Mediterranean Marine Science

Vol 24, No 3 (2023)

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doi: 10.12681/mms.30322

Research Article

Mediterranean Marine Science
Indexed in WoS (Web of Science, ISI Thomson) and SCOPUS
The journal is available on line at http://www.medit-mar-sc.net
www.hcmr.gr
DOI: http://doi.org/10.12681/mms.30322

Marine soundscape and its temporal acoustic characterisation in the Gulf of Oristano, Sardinia (Western Mediterranean Sea)

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Contributing Editor: Stelios SOMARAKIS

Received: 28 May 2022; Accepted: 18 June 2023; Published online: 21 September 2023

Abstract

The soundscape of the marine environment is a combination of *geophony, biophony* and *anthropophony*. Here, the soundscape of the Gulf of Oristano, a shallow inlet on the western coast of Sardinia including a special conservation area (Habitat Directive) and a national marine protected area, was investigated. Data collection was performed during July 2019, November 2019 and May 2020 using underwater acoustic equipment. The goal of this study was to characterise the ambient sound levels (Sound Pressure Level dB re 1 µPa) and describe the main soundscape components. The soundscape exhibited significant circadian and seasonal variations: the lowest and highest median SPL values were observed in the Spring (120–140 dB re 1 µPa; *post-COVID-19 pandemic lockdown*) and the Summer (128–150 dB re 1 µPa) respectively. *Biophony* was identified and characterised as dolphins' 'clicks' and crustaceans' 'snapping'. Shrimp activity was dominant in the summer, while dolphin passages were observed across all sampling periods, accounting for 46.4% of the total recordings. *Anthropophony*, namely vessel passages, was predominant in the summer during the day-time and represented up to 42% of the acoustic space in the low-frequency band. *Geophony* increased low-frequency noise, and represented a highly variable component of the local soundscape. The marine soundscape is a valuable tool for defining integrated management plans for marine ecosystems, allowing the assessment of habitat quality, characterisation of sound sources and evaluation of the impact of anthropogenic activities.

Keywords: passive acoustic monitoring; anthropogenic noise; acoustic behaviours; Mediterranean habitat; marine soundscape; COVID-19 pandemic.

Introduction

The sources and acoustic characteristics of environmental biotic and abiotic sounds are collectively defined as the "soundscape" (Pijanowski, *et al*., 2011; Urick, 1983), which has great potential in describing the characteristics of marine ecosystems and detecting changes within them (Farina *et al*., 2014; Schoeman *et al*., 2022). It represents an effective and complementary tool for understanding the dynamics of marine ecosystems and potential biological associations over a wide range of spatial and temporal scales. The soundscape can be split into three principal sound aggregations: "Anthropophony" – human-made sounds deriving, for example, from naval traffic and shipping, underwater construction and seabed exploration (Hildebrand, 2009); "geophony" – sounds generated by geophysical and meteorological events, such as wind, atmospheric precipitation and breaking waves (Nystuen *et al*., 1993; Haxel *et al*., 2013); and "biophony" – sounds produced by biota (Krause, 2008 Pijanowski, *et al*.; 2011). The habitat complexity in terms of community structure can be connected to the diversity of the biophonic sources (Kennedy *et al*., 2010). A high number of coastal marine species emit sound across a wide frequency interval, ranging from 10 Hz to over 20 kHz, and contribute to the marine shallow-water soundscape. Crustaceans, such as snapping shrimp (*Synalpheus sp*.) (Au *et al*., 1998) and the spiny lobster (*Palinurus interruptus*) (Patek *et al*., 2009), and urchins (Radford *et al*., 2008) produce antagonistic or feeding sounds; additionally, fish (Amorim, 2006) usually communicate via sound to increase social cohesion (van Oosterom *et al*., 2016) and for courtship rituals, as well as territorial protection. Finally, the most studied species are dolphins and whales, which have the most complex vocal repertoire (Tyack, 2000). In shallow waters, *geophony* includes sounds generated by rainfall, wind and waves in the underwater environment. Wind-dependent noise is the prevailing sound in many of the world's seas and its frequencies are between 100 Hz and 20 kHz, typically peaking around 500 Hz (Knudsen, 1948; Wenz, 1962; Haxel *et al.*, 2013;). The increase in anthropogenic activity in the coastal areas comes with a high risk of pollution (Duarte *et al.*, 2021), and several coastal habitats are exposed to different levels of human pressure due to fisheries, commercial shipping and touristic activities (Halpern *et al.*, 2008). In coastal waters, ship noise is the main anthropogenic source, representing up to 90% of the acoustic energy spread by humans into the sea, including low-frequency acoustic signals ranging from 125 Hz to 2 kHz (Dahl, 2007). Indeed, noise is a critical component of marine environments, and over the last three decades, underwater noise levels have increased dramatically at a rate of 3 dB per decade (Andrew *et al.*, 2002; Pine *et al.*, 2016). The European Marine Strategy Framework Directive (MSFD 2008/56/EC) recognised underwater noise as an environmental pollutant. The Directive identified underwater noise as one of the eleven environmental quality descriptors in order to mitigate its effects on biodiversity. Descriptor 11 "underwater noise" includes two criteria regarding the monitoring and assessment (spatial distribution, temporal extent and levels of sound sources) of anthropogenic sounds in water: 1. evaluating impulsive sounds, described as the monopole energy or zero to peak monopole source levels over the frequency band of 10 Hz–10 kHz; and 2. evaluating the annual average (or other suitable metric) of the squared sound pressure from continuous low-frequency sources in each of the two 1/3 octave bands, centred at 63 Hz and 125 Hz. Anthropogenic noise represents a stressor for marine species as it can mask vocal communication and alter their health and fitness, thus affecting their survival (Filiciotto *et al.*, 2014; Papale *et al.*, 2015; Erbe *et al.*, 2016). Although more studies on biological sounds are being conducted, there are still little data available for evaluating the real impact of anthropogenic noise on marine species and ecosystems. A simple visualisation of acoustic data contributes to understanding the marine ecology complexity and supports the interpretation of ecological processes aimed at improving marine environmental management (Van Opzeeland & Boebel 2018; Weiss *et al.*, 2021). Worldwide, a few studies have investigated the marine soundscapes at coral reef sites in the Pacific (Andrew *et al.*, 2002; McWilliam *et al.*, 2013; Bertucci *et al.*, 2015), Atlantic (Axelrod *et al.*, 1965; Staaterman *et al.*, 2013), and Indian (Cato *et al.*, 2002; Parsons *et al.*, 2013) Oceans, and Mediterranean Sea habitats (Buscaino *et al.*, 2016; Pieretti *et al.*, 2017; Ceraulo *et al.*, 2018). This work aims to identify the main contributing components of the marine underwater soundscape in the shallow waters of the Gulf of Oristano (Western Mediterranean Sea), describe the environmental sound pressure levels (SPLs) for the 63 Hz to 64 kHz octave bands and the broadband SPLs, and also provide information on the changes in the marine underwater soundscape resulting from the COVID-19 pandemic lockdown. Finally, it could be considered as a contribution to the general targets of the MSFD.

