, Tuia et al. 2022, Rasmussen et al. 2024).

Evolutionary analysis suggests that 85% of fish families may make sounds, and many of these could be used for acoustic monitoring (Rice et al. 2022). For example, in the region of focus for this study, the Caribbean Sea, of the 1122 reef-associated fish species (Robertson and Van Tassell 2023), 736 (66%) are in likely sonic families (Fig. 2; Supplement 1). A search of online sources detailed in Supplement 1 found records of 174 of these species with identified sounds, of which 132 have publicly available recordings. Only 33 species have recordings of free behaviors, 11 in nature. This means that less than 1.5% of Caribbean reef-associated fish species that likely make sound have available recordings from nature that have been ascribed to them. Thus, recordings from a hydrophone on a Caribbean coral reef will have hundreds to thousands of likely fish sounds every minute, with variable call types that suggest a wide diversity of sources. However, ascribing those sounds to individual species is exceedingly difficult (Kumpf 1964, Lobel 2005, Mouy et al. 2018, Mouy et al. 2023) because the species-specific vocalizations have

not been identified. We have developed an approach to fill this knowledge gap and begun doing so for Caribbean fishes.

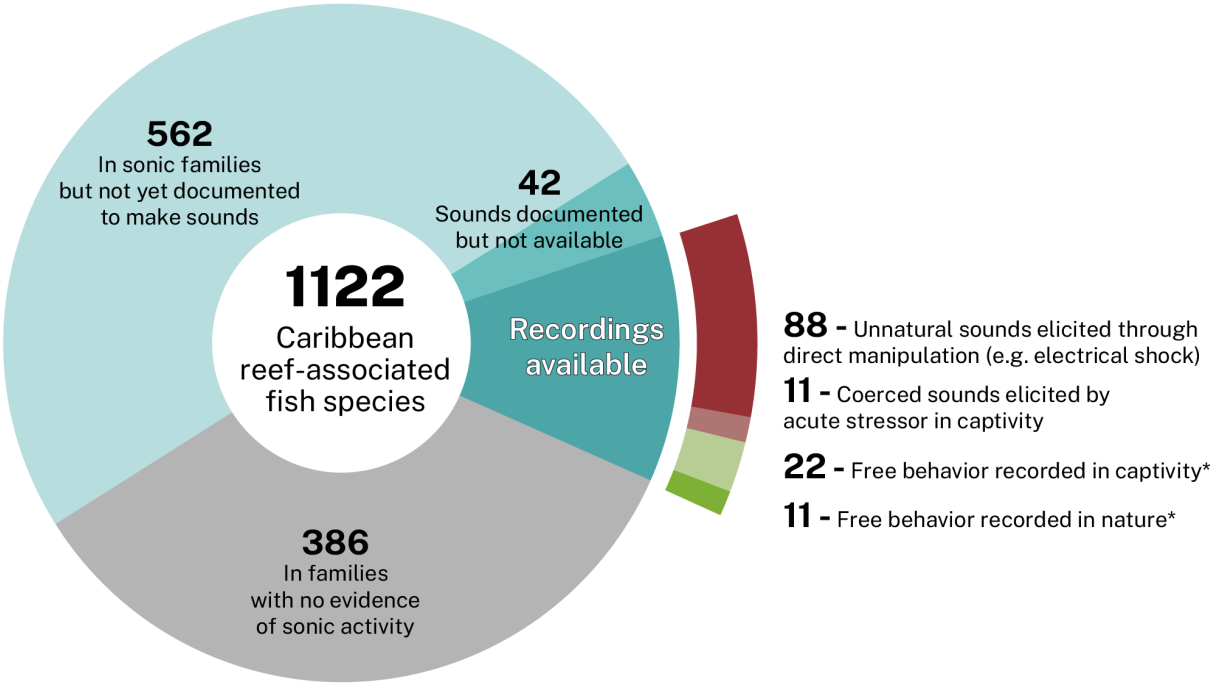

Fig. 2. Summary of what is known about sounds for Caribbean reef-associated fishes. Of the total number of reef-associated fish in the Caribbean, 735 are in families that are likely to make sound (based on Rice et al. 2022). A much smaller fraction of these species (174) has published evidence of acoustic behavior. Of these, we were able to find publicly available sound recordings for 132 species. We classified these recordings to grade their potential utility for PAM analysis. Most (88) of these sounds were elicited through direct manipulation of fish using techniques such as electric and manual stimulation. From top to bottom, the color of the "recordings available" relates to the utility of those recordings in analyzing in situ PAM recordings. We found only 11 Caribbean fish species with free behaviors recorded in nature. Details are in the supplementary text. *These species names and links to the recordings are provided in table S1.

Approaches to species identification

Despite fish sounds being common on coral reefs, ascribing those sounds to specific species is difficult. Underwater, humans can hear some fishes, but the ability of the human auditory system to localize sound underwater is minimal (Brandt and Hollien 1967, Casper and Babina 2022). Additionally, most fish sounds are made by cryptic stridulation or internal mechanisms without conspicuous visual correlates (Fine and Parmentier 2015). Because of this difficulty in making unaided observations, other methods have been used to try to ascribe sounds to fish species.

