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Fast Pulse Train Sounds in a Noisy Coastal System: Structure, Distribution, and Environmental Controls

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Abstract

Pulsed sounds are widespread in marine soundscapes, yet they still lack systematic characterization and information on their emitting species. This study investigates the consistency and spatio-temporal distribution of Fast Pulse Train (FPT) sounds, an abundant sound type recorded in the Venice inlets during three acoustic campaigns conducted at 40 listening points in summer 2019 and 2020. Although FPTs show variability in their temporal and spectral features, clustering analyses revealed no clear separation among extracted signals, supporting the coherence of the current classification; however, when focusing on the more characteristic sounds, three slightly acoustically different groups emerged. The role of temporal, morphological, spatial, hydrodynamic and anthropogenic variables in explaining the distribution of FPT groups was statistically evaluated using generalized linear models. Background noise in the 200–630 Hz range was the only significant predictor, exerting a negative effect on FPT occurrence, likely driven by vessel noise rather than biological chorusing. This, however, does not provide additional cues for identifying the emitting species. Although FPT characteristics remain compatible with fish vocalizations, expanding comparative studies will be essential to refine the definition of this sound type, assess potential sub-categories, identify habitat associations, and ultimately develop robust hypotheses on its biological sources.

Keywords: Adriatic Sea; biophony; passive acoustic monitoring

1. Introduction

Each underwater location, much like terrestrial environments, possesses an acoustic landscape that reflects the distribution and behavior of its inhabitants. Consequently, detecting and characterizing marine sounds is an effective way to describe the acoustic biodiversity of a habitat [1,2]. The diversity of biological sounds lends itself well to acoustic diversity metrics [3], supporting the use of biophony as an indicator of marine environmental status [4]. Within this framework, recording sounds by using Passive Acoustic Monitoring (PAM) is a cost-effective, non-intrusive tool that is becoming invaluable for aquatic surveys [5]. PAM complements traditional biodiversity assessments because acoustic measurements provide continuous information that cannot be obtained through other approaches, such as visual censuses or fishing surveys, which are inherently time-limited. As a result, an increasing number of studies have focused on describing the acoustic fish

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community across a wide range of marine areas [3,6–11]. To avoid ambiguous terminology and improve comparisons among regions, a dichotomous nomenclature has been standardized to classify field-recorded signals (see for example [3,10]). This need also arises from the evidence that, in most of the studies, the emitter of the sound types, as well as the behavioural context in which they are produced, is unknown [12]. A recent inventory of animals confirmed or expected to produce sound underwater [13] reports that roughly seven hundred marine species are documented as producing sounds under natural conditions. However, based on taxonomic inference, more than twenty-one thousand species are deemed to produce sounds that have never been unequivocally described. Fish represent the largest group of unconfirmed likelyvocal species [13].

In general, fish produce predominantly low-frequency, pulsed and usually short sounds [14,15]. A single species may exhibit a broad vocal repertoire by varying pulse number or temporal patterning (e.g., [16]). It is therefore unsurprising that pulsed series are abundant in field recordings, highlighting the need for clear categorization. Pulsed sound series have been grouped according to features such as frequency, duration or inter-pulse interval, and pulse number, although not always considering all variables simultaneously. Recently [10], Atlantic pulsed sounds have been classified into low- and high-frequency categories (below and above 500 Hz, respectively), and into fast and slow pulse trains, defined by pulse periods shorter than 50 ms and between 30 and 3500 ms, respectively. A more detailed nomenclature, summarized in Table 1, has been developed for pulsed sounds in marine recordings from the Mediterranean Sea [17–20].

Table 1. Summary of the main pulsed-sound types described in Mediterranean marine recordings, including their defining acoustic features, frequency and temporal parameters, associated species; (when available), and key literature sources. N.A. denotes data not available.

Name	Abbreviation	Definition	Peak Frequency	Pulse Period	Emitting Species	References
Alternating Pulse-Period Pulse Series	APPPS	Stereotyped accelerating pulse series with alternating pulse period			*Ophidion rochei*; [21]	[3,17,19,20]
Regular Pulse Series	RPS	Stereotyped pulse series			*Sciaena umbra*; [22]	[3,17,19,20]
Ultra-Fast Pulseseries	UFP/kwa	Pulsed sound around 800 Hz with ultra short pulse periods that appear as 'pseudo-harmonics', i.e., pulse period between 10 and 20 ms, with high stereotyped pulse envelop	Around 800 Hz	10–20 ms	*Scorpaena* sp.; [23]	[3,17,19,20]
Fast Pulse Train	FPT	Pulse sequence with very small, aurally almost undetectable pulse periods with a peak frequency $\geq$ 200 Hz and pulse period < 10 ms	$\geq$200 Hz	<10 ms	N.A.	[3,17–19]
Low-frequency Pulse Sequence	LPS	Sequence of similar pulses (at least three) with irregular pulse periods, a peak frequency around or $\leq$200 Hz and a bandwidth between 20 and 200 Hz	Around or $\leq$200 Hz		*Epinephelus marginatus*; [24]	[3,19,20]
Low-Frequency Fast Pulse Train	LFPT	Pulse train with very small, aurally almost undetectable pulse periods with a peak frequency $\leq$ 200 Hz and Pulse period < 10 ms	$\leq$200 Hz	<10 ms	N.A.	[3,17,19]
Pulse series	PS	Sequence of similar pulses (at least three) with irregular pulse periods and a peak frequency $\geq$ 200 Hz	$\geq$200 Hz	Irregular	N.A.	[3,18,19];

