



Acoustic fish community in the Madeira Archipelago (North Atlantic Ocean): Characterization of sound diversity and daily patterns

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ABSTRACT

Marine ecosystems are increasingly subjected to anthropogenic pressures, which demands urgent monitoring plans. Understanding soundscapes can offer unique insights into the ocean status providing important information and revealing different sounds and their sources. Fishes can be prominent soundscape contributors, making passive acoustic monitoring (PAM) a potential tool to detect the presence of vocal fish species and to monitor changes in biodiversity. The major goal of this research was to provide a first reference of the marine soundscapes of the Madeira Archipelago focusing on fish sounds, as a basis for a long-term PAM program. Based on the literature, 102 potentially vocal and 35 vocal fish species were identified. Additionally 43 putative fish sound types were detected in audio recordings from two marine protected areas (MPAs) in the Archipelago: the Garajau MPA and the Desertas MPA. The Garajau MPA exhibited higher fish vocal activity, a greater variety of putative fish sound types and higher fish sound diversity. Lower abundance of sounds was found at night at both MPAs. Acoustic activity revealed a clear distinction between diurnal and nocturnal fish groups and demonstrated daily patterns of fish sound activity, suggesting temporal and spectral partitioning of the acoustic space. Pomacentridae species were proposed as candidates for some of the dominant sound types detected during the day, while scorpionfishes (*Scorpaena* spp.) were proposed as sources for some of the dominant nocturnal fish sounds. This study provides an important baseline about this community acoustic behaviour and is a valuable steppingstone for future non-invasive and cost-effective monitoring programs in Madeira.

1. Introduction

Understanding soundscapes can provide unique insights into the ocean status that reveal occurrence, and interactions between geophysically, biologically and anthropogenically driven sounds and their sources (Pijanowski et al., 2011; Miksis-Olds et al., 2018). These different sources of the marine soundscape can be divided into geophony (sounds from processes such as wind and rain), biophony (sounds resulting from animal movement or other actions, and active sounds

produced by marine mammals, fishes, and invertebrates) and anthropophony (sounds derived from human activities such as shipping or seismic surveys). The analysis of soundscapes recorded through passive acoustic monitoring (PAM) can be useful for registering communication sounds that may allow species detection and can provide important information on the ecology of marine organisms (Carriço et al., 2019; Duarte et al., 2021). Additionally, acoustic space can be considered a resource that organisms may compete for, which can be partitioned both spectrally (considering frequency characteristics of the signals) and

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temporally. Expanding from the ecological niche concept (Hutchinson, 1957), the acoustic niche hypothesis (Krause 1987, 1993) proposes that signalling behaviour has evolved to minimise overlap with hetero-specific calling individuals. If acoustic signals overlap in frequency and time, acoustic interference and/or signal masking may happen, hindering communication (Hart et al., 2021). Reports of acoustic partitioning in fishes are growing, which might give some evidence to the existence of these acoustic niches (Staaterman et al., 2013; Hastings and Sirović 2015; Ruppé et al., 2015; Bertucci et al., 2020).

Active sound production in fishes is widespread. More than 980 species of fish around the world are known to be vocal, however, this number is probably higher and it is estimated that a third of the total living fish species can produce active sounds (Rice et al., 2022; Looby et al., 2022). These sounds are species-specific and are associated with courtship, spawning, parental care, feeding, agonistic or territorial behaviours, and can be effective indicators of fish species richness and diversity in biological processes (Amorim 2006; Desiderà et al., 2019; Parsons et al., 2022). Due in part to cost reduction, and in part to technological improvements, PAM of fish sounds is becoming increasingly more common (Parsons et al., 2022; Rice et al., 2016; Tricas and Boyle 2014; Wall et al., 2012). Besides having a negligible impact on biota, PAM can support long-term field studies of fish activities across multiple temporal scales and is a useful tool in the conservation and management of vocal species (Parmentier et al., 2018). However, although many fish are vocal, only a small proportion of their sounds and repertoires have been identified (Mouy et al., 2018; Looby et al., 2022).

The Madeira Archipelago is located in the Northeast Atlantic Ocean. It is part of the Macaronesia ecoregion, which historically includes three additional archipelagos of volcanic origin: Azores, Canary Islands, and Cabo Verde (Castro et al., 2022; McIvor et al., 2022). Those archipelagos are separated from the nearby continental areas or other natural species source regions by water depths exceeding 1300–1500 m (Freitas et al., 2019). The Madeira Archipelago has a unique underwater landscape which is characterised by shelf breaks close to the shoreline, steep slopes, and large submarine tributary systems (Quartau et al., 2018; Braga-Henriques et al., 2022) that induce local upwelling and boost biological productivity in oligotrophic waters, providing in this way potential for hotspots of marine biodiversity (Gove et al., 2016). Information on coastal and shallow submerged biota has traditionally been acquired with Underwater Visual Censuses (UVC) and scientific diving (Ventura et al., 2016; Loya et al., 2019), and in the case of Madeira Archipelago they have provided very important information about marine species e.g., distribution, presence, range expansion, indications of tropicalization, and behaviour (Schäfer et al., 2019, 2021; Schäfer, 2023; Castro et al., 2021; Freitas et al., 2022; Chebaane et al., 2024). PAM can complement these traditional survey methods by overcoming some of their limitations, like sampling difficulty to access habitats, especially under adverse weather conditions, changing tides, turbidity, complex benthic structures, and nocturnal animal activity (Van Hoeck et al., 2021) as well as reduction of observer bias or artefacts that can occur in visual census due to the observer's presence (Van Parijs et al., 2009).

The Madeira Archipelago has an important fish richness, with 226 species listed in its coastal waters (Wirtz et al., 2008), including several vocal species as the dusky grouper *Epinephelus marginatus* and the Canary damsel *Similiparma lurida* (Fish and Mowbray 1970; Mooney et al., 2005). However, no characterization of the acoustic community of vocal fishes in this archipelago has been reported until now. Increasing the information about this acoustic fish community can improve and complement conservation efforts. The principal aim of this research was to provide the first descriptive reference of the marine soundscapes of the Madeira Archipelago, focusing on fish sounds, as a basis for a long-term passive acoustic monitoring program. Based on underwater sound recordings made in two marine protected areas (MPAs), the Garajau Partial Nature Reserve and the Desertas Islands Nature Reserve, we

aimed to (1) elaborate the first checklist of vocal and potentially vocal fish for the archipelago; (2) create the first fish sound catalogue for this area; and (3) analyse fish sound abundance and diversity, daily patterns of fish sound activity, acoustic partitioning, and compare possible differences between these MPAs.

2. Materials & methods

2.1. Study area

The Madeira Archipelago lies in the southwest of continental Europe and 700 km off the Moroccan coast (Schäfer et al., 2021). It consists of two populated islands: Madeira – the largest island (in which the capital city, Funchal, is located), and Porto Santo. Additionally, it includes two groups of uninhabited islands: the Desertas Islands and the sub-archipelago of the Selvagens Islands (Fig. 1). The Garajau MPA, located on the southern coast of Madeira Island and established in 1986, was the first marine reserve in Portugal and is currently managed and monitored by the Institute of Forests and Nature Conservation (IFCN 2022a). This MPA extends along 6.7 km of the coast east of Funchal city, from the shoreline to a depth of 50 m. With an approximate surface area of 3.7 km², Garajau Partial Reserve covers 0.03% of Madeira Territorial Sea (Alves et al., 2019; IFCN 2022a). Within the reserve, the harvesting, capturing, slaughtering or keeping specimens of living beings, as well as the destruction of their natural habitats, motorboat navigation, and extraction of sand or other geological materials are prohibited (rare exceptions for scientific and military purposes). On the other hand, recreational activities like snorkeling and scuba diving are allowed but require permission. The Desertas Islands have been legally protected since 1990 and became a Nature Reserve in 1995 to preserve a small colony of Mediterranean monk seals (IFCN 2022b). The Desertas MPA includes three islands (Ilhéu Chão, Deserta Grande and Bugio), adjacent islets, and the surrounding marine area up to a depth of 100 m, covering about 125 km² (IFCN 2022b). The Desertas MPA has two legal protection frameworks. The area north of Ponta da Doca and Ponta da Fajã Grande, up to a depth of 100 m, has Partial Protection Type I status. This means some natural elements are protected and human activities are allowed but regulated, for example touristic vessels. In contrast, the area south of Ponta da Doca and Ponta da Fajã Grande, also up to 100 m deep, has Full Protection status (*sensu* Grorud-Colvert et al., 2021). The goal is to safeguard the natural heritage by prohibiting human activities, except for specific scientific or military purposes. In this sense, both Garajau and Desertas MPAs include fully protected zones. The study sites were selected based on their conservation significance and the potential for using PAM as a targeted monitoring and management tool for *Epinephelus marginatus* and the Mediterranean monk seal *Monachus monachus*, two species known to be present in these MPAs and of special interest for conservation. To use PAM loggers at sea one should consider a place representative of the area to be sampled, with a convenient location for a stable deployment (e.g horizontal substrate with no risks of deposition or removal of sediments), not subject to fishing net trawling or other human extraction activities, and if possible avoiding exposure to strong currents that will induce noise in the recordings. Additionally, there is independent UVC data from these locations that can help list the most common fish species. Finally, both sites benefit from daily surveillance from park rangers. However, the Garajau MPA is closer to populated areas and dive operators, having significantly more visitors than the Desertas MPA. This proximity also provides the upside that local dive guides can assist with deploying and maintaining acoustic loggers.