The most direct method to collect species-specific sounds is to record fish in a tank or other enclosure (Fig. 3A) (e.g., Fish and Mowbray 1970). Some fish are amenable to vocalizing in captivity (Rice and Bass 2009, Širović and Demer 2009), but for other species, natural behavior is uncommon under these circumstances, so many captive sounds have been recorded by subjecting the fish to unnatural stressors, including manual stimulation and electric shock (e.g., Fish and Mowbray 1970). These sounds might mirror natural distress calls but not the territoriality, courtship, or nest defense sounds that would be helpful in monitoring populations (Clark and Dunn 2022). In some cases, sounds have been recorded from habituated captive fish that may mirror a limited set of free behaviors (Rountree et al. 2006). However, the acoustic properties of tanks can make applying these recordings to PAM analysis challenging (Akamatsu et al. 2002). In nature, during group spawning aggregations or in rare cases where species are isolated, hydrophone recordings alone have enabled species identifications. The majority of the 11 Caribbean field identifications were collected with this method, with only audio recordings (Locascio and Burton 2016). However, assigning identifications to sounds recorded in nature is fraught with the potential for misattribution (Sprague and Luczkovich 2001).

In a diverse environment, adding synchronous video recordings can enable verification of identifications and provide greater certainty of species isolation. The coupling of video and audio has been accomplished with remote cameras (e.g., Mann et al. 2010, Banse et al. 2024) and by divers (Lobel 1992). Scuba divers have the flexibility to search for soniferous behaviors, and the most successful diver recordings have used closed-circuit rebreathers to minimize diver disturbance (Lobel 2005, Tricas and Boyle 2014). However, diver time underwater is limited, so recording with divers is more time-limited compared to fixed autonomous installations. For both remote cameras and divers, there is a high chance of misattribution because they use directional cameras and omnidirectional hydrophones. Therefore, the individual fish within the limited FOV may not be the source of the sounds recorded (Fig. 3B, C) (Mouy et al. 2018, Mouy et al. 2023).

To address the potential for misattribution, one method has paired remote cameras with a hydrophone array for acoustic localization (Fig. 3D) (Mouy et al. 2023). The multichannel recordings are used for acoustic localization. Sounds are only ascribed to individuals when the localization points to a fish within the FOV. Sometimes, localization is precise enough to distinguish between sources when more than one fish is visible within the FOV. However, the cameras used in this method have a limited directional FOV, and localizations that are sufficiently precise to ascribe sounds can only be made in small regions (Mouy et al. 2023).

Here, we describe and apply a novel technique (Fig. 3E) to a remote camera solution that avoids the pitfalls of previous methods, such as limited FOV, human disturbance, and misattribution. This technique is far more productive than previous methods, allowing the identification of many sounds each day of recording. Thus, we demonstrate that a scalable and generalizable fish sound

library can be built. Such sounds and recordings can improve PAM analysis and deliver critical insight into community assemblage and ecosystem function.