This work, through the use of the passive acoustic monitoring (PAM) approach in marine ecosystem studies, aims to provide useful baseline information for management strategies in a coastal zone where protected areas (a special area of conservation, ITB030080 Directive 92/43/EEC, and a national marine protected area) and human activities (fishing, fish farming, an industrial harbour and commercial shipping traffic) coexist. PAM has been recently recognised by the Global Ocean Observing System (GOOS) Commission as a reliable tool for assessing the status of the ocean's biodiversity, with the designation of underwater sound as an essential ocean variable (EOV) (Tyack *et al.*, 2017).

Materials and Methods

Study Site

Data collection was performed in the shallow waters of the Gulf of Oristano, which is located along the western coast of Sardinia (Italy), the second-largest island in the Mediterranean Sea. The acoustic recordings were obtained from a selected site within the Gulf, a semi-enclosed water basin with an average depth of approximately 15 m and a maximum depth of approximately 25 m. The Gulf covers an area of 150 km^2 and is connected to the Sardinian Sea across a span of 9 km. The dominant winds are Mistral from the north-west, Libeccio from the south-west and Sirocco from the south-east (Pinna, 1989). The Gulf of Oristano is distinguished by its high marine biodiversity: the seafloor consists of over 70% *Posidonia oceanica* meadows (Directive 92/43 of the EEC, Habitats Directive) and approximately 30% sand and rocks, representing a substrate suitable for a variety of organisms, such as fish, crustaceans and molluscs (Magni *et al.*, 2008, Cancemi *et al.*, 2000; de Falco *et al.*, 2006; Coppa *et al.*, 2019). In addition, it appears to be a potential feeding area for small cetaceans (Corrias *et al.*, 2019; Bearzi *et al.*, 2011).

Acoustic sampling and data acquisition

Underwater acoustic recordings were acquired from the location defined by the geographic coordinates 39.884167°N, 8.500833°E, as shown in Figure 1A. Three recording sessions of 10 days each, from July 2019 to May 2020, were carried out as follows: summer 2019 (July 8–18; SU19), autumn 2019 (November 8–18; AU19) and spring 2020 (May 8–18; SP20). Data were collected using a PAM station equipped with an autonomous recorder [model Urek 384 (NAUTA Srl)] consisting of an omnidirectional hydrophone (Sensor Technology SQ26-05) with a sensitivity of −169 (± 2) dB re V/μPa from 0.1 to over 50 kHz and frequency range of 0.1–96 kHz with a duty cycle of 20%. The recorder was programmed to acquire sounds for 3 minutes every 12 minutes for a total of 12 minutes every hour at a sampling rate of 192 k-samples s^{-1} and 16-bit resolution without further preamplification; no filters were applied during the recordings and the UM-

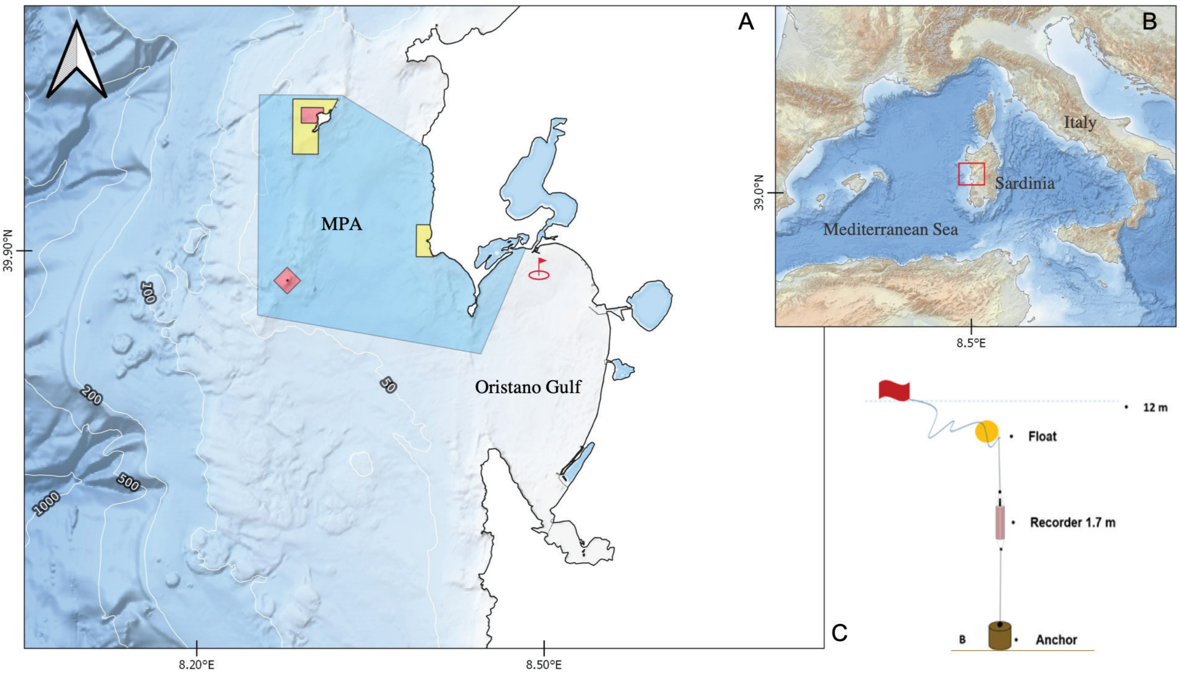

Fig. 1: A-B) Map of the study area (Oristano Gulf) located on the western coast of Sardinia in the Mediterranean Sea, Italy. The red symbol indicates the site where the deployment system was located; differently coloured areas correspond to different protection level, of the Penisola del Sinis – Isola di Mal di Ventre MPA. C) Scheme of the underwater recorder deployment.

283BLE application developed by Dodotronic Srl was used for the set-up and management of the acoustic data. The autonomous recorder was deployed on the seabed together with a 15 kg stone ballast and a small buoy to keep the hydrophone in a vertical position (Fig. 1-C). The device was located at a depth of 12 m, 1.5 NM from the boundaries of the local Marine Protected Area (MPA) Penisola del Sinis – Isola di Mal di Ventre (partial reserve) and approximately 1 nm from the fishing harbour. Moreover, it was deployed between a mussel farm and a fish farm.

Acoustic data processing and analysis of the main soundscape components

The entire dataset was aurally and visually inspected through a spectrogram consisting of a time vs. frequency graph (1024 Fast Fourier Transform size point, overlap 50% Hamming window and logarithmic frequency scale) using the RX5 audio editor software (iZotope Cambridge, MA, United States) to assess the quality of the recordings and eliminate noises generated by the acoustic instrument. The more suitable acoustic recordings were scrutinised to detect the main soundscape components and obtain a qualitative representation of soniferous species (*Biophony*), anthropogenic sources (*Anthropophony*), and marine weather events (*Geophony*). Acoustic signatures were identified and described by combining manual and automatic analyses. First, all of the acoustic signatures were manually analysed in the 0.2–96 kHz frequency broadband and in the time domain by an expert operator. As the identification of some biological sources was not entirely certain, they were characterised acoustically. Furthermore, social communication signals (whistles) were also observed in the audio files, but these were not analysed and integrated with the present study. Owing to the disturbance of ship passages and rainfall (100 Hz–1 kHz), the few fish signals present in the dataset were not identifiable and the parameters could not be acoustically characterised.

