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Characterization of the fish acoustic communities in a Mozambican tropical coral reef

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ABSTRACT: Coral reefs are biodiversity hotspots in urgent need of protection in most areas of the tropical belt due to increasing local anthropogenic pressures and climate change. Sounds produced by fishes are an important component of soundscapes in these ecosystems, making passive acoustic monitoring (PAM) an effective tool to map the presence of target species or to estimate changes in biodiversity. The present study aims to identify sound-producing fishes in Mozambican coral reefs based on the literature and to catalogue fish sound types recorded *in situ*. Based on the literature, we found 183 potentially soniferous species and 29 soniferous species with characterized sound production. Using acoustic recordings from coral reefs near Mozambique Island in March–April 2017 and 2018, a total of 47 putative fish sound types were recognized, from which the 37 most common were further characterized for several temporal and spectral features. A dichotomous classification of the major fish sound categories was prepared. Additional video recordings allowed identification of 4 sound-producing species: *Chromis weberi*, *Dascyllus trimaculatus*, *Amphiprion akallopisos* and *A. latifasciatus*. This study provides the first fish sound library for Western Indian Ocean coral reefs. Here, we also discuss how these simple methodologies can provide baseline knowledge to acoustically monitor marine habitats like coral reefs. Such knowledge may pave the way to use sounds to assess changes in single-fish species or reef fish biodiversity.

KEY WORDS: Passive acoustic monitoring · Mozambique · Coral reefs · Fish sounds · Acoustic communication · Acoustic hotspot

1. INTRODUCTION

Although coral reefs cover less than 1% of the ocean floor, they contain more than a quarter of all known marine species (Holbrook et al. 2015), supporting a high diversity of fishes and providing goods and services to tropical maritime countries (Moberg & Folke 1999). Nevertheless, increasing anthropogenic pressures such as land-based pollution, overfishing, and climate change have posed a threat to coral reefs worldwide (Hughes et al. 2017, Bellwood et al. 2019). To address impacts and monitor coral reef habitats, passive acoustic monitoring (PAM) may offer a fast, non-invasive method for assessing ecosystem health and fish biodiversity, providing key information for conservation and management (Luczkovich et al. 2008, Bertucci et al. 2016, Elise et al. 2022). PAM captures the underwater acoustic land-

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scape or 'soundscape' and can be used to monitor biological ('biophony'), geophysical ('geophony') and human-made sounds ('anthropophony') (Farina 2013). By eavesdropping on local acoustic processes, PAM can unveil ecosystem health changes by monitoring acoustic communities (e.g. Tricas & Boyle 2014) and anthropogenic sounds (Ferrier-Pagès et al. 2021)

Coral reef soundscapes contain a wealth of biological sounds reflecting the activity of fishes and invertebrates (Nedelec et al. 2015). Notably, active fish sounds can dominate these soundscapes and raise the ambient sound level for extended periods (McWilliam et al. 2017). Active sounds are commonly defined as being produced intentionally by the animal (Looby et al. 2022); however, in several cases, further studies are needed to classify the sounds according to their intentionality. The most conspicuous sounds intentionally produced by fishes are communication signals that play a major role in the behaviour of many fish species, namely in territorial defence and reproduction (Amorim 2006). For example, some damselfish (Pomacentridae) males make 'chirps' (trains of pulses) while advertising their territory or courting a female and can repeat these sounds hundreds of times a day (Mann & Lobel 1995, Parmentier et al. 2016). When soniferous fishes form spawning aggregations, such as in the Pomacentridae (Gladstone 2007), Serranidae (Rowell et al. 2015) and Sciaenidae (Vieira et al. 2021), they can create a continuous sound that can propagate over great distances (e.g. up to 2 km, Raick et al. 2021). Moreover, fish soniferous activity exhibits spatial and temporal patterns providing insights into the ecology of vocalising fish species (e.g. McWilliam et al. 2017, Vieira et al. 2022). Fish vocalisations thus constitute a major ecosystem feature accessible through PAM in coral reef habitats.

Documenting biotic sound sources is fundamental to assess sounds both individually and as components of the whole soundscape (Mooney et al. 2020). However, the increasing use of PAM in aquatic environments is raising awareness on the lack of knowledge regarding biological sound sources, namely fish sounds (Rountree et al. 2020, Looby et al. 2022, Parsons et al. 2022). The objective of the present study was to catalogue and describe fish sound diversity from coral reefs around Mozambique Island off the north-eastern coast of Mozambique. The coastline of Mozambique is rich in coral reefs, which constitute an important resource for fisheries and marine ecotourism activities (Pacule et al. 1996, Bjerner & Johansson 2001). However, the exponential demographic growth and increasing resource extraction is creating increasing pressure on these ecosystems (Costa et al. 2005, Obura et al. 2019). Therefore, this study ultimately aimed to investigate the acoustic fish community from these reefs to allow establishing PAM as a non-invasive method to monitor changes in the fish communities and, as such, inform management measures.

2. MATERIALS AND METHODS

2.1. Study area

Field work was conducted around the Island of Mozambique, located in a bay in northern Mozambique (15° 02′ 3″ S, 40° 44′ 8″ E; Fig. 1). This area is delimited from the ocean by a barrier reef and is home to habitats as varied as coral reefs, seagrass beds, beaches and sandy bottoms (coral sand), mangroves and mud bottoms. The barrier creates small islands of coral origin, such as Sete Paus, Goa and Cobras Islands.

2.2. Fish community and reported soniferous species

To identify soniferous or potentially soniferous species (see below) present in Mozambican coral reefs, a bibliographic search was conducted using the fauna reported by Pereira et al. (2003). For each species described for the Mozambican coral reefs, a literature search was conducted to determine if it was reported as being soniferous. The search was performed on Google Scholar with the terms 'vocal', 'call', 'sound', 'sound production' or 'acoustic' and the names of the species. Only the first 2 result pages were considered since prior ad hoc testing showed that after the first page, no relevant publications were included. Additionally, the databases FishSounds and FishBase were consulted for each species (Froese & Pauly 2023, Looby et al. 2023). Grey literature was not excluded. References used are listed in Table S1 in Supplement 1 at www.int-res.com/articles/suppl/m727p143_supp/. Fish species not described as soniferous were classified as potentially soniferous if belonging to families containing soniferous species; otherwise, the species were classified as potentially non-soniferous (as reported by Rice et al. 2022).