2.2. Checklist of vocal and potentially vocal fish species

The checklist of coastal fish species of the Madeira Archipelago (Wirtz et al., 2008) was used as a base reference of the fish species reported in the archipelago down to 60 m depth. Given that

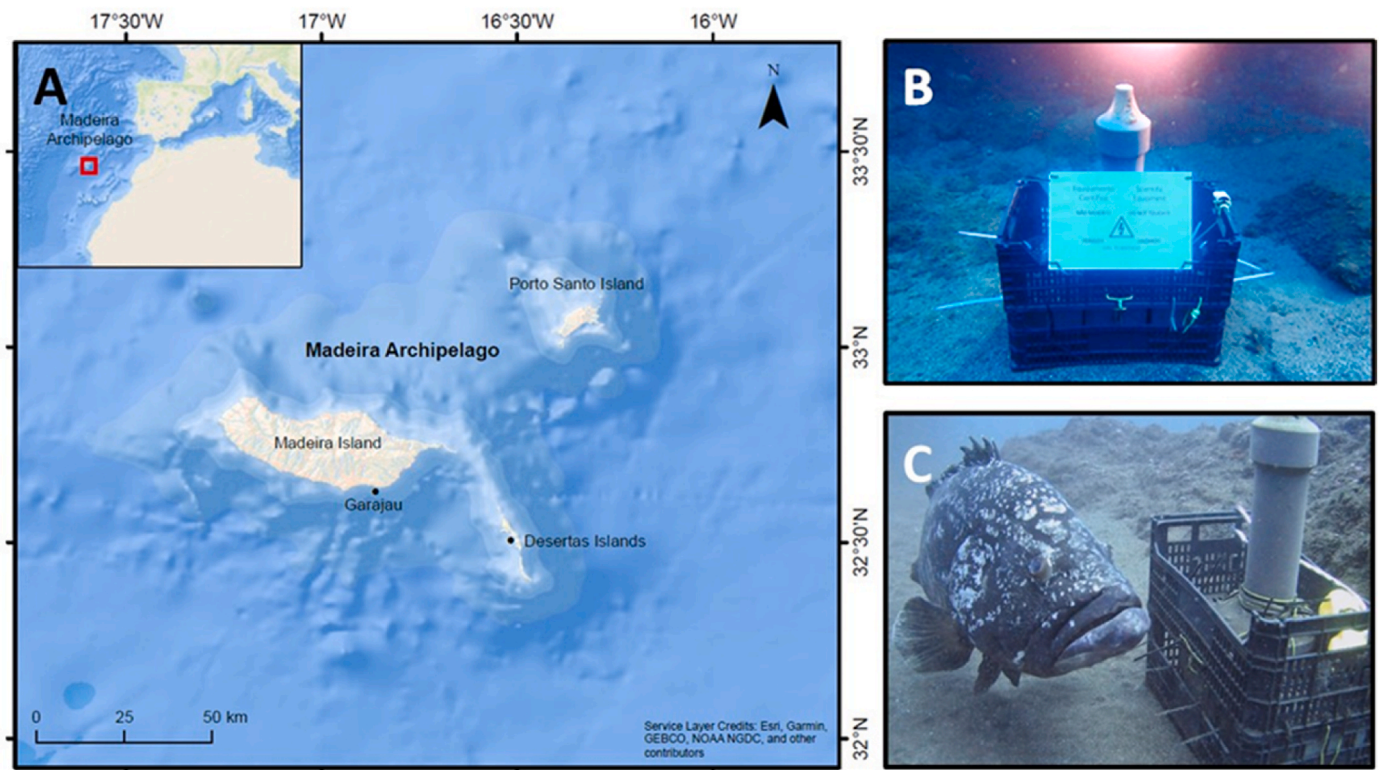


Fig. 1. Location of the acoustic data logger deployments. (A) Deployment locations in the Madeira Archipelago (black dots). Photos of (B) the Desertas and (C) the Garajau MPAs showing the typical bottom characteristics of the area around data loggers and the presence of a dusky grouper *Epinephelus marginatus*.

chondrichthyan fish species are not known to possess sonic organs or to produce sounds (Ladich and Winkler 2017), except for some stingrays (Fetterplace et al., 2022), they were not included. Likewise, any species lacking confirmation of being present in Madeira were not considered. All the species names were taxonomically updated following the authoritative Eschmeyer's Catalog of Fishes (Fricke et al., 2024).

Bibliographic research was carried out to identify species known to produce active sounds (Looby et al., 2022). Incidental sounds, like those produced by feeding or swimming movements, were not included. Each species was checked for belonging to families containing vocal species by consulting Rice et al. (2022), which includes the most comprehensive dataset of vocal fishes at the family-level. Then the ability of species to produce sounds or if they belonged to genera with vocal species was checked by consulting the open access databases and libraries Fish-Sounds (Looby et al., 2021), FishBase (Froese and Pauly 2009), Macaulay Library (2023) and The British Library (2023). Additionally, a Google Scholar search was performed using the keywords "scientific name (for each species) + sound" to look for possible additional papers or documents reporting sound production. Only the first 2 result pages were considered for relevant publications.

To propose candidates for several fish sound types identified in the recordings, two scientific divers of the Marine and Environmental Sciences Centre (MARE) in Madeira, that routinely dive in the locations where the acoustic data loggers were deployed, were asked for which were the most common fishes they observe while diving in those places. Additionally, to visually inspect for vocal fish species, a diving session was carried out in the Garajau MPA in March 2023, in the company of one of the MARE scientific divers. Photos and video recordings were obtained during this diving session using an action camera model GoPro Hero 9, configured in the automatic mode.

2.3. Acoustic recordings

One acoustic logger was deployed in the Garajau MPA (32.636588 N,

–16.853396 W; datum WGS84, depth = 28 m) and another in the Desertas MPA (32.511966 N, –16.50834 W; datum WGS84, depth = 16 m). In both cases, the loggers were positioned on the seafloor in June and retrieved in September 2021, recording ca. 3.5 months. Fig. 1 shows the location and photos of the deployments and nearby areas, which presented a low slope and a sandy substrate surrounded by several rocky formations. The acoustic loggers used for the recordings were custom-made and had low-cost data loggers (Audiomoth 1.2.0; Hill et al., 2018) connected to custom-made hydrophones (Piezo tubes PTZ-P5 with $24 \times 20 \times 20$ mm, with a custom-made signal pre-amplification of $50 \times$). The sensitivity of these custom-made hydrophones was ca. -184.5 dB re. $1\text{V}/\mu\text{Pa}$ at 1 kHz. A comparison of the acoustic recordings with a commercial SoundTrap logger is shown in Fig. S1. The acoustic loggers recorded WAV audio files at a sampling rate of 48 kHz on duty cycles of 10 min of recording and 10 min off, resulting in 72×10 min audio files per day.

2.4. Acoustic analysis

A subsampling approach was used since each audio file's visual and aural analysis was highly time-consuming, a total of eight days (four days from mid-June to mid-July and four days in September 2021) were selected. In order to sample days at regular intervals during the chosen periods, the moon phase (crescent, full, waning, and new moon) was used to select days. Similarly, four periods of 30 min (made up of three 10-min audio files) were used for the analysis on each chosen day; these periods corresponded to midnight, sunrise, noon, and sunset at each location (NOAA, 2023). A total of 32 samples of 30 min for each location were selected. The same days and day periods were analysed at the Garajau and Desertas MPAs. Considering the typical low frequency bandwidth for fish sounds (Fish and Mowbray 1970; Myrberg et al., 1978), the selected sound recordings were downsampled to 8 kHz to reduce file size and facilitate file transferring and use.

2.5. Fish sound catalogue

To determine if a sound could be considered a putative fish sound, the files were analysed aurally and visually, using Raven Pro 1.6 software (Cornell Lab of Ornithology – United States, N.Y.) to produce spectrograms (fast Fourier transform (FFT) size, 128; window, 96 points;

window type, Hann; frequency range, from 0 up to 4 kHz) and associated oscillograms, which were visually inspected. Generally, fish produce low frequency pulsed sounds that differ among species by their spectral characteristics, number of pulses or pulse period (Amorim 2006; Amorim et al., 2008a, Colleye et al., 2011). Putative fish sounds were identified based on their similarity to reported fish calls' frequency