Crustacean and dolphin impulse signals were selected and extracted from the best acoustic files, i.e., those in which neither vessel passages nor other disturbances occurred and with a high-quality signal-to-noise ratio. The analysis was performed using the ‘Pulse Train Analysis’ semi-automatic routine in Avisoft-SAS Lab Pro (Bioacoustics, Germany) with predefined threshold values for both single and trains of signals. For each pulse signal from crustaceans and click train from dolphins, the following acoustic parameters were measured: duration (s), peak frequency (Hz) and bandwidth (Hz) for single signals, and the number of pulses (n) and pulse rate (n/s) for trains of signals. In addition, to describe the circadian activities of crustaceans, the power spectrum density (PSD) for a subsample of 24 hours during the greatest acoustic activity occurring on the days with a full moon (14.07.19; 12.11.19; 08.06.20) was also calculated (Lammer *et al*., 2008) using FFT 512 (50% overlap and 1-sec windows) for the frequency band value of 16,500 Hz at which the maximum crustacean activity occurred. The total seasonal occurrence of dolphins in the area was calculated as the percentage of the acoustic presence (click signals) from the total number of recordings. The total number of vessel passages was counted manually for all files, while the presence of fishing gear [sonar and acoustic deterrent devices (ADDs)], and rain and wind events were considered within each file. Each group of sound sources was tested for non-normal distribution in order to evaluate differences in their seasonal composition and a Mann–Whitney pairwise test was conducted.

Acoustic measurements and temporal pattern of sound pressure level

The sound level variation pattern was investigated for all data acquired during the sampling periods (SU19, AU19 and SP20); the broadband and octave band SPLs (SPL dB re 1 µ Pa) were calculated. More specifically, for each .wav file (12 minutes per hour), the SPLs were calculated for eleven octaves bands centred at 63 Hz, 125 Hz, 250 Hz, 500 Hz, 1 kHz, 2 kHz, 4 kHz, 8 kHz, 16 kHz, 32 kHz and 64 kHz. The broadband SPL was determined to compare the seasonal variations in sound levels, whereas the octave band SPLs were used to investigate the seasonal and daily trends (day from 09:00 a.m. to 04:00 p.m. and night from 09:00 p.m. to 04:00 a.m.). The analysis was performed via an automatic routine with a temporal observation window of 3 minutes using Avisoft SAS Lab Pro software (Avisoft bioacoustics, Glienicke, Germany). The median, 5th percentile and 95th percentile were calculated for the broadband and octave band SPLs. The data were not normally distributed; therefore, the Kruskal–Wallis test was used to assess the differences in broadband SPLs between seasons, while the Mann–Whitney U test was used to highlight differences between day- and night-time. Finally, to evaluate the seasonal differences in the octave band SPLs, the Mann–Whitney pairwise test was used. In this work, statistical analysis was performed using STATISTICA v.7.0 (Stat Soft, Tulsa, OK, USA).

Results

The results presented here illustrate the temporal patterns of the main underwater soundscape components and the variations in the broadband and octave band SPLs in the study area for three sampling periods: SU19 (n = 2,642 .wav files), AU19 (n = 2,016 .wav files) and SP20 (n = 1,996 .wav files) (after *COVID-19 pandemic lockdown*), with a total of 6,664 .wav files recorded and approximately 144 hours processed.

Main soundscape components identification, description and variation in acoustic signatures

Each season showed distinct abiotic and biotic occupancy of the 'acoustic space' in the Gulf of Oristano. A 'snapshot' of the predominant components and details of the seasonal and hourly variations in the acoustic sources of the soundscape are shown in Figure 2 (A–B). Within the main soundscape components, nine different acoustic signatures were obtained by manual detection. Six typologies of anthropogenic signatures were identified. Four of them were identified as vessels (Fig. 3; 1–4), all falling in the low-frequency range of 100–2000 Hz and in the central hours of the day; two other typologies were identified as recurrent impulsive signals, belonging to the most common fishing gear (sonar and ADDs), with frequencies of 40 and 70 kHz, respectively (Fig. 3; 5–6).

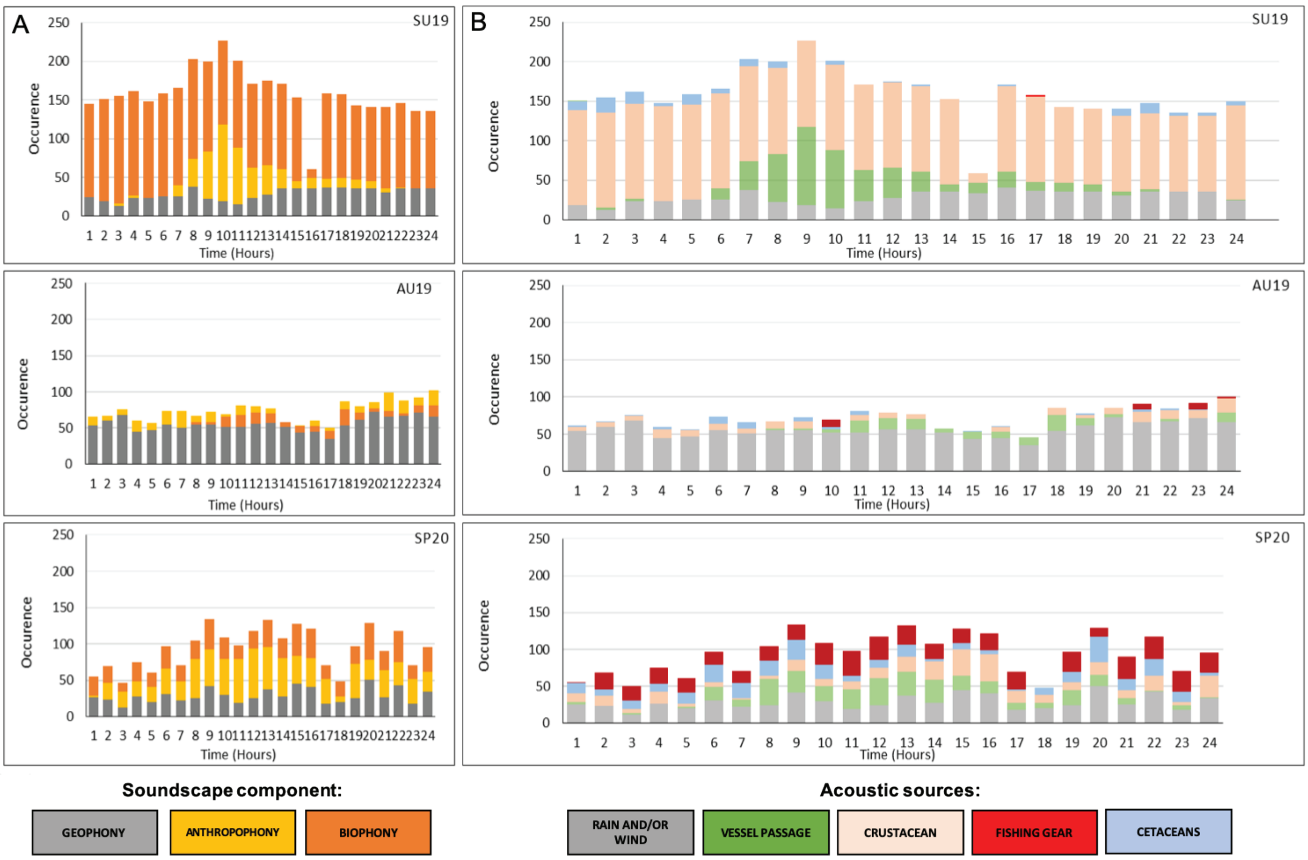

Fig. 2: A) Soundscape component *Biophony, Geophony and Anthropophony*, detected in the study area as a function of different seasons Summer 19 (SU19); Autumn 19 (AU19); Spring 20 (SP20) and time of the day (24 hours). B) "Snapshot" of hourly changes of acoustic sources.