2.3. Acoustic recordings

Soundscapes were recorded through 33 deployments of ca. 24 h using autonomous custom-made

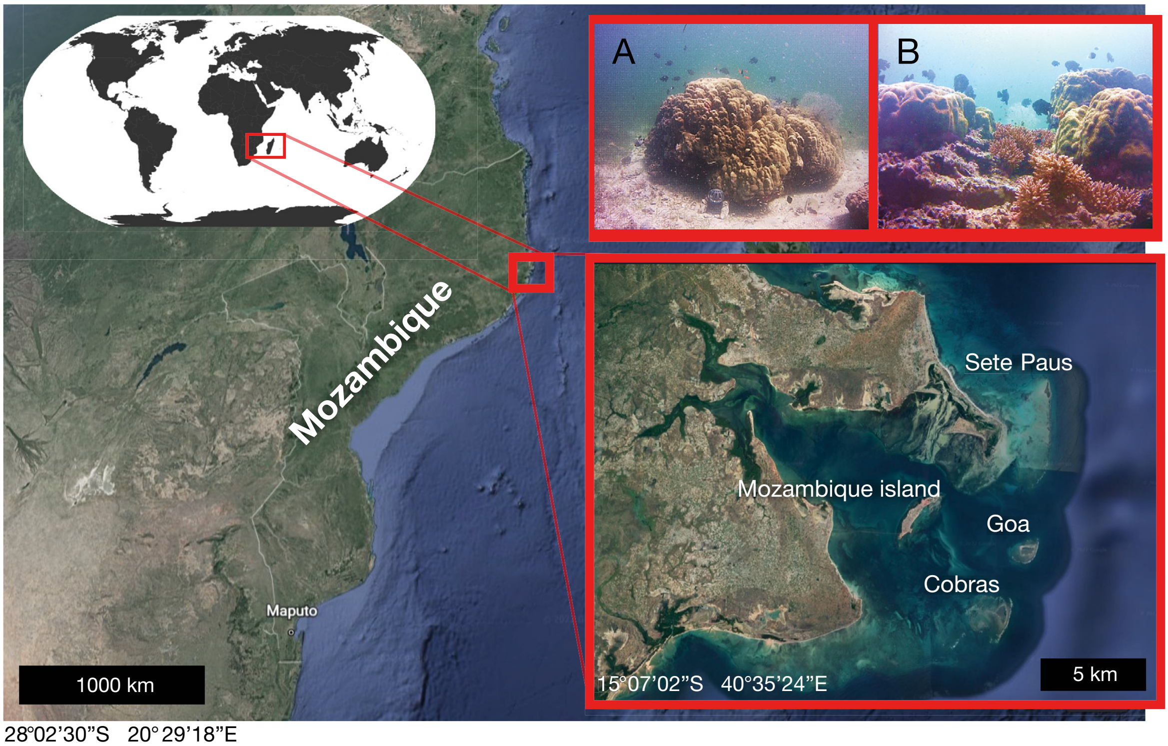

Fig. 1. Mozambique Island and surrounding areas where recordings were made. (A,B) Examples of 2 recording sites. Satellite images were obtained from Google Earth (earth.google.com/web/)

sound recorders at different sites in the study area (deployments occurred opportunistically in April–May of 2017 and 2018). The selection of the sampling sites was based on the variability of the reef in this area, also considering archaeological remains, highly fished areas and locations used in underwater touristic activities. The recorders were bottom-moored using a concrete 'donut' and registered ca. 24 h at each site at a depth of 3–12 m, mainly in the inner part of the reef including both relatively undisturbed and intensively human-impacted areas. Recorders were very stable and well supported in the water currents. Recordings were performed continuously at a sampling rate of 44.1 kHz (16 bit). Three custom-made data loggers were used with different transducers. One of the recorders was equipped with an HTI 94 SSQ hydrophone (sensitivity of −165 dB re 1 V/μPa, flat frequency response up to 6 kHz ± 1 dB; High Tech) while the other 2 used a commercial piezoelectric ceramic disc transducer (Ø 35 × 0.47 mm). The acoustic loggers used a Raspberry Pi 4 model B microprocessor board powered by a 10 000 mAh power bank. A PVC cylindrical box was used to encapsulate the recording devices. Sensitivity of these custom-made recorders was not characterized, but Fig. S1 in Supplement 1 compares acoustic recordings between the research-grade hydrophone (HTI 94 SSQ) and the piezoelectric disc.

2.4. Acoustic analysis

Fish vocalisation sounds were manually annotated through both visual and aural inspection of the recordings using Raven Pro Sound Analysis Software 1.6 (Cornell Lab of Ornithology; K. Lisa Yang Center for Conservation Bioacoustics, 2023). Fish-like sounds were identified based on their similarity to reported fish calls, frequency range and duration. Generally, marine fish acoustic signals are low-frequency sounds (usually with most energy below 3 kHz but mostly under 1 kHz; Amorim 2006) that can differ among species by their spectral characteristics, number of pulses or pulse period, potentially allowing for species identification (Amorim et al. 2008a, Colleye et al. 2011). Note that while fishes may also produce sounds incidentally as the result of other activities and not for the purposes of communication (Looby et al. 2022), this catalogue considers what appears to be conspicuous active sounds comparable with known fish communication sounds. Given the challenge to manually analyse our full acoustic dataset, the data were subsampled. To account for daily variability, the acoustic recordings were analysed according to time of day (Mozambique time zone: GMT+2): 05:30–06:00 h (dawn), 11:30–12:00 h (mid-day), 17:00–17:30 h (dusk) and 23:30–00:00 h (mid-night), providing 2 h for data analysis per deployment. We analysed 66 recording hours (2 h on each of the 33 days recorded). When possible, at least 8 sounds with good signal to noise ratio (SNR) were selected for further sound type (ST) characterization. The following acoustic parameters were measured using Raven Pro 1.6. When sounds were pulsed (for more about classification of STs based on spectral characteristics and the existence of a pulse structure, see Winn 1972, Fine et al. 1977, Lobel et al. 2010), sound duration (s), pulse period (ms), pulse duration (ms) and number of pulses were considered. For all sounds, spectral parameters were measured from power spectra (Hanning window, 2048-point Fast Fourier Transform (FFT), resolution 21.5 Hz): peak frequency (frequency with the highest energy in the power spectrum, Hz); minimum and maximum frequency (the lowest and the highest frequencies manually measured for each sound, Hz); centre frequency (the median frequency, Hz); first and third quartile frequencies (Q1, which represents the frequency at 25% of the spectral frequency range, and Q3, which provides the frequency at 75%, Hz); 90% frequency bandwidth (difference between the 5 and 95% frequencies, Hz); and peak frequency contour (PFC) average and maximum slope (the average and maximum slope of the array of peak frequency measurements for the spectrogram slices in a selection, Hz ms^{-1}). Based on visual and aural inspection of the putative fish sounds, an ad hoc classification of STs was made.

2.5. Video recordings and analysis

In an attempt to uncover some of the sound-producing species, additional video recordings were obtained at the same sites in the months of April and May 2022. The recordings were performed using paired underwater action video cameras positioned back to back (YI Discovery Action Camera, YI Technology). We recorded in 4 different areas at each site, usually 15 min in each area. All videos were visually and aurally inspected for situations where the sound-producing fish could be recognized.