Table 1. *Cont.*

Name	Abbreviation	Definition	Peak Frequency	Pulse Period	Emitting Species	References
Pulse series 1	PS1	Sequence of similar pulses (at least three) with pulse period above 80 ms and peak frequency above 600 Hz	Above 600 Hz	Above 80 ms	N.A.	[17]
Pulse series 2	PS2	Sequence of similar pulses (at least three) with pulse period below 60 ms and peak frequency above 300 Hz	Above 300 Hz	Below 60 ms	N.A.	[17]
Pulse series 3	PS3	Sequence of similar pulses (at least three) with pulse period above 80 ms and peak frequency below 400 Hz	Below 400 Hz	Above 80 ms	N.A.	[17]
Pulse serie 4	PS4	Sequence of similar pulses (at least three) with quick pulse period (below 22 ms) and peak frequency above 900 Hz	Above 900 Hz	Below 22 ms	N.A.	[17]
Pulse serie 5	PS5	Sequence of similar pulses (at least three) with pulse period above 200 ms and peak frequency between 400 and 600 Hz	400–600 Hz	Above 200 ms	N.A.	[17]
Pulse serie 1	PS1	Long series of more than 20 pulses with peak frequency around 600 Hz, pulse rate of about 1 s	Around 600 Hz		N.A.	[20]
Pulse serie 2	PS2	Series of five–seven pulses, with peak frequency around 300 Hz and duration shorter than 1 s	Around 300 Hz		N.A.	[20]
Pulse serie 3	PS3	Series of three pulses, with peak frequency around 600–700 Hz and pulse rate of around 0.1 s	600–700 Hz		N.A.	[20]
Pulse serie 4	PS4	Series of six pulses, with peak frequency between 600 and 800 Hz, and pulse rate around 1 s	600–800 Hz		N.A.	[20]
Pulse serie 5	PS5	Series of three–four pulses with peak frequency around 250 Hz and duration of 0.4 s	250 Hz		N.A.	[20]
Pulse serie 6	PS6	Series of three–four pulses, with peak frequency around 600 Hz, longer than 2 s	600 Hz		N.A.	[20]
	PS1	Stereotyped pulse series with increasing pulse period			N.A.	[18]
	PS200	Pulse series with peak frequency around 200 Hz sharing similarities with *S. umbra* calls; average pulse duration: 0.08 s and pulse periods: 0.27 s	200 Hz	270 ms	N.A.	[18]
	PS400	Pulse series with peak frequency around 400 Hz with variable pulse periods	400 Hz	Variable	N.A	[18]
	PS600	Pulse series with peak frequency around 600 Hz with irregular but rather long pulse periods ranging between 0.3 s and 1.4 s	600 Hz	300–1400 ms	N.A.	[18]
	PS800	Pulse series with peak frequency around 800 Hz, pulse durations of around 0.007 s and regular pulse periods (~1 s)	800 Hz	1000 ms	N.A.	[18]
	PSHF	Pulse series of higher frequency 900–1000 Hz without a regular temporal pattern	900–1000 Hz	Variable	N.A.	[18]
	PS-Slow	Pulse series with long (>3 s) pulse periods			N.A.	[18]

Beyond sounds attributed to known species such as *Ophidion rochei* [21], *Sciaena umbra* [22], *Scorpaena* sp. [23] and *Epinephelus marginatus* [24], most efforts have focused on definingsub-categories of pulse series based on a combination of acoustic features, sometimes using statistical clustering approaches (i.e., [20]). In contrast, the category of Fast Pulsed Trains (FPT), typically defined as "pulse sequences with very small, aurally almost undetectable pulse periods and a peak frequency $\geq$ 200 Hz", has received less attention. Despite the limited focus, FPTs appear relatively abundant in some recording sites (e.g., [19,20,25]), underscoring the need for further investigation. In fact, alongside the importance of sharing information on the sound characteristics of both known and unknown biological sources [26], there is a clear need to expand fundamental knowledge of the categorized sound types: such understanding is essential for using biological sounds as indicators of animal presence, activity, and responses to environmental conditions and stressors, accordingly with the strengths of the PAM techniques [2].

An analysis of the soundscape of the three Venice inlets (Northern Adriatic Sea), which connect the Venice lagoon, the largest lagoon in the Mediterranean, to the open sea, has been carried out in recent years. The Venice inlets represent a discontinuity within the north-western Adriatic's muddy seabed, as they are composed of structurally homogeneous artificial rocky blocks with cavities adjacent to soft substrates that can serve as feeding grounds. As a result, they have the potential to attract and aggregate local pelagic and benthic fauna that prefer rocky habitats, consistent with observations from other artificial coastal structures [27]. In such an area where other monitoring techniques, such as visual census, are partially limited, acoustic monitoring can help reveal the presence of sound-producing fish species. At the same time, due to intense traffic from cargo and cruise ships, fishing vessels, and a high density of recreational and small boats, the inlets are characterized by elevated levels of underwater anthropogenic noise levels [28], making them an interesting, extreme case study for underwater noise pollution. The mating vocalizations of the brown meagre *Sciaena umbra*, listed as Vulnerable by the International Union for Conservation of Nature (IUCN), have recently been documented in the inlets [28], confirming that the species reproduces in this area. Notably, the brown meagre's choice of breeding site within the inlets was not influenced by boat-induced pressure [29]. In addition to these fish calls, FPT sounds have been identified, where they appear to be particularly abundant [25]. These sounds are relatively poorly stereotyped, having an intrinsic variability in acoustic features such as number of pulses, peak frequency and duration [25]. This study aims to characterize the acoustic consistency of Fast Pulse Train sounds, investigate their spatio-temporal distribution across the Venice inlets, and evaluate the environmental and anthropogenic factors shaping their occurrence and grouping.

2. Materials and Methods

2.1. Data Collection

The Venice Lagoon, one of the largest lagoon systems in the Mediterranean, lies in the northern Adriatic (45.2–45.6° N, 12.2–12.6° E) within one of the most industrialized marine areas of the basin. It is traversed by intense cargo, cruise, and fishing traffic, whose movements are funnelled through the three deep and wide inlets that provide passage between the lagoon and the Adriatic Sea, also accommodating a substantial flow of recreational and small-sized boats.