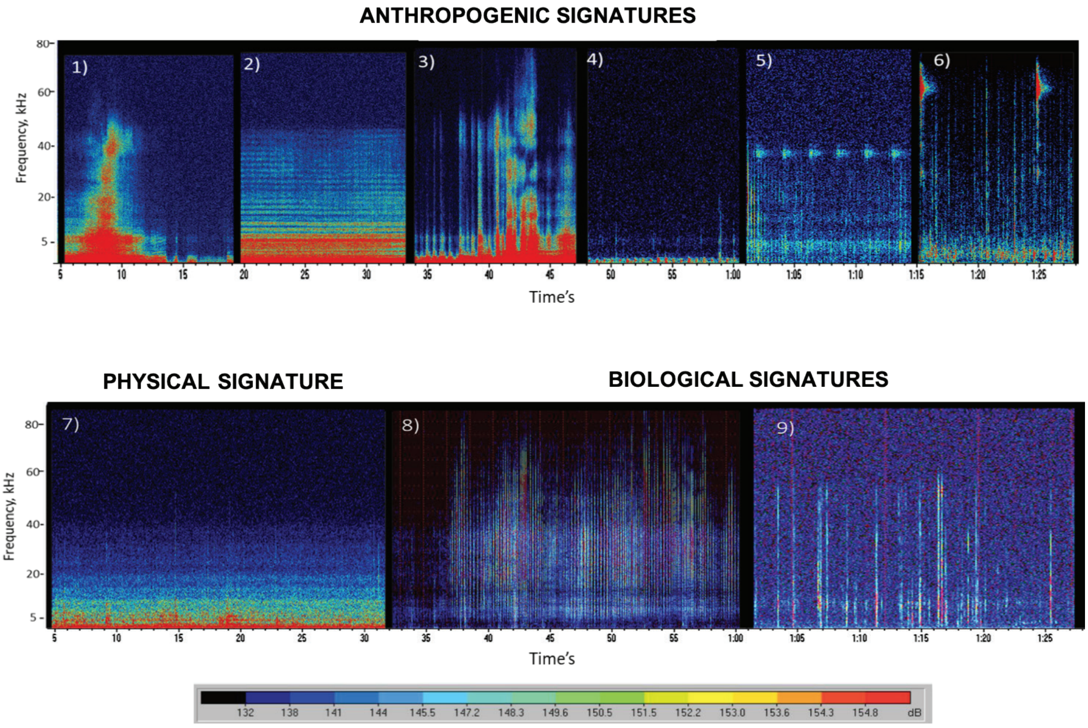

Fig. 3: Spectrogram of anthropogenic, biological, and physical (FFT length=1024 points, hamming window and 50% overlap). Spectrograms of different signatures generated by vessels (1-4); by fishing gear and acoustic deterrent device (5-6), rain (7), dolphins "click" (8) and crustacean "snap" (9). The colour bar shows the Power spectral density dB re 1 μPa^2/Hz. Note the different durations.

A rain event is also shown, with a frequency of up to 10 kHz (Fig. 3; 7). A single pulse ('snap') and a pulse train ('click pulse') were identified within the high-frequency broadband (10–80 kHz) as two biological signatures (Fig. 3; 8–9). Dolphin passages occurred overnight in SU19 and AU19; on the contrary, during SP20 (post-lockdown period in Italy), their presence was regular throughout the day-time. A total of 8560 click pulses and 705 high-quality snap signals were characterised; the former was ascribable to the free-ranging dolphins, and the latter to the 'snapping shrimps' identified as *Alpheidae* (Au *et al.*, 1998). In Table 1 the main acoustic parameters of signals obtained by the 'pulse train analysis' are reported, and the spectrogram and waveforms of these signals are shown in Figure 4A. Significant differences in the seasonal occurrences of acoustic signatures were found (verified by the Mann–Whitney pairwise test with $p < 0.05$) among the sampling periods (Table 2).

In AU19, the fewest passages and the highest percentage of rain events were recorded. Geophony was present in all sampling periods, and differences were observed between AU19 and SP20–SU19. The highest proportion of dolphins' acoustic presence was recorded in SP20 (32%), while crustacean activity was predominant in SU19 (91%). For both of these acoustic components, significant differences between sampling periods were

Table 1. Mean ± Standard Error (SE) of the best signal's features measured for principal biological sources individuated on each sampling period. Clicks and Snap were identified through the Pulse Train Analysis in Avisoft SAS-Lab Pro (Avisoft Bioacoustics, Germany), using the methods of envelope modification "RMS+Decimation" and pulse detection "Peak search with Hysteresis".

Acoustic signals	Number pulse/ train	Acoustic parameters	Unit	Mean ± SE
Cetacean's signals	8056 pulse	Duration of pulse	sec	0.0012 ± 0.0008
		Bandwidth	kHz	55.5 ± 33.9
		Peak frequency	kHz	3.3 ± 16.3
	24 train	pulse of train	N	34 ± 33.8
		Pulse rate	N/sec	21.3 ± 9.6
Crustacean's signals	705	Duration of pulse	sec	0.0004 ± 0.001
		Bandwidth	kHz	82.7 ± 28.5
		Peak frequency	kHz	1.01 ± 7.3
		N. pulse of train	N	-
		pulse rate	N/sec	-