2.6. Multivariate analyses of putative fish sounds

To determine the similarity among the described STs and confirm their categorization as different STs, a flexible discriminant analysis was performed (Hastie et al. 1994). Because pulse period and duration were only measured in pulsed sounds, separate analyses were used for pulsed and continuous sound categories. Preliminary analysis considered all sound variables. However, since several features were highly correlated (peak, centre and Q1 frequencies, and sound duration and number of pulses, had Pearson correlation coefficients higher than 0.5), only the most non-redundant variables were selected for each model (according to partial Wilks' lambda). Although minimum and maximum frequency can be very informative to perform visual inspection of spectrograms, these variables were excluded from this analysis because of their subjectivity. For pulsed sounds, the final model for sounds with more than 1 pulse contained pulse period, pulse duration, number of pulses, Q1 and Q3 frequencies, 90% frequency bandwidth and PFC maximum slope. In a separate model for sounds with only 1 pulse, pulse period and number of pulses were excluded. The model for continuous sounds used sound duration, Q1 and Q3 frequencies, 90% frequency bandwidth and PFC maximum slope. This statistical analysis was conducted in R using the packages 'mda' and 'rrcov' (Hastie 2017, Todorov & Todorov 2022).

3. RESULTS

3.1. Fish community and reported soniferous species

The Mozambique shallow coastal reefs were found to host at least 230 fish species, of which 29 species were confirmed as soniferous and 181 as potentially soniferous (Fig. 2), while only 20 were considered possibly non-soniferous species (note that non-soniferous species may be shown to produce sounds upon further study; Table S1). The soniferous species (Table 1) belong to 11 different families: Acanthuridae (2 species); Chaetodontidae (3 species); Holocentridae (4 species); Lutjanidae (1 species); Pomacanthidae (2 species); Pomacentridae (7 species); Scorpaenidae (1 species); Serranidae (1 species); Balistidae (5 species); Ostraciidae (2 species); and Sphyraenidae (1 species). All soniferous species documented in the Mozambican coral reefs have a conservation status of either 'Least Concern' or 'Not Evaluated' on the IUCN Red List and occur, at least partially, at 10 m or shallower depths. The families that include soniferous and potentially soniferous species produce mostly pulsed sounds but also some tonal sounds. Table 2 summarizes some of the sounds known in these families.

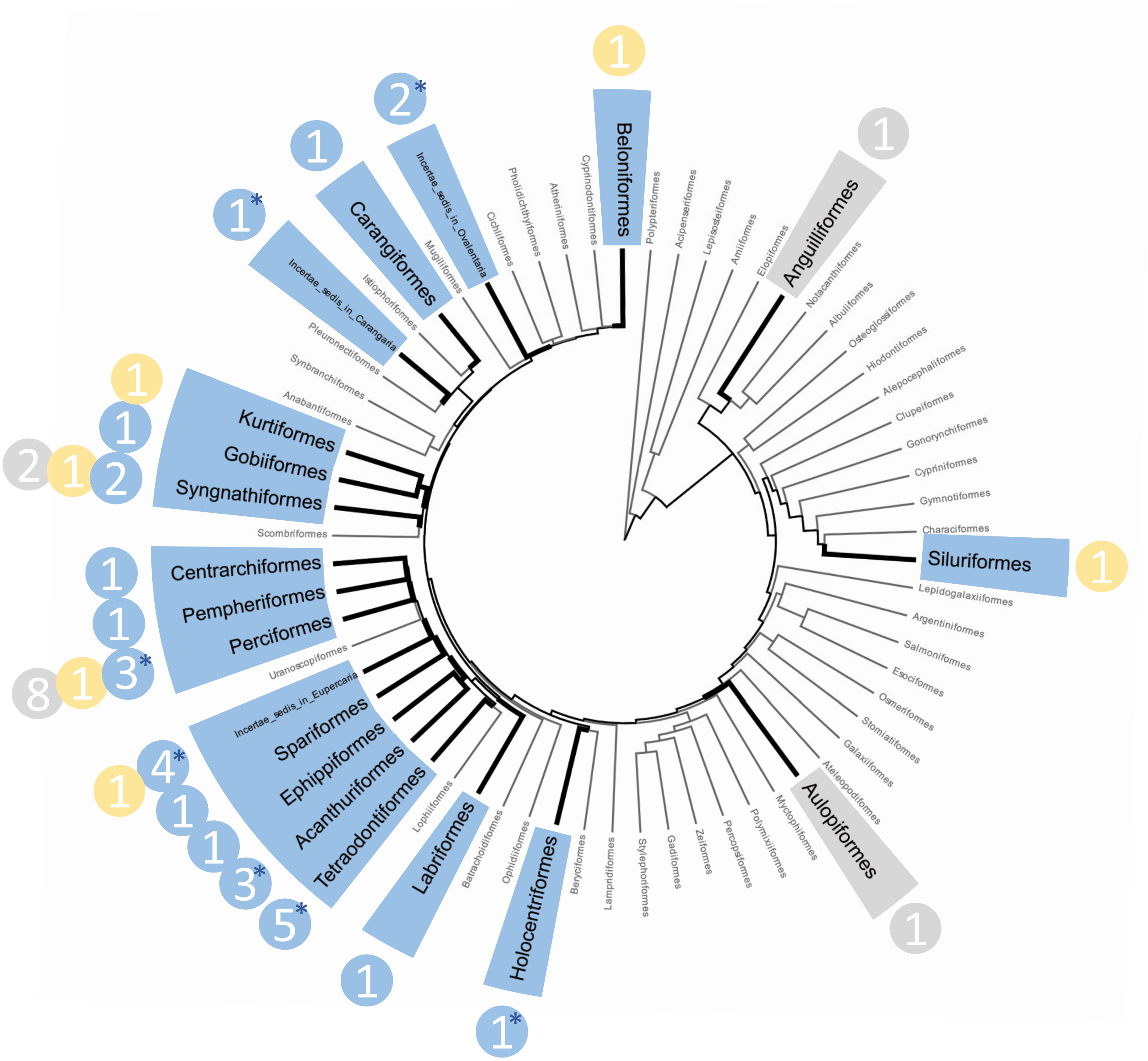

Fig. 2. Order-level phylogenetic tree of actinopterygians, depicting the presence of soniferous fishes in Mozambique reefs (coloured orders). In total, based on the species reported by Pereira et al. (2003), 29 soniferous species (see Table 1), 184 potentially soniferous species and 20 possibly non-soniferous species were recognized. Soniferous families were defined according to Rice et al. (2022), and the phylogenetic tree is based on Rabosky et al. (2018)