During the summer of 2019 and 2020, three acoustic monitoring campaigns were performed across 40 stations positioned along the highly anthropized three channels linking the Venice lagoon with the Adriatic Sea (Figure 1). The inlets are lined by long stone jetties and dredged to maintain deep navigation channels. The presence of the MOSE mobile barriers installed on the seabed at all three inlets, which temporarily close the channels during high-tide events, further modifies their structure and operational dynamics [30,31].

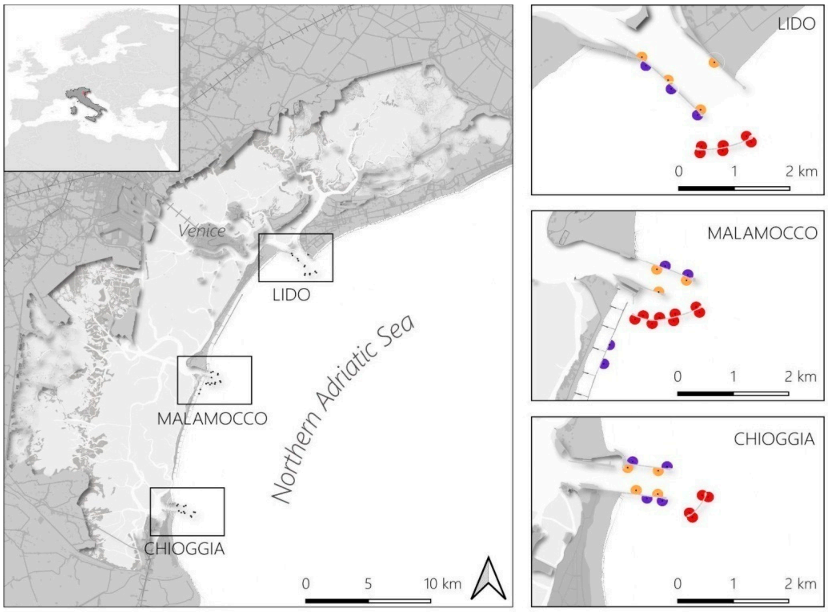


Figure 1. Overview of the study area with the detailed locations of the listening points within the areas of the sea inlets; internal inlet (yellow dots); external inlet (purple) and lunata stations (red) are indicated.

The listening stations were distributed among the inlets as follows: 13 at the Lido inlet on the north-eastern side, 15 at the central Malamocco inlet, and 12 at Chioggia in the south-west. Sampling locations were arranged with an approximate spacing of 300 m on both the internal-facing and sea-facing sides of each inlet and along the "lunate", which are detached breakwaters that represent artificial rocky substrates, built up to protect the coasts from erosion (see [32] for details).

The stations were inspected in random order during each field survey to ensure variability in recording times across sampling points over the 2-year monitoring periods. At each listening point, 5 min acoustic recordings were taken twice per day: one recording was made in the late afternoon, coinciding with a local peak in summer boat traffic (17:00–19:00), and a second one was collected later in the evening (19:30–23:00). This sampling schedule and the 5min window length were dictated a priori by the protocol of a broader monitoring programme dedicated to *Sciaena umbra* [28,29]. Consequently, this study relies opportunistically on a framework specifically tailored to target the late afternoon and evening acoustic peaks typical of vocal sciaenids. Nonetheless, this design has proven highly effective in providing standardized and comparable snapshots of acoustic activity in the study area.

Acoustic data were recorded using a pre-amplified and calibrated Colmar GP1280 hydrophone (sensitivity −170 dB re 1 V/µPa; frequency response 5–90 kHz), connected to a Tascam Handy Recorder (Tascam Corporation, Santa Fe Springs, CA, USA; 44.1 kHz sampling rate, 16-bit), producing Waveform Audio File Format (.wav) files. The hydrophone was deployed from a 7 m vessel and positioned at a depth corresponding to half of the local water column, with an overall mean deployment depth of approximately 4 m across stations. Sampling was conducted only when sea conditions were below level two on the Douglas scale. Before each recording, surface water temperature was measured with a digital thermometer (HANNA Checktemp® 1 HI98509, Padova, Italy; ±0.1 °C), yielding an average temperature of 27.4 °C (range: 26.6–28.5 °C).

A total of 440 5 min acoustic samples (equal to 2200 min) were collected, in particular: (i) 143 files were collected at the Lido inlet (I campaign: 28 June 2019 and 26 June 2020; II campaign: 5 August 2019 and 23 July 2020; III campaign: 29 August 2019 and 20 August 2020); (ii) 165 files were collected at the Malamocco inlet (I campaign: 1 July 2019 and 22 June 2020; II campaign: 29 July 2019 and 21 July 2020; III campaign: 28 August 2019 and 18 August 2020); and (iii) 132 files were collected at the Chioggia inlet (I campaign: 5 July 2019 and 24 June 2020; II campaign:1 August 2019 and 20 July 2020; III campaign: 27 August 2019 and 19 August 2020).

Local traffic quantification relied on visual counts of vessels during each recording session, and these observations were corroborated by analyzing the number of uniquely identifiable vessel sounds present in the acoustic data.

2.2. Sound Acoustic and Statistical Analysis

The acoustic samples were manually scrolled: spectrograms were aurally and visually assessed by using the Adobe Audition and Raven software (sampling rate 44.1 kHz, 16 bit, re-sampled at 6 kHz, Fast Fourier Transform—FFT = 512, and 50% overlap).