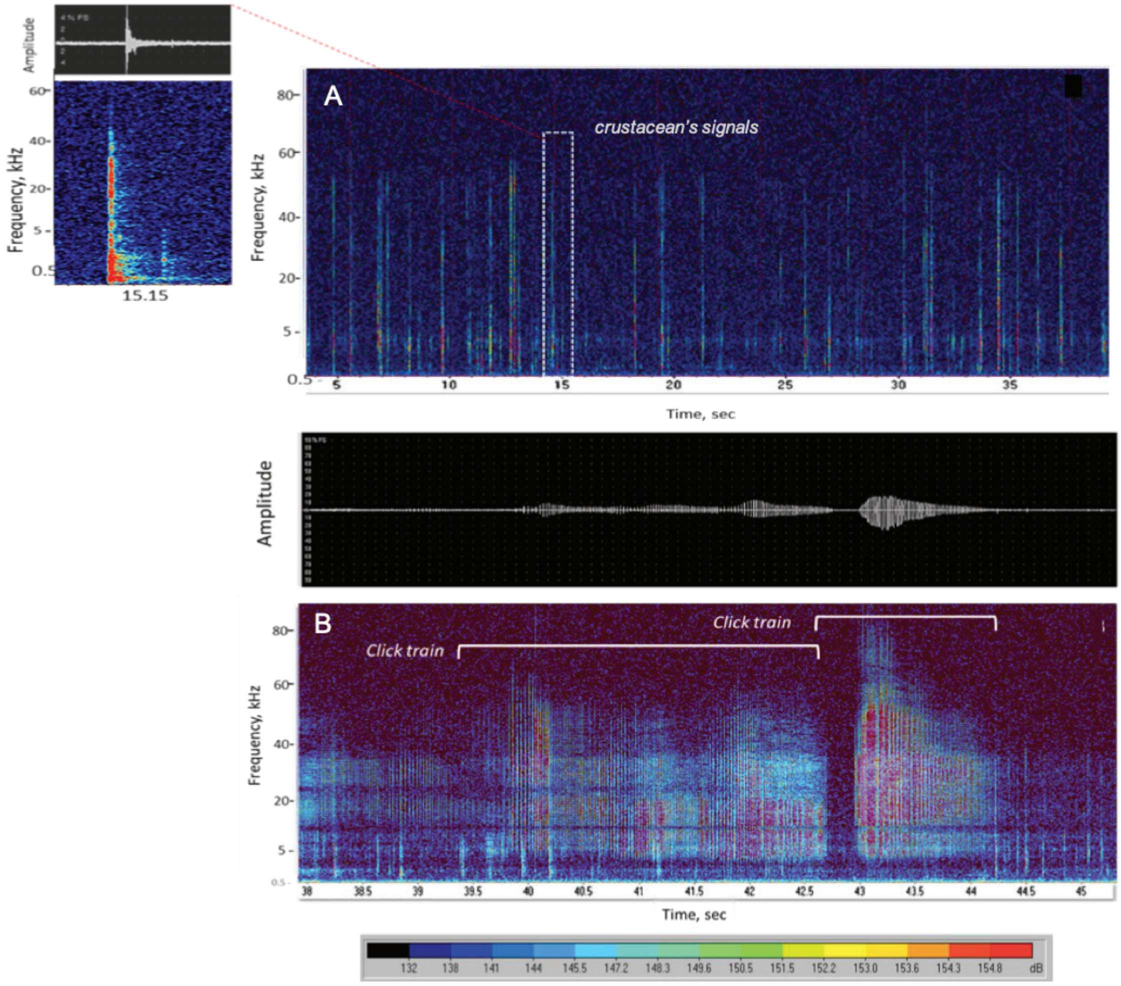

Fig. 4: Spectrogram of the principal biological signals. A) Impulsive crustacean's signals. B) Pulse Train of dolphin's signals. Colour bar shows the power spectral density (dB re 1 μPa^2/Hz).

found. During SP20, a high percentage (25%) of ADD sound was observed.

The PSD in the 16.5 kHz-frequency band (dB re 1 μPa) represents the average energy produced by crustacean activity shown in selected high-quality signals. Figure 5 presents the circadian rhythm for each sampling period. The maximum activity of snaps was concentrated in short intervals during the day-time in both SU19 and SP20.

Seasonal pattern in the marine shallow-water soundscape

Significant seasonal and daily differences in the soundscape were observed in the Gulf of Oristano. Table 3 describes the SPL values (dB re 1 μPa) for 10 days (a total of 24 h of recordings) of each sampling period considering two time intervals: day-time (09:00 a.m.–04:00 p.m.) and night-time (09:00 p.m.–04:00 a.m.). Significant differences in the mean broadband SPL values (dB re 1 μPa) between seasons were observed (Fig. 6). The lowest level of overall sounds was recorded in SP20 (150 dB re 1 μPa) and the highest was recorded in SU19 (169 dB re 1 μPa).

The seasonal variations of the octave bands are shown in Figure 7. The pairwise comparison of the seasonal SPL values of the octave bands showed significant differences, except for the band of 250 Hz between SU19 and SP20 and the band of 16 kHz between SP20 and AU19. The frequency bands centred at 250 Hz showed similar values in SP20 and SU19 (136 dB re 1 μPa), as well as the bands at 16 and 64 kHz in SP20 (140 dB re 1 μPa) and AU19 (137 dB re 1 μPa). SP20 showed equivalent values of SPL for bands 1, 2, 4 and 8 kHz (140–140.6 dB re 1 μPa). AU19 showed the maximum value for the band of 4 kHz (145.9 dB re 1 μPa), and lower values for higher-frequency bands (8, 16, 32 and 64 kHz). Figure 8 shows the significant day-time and night-time variations in the octave band SPLs (dB re 1 μPa) for each season (Mann–Whitney U test with $p < 0.001$). Significantly higher values in the low-frequency bands occurred in SP20 (from 62.5 Hz to 2 kHz) and SU19 (from 2 to 16 kHz) during the day-time. In contrast, higher values in the low–medium-frequency bands from 250 to 8 kHz were observed in AU19 at night.

Discussion

Here, a study evaluating the marine soundscape of the shallow waters of the Gulf of Oristano (Western Mediterranean Sea) using PAM is presented. Recordings from acoustic sources provide a 'snapshot' of the underwater

Table 2. Percentage of files with occurrence of diverse acoustic sources within each sampling period along with results of Mann-Whitney pairwise test for differences for all comparison between periods. Number of total files: SP20 =1996; SU19 =2642; AU19= 2016.

Acoustic source and percentage of occurrence			Comparison of the acoustic sources		
ANTHROPOPHONY	**Vessel passage**		**SP20**	**SU19**	**AU19**
	17%	**SP20**	-	p-level = 0,7335	p-level < 0.01
	18%	**SU19**	p-level = 0,7335	-	p-level < 0.001
	7%	**AU19**	p-level < 0.01	p-level < 0.001	-
	Fishing gear		**SP20**	**SU19**	**AU19**
	25%	**SP20**	-	p-level < 0.001	p-level < 0.001
	0,1%	**SU19**	p-level < 0.001	-	p-level = 0,1501
	1%	**AU19**	p-level < 0.001	p-level = 0,1501	-
GEOPHONY	**Rain and Wind**		**SP20**	**SU19**	**AU19**
	30%	**SP20**	-	p-level = 0,7408	p-level < 0.001
	24%	**SU19**	p-level = 0,7408	-	p-level < 0.001
	67%	**AU19**	p-level < 0.001	p-level < 0.001	-
BIOPHONY	**Cetacean**		**SP20**	**SU19**	**AU19**
	32%	**SP20**	-	p-level < 0.001	p-level < 0.001
	9%	**SU19**	p-level < 0.001	-	p-level < 0.001
	5%	**AU19**	p-level < 0.001	p-level < 0.001	-
	Crustacean		**SP20**	**SU19**	**AU19**
	17%	**SP20**	-	p-level < 0.001	p-level < 0.01
	91%	**SU19**	p-level < 0.001	-	p-level < 0.001
	3%	**AU19**	p-level < 0.001	p-level < 0.001	-