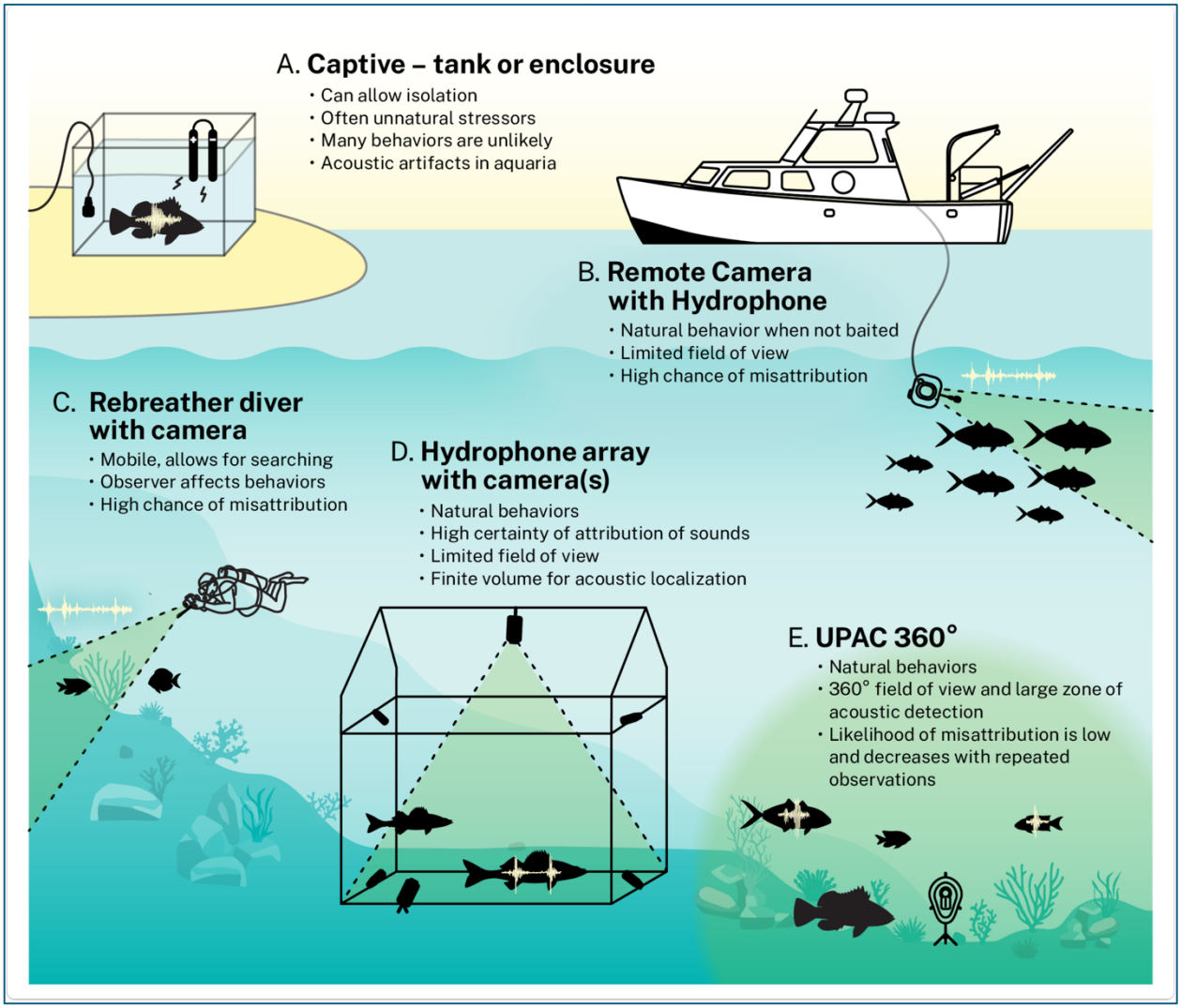

Fig. 3. Methods of ascribing fish sounds to species using audio and video. It is challenging to ascribe sounds to fish species. Most studies typically use one of these methods, each with pros and cons. (**A**) Captive fish can be recorded in isolation, so species attribution is clear, but natural behavior is rare. (**B**) Remote cameras with hydrophones can capture natural behavior but with a narrow FOV and a high probability of misattribution. (**C**) Rebreather divers have a flexible FOV but retain similar limitations. (**D**) A method to increase the certainty of attribution uses hydrophone arrays to ensure that a sound is coming from the location of a visible fish. (**E**) our approach uses a 360° unbounded FOV with a compact hydrophone array, providing a small footprint, low impact on fish behavior, and a large zone of detection.

Methods

We created a novel approach to ascribing sounds to fish species, which we describe as an omnidirectional (360°) Underwater Passive Acoustic Camera (UPAC 360°). It combines underwater ambisonics recordings with concentric 360° video, coupling commercially available technologies with publicly available spatial audio techniques. Visualizations of the detected sound field are overlaid on the video, revealing the source of the received acoustic signal.

Hardware Details

Our acoustic array (Fig. 4A) is modeled on an earlier version of a tetrahedral underwater ambisonics array, which successfully tracked a scuba diver in a pool (Delikaris-Manias et al. 2018). Due to the uniform placement of the hydrophones, the performance of the algorithms is independent of the direction of the sound source. We paired the geometry of that array with an extruded acrylic frame that holds the four hydrophones (a prototype of the A5 hydrophone from Aquarian Audio and Scientific, Anacortes, WA) in a tetrahedral pattern. The frame is designed to position the array around a 360° camera (Insta 360, X3, Shenzhen, Guangdong, China) with an underwater housing. The frame is not visible because objects close to the camera in the plane between the lenses are not visible in the composite image. The one hydrophone and cable in the FOV are visible, but because of the clear acrylic, the small size, and the orientation of the hydrophone, its visual footprint is minimized (Fig. 4B).

The videos were recorded at 5760 x 2880 resolution at 30 frames per second in automatic exposure mode. The audio was recorded on a Zoom F6 field recorder (Zoom Corporation, Tokyo, Japan) set to 48 kHz sample rate and 32-bit depth, with the channel gains locked to

record in Ambisonic A format. The audio recorder was housed in a pressure housing (Blue Robotics Inc., Torrance, CA).

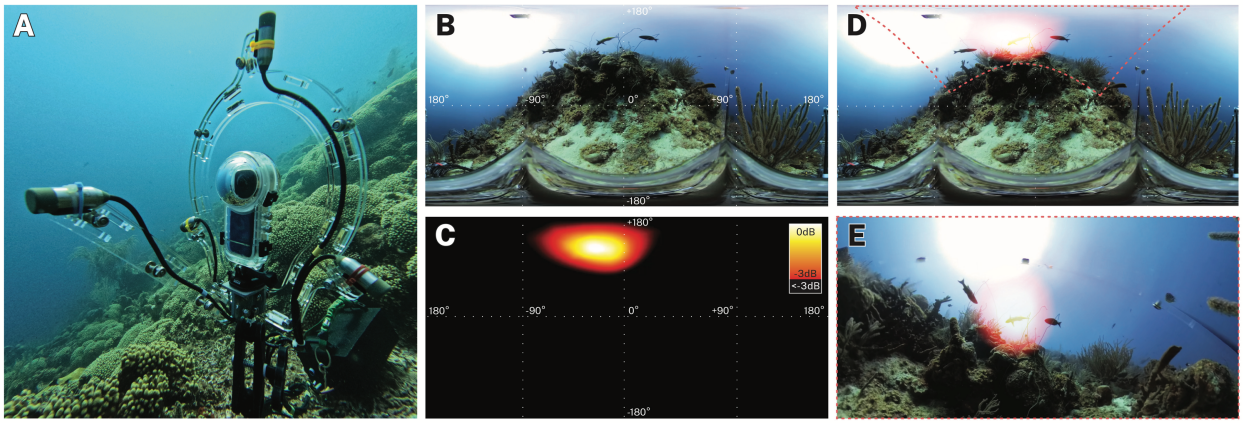

Fig. 4. Hardware and Analysis Summary (**A**) The UPAC-360 consists of a sensor package of four hydrophones in a compact tetrahedral array with a commercial 360° camera at the array's center. (**B**) Shows the equirectangular (EQR) image from the camera after processing (stitching) the images from its two sensors. The obstruction at the bottom of the frame is the camera housing. (**C**) The powermap is a visualization of the sound field energy distribution at the moment of a fish sound. We display the top 3dB of this map on the same EQR projection. (**D**) we overlay the powermap visualization onto the video. (**E**) We reframe the image to "look" in the direction of the detection to see if there is an overlapping sound source. In this example, all three fish within the zone of detection are *Clepticus parrae*, so we can ascribe the sound to that species. Using behavioral cues from the video, we can further ascribe the sound to the fish at the center.