Inspection of spectrograms and associated sound waveforms was used to identify and manually select biological sounds, which were extracted (noting time and location of recordings), filtered by excluding environmental noise at higher and lower frequencies, and analyzed. They were classified based on their acoustic characteristics following catalogs of known sounds from the Mediterranean Sea [3]. Out of a total of 441 biological sounds found in the recordings, 319 sounds could be described as FPT (Fast Pulse Train) sound types. The following features of the FPT sounds were measured: (i) peak frequency (Peak Freq., Hz; the frequency with the highest energy); (ii) 5% frequency (Hz; the frequency that divides the spectral content into two intervals containing 5% and 95% of the energy); (iii) 25% frequency (Hz; the frequency that divides the spectral content into two intervals containing 25% and 75% of the energy); (iv) 75% frequency (Hz; the frequency that divides the spectral content into two intervals containing 25% and 75% of the energy); (v) 95% frequency (Hz; the frequency that divides the spectral content into two intervals containing 95% and 5% of the energy); (vi) sound duration (ms; the time from the onset of the first pulse to the offset of the last pulse); and (vii) number of pulses.

For each sampling station, a Sound Pressure Level (hereafter SPL) value was derived for the 1/3-octave bands by computing a 5 min root-mean-square average. SPLs were calculated for the 200–630 Hz range (SPL200–630; corresponding to 178–708 Hz), including the FPT sound peak frequency bands [25]. These levels were obtained by summing the energy across all relevant 1/3-octave bands using a logarithmic summation in the decibel domain.

To explore patterns of variation among FPT acoustic signals, a Principal Component Analysis (PCA) was performed on the standardized acoustic descriptors. Because of continuous structure in the data, a fuzzy clustering approach was adopted, and a gap statistic was performed to check the presence of distinct clusters. Fuzzy clustering allows each observation to belong to multiple clusters with different degrees of membership, providing a more appropriate representation of transitional acoustic signal types. Clustering was performed using the clusGap function and FANNY algorithm implemented in the cluster R package (version 2.1.8.1) [33,34]. For the fuzzy clusters, only the sound with a strong membership (>0.7) was assigned to a cluster, leaving the others as ambiguous.

2.3. Study Site Characterization and Environmental Correlations

Morphological characteristics (including bathymetry, seabed slope, and roughness) and hydrodynamic parameters (floodtide and residual currents) associated with each listening station in the study area (Figure 1) were quantified using a 100 m radius buffer around each location. Morphological data were derived from high-resolution multibeam surveys of the Venice lagoon inlets, as reported in [30,35,36]. Hydrodynamic information was obtained from [37]. For both morphological and hydrodynamic variables, the mean, standard deviation, and 90th percentile of all values within the 100 m buffer were calculated to describe local variability. Additionally, for every acoustic recording, the corresponding tidal level was retrieved from tide gauges operated by the ISPRA Sea Level Measurement Network (www.venezia.isprambiente.it). For additional details on these variables, refer to [30].

The relationship between FPT acoustic signals and environmental variables was investigated using generalized linear models with binomial error distribution (GLMs [38]). Two complementary modelling approaches were implemented:

- Cluster-based model, where presence–absence of single acoustic clusters as previously identified (see Section 2.2) was used as the response variable. These models were fitted using only signals with strong cluster membership (membership > 0.7).
- Signal-level model, where the presence of FPT acoustic events was analyzed without separating signals into clusters. In this case, all detected FPTs were included in the analysis to evaluate the overall relationship between acoustic activity and environmental conditions.

The model structure aims to evaluate the contributions of different predictors (see below) on response variables. Temporal predictors related to the recordings (year, campaign and time of the day) have been taken into account since they are known to affect biological animal vocal activity [39]. Morphological features and hydrodynamic variables have been included due to their potential relevance on animal site-selection. The position of the listening point (external, internal, lunate; see Figure 1 as reference) has been further evaluated as well as the role of the single inlet (Lido, Malamocco, Chioggia): they were considered relevant as other significant biotic or abiotic site- and habitat-specific features (e.g., local prey distribution or local angling fishing pressure) were not available. The role of the anthropogenic variables was tested according to the case of *Sciaena umbra* studied in the same area [29]: the anthropogenic pressure was inferred by the background noise calculated as Sound Pressure Levels "SPL200–630"and by the boat abundance. At the end, the presence of *S. umbra* chorusing as a predictor was also tested for the case of the signal-level model, assuming it as a potential acoustic competitor for the detection of FPT sounds.

According to this rationale, we applied a hierarchical model-selection framework, following the approach of [29,40]. This tested different assumptions regarding the relative contribution of the predictor categories previously described—namely temporal, morphological, hydrodynamic, and spatial variables among the environmental predictors, and ship counts and SPLs among the anthropogenic ones.

- For the cluster-based models, five model groups were examined, each corresponding to a specific hypothesis: the response variables are unaffected by any predictor (null model, m0);
- the response variables depend solely on temporal factors (m1);
- the response variables are influenced by both temporal and morphological features (m2);
- hydrodynamic variables also contribute (m3);
- local spatial structure (inlet identity and position within the inlet) plays an additional role (m4);
- anthropogenic factors (background noise and boat presence) (m5) help explain the distribution of FPT sounds;
- presence of the *S. umbra* chorus (m6) affects the above-mentioned distribution.

For each response variable (presence/absence in each recording event of FPT), the most suitable model within each category was identified using the Akaike Information Criterion (AIC [41]). When two competing models showed insufficient evidence to distinguish a clear best option (ΔAIC < 4), the model with fewer parameters was chosen. Each subsequent model category was then constructed by adding new predictors to the best-performing model from the previous step.

To further investigate the relationships among biological activity, anthropogenic pressure and underwater noise, we used a piecewise structural equation modelling (SEM) approach implemented in the R package, piecewiseSEM [42]. The SEM framework allows the simultaneous evaluation of multiple direct and indirect pathways while accommodating different error distributions among component models. The final SEM consisted of three component models. The occurrence of FPTs (binary response) was modelled as a function of time since sunset using a binomial generalized linear model (GLM). The occurrence of brown meagre (*Sciaena umbra*) choruses (binary response) was similarly modelled as a function of time since sunset using a binomial GLM. Underwater noise levels in the 200–630 Hz frequency band were modelled using a linear model including FPT occurrence, brown meagre chorus occurrence, boat abundance, cargo vessel abundance and time since sunset as predictors.

