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ORIGINAL RESEARCH

Impact of pile-driving and offshore windfarm operational noise on fish chorusing

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Abstract

Offshore windfarms have recently emerged as a renewable energy solution. The effects of pile-driving and long-term impacts of operational noises on fish chorusing still, however, remain largely unknown. In this study, we investigated the variations of fish chorusing intensity and duration during the construction (2016) and operational phases (2017–2018) of a windfarm at the Eastern Taiwan Strait (ETS). At the ETS, two types of fish choruses (Types 1 and 2) were found to repeat over a diurnal pattern. In the 2 days after the pile driving, Type 1 chorusing showed lower intensity and longer duration, while Type 2 chorusing exhibited higher intensity and no changes in its duration. During the operational phases in 2017 and 2018, both choruses were longer in duration (2–3 h for Type 1; 0.5–1 h for Type 2). The intensity of Type 1 chorus increased by 5–10 dB, but no significant variation was recorded for Type 2. Our findings document, for the first time, different behavioral responses of two chorusing types exposed to pile-driving and windfarm noise pressure. Fish choruses have been associated with several behavioral functions. Deviation from a regular pattern might affect fish reproductive success, cause migration, augmented predation, or physiological alterations. Because offshore windfarms installations are growing in magnitude and capacity worldwide, this study provides essential insights for policymakers and constitutes an important reference for assessing the effects of noise from pile driving and windfarms on fishes.

Introduction

In recent decades, offshore windfarms have globally emerged as a viable source of marine renewable energy to meet the increasing global energy demand by limiting CO_2 emissions, which are the main trigger for climate changes (Breton & Moe, 2009; Kaldellis & Zafirakis, 2011). Because wind speeds can reach up to 12 m/s, the Taiwan Strait offers unique conditions for energy production by offshore windfarms. The Taiwanese government initiated the ‘Thousand wind turbines project’ to generate 5.2 GW by 2030 and plan to install 600 turbines offshore (Yang et al., 2013). Once operational, each turbine will generate power with a capacity exceeding 3.2 MW [37]. Taiwan mandatorily requires an environmental impact assessment of offshore windfarms to evaluate the scale of their environmental impact. Environmentalists, ecologists, and policymakers have extensively debated the effects of windfarms on marine species (Tseng, Lee, & Liao, 2017).

The offshore windfarm life-cycle includes planning, construction, installation, operation maintenance, and decommissioning (Musial & Ram, 2010). The noise and vibrations generated by offshore wind turbines during the construction and operation phase have recently been found to negatively impact hearing sensitivity and cause behavioral changes in numerous marine organisms even at ranges of many kilometers distance from the windfarm (Nedwell, Langworthy, & Howell, 2003; Thomsen et al., 2006; Vella et al., 2001). During the construction of offshore windfarms, the most conspicuous sources of noise and vibrations are piling and dredging (Nedwell et al., 2007), which produce sound pressure level peaking at up to 187 dB re 1 μPa (Chen et al., 2017). Shipping in the area also contributes to increasing noise levels as the turbine towers, and their foundations are brought out to sea and emplaced (Bailey, Brookes, & Thompson, 2014). During the operational stage, turbines generate harmonic vibrations associated with sustained low-frequency noise (below 1 kHz) ranging from 80 to 150 dB re 1 μPa depending on the wind speed (Betke, Schultz-von Glahn, & Matuschek, 2004).