Field Effort

The recording system was deployed at a diversity of coral reef sites at depths of 3-45 m off the Curaçao Sea Aquarium in Bapor Kibrá, Willemstad, Curaçao (12.084°N, 68.896°W) in June-July 2023, December 2023, and July 2024. Here, we are reporting on the analysis of 20 hours of recordings from June 2023. Analysis of the remaining materials is ongoing. The June recordings were made over four days in six locations.

Analysis Methodology

Raw video files were exported as 5760 x 2880 EQR files using Insta360 Studio (Fig 4B). We then aligned audio and video in DaVinci Resolve v. 19 (Black Magic Design, Freemont, CA, USA), using diver-generated and natural sounds as reference points. We excised the audio sections that align with each camera deployment for further analysis. We converted the four-channel audio captured with the hydrophone array to first-order ambisonic signals through a spherical harmonic transformation adopted for the hydrophone array configuration (McCormack et al. 2018).

The fish sound detection was performed manually familiar with fish sounds inspecting spectrograms. We then utilized the ambisonic signals to visualize the energy of the soundfield in

Adobe Audition (Adobe, San Jose, CA, USA) using the SPARTA VST toolbox to inspect if there was an energy peak at the same time (McCormack et al. 2018). We marked these calls for subsequent analysis that uses a combination of Multiple Signal Classification (MUSIC) (Schmidt 1986) and Cross-Pattern Coherence (CroPaC) algorithms (Delikaris-Manias and Pulkki 2013) to visualize the soundfield energy. The sound analysis was performed in the frequency range of 200-2500 Hz, encompassing most known fish sounds. We normalized each section to its energy peak, and the soundfield visualization depicts the highest 3 dB (Fig 4C). We screen-composited these maps over the camera's video in DaVinci Resolve and adjusted opacity to allow the video to show through (Fig. 4D). To focus on the event, we reframed 360° video into standard framing using the Karta VR plugin V.5.7 (Kartaverse, https://kartaverse.github.io/) (Fig. 4D).

Assigning sounds

Our recordings have hundreds of likely fish sounds every hour, but we cannot assign most of them to individuals or species. The reasons are: 1) Many sounds recorded by the array come from sources beyond our visual range. The visual range is limited by light level, water visibility, and camera resolution. 2) The topography and coral coverage obscure many fish wholly or partially. 3) Many fish are visually cryptic during the day. 4) Color variations mask distinguishing features between closely related species. 5) The spatial detection area for these sounds overlaps with more than one species. However, we can overcome some of these challenges using additional evidence. For example, sound production often coincides with conspicuous or subtle movements, allowing us to discriminate between individuals. While single events of sound production may be difficult to ascribe to species with certainty, multiple examples lend weight to evidence.

Integrating UPAC-360 Data with PAM Recordings

To demonstrate how validated sounds through the UPAC-360 approach could be used in traditional PAM approaches, we deployed the UPAC-360 next to a bottom-mounted archival acoustic recorder (SoundTrap ST600, Ocean Instruments, Auckland, NZ) sampling at 48 kHz. The SoundTrap was mounted to an old car tire found on the reef. A random five-minute segment of the audio from the SoundTrap was chosen for annotation. Identifiable sounds to the lowest taxonomic resolution (following Robertson and Van Tassell 2023) were annotated through visual spectrographic analysis in Raven Pro 1.6.5. Unidentifiable sounds were manually sorted into classes based on the similarity of distinct spectral and temporal features.

Results

The UPAC-360 with MUSIC and CroPaC is able to localize many sounds, even when the reef is crowded with activity (Figs. 5, Video S1). Within this video frame, more than 121 individuals are from at least six species. The detection zone overlaps only one individual, and that individual can be identified as a *Stegastes partitus* (Bicolor Damselfish) just before and after the rapid dive that this species does while making this sound.

Fig. 5. Ascribing sounds to individuals. The UPAC-360 is able to isolate which individual is the sound source in a coral reef. In this example, we can identify at least 121 individuals from six species, including 58 *Stegastes partitus,* greater than 53 *Azurina multilineata*, 1 *Lactophrys bicaudalis*, 1 *Halichoeres garnoti*, 2 *Canthigaster rostrata*, and 5 from the family Gobiidae. However, the 3 dB zone overlaps only one individual *S. partitus.* The visual ID is based on video before and after the soniferous event (Video S1). The bottom left shows the Blue Robotics housing for the Zoom recorder. In the bottom right corner is an Ocean Instruments SoundTrap ST600 recorder is the bottom right corner, the source of the data for Fig 7.