A correlated error term between FPT occurrence and brown meagre chorus occurrence was included to account for potential shared biological drivers not explicitly represented in the model. Model fit and path significance were evaluated using the procedures implemented in piecewiseSEM [42]. The final path diagrams were generated using DiagrammeR [43].

All statistical analyses were carried out in R version 4.5.2 [44], employing the DHARMa package to assess model residuals [45].

3. Results

On average, 'Venice' FPT-sound consists of a series of six pulses with a peak frequency of approximately 400 Hz and a duration of about 160 ms (n = 319), although the sound type has been found to be only weakly stereotyped [21]. To explore this variability, a PCA was performed on the dataset (Figure 2): the analysis did not reveal any clear separation among distinct signal groups. Consistently, neither the elbow method (Figure 3a) nor the gap statistic (Figure 3b) identified a clear optimal number of clusters. The WCSS (Within-Cluster Sum of Squares) curve, however, showed its main inflection at k = 3, suggesting that additional clusters would yield only marginal reductions in within-cluster variance. Based on this, three clusters were retained and subsequently modelled using a fuzzy clustering approach.

When considering only the events with high membership level to the three fuzzy clusters (Figure 2), which reduced the sample size from 319 to 119 sounds, three non-overlapping FPT series emerged: group A (n = 28), group B (n = 14), and group C (n = 77). Sounds with lower frequency, longer duration, and higher pulse rate were assigned to group A; group B, in contrast, was characterized by higher frequencies, broader bandwidths, and fewer pulses. FPTs assigned to group C exhibited intermediate peak frequencies and durations relative to the other two groups (Figure 4). The distributions of groups A, B, and C are shown in Figure 5.

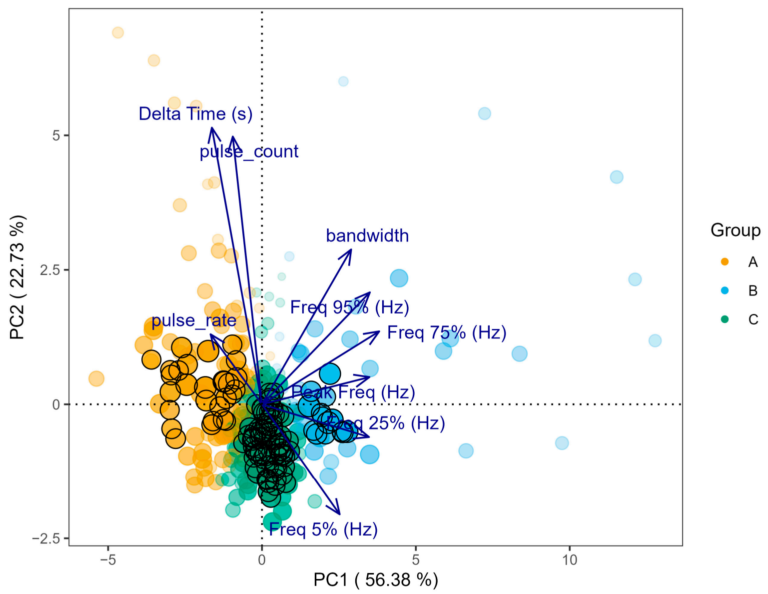


Figure 2. Principal Component Analysis (PCA) of acoustic signals: points represent individual signals; they are further coloured according to the fuzzy cluster assignment (groups A–C). Signals with strong cluster membership (membership coefficient > 0.7) are highlighted with circles.

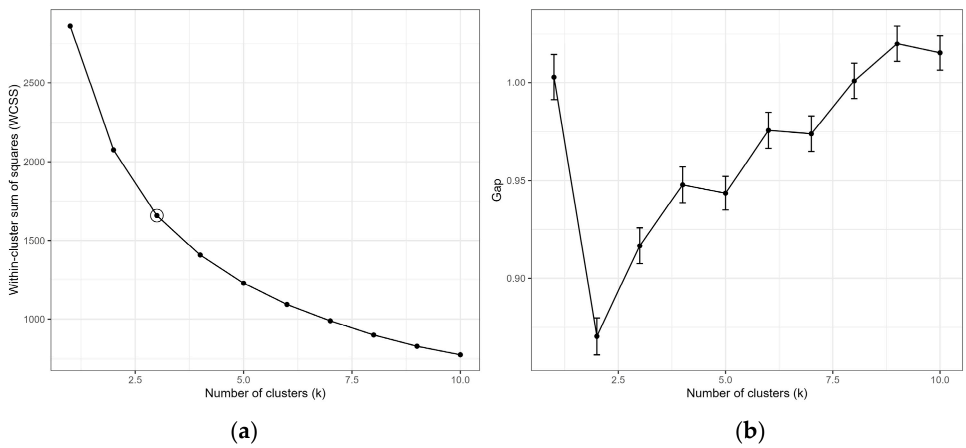


Figure 3. (**a**) Elbow plot showing the within-cluster sum of squares (WCSS) for increasing numbers of clusters (k); (**b**) gap statistic for k-means clustering. Error bars represent the standard error of the gap statistics.