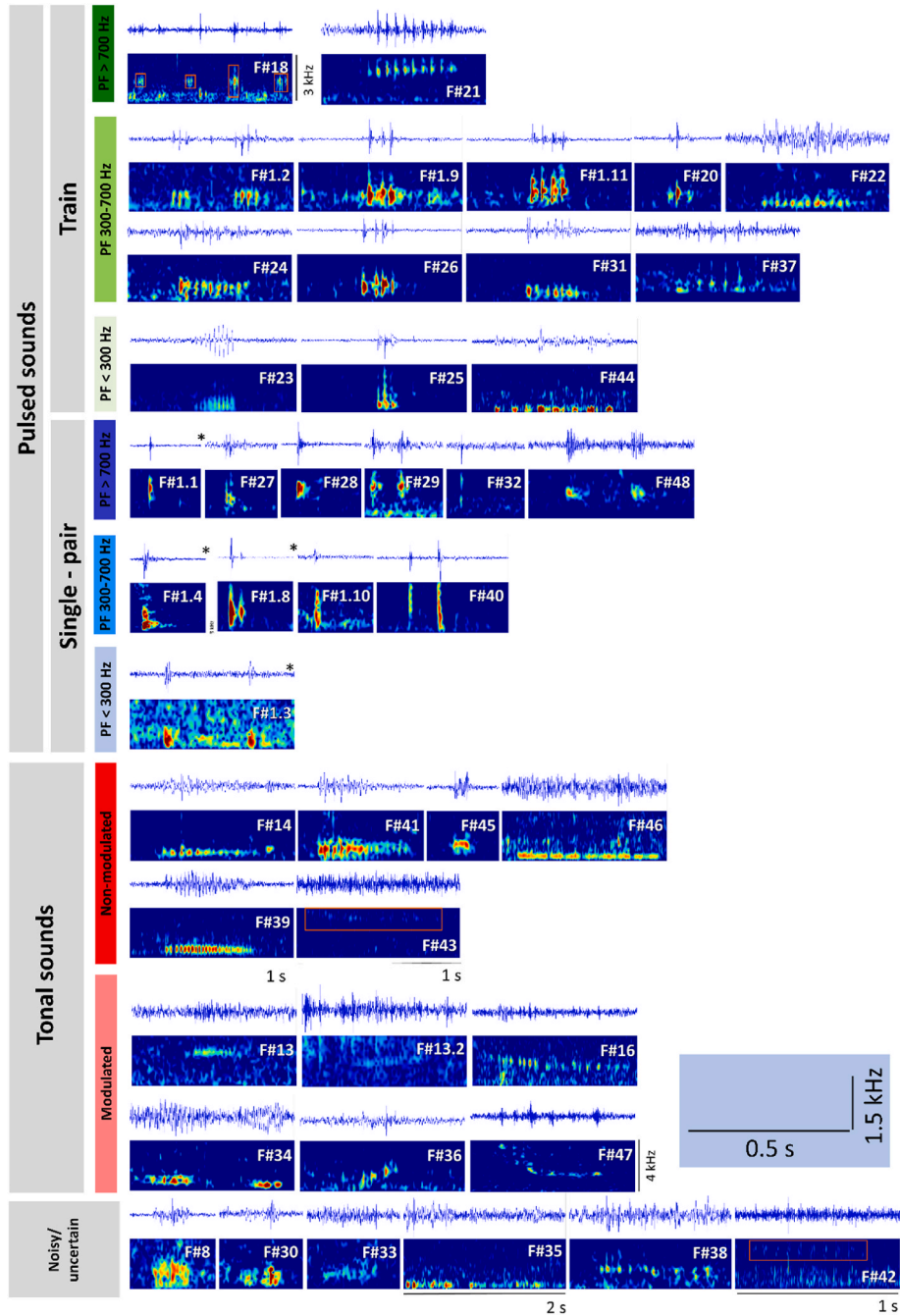


Fig. 2. Madeira fish sound catalogue. Every sound type identified is tagged with a code starting by “F#” in the spectrogram representation for each sound; the respective oscillogram representation of a given sound can be found right above every spectrogram. Spectrograms were produced with fast Fourier transform = 128, frequency range from 0 up to 1.5 kHz, and a time frame of 0.5 s. Some exceptions in the frequency and time frames are indicated with the respective scales. Warmer colours in spectrograms indicate higher sound energy. The orange rectangles in some spectrograms help to highlight the sound of interest. Sounds are organised in nine groups indicated by a colour in the title of the category. Pulsed sounds have individual pulses that can be aurally and visually discriminated, tonal sounds are in general continuous sounds with energy concentrated in a narrow band of the frequency spectrum. Tonal sounds are not necessarily continuous and may be composed by pulses, but are perceived as such through aural and visual inspection; an example is sound type F#16 in which pulses are aurally perceived as continuous. Noisy/uncertain sounds are those sounds that do not fit the previous characteristics but still were considered as putative fish active sounds. In the ‘Single-pair’ group, the (*) symbols indicate that some examples were found with more than two isolated pulses. Audio files are available on the Fish Bioacoustics Lab website (<https://www.fishbioacoustics.pt/sounds>).

range and duration. Carriço et al. (2019) descriptions and audio recordings were the main reference used. Once a sound was selected and classified as a putative fish sound, it received a sound type code in the format “F#x” where F# is constant, and x represents a serial number (which increases every time a new sound type is detected, for example: F#23, F#24, F#25, etc.). In some cases, however, some sounds were considered as new sound types but relatively similar to a pre-existing one; so the format went as “F#x.y”, having the same root code (F#x) and a second number separated by a point (.y), for example F#1.1, F#1.4, F#13.2, etc. In some other cases, some sounds initially considered possibly being produced by fish were removed after a more detailed inspection or reclassification, and their codes were discarded. A classification tree proposal to categorise the fish sound catalogue of the Madeira Archipelago (Fig. 2) was elaborated, adapting Desiderà et al. (2019) proposal. Peak frequency (PF) (Hz), first and third quartile frequencies (Q1 and Q3) (Hz), and duration (s) were measured on every annotated sound using Raven Pro version 1.6. Peak frequency is the frequency with the highest power within the selection. The first and third quartile frequencies represent the frequency at 25% of the spectral frequency range and the frequency at 75%, respectively. The sound duration was manually measured from the spectrograms. A qualitative description table for all the sound types found is provided, as well as a quantitative description table for the sound types with at least 14 occurrences (following Carriço et al., 2019) derived from manual annotations. The average, standard deviation and range of values for the measured features of the sound signals were considered; no outlier values were included.

2.6. Quantification of fish sounds and statistical analysis

All individual putative fish sounds were annotated using Raven to allow abundance calculation. Considering that manual sound selection was very time consuming for some common sound types, an estimation scheme was applied. For fish sound types that could be produced in high density, manual selections of individual signals were made and counted in a period of 10 s for each 10-min audio file. Then, the total number of sounds was estimated for the entire length of the file by multiplying the number of individual signals selected in the 10 s period by 60. For the most common sound types (F#1.4, F#1.3 and F#1.8), the result of the estimation process reflected the manual assessment of an entire audio file (percentage of error = 19.7%), suggesting a reliable method.

The abundance of sounds, sound type richness (total number of different sound types), exponential Shannon and inverse Simpson indices were obtained to characterise differences between locations. Similarly to the measurements of species diversity, in the exponential Shannon each individual (sound) is counted equally, and each species (sound type) is weighted in proportion to its abundance, focusing on common and abundant species. Inverse Simpson disproportionately favours individuals (sounds) of abundant species (sound types) and represents the number of very abundant species (sound types). Differences between locations were evaluated by applying parametric (*t*-test) or non-parametric (Wilcoxon test) tests depending on whether data followed parametric test assumptions, i.e., normal distribution and homogeneity of variances. Additionally, sound abundance was compared at different moments of the day (night, sunrise, day, and sunset) in each location using non-parametric Kruskal-Wallis followed by Dunn's post-hoc tests for pairwise comparisons. The Shapiro-Wilk test (normality) and Bartlett's or Levene's test (homogeneity of variances) were applied to test the model assumptions. The alpha value (α) was 0.05 for all the statistical tests. Statistical analysis was conducted using R version 3.5.1 (R Core Team, 2018).

3. Results

3.1. Checklist of vocal and potentially vocal fish species

A total of 35 vocal fish species were identified to occur in the Madeira Archipelago (Table 1), representing 18.6% of the total of 188 ray-finned fish reported by Wirtz et al. (2008). In addition, 39 species (20.7% of the total) were identified as potentially vocal since they belong to a genus with vocal species (Table 2), while 63 fish species (33.5% of the total) belong to a family with known vocal species (Table 3) and were considered potentially vocal too. Please note that the fish species counts were done ensuring that each species considered belonged to only one of the three categories to avoid recounting the species between such categories. Hence, 137 species were considered vocal or potentially vocal (72.8% of the total). Some vocal and potentially vocal fish species were visually detected nearby the acoustic logger during the aforementioned diving session carried out to visually inspect for vocal fish species in the Garajau MPA. These included *Sparisoma cretense*, *Thalassoma pavo*, *Scorpaena* spp., *Sphyræna viridensis*, *E. marginatus*, *Aulostomus strigosus*, *S. lurida* and *Chromis limbata*, the last being the two the most frequently observed species (Fig. S2). Additionally, MARE divers referred to these two Pomacentridae species as among the most abundant and commonly observed during routine diving sessions, both in the Garajau and the Desertas MPAs.

3.2. Fish sound catalogue

A total of 43 putative fish sound types corresponding to pulsed (sounds in which individual pulses can be aurally and visually discriminated), tonal (continuous sounds with energy mostly concentrated in a narrow band of the frequency spectrum), and noisy/uncertain sounds (representing those sounds that do not fit the previous characteristics but still were considered as putative fish active sounds) were identified (Fig. 2) and described qualitatively (Table S1). These sound

Table 1

Coastal fishes of the Madeira archipelago reported to produce sounds. All the species in the table are registered as vocal in FishSounds database (Looby et al., 2021), except species with (a) and (b) superscripts (sources for these species are referred to in the notes of this table). Species with * symbols were considered as commonly observed in diving sessions by the MARE scientific divers who were asked about.

Species	Family	Species	Family
<i>Anguilla anguilla</i>	Anguillidae	<i>Aluterus scriptus</i>	Monacanthidae
<i>Balistes capricus</i>	Balistidae	<i>Stephanolepis hispidus</i>	Monacanthidae
<i>Canthidermis sufflamen</i>	Balistidae	<i>Chelon auratus</i>	Mugilidae
<i>Lipophrys pholis</i>	Blenniidae	<i>Parophidion vassali</i> ^(b)	Ophidiidae
<i>Parablennius parvicornis</i>	Blenniidae	<i>Abudefduf saxatilis</i>	Pomacentridae
<i>Capros aper</i>	Caproidae	<i>Similiparma lurida</i> *	Pomacentridae
<i>Caranx crysos</i>	Carangidae	<i>Pomatomus saltatrix</i>	Pomatomidae
<i>Caranx latus</i>	Carangidae	<i>Heteropriacanthus cruentatus</i> *	Priacanthidae
<i>Seriola dumerili</i>	Carangidae	<i>Epinephelus marginatus</i>	Epinephelidae
<i>Trachinotus ovatus</i> ^(a)	Carangidae	<i>Sphyræna barracuda</i>	Sphyrænidae
<i>Carapus acus</i>	Carapidae	<i>Hippocampus hippocampus</i>	Syngnathidae
<i>Chilomycterus reticulatus</i>	Diodontidae	<i>Chelidonicichthys cuculus</i>	Triglidae
<i>Engraulis encrasicolus</i>	Engraulidae	<i>Chelidonicichthys lastoviza</i>	Triglidae
<i>Gobius paganellus</i>	Gobiidae	<i>Chelidonicichthys lucerna</i>	Triglidae
<i>Pomatoschistus pictus</i>	Gobiidae	<i>Eutrigla gurnardus</i>	Triglidae
<i>Kyphosus sectatrix</i>	Kyphosidae	<i>Trigla lyra</i>	Triglidae
<i>Megalops atlanticus</i>	Megalopidae	<i>Zeus faber</i>	Zeidae
<i>Mola mola</i>	Molidae		

Notes. ^aFish & Mowbray (1970), ^bParmentier et al. (2022).