3.2. Characterization of fish sounds

STs were grouped into 8 different categories that were defined according to sound characteristics and previous description of fish sounds (Table 3). Fish sounds were initially grouped into 2 main categories: pulsed sounds and continuous sounds. Pulsed sounds are stereotyped or irregular signals with duration ranging from <100 ms to ca. 3 s, composed of single pulses or pulse trains. Thus, pulsed sounds were grouped in single or 2 pulsed sounds and pulse trains, with pulse trains subdivided into sounds with similar pulses and sounds with easily distinguishable different pulses. Moreover, pulsed sounds were also

Table 1. Summary of soniferous fish species reported within the Mozambique Island reefs. Conservation status from IUCN (2022): LC: Least Concern; NE: Not Evaluated. Depth ranges from FishBase (Froese & Pauly 2023) and IUCN (in brackets). Table ordered alphabetically by family

Species	Family	Conservation status	Depth range (m)	Reference for sound production
Ctenochaetus strigosus (goldring bristletooth)	Acanthuridae	LC	1–113	Tricas & Boyle (2014)
Paracanthurus hepatus (palette surgeonfish)	Acanthuridae	LC	2–40	Fish (1948)
Balistapus undulatus (orange-lined triggerfish)	Balistidae	NE	2–50	Raick et al. (2018)
Melichthys niger (black triggerfish)	Balistidae	LC	0–75	Tricas & Boyle (2014)
Rhinecanthus aculeatus (lagoon triggerfish)	Balistidae	NE	0–50	Raick et al. (2018)
Rhinecanthus rectangulus (reef triggerfish)	Balistidae	NE	10–20	Raick et al. (2018)
Sufflamen bursa (boomerang triggerfish)	Balistidae	NE	3–90	Tricas & Boyle (2014)
Chaetodon auriga (threadfin butterflyfish)	Chaetodontidae	LC	1–60 (1–61)	Tricas & Boyle (2015)
Chaetodon kleinii (sunburst butterflyfish)	Chaetodontidae	LC	4–61 (2–61)	Tricas & Boyle (2015)
Forcipiger flavissimus (yellow longnose butterflyfish)	Chaetodontidae	LC	2–145	Tricas & Boyle (2015)
Myripristis murdjan (pinecone soldierfish)	Holocentridae	LC	1–50	Chen (2006)
Neoniphon sammara (Sammara squirrelfish)	Holocentridae	LC	0–46 (1–46)	Chen (2006)
Sargocentron diadema (crowned squirrelfish)	Holocentridae	LC	1–60	Parmentier et al. (2011)
Sargocentron spiniferum (sabre squirrelfish)	Holocentridae	LC	1–122	Parmentier et al. (2011)
Lutjanus kasmira (common bluestripe snapper)	Lutjanidae	LC	3–265	Tricas & Boyle (2014)
Ostracion cubicus (yellow boxfish)	Ostraciidae	NE	1–280	Parmentier et al. (2019)
Ostracion meleagris (whitespotted boxfish)	Ostraciidae	NE	1–30	Lobel (1996)
Apolemichthys trimaculatus (threespot angelfish)	Pomacanthidae	LC	3–60 (10–80)	Tricas & Boyle (2014)
Pomacanthus imperator (emperor angelfish)	Pomacanthidae	LC	1–100	Thresher (1982), Amorim (1996a)
Abudefduf sordidus (blackspot sergeant)	Pomacentridae	LC	0–3	Lobel & Kerr (1999)
Abudefduf vaigiensis (Indo-Pacific sergeant)	Pomacentridae	LC	1–15	Tricas & Boyle (2014)
Amphiprion akallopisos (nosestripe clownfish)	Pomacentridae	LC	3–25 (1–25)	Parmentier et al. (2005)
Chromis viridis (green chromis)	Pomacentridae	NE	1–20	Amorim (1996b)
Dascyllus aruanus (whitetail dascyllus)	Pomacentridae	NE	0–20	Parmentier et al. (2006)
Dascyllus trimaculatus (domino damselfish)	Pomacentridae	NE	1–55	Luh & Mok (1986)
Plectroglyphidodon lacrymatus (whitespotted devil)	Pomacentridae	NE	1–40	Parmentier et al. (2006)
Pterois miles (devil firefish)	Scorpaenidae	LC	25–85 (2–80)	Beattie et al. (2017), Schärer-Umpierre et al. (2019)
Cephalopholis argus (peacock grouper)	Serranidae	LC	1–40	Tricas & Boyle (2014)
Sphyraena barracuda (great barracuda)	Sphyraenidae	LC	0–100	Fish & Mowbray (1970)

grouped according to their dominant frequencies (low and high frequency). Continuous sounds include tonal sounds with or without frequency modulation, and wideband sounds with high entropy levels. Frequency modulation refers to changes in frequency across the sound (e.g. initial frequency being different from the final frequency). Sounds that did not fit into any of the previous categories were considered 'oddities'.

We recognized 47 STs. Putative fish sounds were assigned into different categories based on their temporal (pulsed) and spectral features (Table 3, Fig. 3). From all STs, 28 were classified as pulsed sounds while 17 were continuous sounds and 2 were oddities. From those, 37 STs (each with 8–20 sound examples) presented a good SNR and were measured for several acoustic parameters (see Table S2). Table S3 qualitatively describes every ST.

3.2.1. Single or 2 pulsed sounds

Within the single or 2 pulsed sounds, Sound Type #1 (ST 1) was the most abundant fish sound, in some recordings reaching more than 50 occurrences within a 5 s window. ST 27 was the single pulsed sound with the lowest frequency components (minimum frequency around 18 Hz and Q3 frequency usually below 300 Hz), and was occasionally found in a sequence of 10–15 sounds. STs like 21.1, 21.2, 21.3 and 67 are composed of 2 pulses and can be differentiated by the spectral characteristics and by the pulse period. STs 21.1, 21.2 and 21.3 have similar structure and were initially classified as one ST, but then divided into 3 different STs. ST 67 has the shortest pulse period, around 20 ms. STs 99A, 99B and 100 are clearly distinguishable wideband pulsed sounds. Because ST 99B always occurred after ST 99A, they are probably a sequence produced by the same individual.

3.2.2. Pulse train sounds

The pulse train category includes STs composed of several pulses. STs 44 and 69 are sequences of long pulses with high pulse periods. STs 15.1, 25, 42 and 70 are grunt-like sounds. STs 8, 18, 31, 63 and 68 are very recognizable purr-like fish sounds found throughout many recordings. STs 12, 30, 32 and 41 are high-frequency sounds that occur mainly as pulse trains. Lastly, ST 29 consists of a sequence of 3 to 4 pulse units, of which the first unit has the highest amplitude. Although multiple observations suggest that this sequence of pulses is created by the same individual, we cannot exclude the possibility of these being soniferous interactions involving 2 individuals of the same species.