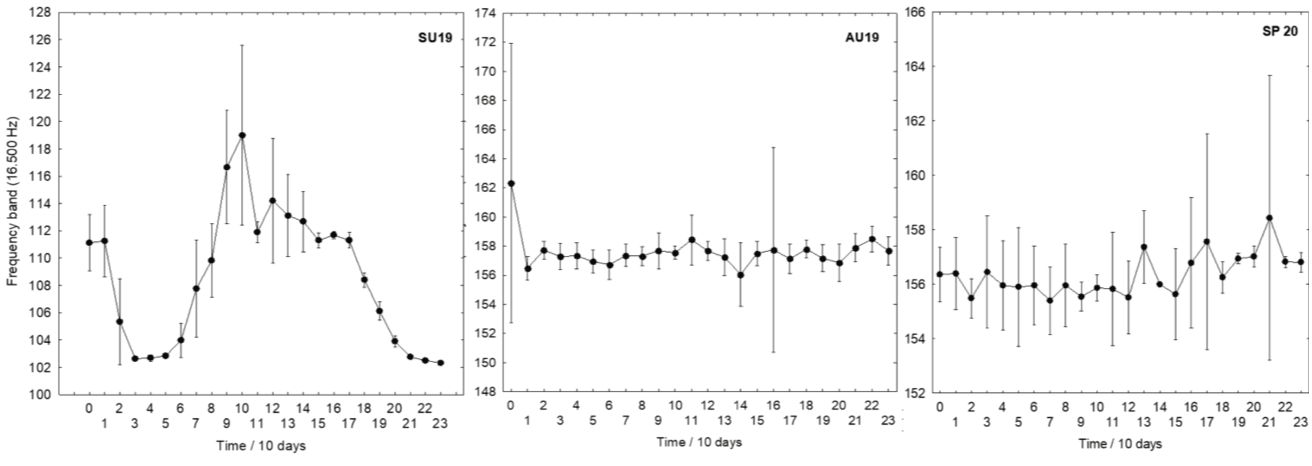

***Fig. 5**:* Median ± 0.95 Conf. Interval of PSD (dB re 1μPa) for crustacean signatures of 10 days (24 hours). PSD was calculated using FFT 512 (50% overlap and averaging window of 1 sec) for the octave band centred at 16,5 kHz, the frequency band in a considerable percentage of which crustacean signals fall. Note the different frequency scale.

environment in the time and frequency domains. Soundscape components are not static, but change daily and seasonally, reflecting the contributions of *geophony, biophony* and *anthropophony*. This study describes, for the first time, the mosaic of acoustic signatures in the marine soundscape of the Gulf of Oristano over time (Fig. 2A-B). Studies on underwater soundscapes have focused on the biophonic component and their niches, as they provide significant information on habitat complexity, which is, in turn, connected to the composition of the biological community (Putland *et al.,* 2017; Carriço *et al*., 2020; Xu *et al*., 2020). Through the qualitative analysis of spectrograms, the acoustic presence of marine organisms belonging to two marine taxa was detected: cetaceans and crustaceans. For the latter, the spectrum (Fig. 3; 9) displays a moderate number of signals included in a broadband with a low-frequency peak between 1 and 5 kHz and energy extending out to 200 kHz, which Au and

Table 3. Seasonal day-time and night-time description before and after Italian lockdown in rms octave band sound pressure level (Median, 5th – 95th percentile. Day-time (9 a.m. 4 p.m.), night-time (9 p.m.−4 a.m.) and total broadband SPL were calculated for 10 days (24 hours of recordings) in each season.

	SUMMER (SU19)									**AUTUMN (AU19)**									**SPRING (SP20)** *after Italian lockdown*								
	24 HOURS			**DAY**			**NIGHT**			**24 HOURS**			**DAY**			**NIGHT**			**24 HOURS**			**DAY**			**NIGHT**		
Octave band	**median**	**5th**	**95th**	**median**	**5th**	**95th**	**median**	**5th**	**95th**	**median**	**5th**	**95th**	**median**	**5th**	**95th**	**median**	**5th**	**95th**	**median**	**5th**	**95th**	**median**	**5th**	**95th**	**median**	**5th**	**95th**
63 Hz	**128.4**	119.9	137.3	**129.2**	128.4	137.3	**128.4**	123.8	137.3	**123.7**	117.7	135.0	**123.9**	123.3	135.5	**123.8**	121.7	135.5	**121.8**	118.4	132.3	**128.0**	118.2	132.7	**121.7**	120.3	129.7
125 Hz	**134.0**	125.2	140.3	**134.4**	133.9	144.8	**133.9**	133.4	144.8	**133.1**	123.3	144.6	**133.1**	131.0	145.5	**133.4**	130.4	145.5	**131.5**	125.9	142.2	**136.0**	125.6	142.7	**130.4**	129,2	138.9
250 Hz	**135.9**	127.3	144,1	**137.1**	135.9	147.9	**139.0**	135.9	147.9	**138.4**	125.1	148.3	**138.5**	134.8	148.9	**139.0**	133.5	148,9	**135.9**	125,9	145.1	**139.0**	128.2	146.5	**133.5**	132.7	141.1
500 Hz	**135.5**	126.6	145.4	**137.6**	135.5	150.2	**142.4**	135.5	150.2	**141.4**	124.6	149.0	**141.4**	137.3	149.3	**142.4**	135.3	149.3	**138.9**	128,0	146.5	**141.0**	127.8	147.6	**135.3**	136.0	144.2
1 kHz	**137.0**	128.3	147,8	**139.8**	137.0	152.2	**145.3**	137.0	152.2	**144.3**	128.5	151.1	**144.0**	138.6	151.5	**145.3**	136.6	151.5	**139.9**	127.9	147.6	**143.0**	128.8	148.8	**136.6**	137.5	145.3
2 kHz	**141.8**	132.8	148.6	**141.8**	141.5	152.1	**146.4**	141.8	152.1	**145.4**	129.8	153.5	**144.8**	139.0	154.1	**146.4**	138.8	154,1	**139.9**	132.8	148.8	**143.0**	132.9	149.6	**138.8**	138.6	146.6
4 kHz	**143.6**	134.5	148.1	**143.6**	142.9	150.6	**146.8**	143,6	150.6	**145.9**	134.9	156.5	**145.6**	139.7	157.4	**146.8**	140.9	157.4	**140.6**	136,2	150.5	**146.0**	135.8	150.9	**140.9**	140.3	148.9
8 kHz	**145.9**	136.1	149.4	**145.9**	145.3	150.7	**145.9**	143.2	150.7	**142.7**	134.9	153.0	**142.2**	140.2	154.6	**143.2**	141.1	154.6	**140.5**	137.4	149.9	**147.0**	137.1	150.5	**141.1**	140.1	148.6
16 kHz	**146.5**	137.1	149.1	**146.5**	146.2	150.4	**146.5**	140.0	150.4	**139.7**	135.6	147.5	**139.5**	139.8	148.6	**140.0**	140.0	148.6	**140.0**	135.5	147.2	**146.0**	137.2	147.4	**140.4**	139.5	145.7
32 kHz	**147.3**	139.9	148,4	**147.3**	147.2	149.2	**147.3**	138.4	149.2	**138.3**	137.0	143.1	**139.4**	138.4	143.3	**138.0**	143.6	143.3	**140.7**	137.7	156.3	**146.0**	137.6	150.5	**143.6**	139.5	157.0
64 kHz	**148.8**	139.9	149.3	**148.8**	148.8	149.7	**148.8**	138.4	149.7	**138.4**	138.3	139.6	**138.7**	138.4	139.6	**138.4**	139.8	139.6	**138.9**	138.4	144.3	**147.0**	138.4	142.0	**139.8**	138.7	144.7
Broadband	**169.0**	160.1	169.3	**169.0**	169.0	169.3	**169.0**	153.3	169.3	**152.6**	145.6	160.5	**153.3**	149.8	161.3	**153.3**	150.8	161.3	**150.9**	146.1	158.5	**155.0**	146.0	158.5	**150.8**	149.6	158.3