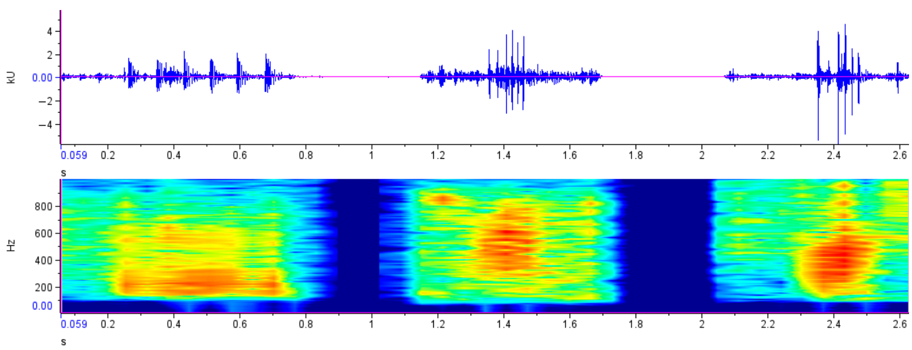


Figure 4. From left to right: waveform (**top**) and spectrogram (**bottom**) of one FPT sound from fuzzy cluster groups A, B, and C. The waveform shows amplitude over time; the spectrogram displays time (X), frequency (Y), and colour-coded amplitude (warm = higher energy, cool = lower). Analysis parameters: Hanning window, FFT size 512, frequency resolution 46.8 Hz.

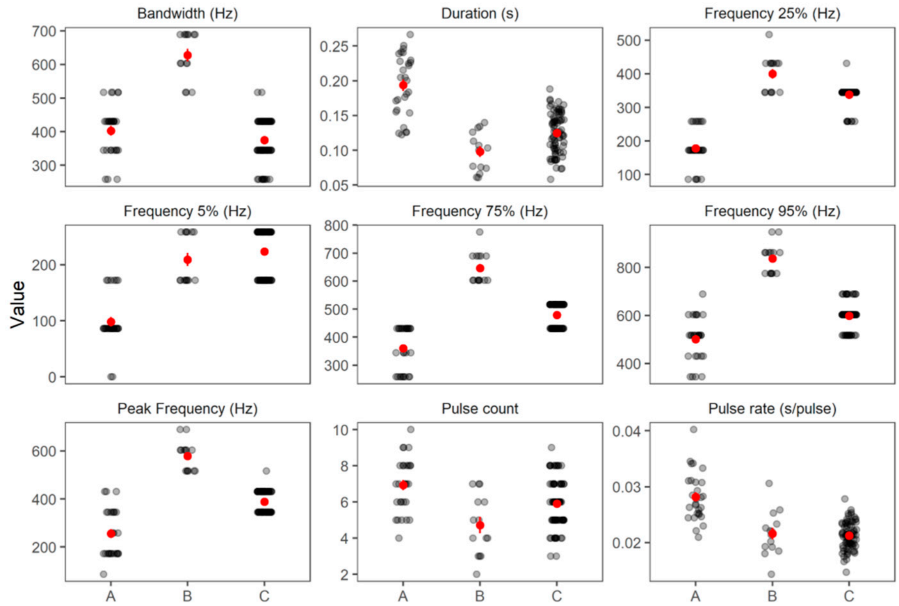


Figure 5. Distribution of acoustic parameters for the three fuzzy FPT cluster groups (A, B, C). Each panel shows the variability of a specific sound-type feature across groups, with individual data points (grey) and associated average (red; ± standard error). Displayed parameters include bandwidth, duration, frequency quartiles (5%, 25%, 75%, 95%), peak frequency, pulse count and pulse rate.

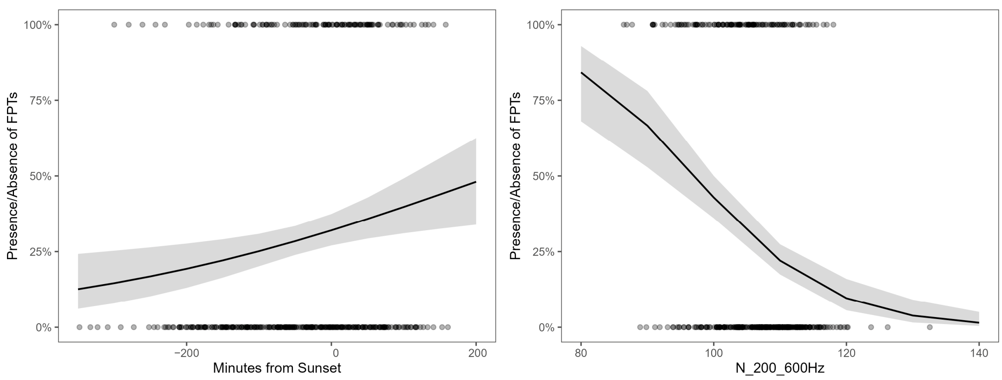
To explore potential relationships between the FPT clusters and the environmental variables, generalized linear models with a binomial error distribution werefitted. None of the temporal (year, month, time of day), morphological (bathymetry, slope, roughness), hydrodynamic (flood-tide and residual currents), or spatial variables (position within the inlets) included in the cluster-based model selection explained the variability in FPT occurrence (clusters A, B, or C). In contrast, background noise, but not boat abundance, was retained in the best-supported models (Table 2). The direction of the effect was consistent across all cluster groups: the probability of detecting FPT A, B, or C sounds decreased with increasing sound pressure levels in the 200–630 Hz frequency range (one-third octave bands).

When the signal-based model was applied to the full dataset (all FPTs), both the time of recording and the sound pressure levels within the selected frequency band were retained as predictors (Table 2), but with opposite effects (i.e., a positive effect for time of recording and a negative one for the background noise levels; Figure 6a,b). Interestingly, the presence of the *S. umbra* chorus was not a significant predictor in this model.

Figure 7 summarizes the modelled interactions between the parameters here considered. The path analysis shows that FPT occurrence is driven by a positive effect of sunset and a strong negative influence of mid-frequency noise, largely generated by vessel traffic. Noise acts as the main suppressor of FPT emissions, while *S. umbra* choruses exert an additional, albeit weaker, inhibitory effect. Together, these pathways indicate that FPT production is highly sensitive to anthropogenic acoustic disturbance, but it is also influenced by the presence of co-occurring strong biological signals.