3.2.3. Continuous STs

We found several continuous STs which were divided into tonal frequency modulated sounds, tonal frequency non-modulated sounds and wideband sounds with high entropy levels. Most of the tonal sounds with frequency modulation exhibit a reduction in frequency along the sound. For example, ST 64 resembles a sweep rapidly decreasing in frequency. ST 46 shows a different pattern in frequency modulation; the frequency is mostly constant throughout the sound except in its final portion, which is characterized by a sharp downward slope. ST 58 is a rare sound that resembles an air-blowing sound including a clear aurally identifiable high frequency (wide bandwidth up to 4 kHz). ST 13 is a long and slightly frequency modulated sound which concentrates most of the energy at the end of the sound. STs 57.1 and 57.2 are frequency modulated sounds usually presenting 3 or more clear harmonics. STs 22, 60 and 101 are tonal frequency non-modulated sounds usually also without amplitude modulation. STs 24, 59 and 65 are amplitude modulated tonal sounds characterized by having an initial higher amplitude and wider frequency band and are mostly discriminated by the sound duration. STs 14, 15.2 and 55 are wideband sounds with an irregular structure. Note that the descriptions of STs 25, 31, 41, 51, 63 and 69 should be taken with precaution because they were rare, with few examples with a good SNR.

3.2.4. Multivariate analyses of putative fish sounds

Multivariate discriminant analyses (see text in Supplement 2 at www.int-res.com/articles/suppl/m727p143_supp/) mostly agreed with the ad hoc classification made by visual and aural inspection of the recordings. Note that these multivariate analyses were performed separately for pulsed and continuous STs (1-pulse sounds: Wilks' lambda = 0.006, $F_{6,20}$ = 234, n = 88, $p < 0.001$, accuracy = 88.37%; pulsed sounds: Wilks' lambda = 0.007, $F_{18,119}$ = 1448, n = 303, $p < 0.001$, accuracy = 61.26%, STs 12, 15.1, 21.1 and 21.3 had correct identification rate <50%; continuous sounds: Wilks' lambda = 0.0002, $F_{12,72}$ = 1473, n = 200, $p < 0.001$, accuracy = 62.38%, STs 22 and 24 had correct identification rate <50%,). See Supplement 2

Table 2. Summary of fish sounds reported for families with soniferous and potentially soniferous species in Mozambican coral reefs

Family	Known sound characteristics	References
Acanthuridae	Generally, both low-frequency single-pulsed sounds and short trains of pulses have been identified.	Tricas & Boyle (2014)
Balistidae	Some species can produce short tonal sounds (<0.1s) and pulse trains. In tropical species (including species present in Mozambique), it is noticeable that different species can produce similar sounds.	Tricas & Boyle (2014), Raick et al. (2018)
Blenniidae and Gobiidae	Many species produce low-intensity sounds, some long trains of pulses or grunt-like sounds, with several species also producing short tonal sounds. However, little information is available for tropical coral reefs.	Tavolga (1958), De Jong et al. (2007), Horvatić et al. (2021)
Carangidae	Species have been reported to produce fast grunts with wideband frequencies (0.2–5 kHz).	Fish & Mowbray (1970)
Chaetodontidae	Have been documented to produce only low-frequency single-pulsed sounds.	Tricas & Boyle (2014, 2015)
Ephippidae	*Platax teira* was suggested to produce wideband and almost tonal sounds with frequency modulation (recorded in Western Australian waters). No confirmation.	Parsons et al. (2017)
Haemulidae	Species have been reported to produce fast grunts with wideband frequencies.	Fish & Mowbray (1970)
Holocentridae	Can produce both wider-band pulses and pulse trains (<4 kHz).	Chen (2006), Parmentier et al. (2011), Tricas & Boyle (2014)
Kyphosidae	Species have been reported as soniferous but with no recent descriptions.	Fish & Mowbray (1970)
Labridae	Known to produce pulsed sounds, with 2 of 30 species described for Mozambique confirmed as soniferous. Specifically, *Thalassoma amblycephalum* emits sounds composed of 2 pulses with a short pulse period.	Boyle & Cox (2009), Tricas & Boyle (2014)
Lutjanidae	Fish belonging to the Lutjanidae were only reported to produce short knocking sounds, including *Lutjanus kasmira* that is present in Mozambique.	Fish & Mowbray (1970), Tricas & Boyle (2014)
Mullidae	*Parupeneus* spp., with 6 reported species in Mozambique emitting either short low-frequency isolated pulses or pulse trains. A relatively high-frequency pulse (averaged peak frequency around 800 Hz) was also observed in a species of the genus *Parupeneus* during courtship behaviour.	Tricas & Boyle (2014)
Ostraciidae	The 2 documented species for Mozambique emit sequences of low-frequency pulses.	Lobel (1996), Parmentier et al. (2019)
Pomacanthidae	Short train of pulses from *Pomacanthus imperator* were characterized in captivity, but qualitative reports from divers also state loud, short agonistic sounds.	Thresher (1982), Amorim (1996a)
Pomacentridae	Highly soniferous family; 7 of 25 species documented inthe Mozambique Island study area have been reported to mostly produce short pulse trains, several described as purr-like sounds.	Amorim (1996b), Lobel & Kerr (1999), Parmentier et al. (2005), Colleye et al. (2009)
Scaridae	The most common sounds reported are passive and associated with crushing of calcareous food.	Fish & Mowbray (1970), Tricas & Boyle (2014)
Scorpaenidae	Lionfish species have been reported to emit pulse trains and short tonal sounds around 250 Hz.	Beattie et al. (2017), Schärer-Umpierre et al. (2019)
Sphyraenidae	*Sphyraena barracuda* (order Carangaria) was reported as soniferous without any other recent study describing the sound production in this family.	Fish & Mowbray (1970)
Zanclidae	Have been documented to produce only low-frequency single-pulsed sounds.	Tricas & Boyle (2014, 2015)

Table 3. Description of the sound type categories found on the analysed recordings

Category				Definition
Pulsed sounds	Single or 2 pulsed sounds		Low frequency	Single or sequence of pulses, with a sound duration <0.2 s. Peak frequency below 600 Hz. Pulse duration varies from 10 to 65 ms.
	Pulse train	Similar pulses	Low frequency	Sound types with several pulses. Slow and very fast pulse rates are included in this class. Most energy below 350 Hz.
			High frequency	Most energy above 350 Hz, higher pitch clearly detected aurally.
		Different pulses		Sounds with distinguishable different pulses.
Continuous sounds	Tonal sounds	Frequency modulated		Sounds with energy restricted to a narrow frequency band. Some with harmonics. Without aural and visual detection of pulses. Frequency changes throughout the sound.
		Frequency not modulated		Little or no change in frequency throughout the sound.
	Wideband sounds with high entropy levels			Continuous sounds with no defined structure and wide frequency band.
Oddities				Irregular sounds with pulses difficult to recognize.

for a detailed description of the results obtained in these analyses.