Using this technique, we have ascribed sounds to species. Figure 6 (and Video S2) shows examples of sounds ascribed to individuals from six species (*Heteropriacanthus cruentatus*, *Clepticus parrae*, *Ocyurus chrysurus*, *Scarus taeniopterus*, *Azurina multilineata*, and *Stegastes partitus*). We documented both active (intentional) and passive (non-intentional) sounds. The sounds from *H. cruentatus*, *C. parrae*, *O. chrysurus*, were active sounds from isolated individuals. The *S. taeniopterus* sound is an epiphenomenon of grazing activities, an example of a passive (non-intentional) sound. In both the *Azurina multilineata,* and *Stegastes partitus* examples, there is more than one individual in the zone of detection, but all are the same species.

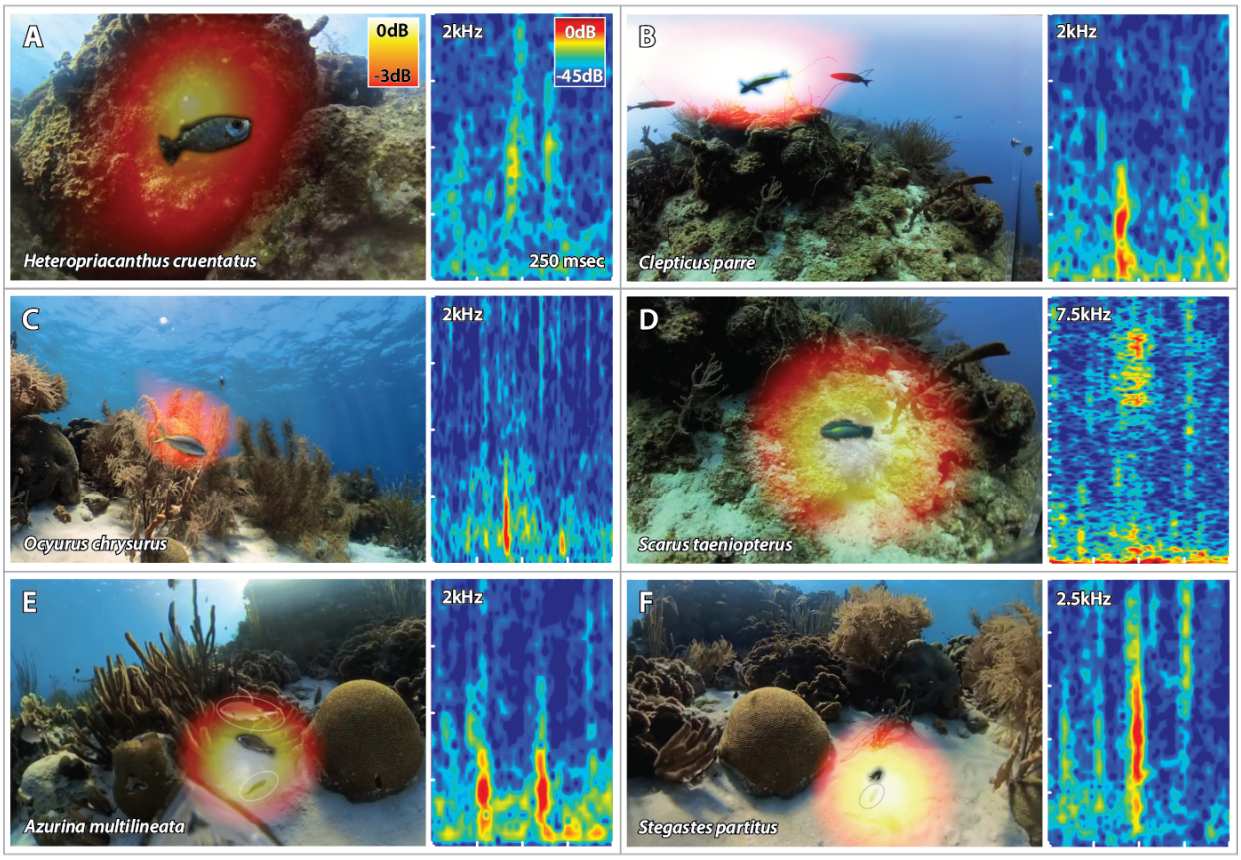

Fig. 6. Ascribing sounds to species. The sounds of (**A**) *Heteropriacanthus cruentatus*, Glasseye Snapper (**B**) *Clepticus parrae*, Creole Wrasse, (**C**) *Ocyurus chrysurus*, Yellowtail Snapper, (**D**) *Scarus taeniopterus*, Princess Parrotfish, (**E**) *Azurina multilineata*, Brown Chromis, and (**F**) *Stegastes partitus*, Bicolor Damselfish. In both the (E) *A. multilineata,* and (F) *S. partitus* there is more than one individual in the zone of detection (white ovals), but all are the same species. We can further identify which individual made the sound by behavior (Movie S2). The powermap data layer is masked around the caller, making the individual visible in this illustration. Spectrograms to the right of each image (frequency in kHz x time over 250 ms) are made on the 0-order spherical harmonic of the ambisonic audio using Raven Pro 1.6.5, Hanning window, 1024-point FFT, 75% overlap.

The combination of 360° video with underwater spatial audio in an integrated visualization allows for a scalable ability to ascribe sounds to fish species in a behaviorally relevant context. From UPAC-360 deployments over four days on reefs in Curaçao, we were able to add the sounds of 34 species to Caribbean reef-associated species (Table 1) belonging to 16 families. While some of these fish have been shown to be soniferous under duress in captivity (16), many of these species have never been previously recorded (15) or lack publicly available recordings (3). None of these species have any previous recordings of free behaviors in nature. The sounds we have collected that have a high degree of certainty and confirmation will be publicly available through our website (library.fisheyecollaborative.org) for future qualitative or quantitative comparison to previous and future acoustic collections from Caribbean soundscape studies. With the ongoing application of the technique, we expect the number of acoustic examples to include new species and specimens to be regularly added to the open-access library.