Table 2. Model selection results for cluster-based and signal-based approaches. Values represent AIC (Akaike Information Criterion) scores for each candidate model across sound groups (A, B, C) and the full dataset. Models are built incrementally by adding groups of predictors (temporal, morphological, hydrodynamic, spatial, and anthropogenic factors). The lowest AIC within each column is highlighted with an underlined value, indicating the best-supported model. ΔAIC values < 4 suggest comparable model support.

		Cluster-Based Model			**Signal-Based Model**
		Group A (n = 28)	Group B (n = 14)	Group C (n = 77)	All Sounds (n = 319)
m0	No predictors	142.2	109.4	269.6	490.3
m1 (m0 + temporal factors)	Year	142.8	109.7	269.5	491.6
	Campaign	143.5	111.2	270.9	490.5
	Time of recording	143.2	110.1	268.1	484.4
m2 (m1 + morphological factors)	Average bathymetry	143.9	110.1	271.6	486.4
	Average roughness	143.4	112.0	270.8	486.0
	Average slope	143.4	112.1	271.4	486.3
m3 (m2 + hydrodynamic factors)	Current speed	143.9	110.8	269.9	486.2
	Tide levels	140.6	109.9	269.0	484.8
m4 (m3 + local spatial factors)	Inlet	145	113.6	269.1	489.3
	Position in the inlets	145	108.7	272.1	486.7
m5 (m4 + anthropogenic factors)	Boat abundance	142.1	111.4	271.5	485.4
	SPL:200–630	136.9	105.2	245.6	454.0
m6 (m5 + *S. umbra* chorus)		136.24	107.24	247.48	453.1



(**a**) (**b**)

Figure 6. Average partial effects of the time of the day (here calculated as the minutes from sunset; (**a**) and sound pressure levels in the frequency of 200–630 Hz (in one-third octave bands; (**b**) on FPT sounds with 95% confidence intervals. This figure shows the predicted probability of FPT sounds as a function of time and background noise in the Venice inlets. The rug-plot shows the distribution of sounds with respect to here-considered parameters.

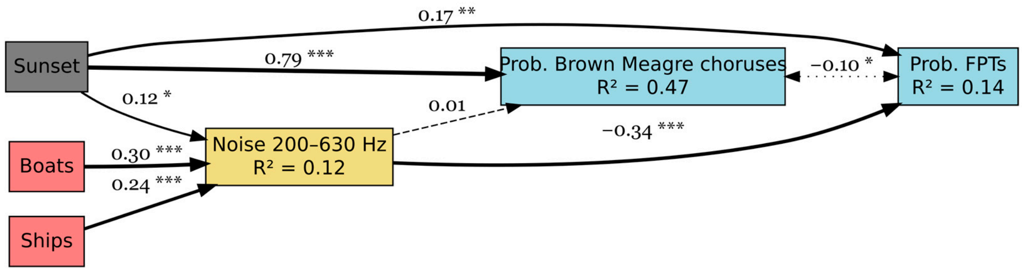


Figure 7. Structural path diagram showing the relationships among environmental variables (sunset), vessel presence (boats and ships), mid-frequency noise levels (200–630 Hz), and the probabilities of *Sciaena umbra* choruses and FPT emissions. Boxes represent observed variables, with associated R^2 values indicating the proportion of variance explained by the model. Arrows denote standardized path coefficients, with solid lines indicating significant effects, dashed or dotted lines indicating weaker or marginal pathways, and asterisks marking significance levels (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

4. Discussion

Pulsed sounds are widespread in marine acoustic recordings and are produced by a broad range of taxa—including invertebrates, fish, and marine mammals—across diverse communicative contexts. Despite their prevalence, our understanding of these signals remains in an exploratory phase. In passive acoustic datasets, new sound types are being detected far more rapidly than their biological sources can be identified; consequently, many remain deprioritized and underreported, even though they represent an elusive yet potentially rich reservoir of ecological information [12]. This gap claims for a systematic description of unidentified sounds to support the development of reference catalogues and robust detection within classification tools.

In this study, the consistency and spatio-temporal distribution of sounds categorized as Fast Pulse Trains (FPT) according to [3] was investigated. These signals represent the most abundant sound type recorded and identified in the Venice inlets after brown meagre reproductive calls [25]. FPTs typically consist of about six pulses, with a peak frequency around 400 Hz and a duration of approximately 160 ms, although their temporal and spectral features can vary substantially. Notably, the analyses presented here reveal no clear separation among the extracted FPTs, supporting the coherence of the current classification and suggesting that transitions between signal types occur along a continuum rather than as sharply defined categories. When non-overlapping groups are nonetheless imposed by applying three fuzzy clusters to a reduced subset of high-membership sounds, three FPT groups emerge: group A, characterized by lower frequencies, longer durations, and higher pulse rates; group B, defined by higher frequencies and broader bandwidths; and group C, the largest group, exhibiting intermediate acoustic characteristics. Interestingly, none of these groups aligns with the only detailed characterization of FPT sounds available in the Mediterranean literature, given by [17], who described FPTs from Crete as sequences of 11 pulses with an average peak frequency of ~450 Hz, an average duration of 71 ms, and a pulse period shorter than 10 ms. This discrepancy suggests that, as observed for other pulsed sound categories, the FPT label likely encompasses a range of acoustically variable sound types and potentially multiple emitting species. Evidence from other ecosystems supports this interpretation: in tropical coral habitats, for example, ref. [9] identified seven distinct sound types that all fall within the FPT category, as defined by [3].

Ref. [19] reported FPT sounds as produced exclusively during daylight hours, accounting for about 3% of more than 1200 biological sounds recorded in the Capo Caccia–Isola Piana MPA. These signals were mostly common in the Zone A integral-protection area, particularly on rocky bottoms interspersed with small patches of *Posidonia oceanica*. In contrast, FPT sounds appear to be relatively rare in audio files from coralligenous reefs across the north-western Mediterranean, as documented by [20].