3.3. Species identification for detected sounds

Video recordings allowed identification of some sound-producing species (Fig. 4). The most common species for which sound production was easy to detect was *Dascyllus trimaculatus* (Fig. 4A). This species, which is known to be highly soniferous (cf. Table 1), normally appeared in groups with some individuals actively producing sounds. *Chromis weberi* was the second most common species to be recorded producing sounds (Fig. 4C), but no reports were found in the literature for this species' acoustic signals. The sounds detected for these 2 species are similar to ST 8. *C. weberi* also produced another sound during agonistic behaviour that was usually more irregular and with higher entropy levels, similar to ST 15 (Fig. 4D). Although in our catalogue we include several irregular and noisier STs, the possibility of several species producing such sounds might increase the challenge of identifying the species or even of identifying these sounds as being produced by a fish.

Video recordings in proximity to anemones allowed identification of sounds from the anemonefishes *Amphiprion akallopisos* and *A. latifasciatus. A. akallopisos,* a species previously identified as soniferous (cf. Table 1), produced a high-frequency pulse train similar to ST 30 (Fig. 4B), whereas *A. latifasciatus* produced low-frequency pulses with a high interonset interval (pulse period usually >150 ms). Each pulse in this ST was similar to ST 1 (Fig. 4E). Furthermore, this species also produced a low-frequency sound with irregular pulses (Fig. 4F). This latter ST was only detected when individuals were biting rocky surfaces near the anemone (which might raise doubts about whether these sounds are intentional or incidental). Additionally, low-frequency buzzes similar to ST 101 were heard in 2 videos at the same time that some fish showed a startled response: one while a group of Acanthuridae was startled (the cause is not obvious from the video) and another while a small grouper that was slowly approaching the camera rapidly bent its body and swam in another direction. Moreover, low-frequency ST 27 sound sequences were heard in the presence of a grouper.

4. DISCUSSION

4.1. Fish community and reported soniferous species

Based on the literature survey, the Mozambique coastal coral reef waters harbour 181 potentially soni-

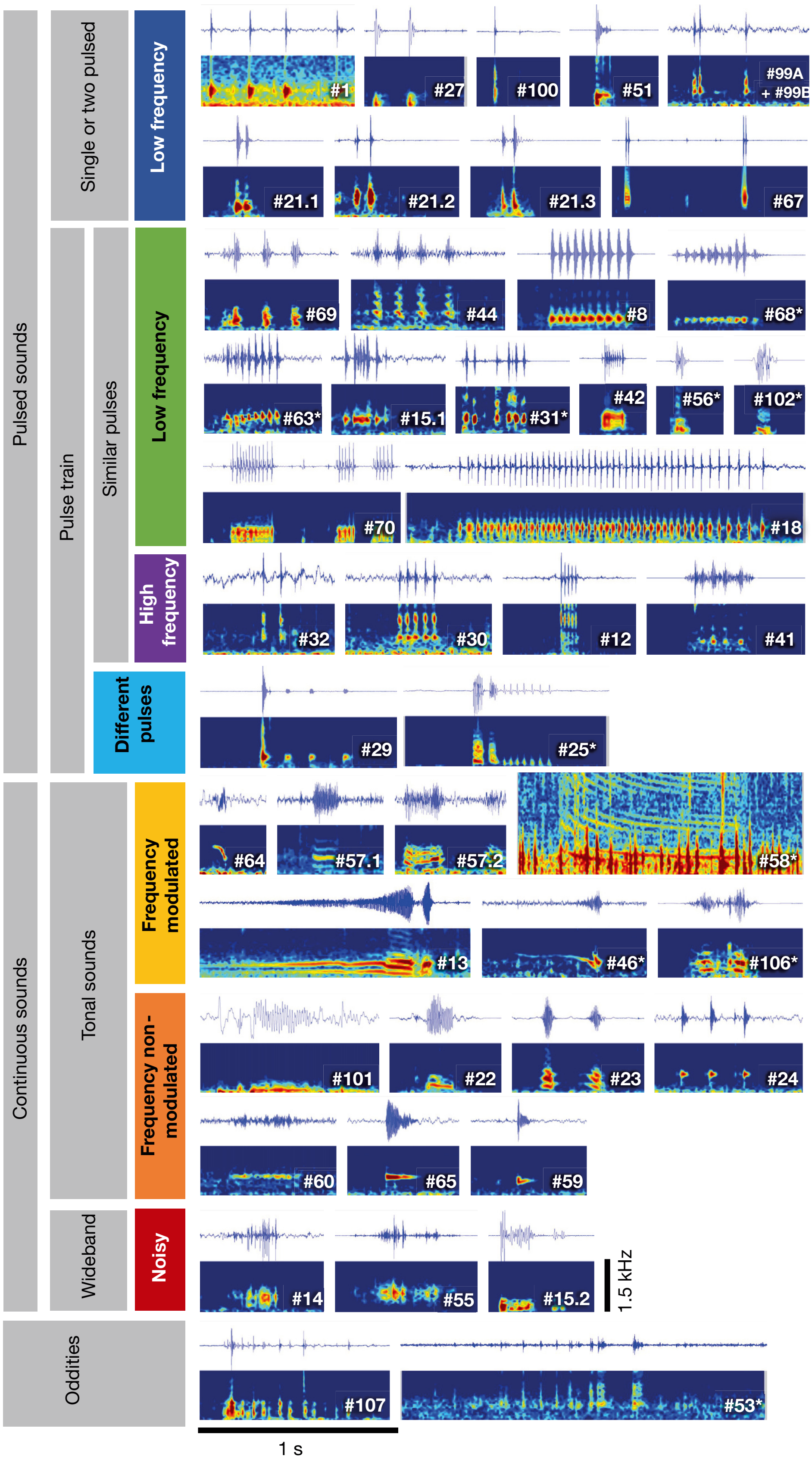

Fig. 3. Oscillogram and spectrogram representations of the 47 detected putative fish sound types. Sampling frequency for calculating these spectrograms, 6 kHz; FFT size, 128 (temporal resolution, 21.3 ms; frequency resolution, 46.9 Hz); window type, Hanning; overlap samples per frame, 50%. 'Noisy' refers to wideband sounds with high entropy levels. * indicates sound types with low number of examples to perform any additional characterization. Audio files are available on the Fish Bioacoustics Lab website (https://www.fishbioacoustics.pt/sounds)

ferous species and 29 soniferous species with characterized sound production. Similarly, a survey on French Polynesian coral reefs showed a low percentage of species effectively confirmed as soniferous (Parmentier et al. 2021). All soniferous and potentially soniferous species at our study site belong to 34 different families (18 orders), of which 6 only have qualitative reports for sound production. Sounds reported for individual species in these families can be very similar (cf. Table 2) and difficult to distinguish, which warrants additional studies. Note also that there is very limited information for each family, except for highly vocal families like the Pomacentridae.