Table 1. List of species with ascribed sounds. Media specimens for 34 species will be available in the FishEye Collaborative Library (library.fisheyecollaborative.org). Up to five high-confidence representative recordings will be included for each species.

Family	Scientific Name	Common Name	Previously Documented Sonifery	Number of media specimens to be published as of Dec 2024
Acanthuridae	*Acanthurus coeruleus*	Blue tang	Y	5
	Acanthurus tractus	Northern ocean surgeonfish	N	2
Aulostomidae	*Aulostomus maculatus*	Atlantic trumpetfish	N	3
Carangidae	*Caranx ruber*	Bar jack	Y	5
Epinephelidae	*Cephalopholis fulva*	Coney	Y	1
Haemulidae	*Haemulon flavolineatum*	French grunt	Y	1
	Brachygenys chrysargyrea	Smallmouth grunt	N	1
Holocentridae	*Myripristis jacobus*	Blackbar soldierfish	Y	5
Kyphosidae	*Kyphosus bigibbus*	Darkfin sea chub	N	2
Labridae	*Clepticus parrae*	Creole wrasse	N	5
	Halichoeres garnoti	Yellowhead wrasse	N	5
	Thalassoma bifasciatum	Bluehead wrasse	N	1
Lutjanidae	*Lutjanus griseus*	Gray snapper	Y	1
	Ocyurus chrysurus	Yellowtail snapper	Y	1
Mullidae	*Mulloidichthys martinicus*	Yellow goatfish	Y	1
Ostraciidae	*Lactophrys triqueter*	Smooth trunkfish	Y	1
Pomacentridae	*Abudefduf saxatilis*	Sergeant major	Y	5
	Microspathodon chrysurus	Yellowtail damselfish	N	4
	*Stegastes diencaeus**	Longfin damselfish	Y	5
	*Stegastes partitus**	Bicolor damselfish	Y	5
	*Stegastes planifrons**	Threespot damselfish	Y	5
	Azurina cyanea	Blue chromis	N	3

	Azurina multilineata	Brown chromis	N	5
Priacanthidae	*Heteropriacanthus cruentatus*	Glasseye snapper	Y	5
Scaridae	*Scarus iseri**	Striped parrotfish	Y	5
	Scarus taeniopterus	Princess parrotfish	N	4
	Scarus vetula	Queen parrotfish	Y	2
	Sparisoma aurofrenatum	Redband parrotfish	Y	5
	Sparisoma rubripinne	Yellowtail parrotfish	Y	1
	Sparisoma viride	Stoplight parrotfish	Y	4
Sciaenidae	*Eques punctatus*	Spotted drum	N	1
Serranidae	*Hypoplectrus chlorurus*	Yellowtail hamlet	N	1
Tetraodontidae	*Sphoeroides spengleri*	Bandtail puffer	N	1
	Canthigaster rostrata	Sharpnose puffer	N	1

(*Species with previous recordings that are not publicly available.)

We analyzed the first five minutes of a PAM recording collected on Dec 17, 2023, on the co-located SoundTrap (seen in Fig. 5). We identified and manually annotated 675 fish sounds in this five-minute section. Using our library of reference sounds, we were able to determine distinct characteristics such as frequency range, number of pulses, and pulse rate, along with a qualitative comparison with the acoustic library for some of the most common species on the reef. We used this information to identify unique species-specific sounds, such as multi-pulsed calls produced by *Clepticus parrae, Stegastes partitus*, and *Azurina multilineata,* with the latter typically occurring at higher frequencies and containing fewer pulses. Other Pomacentridae species produce similar pulsed sounds in similar frequency ranges; therefore, in cases where we were uncertain about any one specific species, we identified these sounds to the family level. There were many sounds that we were not able to identify, largely low-frequency, extremely quiet, or harmonic sounds produced by fish that we either do not yet have a substantial set of sounds for or have not yet recorded. In these cases, we grouped the unknowns into 13 distinct acoustic classes based on similarity (Fig. 7). The wide range of unknowns shows the incredible diversity in sounds and likely cryptic species in even a short excerpt of a PAM recording. Given the long-term recording capabilities of PAM devices and our ability to continuously grow a robust library of confirmed fish sounds, it is likely that these unknown sounds will become identifiable, and the number of species that can be confirmed through PAM recordings will grow.