Table 2

Potentially vocal coastal fish species of the Madeira Archipelago that belong to the same genus of a reported vocal species. All the genera of this table are registered in the FishSounds database (Looby et al., 2021). Species with * symbols were considered as commonly observed in diving sessions by the MARE scientific divers who were asked about.

Species	Family	Species	Family
<i>Lipophrys trigloides</i>	Blenniidae	<i>Aluterus monoceros</i>	Monacanthidae
<i>Parablennius incognitus</i>	Blenniidae	<i>Chelon labrosus</i>	Mugilidae
<i>Parablennius ruber</i>	Blenniidae	<i>Mullus surmuletus</i> *	Mullidae
<i>Caranx lugubris</i>	Carangidae	<i>Chromis limbata</i> *	Pomacentridae
<i>Selene dorsalis</i>	Carangidae	<i>Priacanthus arenatus</i>	Priacanthidae
<i>Seriola fasciata</i>	Carangidae	<i>Scorpaena canariensis</i>	Scorpaenidae
<i>Seriola rivoliana</i>	Carangidae	<i>Scorpaena maderensis</i> *	Scorpaenidae
<i>Trachurus picturatus</i>	Carangidae	<i>Scorpaena scrofa</i>	Scorpaenidae
<i>Trachurus trachurus</i>	Carangidae	<i>Serranus atricauda</i> *	Serranidae
<i>Mycteroperca fusca</i>	Epinephelidae	<i>Serranus cabrilla</i>	Serranidae
<i>Gobius gasteveni</i>	Gobiidae	<i>Diplodus cervinus</i> *	Sparidae
<i>Kyphosus incisor</i>	Kyphosidae	<i>Diplodus sargus</i>	Sparidae
<i>Labrus bergylta</i>	Labridae	<i>Diplodus vulgaris</i>	Sparidae
<i>Labrus mixtus</i>	Labridae	<i>Pagrus auriga</i>	Sparidae
<i>Symphodus mediterraneus</i>	Labridae	<i>Sphyræna viridensis</i> *	Sphyrænidae
<i>Symphodus trutta</i>	Labridae	<i>Canthigaster capistrata</i> *	Tetraodontidae
<i>Sparisoma cretense</i>	Labridae*	<i>Lagocephalus lagocephalus</i>	Tetraodontidae
<i>Thalassoma pavo</i>	Labridae	<i>Sphoeroides marmoratus</i>	Tetraodontidae
<i>Lutjanus gorensis</i>	Lutjanidae	<i>Chelidonichthys obscurus</i>	Triglidae
<i>Masturus lanceolatus</i>	Molidae		

types were divided into a total of nine groups. Concerning pulsed sounds, three groups of pulse trains were divided by PF (PF, the frequency with maximum power) as (1) “>700 Hz”, (2) “300–700 Hz”, and (3) “<300 Hz”. Three groups of single-pair pulses were also categorised by their PF, as (4) “>700 Hz”, (5) “300–700 Hz”, and (6) “<300 Hz”. Tonal sounds were classified into two groups: (7) “non-modulated” and (8) “modulated” sounds. Note that tonal sounds are not necessarily continuous and may be composed by pulses. However, they were classified as such through aural and visual inspection. i.e., they are perceived as tonal. The last group was the (9) “Noisy/uncertain” sounds. In all cases, only manually selected sounds were used for the quantitative and qualitative descriptions.

In total, 25 sound types corresponded to pulsed sounds, representing more than half (58.1%) of all the sound types, followed by tonal sounds with a total of 12 sound types (27.9%) and noisy/uncertain sounds with 6 sound types (13.9%). Half of the tonal sound types were classified as modulated, and the other half as non-modulated. A higher quantity of pulsed sound types corresponded to trains of pulses, with a total of 14 sound types (56.0% of the pulsed sounds); trains of pulses were more common when PF was in the range of 300–700 Hz. In the case of single-pair pulsed sounds, the higher number of sound types identified corresponded to the group with PF > 700 Hz. The fish catalogue shown here is conservative considering that some sound types, especially the ones of pulsed nature, include sound signals with acoustic characteristics that could allow a more detailed classification. This is the case of the sound F#1.4 classified as a single or pair pulsed sound with PF range of 300–700 Hz, which potentially is composed of several different sounds, given that some signals had more than two isolated pulses. However, a more detailed analysis was not performed, given an overall high within-variability. Similarly, this also applies to sounds F#1.1, F#1.3 and F#1.8, for which an in-depth acoustic analysis may allow a more detailed within-group classification in the future.

Table S2 shows quantitative descriptions for the 20 putative fish sounds having at least 14 occurrences, considering statistics for PF, Q1, Q3 and sound duration; most of these sounds are pulsed (single-pair

Table 3

Potentially vocal coastal fish species of the Madeira Archipelago that belong to the same family of reported vocal species and referred to by Rice et al. (2022). Species with * symbols were considered as commonly observed in diving sessions by the MARE scientific divers who were asked about.

Species	Family	Species	Family
<i>Sardina pilchardus</i>	Alosidae	<i>Xyrichtys novacula</i>	Labridae
<i>Anthias anthias</i>	Anthiidae	<i>Ranzania laevis</i>	Molidae
<i>Apogon imberbis</i> *	Apogonidae	<i>Oedalechilus labeo</i>	Mugilidae
<i>Aulostomus strigosus</i> *	Aulostomidae	<i>Phycis phycis</i>	Phycidae
<i>Belone belone</i>	Belonidae	<i>Polyprion americanus</i>	Polyprionidae
<i>Coryphoblennius galerita</i>	Blenniidae	<i>Acanthocybium solandri</i>	Scombridae
<i>Ophioblennius atlanticus</i>	Blenniidae	<i>Auxis rochei</i>	Scombridae
<i>Campogramma glaycos</i>	Carangidae	<i>Katsuwonus pelamis</i>	Scombridae
<i>Decapterus macarellus</i>	Carangidae	<i>Sarda sarda</i>	Scombridae
<i>Decapterus punctatus</i>	Carangidae	<i>Scomber colias</i>	Scombridae
<i>Lichia amia</i>	Carangidae	<i>Scomber scombrus</i>	Scombridae
<i>Naucrates ductor</i>	Carangidae	<i>Thunnus alalunga</i>	Scombridae
<i>Pseudocaranx dentex</i>	Carangidae	<i>Thunnus albacares</i>	Scombridae
<i>Ariosoma balearicum</i>	Congridae	<i>Thunnus obesus</i>	Scombridae
<i>Conger conger</i>	Congridae	<i>Thunnus thynnus</i>	Scombridae
<i>Heteroconger longissimus</i>	Congridae	<i>Boops boops</i>	Sparidae
<i>Paraconger macrops</i>	Congridae	<i>Centracanthus cirrus</i>	Sparidae
<i>Sardinella aurita</i>	Dorosomatidae	<i>Dentex dentex</i>	Sparidae
<i>Sardinella maderensis</i>	Dorosomatidae	<i>Dentex gibbosus</i>	Sparidae
<i>Gaidropsarus guttatus</i>	Gaidropsaridae	<i>Lithognathus mormyrus</i> *	Sparidae
<i>Chromogobius britoi</i>	Gobiidae	<i>Oblada melanura</i>	Sparidae
<i>Crystalllogobius linearis</i>	Gobiidae	<i>Pagellus acarne</i>	Sparidae
<i>Gnatholepis thompsoni</i>	Gobiidae	<i>Pagellus bogaraveo</i>	Sparidae
<i>Lesueurigobius heterofasciatus</i>	Gobiidae	<i>Pagellus erythrinus</i>	Sparidae
<i>Mauligobius maderensis</i>	Gobiidae	<i>Pagrus pagrus</i>	Sparidae
<i>Thorogobius ephippiatus</i>	Gobiidae	<i>Sarpa salpa</i> *	Sparidae
<i>Vanneogobius canariensis</i>	Gobiidae	<i>Sparus aurata</i>	Sparidae
<i>Parapristipoma octolineatum</i>	Haemulidae	<i>Spondyliosoma cantharus</i>	Sparidae
<i>Pomadasyus incisus</i> *	Haemulidae	<i>Nerophis ophidion</i>	Syngnathidae
<i>Bodianus scrofa</i> *	Labridae	<i>Syngnathus acus</i>	Syngnathidae
<i>Coris julis</i>	Labridae	<i>Uranoscopus scaber</i>	Uranoscopidae
<i>Lappanella fasciata</i>	Labridae		

sounds and trains of sounds). Also, most of those sounds have an average PF below 1 kHz and are very short (<1 s on average). In addition, there is a high variability at the level of each identified signal for several sound types and, according to the standard deviation and the range of the values, it is possible to observe that the duration of sounds F#1.1, F#1.3, F#1.4 and F#1.8 is especially variable. Considering the 23 sound types having less than 14 occurrences (included in Table S1), pulsed sounds (mainly representing trains of pulses) are the ones with higher representation, summing up a total of 10 sound types of pulsed nature, followed by eight tonal sound types and five noisy/uncertain sound types.