The present study investigates the spatio-temporal distribution of the FPT recorded along the Venice inlets, which connect the lagoon with the open sea. The area does not represent a structurally homogeneous habitat but is instead characterized by marked environmental variability. Sectors facing the inner channels of the inlets are generally deeper, noisier, and subject to stronger currents, whereas the areas exposed to the open sea exhibit gentler bottom slopes. An intermediate depth, combined with high slope and seabed roughness, characterizes the so-called “lunate” area. Boat abundance also varied across inlets, with higher numbers recorded at Lido and Chioggia compared to Malamocco, particularly during afternoon surveys. Given this heterogeneity, the presence of distinct habitat patches was expected, potentially corresponding to the detection of different groups of FPTs. However, the distribution of any of the FPT groups was found not to be influenced by any of the temporal, morphological, hydrodynamic, or spatial variables considered. The lack of any spatial or habitat-related predictor associated with the groups further suggests that the vocalizing species may behave as a habitat generalist; alternatively, it may indicate that the detected signals originate from a pool of species/a family rather than a single habitat-specialist emitter. Notably, background noise—measured as sound pressure levels in the 200–630 Hz one-third-octave bands—emerged as the only significant, albeit negative, predictor for the occurrence of all FPT groups.

When considering all recorded FPT sounds collectively, two factors were found to be predictive of their presence: recording time, acting as a positive driver (with increasing likelihood of recording FPTs late in the afternoon or after sunset, in contrast with [19] and potentially supporting the idea of multiple FPT sound types occurring in the marine environment), and background noise, which acted as a negative one. In line with the path analysis, mid-frequency noise largely generated by vessel traffic represents the main suppressor of FPT emissions, while *S. umbra* choruses contribute an additional, albeit weaker, inhibitory pathway. Interestingly, *S. umbra* chorusing did not act as a negative predictor in the generalized models, despite being a major biological contributor to the same frequency band, reinforcing the interpretation that the inhibiting effect on FPT production is most plausibly attributable to anthropogenic rather than biological acoustic sources. A clear limitation of this study lies in the restriction of data collection to the 17:00–23:00 timeframe, meaning that a full 24 h daytime control is lacking. As detailed in the Methods section, this constraint stems from the opportunistic nature of the present work, which relies on recordings originally designed to monitor *Sciaena umbra* [28,29]. Since marine biophony often exhibits strong diel cycles, the absence of acoustic data during late night, morning, and early afternoon hours prevents a comprehensive, round-the-clock characterization of FPT daily rhythms. It is possible that alternative FPT sound types or different acoustic behaviors occur during daylight hours under distinct ambient noise regimes. However, because many vocal fish species concentrate their acoustic displays around dusk and early night, this targeted window still captures a critical period of intense biological activity and sonic interaction. While full-diel recordings will be essential in future studies to fully map the circadian timing of FPT production, the present dataset remains robust for assessing how anthropogenic noise modulates these emissions during their known evening periods of prevalence.

The acoustic characteristics of FPT sounds—low-frequency pulsed signals—are consistent with fish vocalizations [14]. Nevertheless, only about 4% of fish species, and an even smaller proportion of marine invertebrates, have been examined for sound production to date, underscoring the vast extent of unexplored acoustic diversity in the seas [12]. Although active sounds are generally species-specific, identifying the emitting species in marine recordings remains challenging for fishes and invertebrates, unlike for marine mammals, unless experimental localization is performed (e.g., [46,47]). Visual confirmation is occasionally possible (e.g., [48]), or the emitter may be inferred through a weight-of-evidence approach based on species present at the recording site and time (e.g., [49]). Reference [32] lists 45 fish species in the Malamocco inlet, including several soniferous families (Gadidae, Carangidae, Pomacentridae, Sciaenidae, Scorpaenidae), none of which are known to produce FPT-like sounds. Although gobies and blennies are vocal, their low source levels and the noisy inlet environment make them unlikely candidates. Considering the species present and these constraints, Sparidae, Serranidae, Mugilidae and Labridae remain the most plausible emitters. Although specific acoustic descriptions of their vocalizations are not yet available in the literature for a direct comparison, these candidate families are identified as vocal based on a global review of the macro-evolutionary distribution of fish sound production [50]. Still, the absence of clear statistical evidence linking FPT occurrence to specific spatial factors—and thus to particular habitats—limits the ability to formulate more detailed hypotheses regarding the potential emitting species. Expanding studies on this sound type across different geographic areas will be essential to refine the definition of FPT sounds, assess whether multiple sub-categories exist, and identify their habitat associations and occurrence patterns. Such comparative efforts will ultimately enable the development of robust hypotheses on the species—or species groups/family—responsible for their production.

5. Conclusions

By characterizing the abundant yet acoustically variable Fast Pulse Train (FPT) sounds within the Venice inlets, this study advances the foundational understanding of unidentified marine signals and helps narrow the gap between predicted vocal fish species and fully described acoustic repertoires. Rather than forming sharply discrete categories, FPTs vary along a continuous acoustic gradient, and—given the absence of spatially structured statistical predictors of their occurrence—they may plausibly originate from a multi-species pool of soniferous, habitat-generalist emitters.

Despite the opportunistic time-restriction to the 17:00–23:00 sampling window, this work disentangles the natural acoustic drivers associated with sunset from the shifting regimes of vessel traffic and demonstrates that anthropogenic vessel noise, rather than biological sonic activity, acts as the primary suppressor of FPT emissions during their evening peak.

By establishing the first standardized baseline for FPT characterization under high anthropogenic pressure, these findings set the stage for essential next steps: 24 h acoustic monitoring to resolve full circadian cycles, targeted experimental validation at local scales, and cross-basin cataloguing efforts aimed at definitively identifying the emitting species and clarifying the behavioural context of these emissions.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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