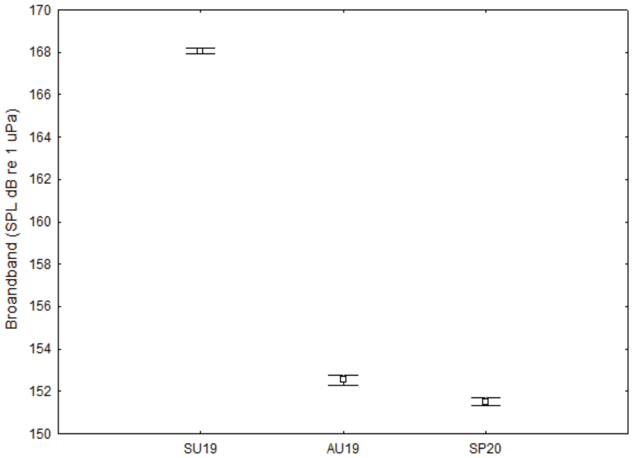

Fig. 6: Comparison of broadband sound pressure levels (SPL, dB re 1µ Pa) among different seasons. Mean ± 0.95 Conf. Interval. (Kruskal-Wallis test: H= 35. 6, p - level < 0.001).

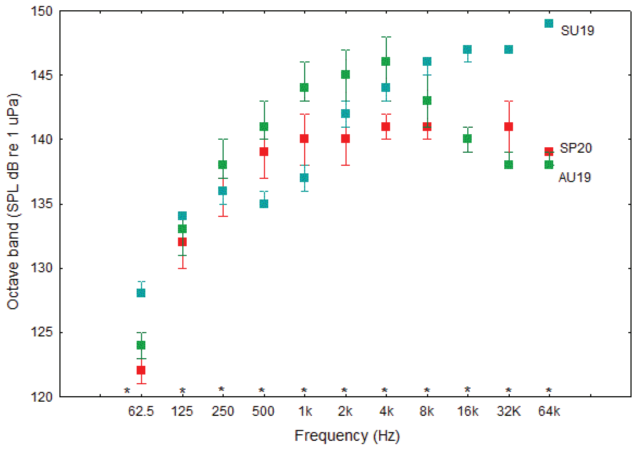

Fig. 7: Seasonal variations of octave band sound pressure levels (SPLs) in the study area for 10 days, (24 hours); SU19 blue boxes (July 2019), AU19 green boxes (November 2019), SP20 red boxes (May 2020). (Mann-Whitney pairwise test, p-level < 0.05).

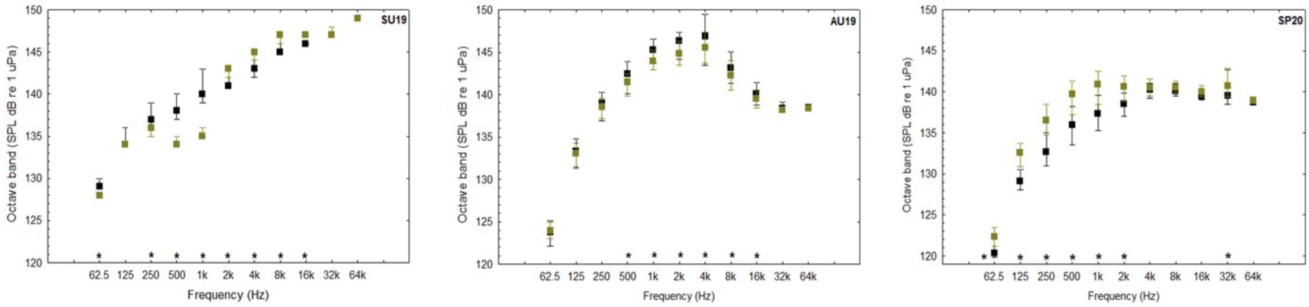

Fig. 8: Differences between day-time (yellow boxes) and night-time (black boxes) in octave band sound pressure levels (median, 40th – 60th percentiles) within the sampling period. Mann-Whitney U test (p-level < 0.001).

Banks (1998) described as the typical snapping of benthic shrimps that produce crackling and sizzling sounds. The acoustic characterisation of crustacean signals allowed the identification of them as *Alpheidae*.

In Table 1, the acoustic parameters of snapping shrimp signals are shown. In the future, it would be appropriate to identify species with an alternative method as well (e.g., visual census) and then combine information from these two approaches. However, visual census could be difficult as the species are cryptogenic which is a benefit of acoustic analysis. Snapping shrimp pulse activities were dominant in SU19 (Fig. 2-B), consistent with previous studies carried out in the Mediterranean Sea (Pieretti *et al*., 2017; Buscaino *et al*., 2016) and other biogeographic regions (Au *et al*., 2012; Radford *et al*., 2010; Staaterman *et al*., 2013). Snapping shrimps are more acoustically active at sunrise and sunset, with higher overall nocturnal sound production (Johnson *et al*., 1947; Everest, 1948; Radford *et al*., 2008; Bittencourt *et al*., 2016; Bohnenstiehl *et al.*, 2016; Lillis *et al*., 2017). Although we analysed a subsample of 10 days (24 hours) per season, the results indicated that snapping shrimp activity was greater during the day in all seasons. Further studies are needed to determine the circadian rhythm patterns as observed in coral reefs (Fig. 5). This behaviour could be affected by the abundance of food in the studied area, as farmed fish are fed during the early hours of daylight, which could stimulate the predatory and feeding behaviours of shrimps. Interest in examining the influence of environmental parameters (temperature, pH, dissolved oxygen and light exposition) in relation to the acoustic behaviour of snapping shrimps, although still poorly understood, is growing as it has been observed that these factors could influence their activities (Lillis *et al*., 2018). Therefore, snapping shrimps could be used on a global scale as key bio-indicator species of shallow waters at broadband frequencies for long-term studies aiming to assess ecological processes, such as changes in habitat composition, acoustics communities or quality, and evaluate their abundance, distribution and use of specific acoustic niches (Lammers *et al*., 2008; Radford *et al*., 2010).

Furthermore, click signals (10–80 kHz) associated with the feeding and navigation behaviour of dolphins were observed. The species may have been *Tursiops truncatus* (Montagu, 1821), which is a unique cetacean species sighted in the Gulf (Bearzi *et al*., 2008). However, no systematic studies on dolphin populations have been yet conducted in this area.