4.2. Characterization of fish sounds

Here, a systematized classification of fish sounds based on 66 h of recordings from coral reefs near Mozambique Island is presented, where STs are grouped under 3 main categories: pulsed sounds, continuous sounds and oddities (cf. Table 3). The present catalogue allowed us to describe the fish acoustic richness in this location (see cumulative curve in Fig. S2). A total of 47 putative fish STs were recognized. The 37 most common STs were further characterized for several temporal and spectral features, from which 61–88 % were correctly discriminated by multivariate analyses, depending on sound category (1 pulse, pulsed or continuous sounds). The high number of sounds encountered is comparable to other reports from tropical coral reefs (Tricas & Boyle 2014, Bertucci et al. 2020) and further establish coral reefs as acoustic hotspots. Detected putative fish sounds occurred mainly in a spectral range below 2000 Hz, and most STs comprised aurally identifiable pulses, which is in accordance with fish sound characteristics (Amorim 2006).

Most pulsed sounds are likely from fish, as they are similar to most described fish sounds: frequency range below 1 kHz, mostly short duration and with no frequency modulation (e.g. Fish & Mowbray 1970, Amorim 2006, Looby et al. 2023). Although some species can produce more than one ST, the number of STs identified could underrepresent the real number of soniferous species because many species may produce similar sounds which, without additional studies, cannot be discriminated. For example, STs 21.1, 21.2 and 21.3 are not only similar, as pointed out by the multivariate analysis, but also very simple, which might hinder a proper distinction between them even if produced by different species. Additionally, the multivariate analysis discriminated all 1-pulse STs (accuracy = 88 %), suggesting that they might be produced by multiple species with different sound-producing mechanisms (Parmentier & Fine 2016). On the other hand, STs 99A and 99B, usually recorded in sequence, are likely produced by the same individuals.

Regarding continuous sounds, we cannot ensure that all were produced by fishes. Even though several species make tonal sounds, this is less common in fishes (e.g. toadfish: Ibara et al. 1983, Van Wert & Mensinger 2019; lionfish: Schärer-Umpierre et al.

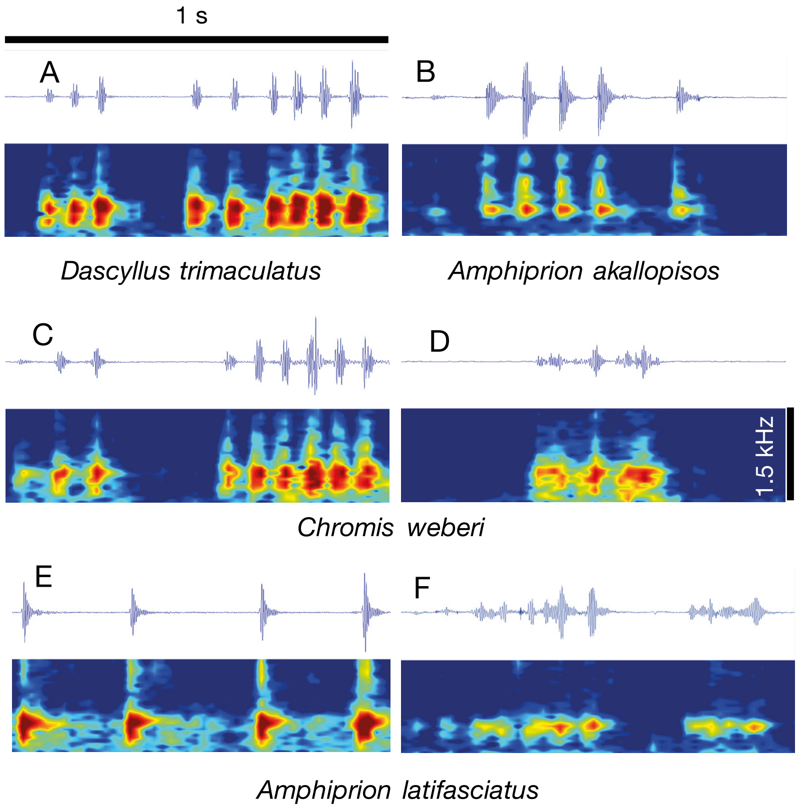

Fig. 4. Fish sounds identified using video camera deployments. Videos (S1–S4) are available at www.int-res.com/articles/suppl/m727p143_supp/. Oscillograms and spectrograms correspond to different species: (A) *Dascyllus trimaculatus*; (B) *Amphiprion akallopisos*; (C,D) *Chromis weberi*; (E,F) *Amphiprion latifasciatus.* Sounds represented in panels A and C can be included in sound type (ST) 8 (see Fig. 3), while panel D is similar to ST 5. The anemonefish sound represented in panel B is similar to ST 30, and each individual pulse in panel E would have been classified as ST 1. Note that ST 1 is the most common and simple ST detected and should include sounds produced by multiple species

2019; gobies: Horvatić et al. 2021). Furthermore, STs 24, 59, 60 and 65 are tonal sounds with a similar dominant frequency that might be produced by the same or similar sources, but further studies to identify these sources are needed. It has been demonstrated that individuals from certain species may have a wide repertoire of STs (Amorim et al. 2008b). Furthermore, Kéver et al. (2012) reported that males and females from the same species may emit distinct sounds, and even sounds from juvenile individuals can differ from those made by adults (Ladich 2015, Pereira et al. 2020).

4.3. Species identification for detected sounds

All soniferous fish species documented in Mozambican coral reefs overlap with the depth range of the autonomous recorder deployments. Most of these species are documented to produce short, pulsed sounds, and thus might be responsible for several of the single or double pulsed sounds described in this study. As reported above, several potentially soniferous species also might produce sounds that fall into this category. For example, after the comparison between fish STs found throughout the recordings and fish sounds from the existing sound libraries (see Parsons et al. 2022 and Looby et al. 2023 for a discussion about the need for more complete sound libraries), some similarities were found between the sound of *Forcipiger flavissimus* (Tricas & Boyle 2015) and ST 1. ST 102 resembles the sounds described for Balistidae species by Raick et al. (2018). However, the association of STs to particular species requires further validation.