3.3. Overall fish sound abundances

Considering signal abundances, more than 100.000 putative fish sounds were considered (Fig. 3), with the sounds F#1.4, F#1.8 and F#1.3 being the most common ones, representing respectively 73.9%, 13.3% and 4.6% of total signals, and accounting together for more than 90.0% of the identified individual sounds of the present study. Also, Fig. 3 shows that most of the putative fish sounds that were identified more than 100 times in the recordings are of the pulsed type, the single-pair types being more abundant than the pulse trains. On the other hand, the rarest sound types were tonal or noisy, many of them with just one detected occurrence, while sounds with an intermediate to low occurrence were mostly pulse trains (represented by green colours in Fig. 3 and found in the central area of the x-axis). Note that the classification of

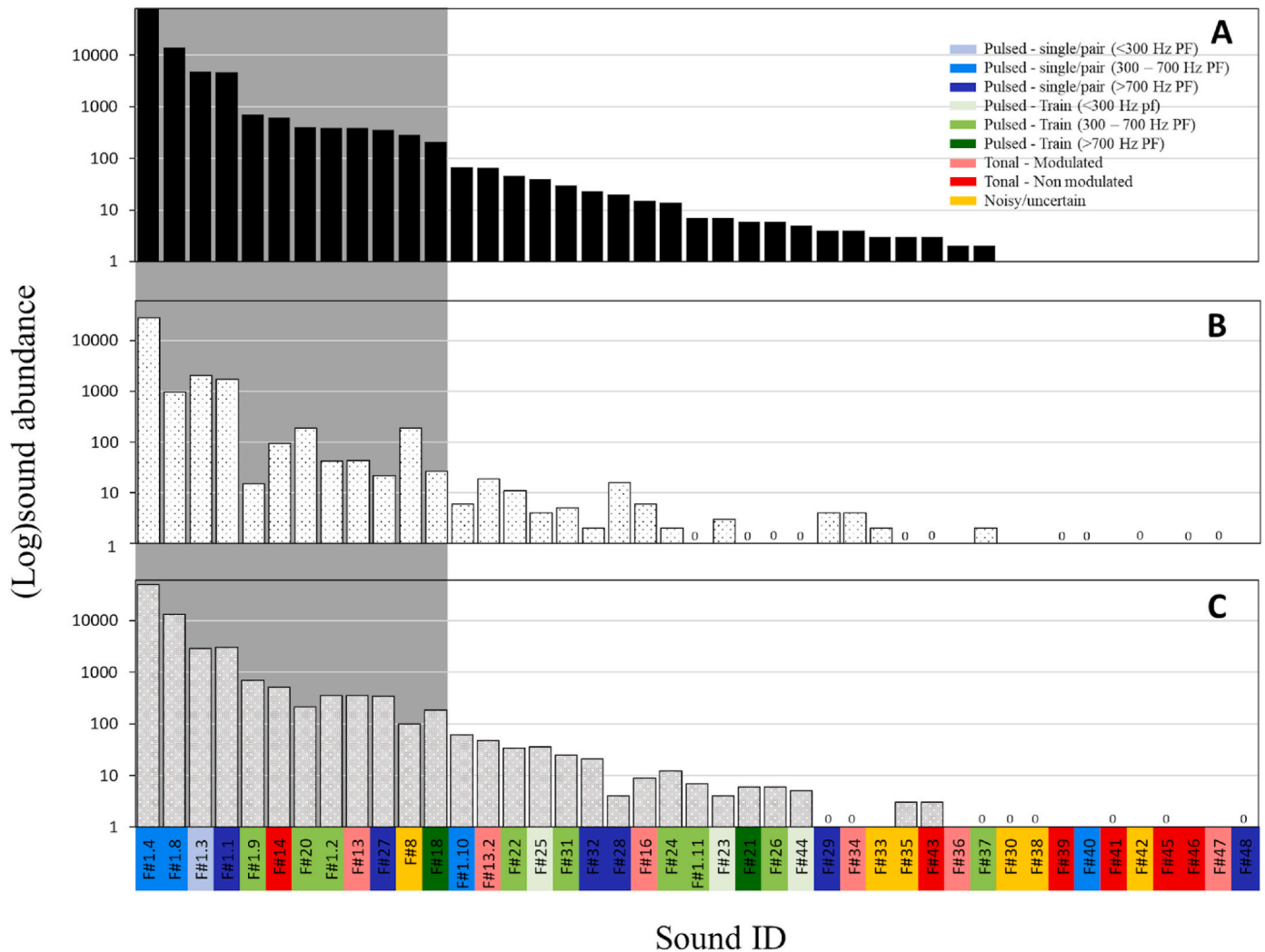


Fig. 3. Abundances of putative fish sounds: (A) total, (B) the Desertas MPA, and (C) the Garajau MPA. The grey area in the background behind bars indicates the sound types with an abundance higher than 100 in the total abundance. Colours in the x-axis, indicate the nine groups of sound types specified in the fish sound catalogue (Fig. 2). Given that the abundances are in logarithmic scale, the 0 values shown represent those cases where no signal was registered.

several sound types should be taken with precaution because they were rare, with only one or few examples throughout all the analysed recordings.

3.4. The Garajau and the Desertas MPAs comparisons

In the Garajau MPA, higher total abundance and richness of fish sounds were registered, with 72311 signals and 35 sound types, while for the Desertas MPA, 33541 signals and 32 sound types were detected. From the total sound richness (43 putative fish sound types), 24 sound types were found to be common to the two locations, representing around half of the sound types (55.8%) (Fig. 3). A more detailed examination of this figure, however, shows that 100% of the sound types with at least 10 total occurrences (21 sound types) were shared in both locations and in general, only very rare sound types were present in only one of the MPAs.

Considering the total abundance by sampling day at each location (Fig. 4), fish sound abundance was significantly higher in the Garajau MPA than in the Desertas MPA (*t*-test, *t* = -4.13, *p* = 0.002). Similarly, the Garajau MPA presented a significantly higher sound type richness (*t*-test, *t* = -2.66, *p* = 0.02) than the Desertas MPA, and exponential Shannon and inverse Simpson were also higher in the Garajau MPA (Mann Whitney *U* test, *W* = 227, *p* < 0.001; Mann Whitney *U* test, *W* =

190, *p* < 0.001) (Fig. 4). Fig. 5 shows sound richness accumulation curves by location highlighting the higher richness values in the Garajau reserve. However, a similar tendency was found in the curves at both locations indicating that more sound types could be detected with an increase in sampling effort.

3.5. Fish sound daily patterns and acoustic partitioning

Considering daily patterns by location (Fig. 6), both the Garajau and the Desertas MPAs present a significant lower abundance at night (the Garajau MPA: Kruskal-Wallis, $X^2 = 19.80$, *p* < 0.001; Dunn test, *p* < 0.05; the Desertas MPA: Kruskal-Wallis, $X^2 = 16.46$, *p* < 0.001; Dunn test, *p* < 0.05), but no differences were found among the other times of the day.

Fig. 7 depicts a colour matrix representing the total abundance of all fish sound types found in this study by the time of the day. This figure shows that a group of sound types appear mostly at night, while others seem more prevalent during the day, at sunrise or sunset. Pulsed single-pair sound types are generally less abundant at night, and the most abundant of these types (F#1.3, F#1.4, and F#1.8) occur mainly at sunset, while the tonal-sound types with the highest total abundances (F#13, F#13.2 and, F#14) were detected mainly at night. The most notable exception is sound F#20, which occurs throughout the 24 h.

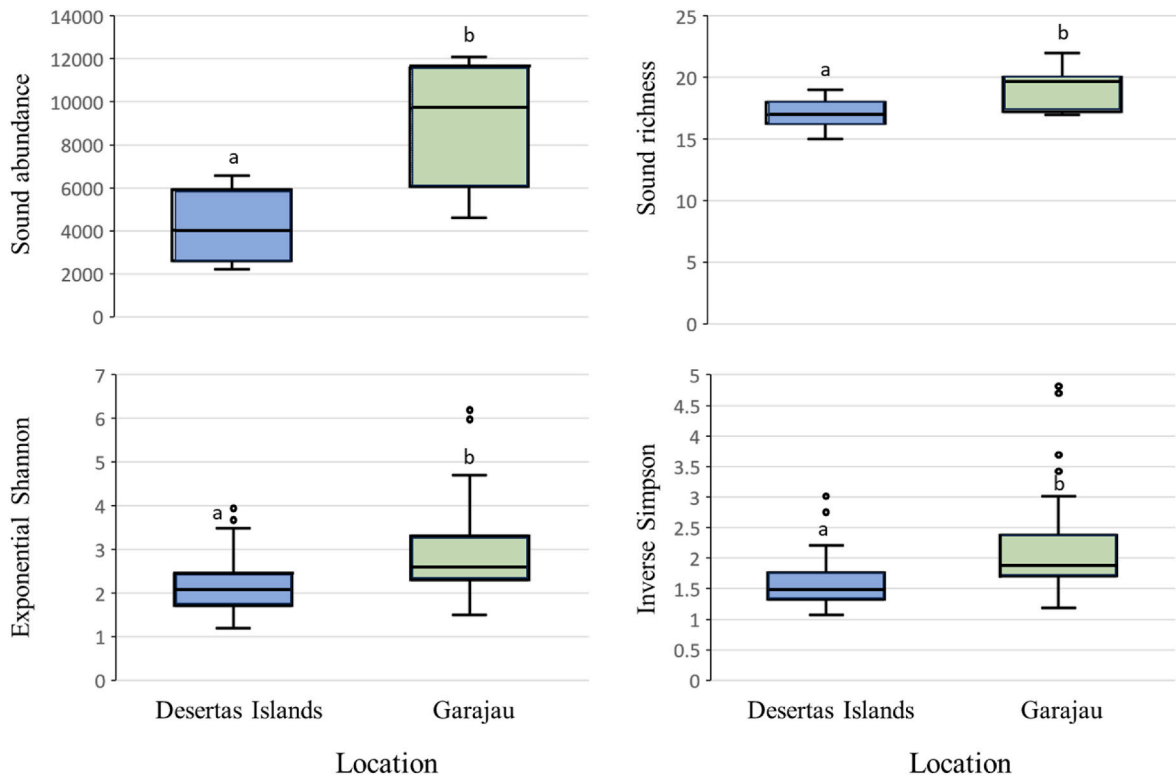


Fig. 4. Sound abundance, richness, exponential Shannon and inverse Simpson at the Desertas and the Garajau MPAs. Different letters show significant differences for $p < 0.05$, provided by t -test and Mann Whitney U test.