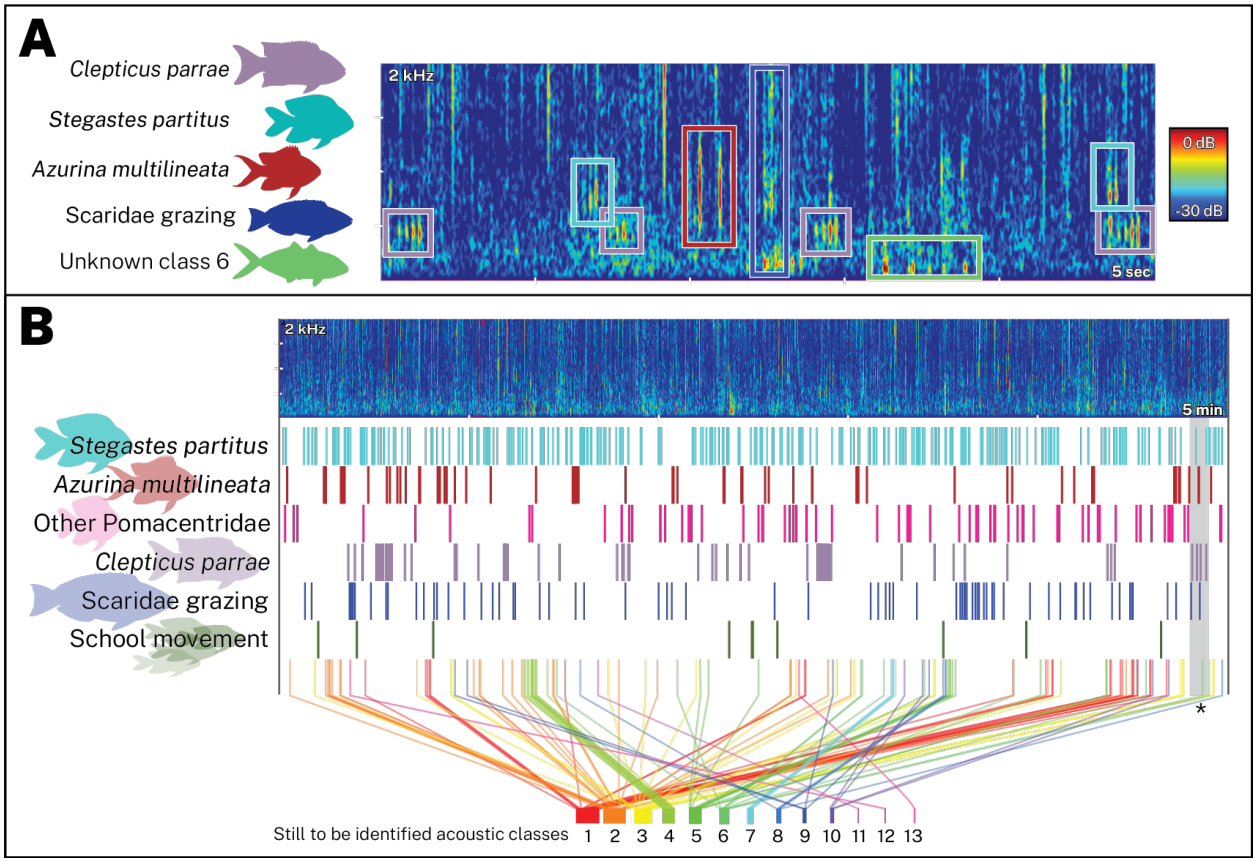

Fig. 7. Identification of species-specific sounds in archival passive acoustic recording. (**A**) Spectrogram of a representative 5 s segment of sound, showing the labeling of five classes of sounds, three to species level (*C. parrae*, *S. partitus*, *A. multilineata*), parrotfish feeding sounds, and a class of sounds of an unidentified species. (**B**) Spectrogram of representative 5 min of archival audio with three classes of sound to species, two classes to family, one class to a behavioral category, and 13 classes of unidentified sounds, with the occurrence in time labeled by a colored bar. *The grey box on the right corresponds to the 5 s spectrogram visible in panel (A). The sound was recorded on a SoundTrap ST600, at 8 kHz sampling rate, 16-bit depth. Spectrograms (frequency in kHz x time) are made using Raven Pro 1.6.5, Hanning window, 256-point FFT, 75% overlap.

Discussion

We have developed an approach that enables the ability to match species with sounds in crowded and complex systems. We have demonstrated the capabilities of this approach for Caribbean reef-associated fishes, but the technique is applicable to reefs around the world as well as in other environments with clear water and fish diversity. We have identified the sounds of many new species, but many more sonic species remain. Therefore, much more sampling and analysis need to be done.

Using reference sounds for analysis

Manually cross-referencing sounds in a PAM recording with validated IDs (e.g., see Fig. 7) is labor-intensive and not scalable. Therefore, automated detector algorithms are required to extract patterns from months or years of PAM data. These detectors can either be traditional feature-based or ML-derived, with ML detectors offering the most promise for fine-scale distinguishing between the sounds many fish make, for which species classification is more challenging than for taxa like birds or whales. The development of both approaches has been stymied for fishes by the lack of sufficient ground-truthed acoustic data sufficient for species identification (Yassir et al. 2023). For ML, the lack of data annotation and class imbalance has led to a reliance on unsupervised approaches, which leads to low classification accuracy and generalizable applicability (Mouy et al. 2024). Traditional models have also struggled to advance without sufficient ground truth information or the capacity to support multiclass supervised approaches, which have proven effective for other taxa (van Merriënboer et al. 2024), particularly birds. Our acoustic library provides this ground truthing of species identification and behavioral context, addressing these shortcomings for both types of models, thereby assisting in the model development that will be necessary to gain the important insights that can come from long temporal and high spatial resolution datasets (Tuia et al. 2022).

Not every sound is common enough on reefs to avoid class imbalance. In these cases, researchers can use identified sounds from reference collections to qualitatively or quantitatively identify the same sounds in their own recordings or publicly available PAM survey data, allowing them to start aggregating validated sounds to build a training dataset for ML models. Publicly accessible reference libraries, such as the one we are building and other global efforts (Parsons et al. 2022, Looby et al. 2023b), will play a critical role in broadening the accessibility of sounds and enable multiple groups to use publicly available data to analyze their sounds.