The waters of the Gulf of Oristano were frequented by dolphins throughout the study and represent up to 46.4% of observations in our acoustic data (total number of .wav files = 6653). The highest numbers of observations were recorded in the summer and spring. It has been hypothesised that the fish farms and artisanal fisheries (100 units) operating in the area may encourage opportunistic feeding (Lopez *et al*., 2008) and cause dolphins to execute a different acoustic repertoire related to stereotypical social cooperation behaviours, such as collective food searching. Focusing on SP20 (the post-lockdown period in Italy), the acoustic presence of dolphins was constant over hours and days (Fig. 2-B); this suggests that the animals frequented the Gulf regularly, likely to search for food, rest, or provide parental care. Recent studies suggest that a reduction in human activity can have rapid and measurable effects on wider underwater environments, with a positive impact on several inhabiting species (Chakraborty & Maity, 2020; Pearson *et al*., 2020; Rosenbloom & Markard, 2020; Zambrano-Monserrate *et al*., 2020). As continuous acoustic signals were observed 24 hours a day, we assumed that they were generated by the fishing-related ADDs used at fish farms to ward off dolphins that became accustomed to frequenting the area during the lockdown.

PAM is a valuable tool for obtaining information on the presence and habits of highly mobile species and could support systematic monitoring plans aimed at managing cetacean species that generally live at low density over large areas and spend most of their time underwater (Marques *et al*., 2009).

The main anthropogenic sources were observed in the low and mid-frequencies, and were described as vessel passages and fishing gear (sonar and ADDs). The percentage of files with vessel passages appeared to be considerably higher in the summer (18%; n=2642 .wav files) and spring (17%; n=1996 .wav files) (Table 2), when stable marine weather conditions encouraged local yachting and fishing activities. Moreover, we hypothesised constant activity from the fish farm operators during the morning hours (08:00 a.m.–01:00 p.m.) in comparison with the night hours. The anthropogenic spectral signatures in the soundscape of the Gulf, both continuous and intermittent, introduced noise to the underwater environment and occupied the acoustic space of the biological components (Fig. 2), potentially causing energetic soundscape masking and altered intra-specific communication and behaviour (Clark *et al*., 2009; Weiss *et al*., 2021; de Vincenzi *et al*., 2021).

The average values of the broadband SPL, which represented the aggregation of all the acoustic signatures of the local soundscape, were significantly higher in SU19 and lower in SP20, indicating a seasonal variation. The SP20 values (SPL dB re 1 μPa) may be attributed to a reduction in maritime traffic due to declined shipping and mobility during the *COVID-19 pandemic* (Millefiori *et al*., 2021; Gibney, 2020) (Fig. 6). This was supported by the lower SPL values for the low-frequency bands in SP20, typical of maritime traffic (62.5–500 Hz) (Fig. 7). Noise emitted by boats is a major source of environmental stress. It is likely that the decrease in noise benefitted ecological processes, such as the recruitment of larvae to preferred habitats (e.g., seagrass meadows). It may have provided a further advantage for biological communities settled in the MPA. Higher levels of SPL in the 16 kHz octave band compared with the other seasons were observed in SU19; this high-frequency band reflects the activity of snapping shrimps, although the day–night variations were not consistent with the results obtained by studies carried out in these sites (Fig. 7 and 8). Higher median octave band SPL levels were observed in AU19 than those in SU19 and SP20, from 62.5 to 4 kHz; the sound pressure levels showed significant differences between the day and night. In AU19, significant differences for the frequency bands from 500 Hz to 16 kHz were found, consistent with the findings of Buscaino *et al*. (2016). In addition, an opposite pattern was found in the summer, where the SPL values in the lower frequencies were significantly higher at night, while those in the higher frequencies were higher during the day. Differences were also found in the spring, when higher SPL values occurred in the low-frequency bands (62.5 Hz, 125 Hz, 250 Hz, 500 Hz, 1 kHz and 2 kHz) during daylight, whereas they occurred in the high-frequency bands (2, 4, 8, 16, 32, and 64 kHz) during the night in Lampedusa Island (Buscaino *et al*., 2016). Owing to the scarcity of information regarding underwater noise in the Mediterranean Sea, small-scale studies are useful for constructing a complete picture of possible anthropogenic noise sources. In the Mediterranean Sea, Codarin & Picciulin (2015) reported a mean ambient noise level of 121.3 dB re 1 μPa in Trieste Gulf (Italy), similar to those reported by Picciulin *et al*. (2013) (129–138 dB re 1 μPa) in the Venice lagoon (Italy). Additionally, values exceeding 100 dB re 1 μPa were reported by Viola *et al.* (2017) in the Sicilian coastal waters and between 92 and 114 dB re 1 μPa in Lampedusa island (Buscaino *et al*., 2016). The range of SPLs in the Gulf of Oristano was 120–150 dB re 1 μPa, similar to the values in the Venice Lagoon and Trieste Gulf. It is important to underline how the Gulf was constantly affected by anthropogenic activities over the seasons, as the main sound sources included vessel passages, fishing boats and fishing gear. The spectral characteristics of these sources fell within the frequency bands centred at 63 Hz, 125 Hz, 500 Hz, 1 kHz, 2 kHz and 40 kHz.

Conclusions

An acoustic signature can distinguish habitats through the description of the specific properties of the collected sounds. The application of the cross-sectional approach to a marine soundscape study can provide important information on coastal habitats and their changes over time. Our results provide a clear picture of the variability in broadband SPLs and the composition of the acoustic sources in the Gulf of Oristano, Italy. We observed how the two biophonic sources found were able to maintain their acoustic niche in both the frequency and time domains. PAM is widely considered as a useful method for assessing anthropogenic pressures on marine habitats, understanding the distribution and abundance of acoustic target species, as well as describing the spatio-temporal variations in acoustics behaviour in relation to noise (Merchant *et al*., 2015). This study highlights the advantages of using PAM and can help local integrated management plans that do not include systematic acoustic monitoring. Future studies would be extremely valuable in determining standard protocols for the monitoring activities of MPAs and Special Areas of Conservation and defining appropriate conservation measures. Vessel passage management in the local MPA is an example of how human noise mitigation measures can be integrated into an MPA's regulatory plan. Nevertheless, MPA soundscapes may also be influenced by sources beyond their limits, also spreading from great distances. Finally, this study may contribute to addressing noise mitigation management objectives by documenting acoustic conditions in marine habitats and providing baseline information for the inception of more territory-level planning capacity.

Acknowledgements

We thank Gaspare Barbera, Fabrizio Pinzuti and Angelo Disabato from the "Riserva Azzurra Srl" for their help during the positioning and recovery of the monitoring station; and Andrea Satta and CEM Group (CNR-IAS) for supporting this work. We are grateful to Michele Manghi (Nauta Srl) for the suggestions provided and *Mar. Eco Osservatorio della Natura* (no-profit) for the supply of the acoustic instrument. We would also like to express our gratitude to Fabio Giardina for his technical support and scientific contribution.

Author Contributions: Conceptualization, V.C and F.F; methodology, V.C; software, F.F.; formal analysis, V.C; investigation, V.C.; resources, G.A.d.L. and F.F; instrument, V.C; data curation, V.C.; writing-original draft preparation, V.C.; writing-review and editing, C.V and F.F.; supervision, F.F and G.A.d.L. All authors have read and agreed to the published version of the manuscript. *Conflicts of Interest:* The authors declare no conflict of interest. *Informed Consent Statement:* Not applicable Data *Availability Statement:* Data are contained within the article.

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