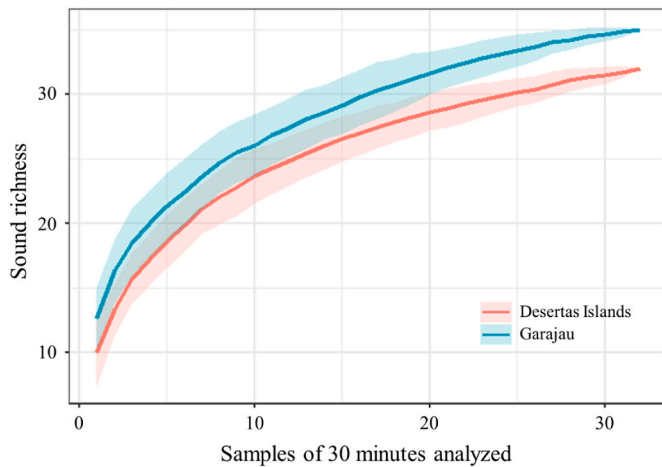


Fig. 5. Sound richness accumulation curves by location. The shaded areas indicate the respective standard deviation based on 100 runs.

Zooming in on the pulsed sound F#1.4 (Fig. 7), it can be seen that its abundance is significantly lower at night than at other times of the day (Kruskal-Wallis test, $X^2 = 20.54$, $p < 0.001$; Dunn test, $p < 0.05$) while for the F#14, which is the tonal sound with higher total abundance, the number of detected signals was significantly higher at night compared to day, but without being significantly different at sunrise and sunset (Kruskal-Wallis test, $X^2 = 11.71$, $p = 0.008$; Dunn test, $p < 0.05$). Fig. 7 also shows rare sound types (with less than 10 occurrences). These sounds also appear to group separately at night or day; however, the low number of detections limits any conclusion. Despite this, the patterning of the different and more abundant sound types suggests the existence of temporal partitioning of the sounds.

Fig. 8 shows that different sound types exhibit the most energy in the

200–1400 Hz range with low overlap, which points to spectral partitioning. The degree of spectral partitioning varies with time of day being more pronounced at night than in the diurnal group. In the latter group, five sound types show overlapping peak frequencies between 400 and 600 Hz.

4. Discussion

In the present study, we characterised, for the first time, different aspects of the acoustic fish communities at two specific locations within two MPAs in the Madeira archipelago. This data provides base information and reference material for future PAM-based research and can contribute to conservation efforts in the area.

4.1. Checklist of vocal and potentially vocal fish species

At least 188 ray-finned fishes have been reported in the literature for the coastal waters of the Madeira Archipelago (Wirtz et al., 2008). In the present study, 35 of those species were confirmed as vocal and 102 as potentially vocal.

The number of vocal fish species compiled in the checklist section is expected to increase, considering that many of the fish species present in the archipelago have not been studied to evaluate their sound production capabilities, as in other areas of the world (Parmentier et al., 2021). In fact, globally, 96% of fish species lack published examinations for sound production (Looby et al., 2022). Moreover, recent estimations consider that families with vocal species contain nearly two-thirds of the actinopterygian species (Rice et al., 2022). This is consistent with an increasing number of studies describing the vocal abilities of marine fish, pointing to acoustic communication as an important aspect of teleost biology (Parmentier et al., 2021). Indeed, if the potential vocal species were eventually confirmed as vocal, it would result that 137 vocal fish species of the Madeira archipelago could be vocal, representing around 70 % of the total number of fish species (not including

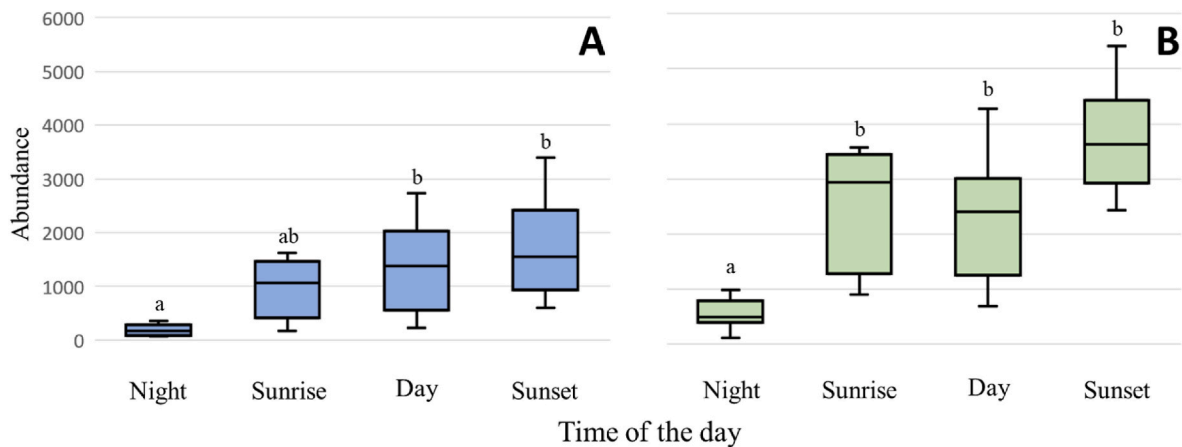


Fig. 6. Sound abundance considering time of the day for (A) the Desertas and (B) the Garajau MPAs. Different letters over boxplots indicate significant pairwise differences for $p < 0.05$, provided by Kruskal-Wallis and post hoc Dunn tests.

chondrichthyans). However, large-scale fish sound production examination efforts are still required to effectively document vocal activity in a wider number of fish species.

There are two classic ways to attribute a specific sound to a particular fish species: *ex situ* studies (captivity conditions) and *in situ* studies (natural conditions) (Luczkovich et al., 2008). Both approaches have advantages and limitations. For example, *ex situ* studies have the advantage of allowing the reduction of natural background sounds such as sounds produced by non-target species, and also to control environmental parameters that are related with acoustic behaviour, such as water temperature (Torricelli et al., 1990). However, captivity conditions could restrict the natural sound repertoire or even prevent sound production in many vocal fish species (Mouy et al., 2023). Captivity conditions may also influence interpretations of acoustic behaviour because unnatural absorption and scattering of sound waves inside aquaria can modify the spectral properties of recorded sounds (Akamatsu et al., 2002). *In situ* studies offer many advantages, especially in terms of not disrupting the animals (Mouy et al., 2023). However, they are not without difficulties as matching sounds to specific species may be difficult in the field (Mouy et al., 2023). It is also important to consider that methodologies used to determine the number of vocal species for a given location can influence the results by focusing on particular species and not considering others. For example, Tricas and Boyle (2014) estimated the ratio of vocal species in Hawaiian reefs, but their methodology was based on daytime scuba diving, excluding fish that produce sounds mostly at night (Ruppé et al., 2015; Picciulin et al., 2018). Despite the above, several studies have successfully provided information to confirm vocal capabilities in different fish species, described specific sounds of particular species and even associated the sounds to a behavioural context, both in the field or in captivity conditions (e.g., Hawkins and Amorim 2000; Amorim et al., 2008b; Branstetter et al., 2012; Picciulin et al., 2013; McIver et al., 2014; Parmentier et al., 2022; Puebla-Aparicio et al., 2024), which could allow to fill knowledge gaps and hence improve the estimations of how many fish species are vocal in a particular area. In this way, the biophony components of marine soundscapes could be better understood.

Compared with the information available about vocal fish communities in the Macaronesian region, a higher number of vocal species in the Madeira archipelago were found relative to the Azores Islands (Carrico et al., 2019). A total of 35 vocal species were listed in the present study for Madeira, while 20 were reported for Azores. Similarly, a higher number of potential vocal fish species were found for the Madeira archipelago than for the Azores Islands, with 102 and 79 species, respectively. By reviewing the checklist by Carrico et al. (2019) for the Azores islands, several of the potentially vocal and vocal fish species are common to these two archipelagos. As mentioned before, the

number of species categorised as vocal can change as knowledge increases, and so more studies are required to update vocal fish checklists for the Madeira archipelago.

4.2. Fish sound catalogue

A total of 43 putative fish sound types were detected, described, and grouped in the present study, 25 of them consisting of pulsed sounds (single or pulse trains). Tonal sounds were also detected and divided into frequency-modulated and not-modulated sounds, summing up 12 sound types in total. The remaining six sound types corresponded to noisy/uncertain sounds. Considering the sound richness accumulation curves for the Desertas and the Garajau MPAs, an increase in sound types can be expected by expanding the subsampling scheme applied, including more days and more or longer periods analysed by day.