However, building a larger set of UPAC-360 validated sounds for each species will be important, as will a wider spatial and geographical application of this approach. Little is known about how fish sounds change with factors such as locality, temperature, and depth, and similar questions remain for reef ecosystems in the Indo-Pacific. As with other taxa, sounds may vary by population (dialects) (e.g., Parmentier et al. 2005). The sounds may point to cryptic species divergence (Parmentier et al. 2022), which would also compromise the geographic applicability of detectors. Therefore, the ID work needs to be applied to more locations and for longer periods to amass larger validated sets. By building a robust and diverse sound repository, we can address data gaps, enabling the development of machine-learning tools that support more effective and scalable monitoring (Ditria et al. 2022).

Behavioral context - more than just species ID

The primary purpose of building a publicly available library of reference fish sounds is to enable the decoding of soundscape recordings made with PAM devices (Mouy et al. 2024). Most conservation-relevant ecological inferences and applications (e.g., presence/absence for direct measures of biodiversity, indicator, and invasive species detection; Fig. 1) can be measured from PAM using just acoustic IDs. But our UPAC-360 method captures more than just sonic IDs; we also capture a record of the behavioral context. The system is semi-autonomous, running unattended for hours once deployed, allowing us to capture natural behaviors (e.g., agonistic, mating/territorial displays, grazing; Movie S3). Because the device has a 360° FOV, we often see the entire context of acoustic events without losing track of individuals that come in and out of the FOV of traditional video. Thus, we gain insights into behaviors that are largely absent from previous studies, few of which have any confirmed behavioral context for their sounds (Looby et al. 2023a). Changes in fish behavior may serve as a leading indicator of ecosystem regime shifts or outcomes of conservation interventions.

Figure 8 (Movie): Determining behavioral context of sounds. Sounds and associated behaviors of (**A**) *Halichoeres garnoti*, Yellowhead Wrasse (**B**) *Stegastes partitus*, Bicolor Damselfish, (**C**) *Myripristis jacobus*, Blackbar Soldierfish, (**D**) *Sparisoma viride*, Stoplight Parrotfish, (**E**) *Acanthurus coeruleus*, Blue Tang, (**F**) *Aulostomus maculatus*, Atlantic Trumpetfish, and (**G**) *Scarus iseri*, Striped Parrotfish. In many cases, the behavioral context is clear, while others are still unknown.

PAM with species ID can address data deficiencies

Marine conservation suffers from significant data deficiencies, making it challenging to formulate actionable policies to address biodiversity loss and coral reef decline (Hochkirch et al. 2021, Langlois et al. 2022). This results in mismanaged Marine Protected Areas (Grorud-Colvert et al. 2021). Coupling technology with traditional methods has proven to progress conservation action (e.g., eDNA and visual surveys; Muenzel et al. 2024). International organizations, such as the United Nations, the International Union for Conservation of Nature (IUCN), the Convention on Biological Diversity (CBD), and the World Bank, have established ambitious conservation goals and metrics (Colglazier 2015, Keith et al. 2015). However, indices to meet these goals are under debate and often unattainable with current technologies, requiring novel approaches (Diaz-Sarachaga et al. 2018). Our methodology and application highlight the power and potential growth of conservation approaches by integrating acoustic monitoring with ongoing efforts, providing tools to evaluate ecosystem health through the actionable metrics outlined in Fig. 1.

Species-specific identifications and passive acoustic recording techniques offer a promising solution to further close the gap of enabling continuous, scalable, and adaptive monitoring (Grorud-Colvert et al. 2021). Conventional monitoring strategies often lack the spatial and temporal resolution necessary for actionable change. While eDNA monitoring is increasingly seen as the primary tool to address data deficiencies, PAM with verified ID has greater spatial and temporal precision, allowing the detection of specific events or places that need protection. This precision is also required to monitor specific impacts, such as spill-over effects of MPAs on surrounding fisheries, as well as the range of those effects. This type of precision and scale are going to be required as KPI if the types of large-scale financing efforts that are growing in prevalence are to have their intended scale of impact.

Rates of biodiversity and habitat loss are at an unprecedented high (Dirzo et al. 2014), and conventional monitoring approaches are insufficient to address these challenges (Langhammer et al. 2024). Classified sound data offer the resolution needed to answer questions about species distributions, abundances, habitat requirements, and threats. Long-term acoustic monitoring provides spatial, temporal, and historical insights that enable global applications. Moreover, acoustic sensors are becoming increasingly affordable and widely implemented across conservation sites. Advancements in technology, such as distributed acoustic systems, are further enhancing spatial resolution beyond single-sensor applications. These are factors that are leading to the growth of PAM in terrestrial and marine habitats around the world. Adding verified IDs to PAM techniques can similarly make acoustics a transformative tool for the conservation of the coral reefs and other nearshore fish habitats that support hundreds of millions of lives, contain a disproportionate level of biodiversity and suffer a disproportionate share of the impacts of climate change and direct human degradation.

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Authors declare that they have no competing interests.

Data and materials availability:

Representative data on each species will be available for open downloading at library.fisheyecollaborative.org for use under a CC BY-NC-ND license. The metadata for all media specimens follows Darwin Core standards and will be published on the Global Biodiversity Information Facility (GBIF). Additional data are available by request. All software algorithms are in the public domain and are referenced.