Through video analysis, 6 sounds were attributed to fish species, including 2 species not reported before as being soniferous. *Dascyllus trimaculatus* (Fig. 4A), the most common and easy to identify as a sound source, is known to produce purr-like sounds similar to ST 8, usually accompanied by jump-like movements known as 'signal jumps' (Parmentier et al. 2009; cf. Table 1; see Video S1 at www.int-res.com/articles/suppl/m727p143_supp/). *Chromis weberi* was the second most common species detected producing sounds (Fig. 4C). Although no sounds were previously described for this species, other species of this genus are known to produce short pulse trains (e.g. *C. viridis*; cf. Tables 1 & 2). Indeed, several species in the Pomacentridae family appear to produce similar purr-like sounds that differ only in minor variations of some acoustic features, even presenting an overlap in the analysed features (Parmentier et al. 2006, 2009). The anemonefish *Amphiprion akallopisos* was observed to produce a high-frequency pulse train similar to ST 30. According to Parmentier et al. (2005), *A. akallopisos* produces 3 STs, namely chirps, long pops and short pops, with peak frequency ranging from ca. 600 to 1000 Hz. The sounds detected in our videos, such as ST 30, can be accommodated as chirps. *A. latifasciatus* produced low-frequency pulses (similar to ST 1) and could be another source of chirps detected in the recordings. No description of sounds of *A. latifasciatus* was found in the published literature. In addition, sequences of low-frequency sounds (ST 27) were heard in the presence of a grouper (unknown species). Although it was not possible to infer that this grouper produced this ST, other studies report sequences of low-frequency sounds (range between 15 and 200 Hz) for the Serranidae family (e.g. Bertucci et al. 2015).

4.4. Importance of these methodologies to document biotic sound sources

In this first analysis of the soundscape of Mozambican tropical coral reefs, the greatest impediment to further advance was the generalized lack of knowledge on these fish sounds (Mann et al. 2016). Thus, here we used 3 simple and reproducible approaches to provide basic information needed to study a fish acoustic community: (1) list soniferous and potentially soniferous species based on a literature review; (2) catalogue putative fish STs using acoustic recordings *in situ*; and (3) identify soniferous species using video cameras.

First, we estimated the number of soniferous fish species at our study site. For this purpose, we reviewed the literature for described sound-producing fishes. However, as only a small percentage of soniferous fish species has been reported thus far (Looby et al. 2022, Parsons et al. 2022, Rice et al. 2022), we also considered potentially soniferous species, i.e. closely related to known soniferous species. This approach attempts to fill in the gap for a more comprehensive inventory of fish sounds (Looby et al. 2023).

Second, we catalogued putative fish sounds found in the recordings. To facilitate the organization of a large amount of STs, we used a dichotomous classification of the major fish sound categories. We recommend the use of a dichotomous classification, as it makes fish sound categorization much more objective and reproducible. To strengthen the confidence on the defined STs, we also applied multivariate analyses. This approach reduces subjectivity and forces the user to rethink the classification, considering possible mistakes and resemblances. For this reason, it is a facultative step that we also highly recommend. Moreover, this approach can also provide insights into which classes might be difficult to recognize with machine learning.

Here, we studied coral reefs, an environment that can be classified as an acoustic hotspot. However, this methodology should be easily applied to other marine environments. For example, listing potentially soniferous species and classifying STs using dichotomous branches have been successfully used in different marine environments such as in the Mediterranean (rocky reefs: Desiderà et al. 2019; deep waters: Bolgan et al. 2020; *Posidonia oceanica* seagrass beds: Bolgan et al. 2022) and at North Atlantic Ocean shallow and deeper seamounts (e.g. Carriço et al. 2019, 2020).

In a third step, we attempted to identify sound sources, which is required for a more detailed characterization of biodiversity or when targeting individual species. We used a simple and low-cost approach: the use of action cameras to register fish behaviour and sound simultaneously, which have been shown to offer the possibility to record audio with enough reliability to document fish sounds (Chapuis et al. 2021). In this study, action cameras allowed us to identify some sound sources (see above), but in many cases it was not easy to identify the individual that was producing each sound. Often multiple species are in the camera field, the sound source can be out of sight, or the sound can be produced far away from the camera. To better understand this soundscape, future studies should include more synchronized audio−visual recordings, use of directional hydrophones or arrays of hydrophones (e.g. Mouy et al. 2023), miniature acoustic recording tags (mostly used on mammals, Johnson et al. 2009) or parallel captivity studies. Note that even though there are several studies that have been conducted to identify fish sounds in captivity (Parmentier et al. 2005, Amorim 2006, Pereira et al. 2020), new studies should follow a combination of field and captivity approaches because naturally induced sounds can be difficult to record in laboratory conditions (e.g. Bolgan et al. 2019, Mouy et al. 2023).

Even if there is a global effort to identify fish sounds and their sources, the documentation rate of known sounds will not be able to keep pace with the rate of unidentified sound detection as the use of PAM expands. Unidentified fish sounds can nevertheless provide valuable information, still allowing assessments of biodiversity and habitat health (Bertucci et al. 2020, Carriço et al. 2020). Databases with putative fish sounds with unknown sources will allow us not only to monitor the general acoustic community but also should become the basis to apply several methodologies to automate the analysis of acoustic recordings (Parsons et al. 2022). Importantly, unknown sounds can be especially relevant to monitor areas that are difficult to access, such as deep-sea areas or coastal areas during night-time, or that lack resources for more costly monitoring programmes (Carriço et al. 2020, Bolgan et al. 2022).

4.5. Local relevance

Although Mozambican coral reefs experience a range of pressures, such as climate impacts (e.g. coral bleaching, increasing severe storms) and fishing, they still retain high biodiversity (Schleyer et al. 1999[1], Obura et al. 2019). Nevertheless, previous reports have documented changes with significant effects on coral reefs due to climate change and overfishing (Hoegh-Guldberg et al. 2007, Zaneveld et al. 2016). Furthermore, the impact of human activities on the coral (e.g. through mechanical damage) and mostly on the fish, mollusc and crustacean communities is expected to get worse due to continuous fishing effort by local populations that depend, at least partially, on these activities for food and economic income (Costa et al. 2005). Therefore, alternative mitigation measures to reduce human impact on the reefs are urgently required. This research aimed to compile the basic information needed to apply PAM, a non-invasive method of simple application and reduced logistics, for monitoring fish biological communities in local coral reefs and thus support management efforts.

5. CONCLUSIONS

We show a remarkably high contribution of fish sounds to the Mozambican tropical coral reef soundscape that could be classified into different STs. Although species-specific sounds have been documented in the literature for some fishes, the vast majority of STs still lack species identification (Looby

[1]Schleyer M, Obura D, Rodrigues MJ (1999) A preliminary assessment of coral bleaching in Mozambique. South African Association for Marine Biological Research. Unpubl Rep 168. https://aquadocs.org/handle/1834/888

et al. 2022). Indeed, the present work revealed a huge shortage of information on fish acoustic communication signals in these habitats. The catalogue presented here contributes to the characterization of the acoustic diversity and complexity of biological communities in this region of East Africa and the Indian Ocean coral reefs in general and provides a stepping stone for future PAM programmes.

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