A considerably high number of putative fish sound types contributing to the marine soundscape of the Madeira archipelago was found. When comparing with highly taxonomically diverse ecosystems as coral reefs, which are known to have numerous vocal fish species (Parmentier et al., 2011), 47 fish sound types were found for Mozambique coral reefs (Puebla-Aparicio et al., 2024), while a total of 22 fish sound types are reported in Moorea Island (French Polynesia) coral reefs (Bertucci et al., 2020), which is almost half of the number of sound types found for the Madeira Archipelago (43 in total). However, in Moorea Island, sound types were composed of at least 12 detections, while in Madeira, several sound types were composed of only one sample, i.e., rare sounds. Considering only sound types with at least 14 occurrences, as is the case of the sounds that were quantitatively analysed in Table S2, the total number of sound types for the Madeira Archipelago would be 20, thus more comparable to the study of Bertucci and colleagues (Bertucci et al., 2020). On the other hand, 85 sound types are present in the Hawaiian coral reef fish communities (Tricas and Boyle 2014), including single event sounds. However, these authors included non-active sound types, such as those derived from feeding and schooling (10 non-active sound types in total for that study). Wang et al. (2017) report for the Pearl River Estuary (China) a total of 66 sound types, while Carrico et al. (2019) identify a total of 20 sound types (named as sequences) as being likely produced by fishes in Condor seamount and Princesa Alice bank, in the Azores Islands (Portugal, Macaronesian region), but only seven sound sequences with more than 14 occurrences. The above examples highlight that there can be important differences in the richness of fish sound types depending on the studied area and methods. Therefore, the standardisation for classifying and identifying sounds is necessary to allow proper site comparisons.

The 43 putative fish sounds identified here for the archipelago of Madeira presented the typical characteristics of fish acoustic signals: low

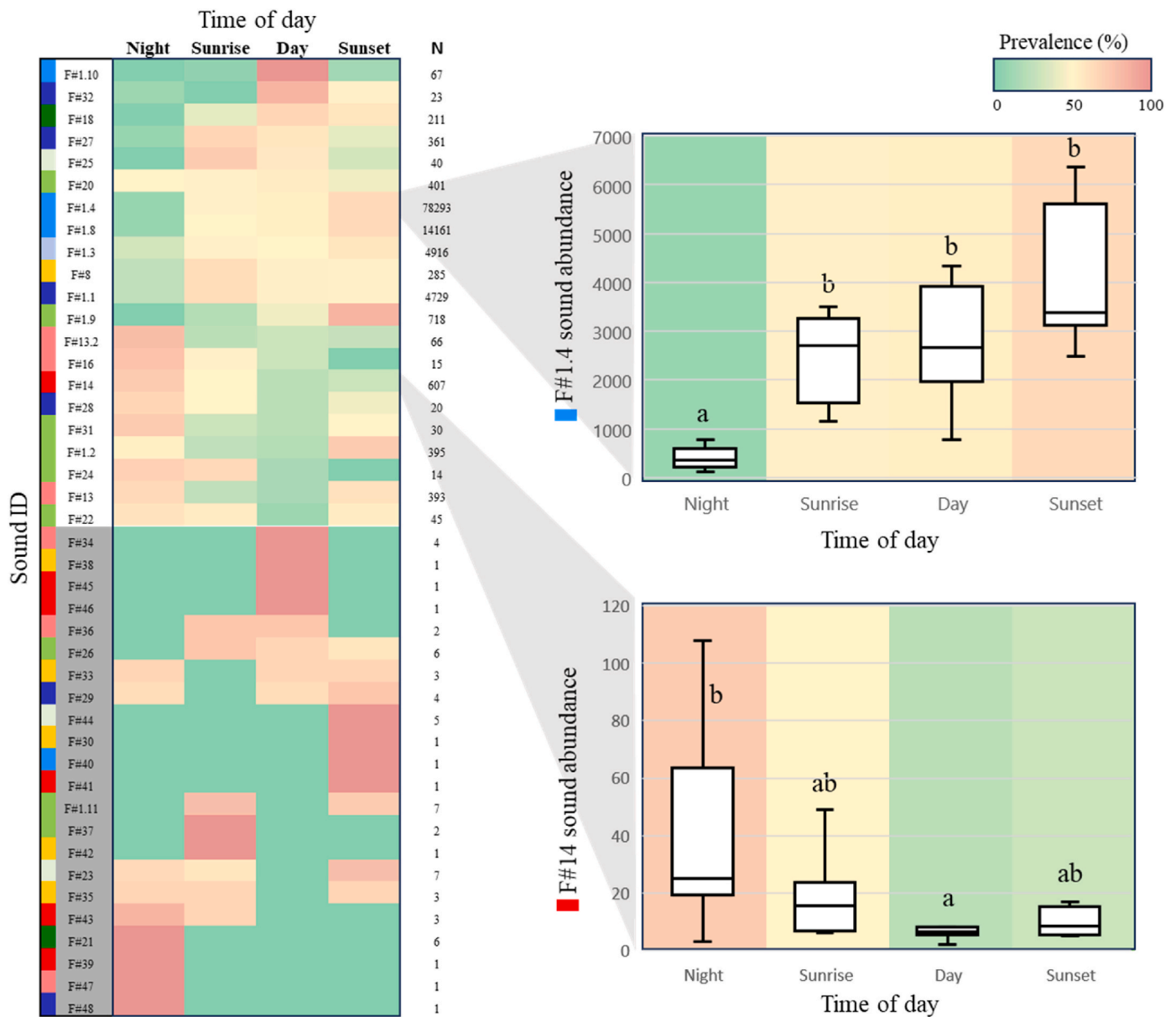


Fig. 7. Matrix of the prevalence of each fish sound type by time of the day. The more reddish colour, the greater the number of sounds, while the darkest green represents the lowest abundance with no occurrence of a sound type in a given time of the day. Different letters associated to the boxplots indicate pairwise significant differences provided by Dunn’s post hoc tests ($p < 0.05$). The colours in the column “Sound ID” (at the left of the matrix) correspond to the nine groups of sounds defined in the catalogue of fish sounds (Fig. 2). Sounds with more than 10 occurrences were ordered according to the prevalence of sounds during the day. Sound ID in grey represents sounds having less than 10 occurrences and were ordered according to the prevalence of sounds in the day and night. All annotations were included (both manual and estimated).

frequency (<3 kHz, mostly <1 kHz), being made up of repetitive elements such as sound pulses (Amorim 2006) and having short duration (<5 s) (Fish and Mowbray 1970). These characteristics allow us to discriminate putative fish sounds from other biotic components of the marine soundscape, such as the sounds produced by invertebrates and cetaceans. Reported invertebrate sounds are usually broadband pulses with frequencies between 2 and 12 kHz (e.g. Radford et al., 2008; Bitencourt et al., 2016). Cetacean vocalisations range from low to very high frequencies (<0.1 kHz–200 kHz), generally having a long duration and showing strong frequency modulation (Richardson et al., 1995). Motorboat noise was detected in some recordings, and they represented only 7% of the total duration of all the audio files considered (5% of the Desertas MPA audios and 9% of the Garajau MPA audios). In addition, diver presence was also identified in one of the analysed audio files corresponding to the Garajau MPA. Both motorboat and diver sounds

were clearly different from fish sounds.

It is also important to consider that the 43 putative fish sound types identified for the Madeira MPAs do not necessarily correspond to 43 different fish species, because some species can produce different sound types, often associated with different behaviours (Amorim 2006; Amorim et al., 2008b). In this sense, more studies are needed to relate sounds to specific fish species and behaviours, such as analysing sound production of specific fish species in captivity conditions, fish sound recognition in the wild with portable audio-video array systems, or *in situ* simultaneous behavioural observations and sound recordings (e.g. while scuba diving), which can allow for a better understanding of the sound sources in a given marine area, as well as offering informative bases for passive acoustic monitoring strategies.

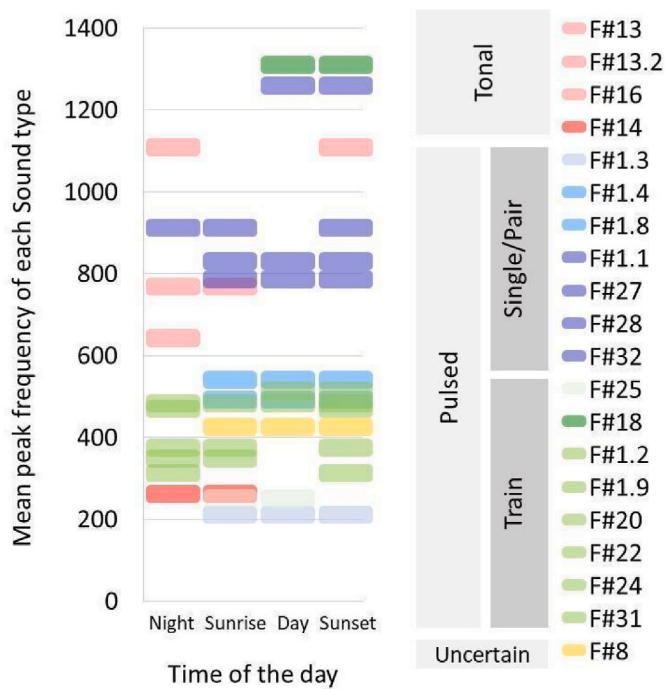


Fig. 8. Mean peak frequency of the sound types occurring at different times of the day. Only sounds with more than 14 occurrences are represented here. Colours are according to the nine groups of sounds defined in the catalogue of fish sounds (Fig. 2). For each sound type, absence was considered in the periods with less than 15.0% of the detections.

4.3. Similarity to previously reported fish sounds

The sound types with higher abundances (F#1.4 and F#1.8) significantly influenced the total sound abundance dynamics in the Madeira Archipelago. It is not totally clear to which species those sounds could correspond. However, considering the visual and aural characteristics of those sounds and the values of the peak frequency and sound duration, they partially match the description for some Pomacentridae fishes (Myrberg 1972; Amorim 1996; Parmentier et al., 2006; Colleye and Parmentier 2012). The vocal species *Abudefduf saxatilis* and *S. lurida* are probable sources for these sounds as well as the potentially vocal *C. limbata*. Sounds produced by *S. lurida* are usually pulse pairs and have a duration of 100 ms and a peak frequency of 400–450 Hz (Mooney et al., 2005). In this sense, they share acoustic characteristics with the F#1.8 sound. No sound characterization was found in the scientific literature for the other two Pomacentridae species mentioned, hindering specific comparisons. Despite that, many members of the Pomacentridae are well known diurnal vocal fishes (Parmentier et al., 2010; Allen et al., 2020) and some species exhibit a very diverse and complex acoustic behaviour (Parmentier et al., 2010), along with a very high acoustic activity with hundreds of acoustic signals emitted per day (Mann and Lobel 1995). Considering those characteristics for Pomacentridae and given that *S. lurida* and the potentially vocal *C. limbata* are very abundant species in the Garajau and the Desertas MPAs, they could explain in part the high abundances obtained for F#1.4 and F#1.8, which dominated over the other sound types. Also, the variability within each sound type could be explained by the fact that Pomacentridae fish can have diverse and complex acoustic behaviour, as referred previously, with species producing different types of sounds. In this case, a deeper acoustic analysis of the F#1.4 and F#1.8 sound types, as well as the F#1.1 and F#1.3 could reveal even more types. Despite the above, specific studies that describe the characteristics of the Pomacentridae fish sounds that occur in the Madeira Archipelago are needed to clearly determine the sound sources, helping in due course to better describe the

marine soundscape.

The sound types F#13 and F#13.2 were found to be aurally and visually similar to the/Kwa/sounds described for genus *Scorpaena*, and also occurred at night (Bolgan et al., 2019). In addition, individuals of this genus were found right in front of the acoustic data logger during the diving sessions (Fig. S2), making it a plausible candidate for these sound types in the Madeira Archipelago. Additionally, several species of the family Haemulidae, which is also present in the Madeira Archipelago, make sounds that visually and aurally resemble the F#25 sound (Fish and Mowbray 1970).

4.4. The Garajau and the Desertas MPAs comparisons

The total sound abundance, richness of putative fish sound types, exponential Shannon, and inverse Simpson were higher in the Garajau MPA than in the Desertas MPA. Around half (55.8%) of the sound types were found to be common to the two locations, and 100% of the sound types with at least 10 total occurrences were present in both locations.

Differences in fish sound abundance and richness between the deployment sites in Garajau and the Desertas MPAs match differences found in general fish densities found in these two sites (MARE-Madeira UVC Database, unpublished). The differences in fish densities found in these locations are likely shaped by multiple compounding factors. One aspect that could influence these observations is the difference in the depth of the data loggers deployments (28 m vs 16 m in Garajau and Desertas MPAs), as depth is a structuring factor in fish communities leading to differences in species composition and size distribution (Andradi-Brown et al., 2016). In addition, despite the relative geographical proximity between these locations, the particular physical characteristics and environmental factors like depth, wind direction, wind exposure, water current, among others, as well as the local biotic interactions, can influence fish communities and even act as barriers between both areas (Gilliam and Fraser 1993; Loera-Pérez et al., 2020; Uspenskiy et al., 2022). More studies are required to relate vocal fish communities and fish activity with environmental factors in the Madeira Archipelago as well as to increase the number of monitored sites to take into account spatial variability. Finally, the study location in the Desertas MPA was characterized by a noisier environment (higher natural abiotic noise), likely due to a lower deployment depth and higher influence from wave action, which could decrease the ability to detect putative sounds of interest (both visually and aurally) compared to the dataset from the Garajau MPA. This, in turn, likely contributes to lower fish sound abundance and richness values.

4.5. Daily patterns and acoustic space partitioning

Acoustic interference and masking may occur if signals overlap either in time of occurrence or in frequency. According to the acoustic niche hypothesis, this can be minimised by partitioning the acoustic space through acoustic behaviour to enhance acoustic communication within a community with multiple vocal fish species. This can involve, for example, producing sounds at different periods of the day or night or diversifying acoustic features of sounds occurring during the same time frame (Staatterman et al., 2013; Hastings and Širović 2015; Ruppé et al., 2015; Bertucci et al., 2020).

We observed that the total abundance of fish sounds was lower at night than in the remainder of the day in both locations, although several studies show higher acoustic activity of fish during night and/or sunset in other locations (Locascio and Mann 2008; Spence 2017; Pagniello et al., 2019; Bertucci et al., 2020; Bolgan et al., 2020; Vieira et al., 2021a). During the day, sounds like F#1.4 and F#1.8, possibly produced by Pomacentridae fish, dominated the soundscape. This is consistent with Bertucci et al. (2020) findings that Pomacentridae sounds dominate over other fish sounds during daytime, while having low acoustic activity at night (Parmentier et al., 2010). At night, we observed sound types like F#13 and F#13.2 that are possibly produced by nocturnal

species belonging to the genus *Scorpaena* (La Manna et al., 2021), which may be taking advantage of a freer acoustic niche.

Fish can use different spectral niches to avoid masking sounds with other species. In the present study, this spectral segregation was clearer at night, where much less spectral overlapping occurred (see Fig. 8). On the other hand, many sound types were produced during the day in overlapping frequency bandwidths. This higher overlap during the day might be a consequence of how species use the sounds. Diurnal species might use multimodal communication where sounds complement visual displays, whereas, for nocturnal species, the acoustic signal may hold more importance as unimodal signals, requiring more specific signals for effective communication. This is consistent with the spectral and temporal partitioning of acoustic fish communities on the coast of South Africa, where acoustic activity allows a clear distinction between diurnal and nocturnal groups of fishes, with reduced spectral partitioning during the day (Ruppé et al., 2015). In contrast, the same study found a clear distinction among nocturnal callers with a clear separation in sound frequency, demonstrating interference avoidance in a fish community (Ruppé et al., 2015).

Further studies should explore spectral and temporal partitioning in this community by looking into different temporal scales (e.g., rhythms in fine temporal scales). For example, vocal fish may listen to nearby calling individuals and adjust the timing of their calls accordingly. Like that, fish might avoid masking even if producing sounds during the same time of the day. Such fine-scale acoustic interactions have been rarely studied and mostly in an intraspecific context (Vieira et al., 2021b). Furthermore, the temporal structure of fish sound sequences might give information about species and context (Vieira et al., 2021b; Burchardt et al., 2021). This might be an additional way for individuals to discriminate sounds of interest in the middle of a cacophony of multiple species using the same time of the day and similar frequency ranges.

5. Conclusions

This study provides the first characterization of the marine soundscape of the Madeira Archipelago, focusing on fish communities in two important MPAs, the Garajau and the Desertas MPAs. Here, we provide the first checklist of the potential and vocal fish species for the Madeira Archipelago, offering valuable information to identify which species we should focus on regarding the characterization of active sound production. A total of 35 vocal fish species were identified to occur in the Madeira Archipelago, while 102 species are potentially vocal.

Importantly, the first fish sound repertory for the Madeira Archipelago encompassed 43 different sound types. These were classified into nine groups according to their acoustic characteristics, providing a base reference for any future study or monitoring program in the area. The proposed repertory allows the classification of putative fish sounds based on their main acoustical features.

Some candidates for these sound signals were proposed. Members of the Pomacentridae family were posit as the probable species associated with the most abundant putative fish sounds. In addition, the genus *Scorpaena* was proposed as a candidate for two of the signals identified as/Kwa/sounds. Additionally, one sound type is potentially produced by a fish species belonging to the Haemulidae family.

The analysis of the temporal patterns of fish sound activity (sound abundance), sound richness, and diversity indices allowed us to describe differences between the Garajau and the Desertas Islands soundscapes. A higher abundance and richness of putative fish sounds was observed in the Garajau MPA than in the Desertas Islands MPA. Moreover, this study evidenced the existence of daily patterns of fish sound activity and acoustic space partitioning, both temporally and spectrally.

This study provides a valuable stepping stone for future non-invasive, cost-effective monitoring programs in the Madeira Archipelago. It also highlights how important it is to increase the knowledge of the acoustic abilities of different fish species to relate the detected sounds to specific species, in order to improve the overall understanding

of the Madeira Archipelago's Marine soundscape and use this knowledge for monitoring and conservation efforts.

CRediT authorship contribution statement

Sebastian Muñoz-Duque: Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation. **Paulo J. Fonseca:** Writing – review & editing, Supervision, Investigation, Conceptualization. **Bernardo Quintella:** Writing – review & editing, Investigation, Conceptualization. **João Gama Monteiro:** Writing – review & editing, Investigation, Conceptualization. **Marc Fernandez:** Writing – review & editing, Funding acquisition. **Rodrigo Silva:** Writing – review & editing, Investigation. **Manuel Vieira:** Writing – review & editing, Writing – original draft, Supervision, Software, Methodology, Investigation, Data curation. **M. Clara P. Amorim:** Writing – review & editing, Writing – original draft, Supervision, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

A .xlsx file with the original data used in the present study is included as supplementary material and audio examples of all the sound types presented can be accessed with a link provided.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.marenvres.2024.106600>.

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