Several studies have reported negative environmental impacts associated with the construction and operation stages of offshore windfarms (Dolman & Simmonds, 2010; Leung & Yang, 2012). The impact of high-intensity pile-driving noise on marine animals has received particular attention (Everley, Radford, & Simpson, 2016; Popper & Hastings, 2009a; Popper & Hastings, 2009b) because it was found to influence fish behavior by causing auditory masking and alteration of foraging patterns, social behavior, and metabolism (Hawkins, Roberts, & Cheesman, 2014; Madsen et al., 2006; McCauley et al., 2000; Slabbekoorn et al., 2010; Wahlberg & Westerberg, 2005). Marine organisms are also vulnerable to wind turbines' operational noise (Reyff, 2012), but we currently have insufficient knowledge regarding its long-term effects (Bailey, Brookes, & Thompson, 2014; Madsen et al., 2006). Recent research has documented that fishes exposed to sustained anthropogenic noise respond in their own species-specific manner, potentially producing disruption in social interactions, hearing loss, increase in the calling amplitude (Holt & Johnston, 2014), and a rise in noise-induced stress (Barton, 2002; Debusschere et al., 2016; Popper & Hastings, 2009b). Fishes with strong social cohesion are likely to be particularly vulnerable to loud and sustained anthropogenic noise (Popper & Hastings, 2009a; Sueur & Farina, 2015). In particular, vocalizations of soniferous fish species that produce well-organized chorusing patterns in the low-frequency range (50–5000 Hz) are heavily masked by the noise produced by operational turbines. In fishes, chorusing is used to attract mates during spawning, communication, and social cohesion (Farina & Gage, 2017; Rice, Soldevilla, & Quinlan, 2017). Disruption of the chorus might, therefore, result in cascade effects on behavioral and ecological processes.

Recent studies have attempted to evaluate the impact of pile-driving noise on marine animals by playing back the pile-driving sound in a controlled environment (Bolle et al., 2012; Debusschere et al., 2016; Everley, Radford, & Simpson, 2016; Halvorsen, Casper, Matthews, et al., 2012; Halvorsen, Casper, Woodley, et al., 2012). Responses from animals kept in captivity cannot, however, be extrapolated directly to the wild environment (Hawkins, Pembroke, & Popper, 2015; Popper et al., 2014). Responses of individuals of the same species may vary in relation to either environmental factors such as water temperature, location, salinity, or individual factors such as size and age. It is, therefore, necessary to couple studies in controlled environments with investigations in the natural habitat (Slabbekoorn et al., 2010). To date, there have been no published studies on the impact of pile-driving and turbine operational noise on the chorusing of soniferous species in their natural habitat.

In this work, we provide, for the first time, an assessment on fish chorusing of a natural habitat exposed to windfarm construction and operation noise in the Eastern Taiwan Strait (ETS). Recent research has shown that ETS experiences a well-defined diurnal chorusing pattern produced by two soniferous species (Siddagangaiah et al., 2019). In particular, our goal is to examine the response in the behavior of the two chorusing types when exposed to: (i) high-intensity pile-driving noise and construction activities, including heavy vessel traffic before/during/after the installation; and (ii) long-term sustained operation noise from wind turbines.

Materials and Methods

Study area

The study area falls in the ETS, which is an ocean strip separating Taiwan from mainland China. The ETS is ~180 km in width and ~300 km in length, and lies in the East China Sea connecting the South China Sea in the south, with a mean water depth of ~30–55 m. The ETS experiences seasonal temperature fluctuations, severe tropical storms, high wind speeds, sediment transportation, and abnormal turbidity due to flooding. Comprising 16 of the world's top 20 ideal wind sites, the ETS is characterized by wind speeds of up to ~12 m/s and has the potential to be one of the best windfarm locations in the world ('Global OffshoreWind Speeds Rankings'). As a part of the Taiwanese 'Thousand wind turbine project,' the pile driving for the first demonstration windfarm was carried-out in September 2016. It was composed of two wind turbines (#21 and #28 Turbines) located along the coast of Miaoli (ETS) ~2 km from the shore (Fig. 1). These two turbines were the part of the Formosa 1 offshore windfarm project (Chen et al., 2017; Tseng, Lee, & Liao, 2017). Turbines were installed at a depth of ~35–55 m on a sandy substrate. The two monopiles were 5.8 m in diameter and ~70 m in height (Chen et al., 2017). Geographical coordinates, pile driving start/end time, duration, and number of strikes are shown in Table 1.

Data collection

Passive acoustic recorders (SM3M and SM4M, Wildlife Acoustics) was deployed at #28 turbine to monitor the

Figure 1. Photograph of the Miaoli windfarm area after the completion of the Formosa 1 offshore windfarm project. Turbines #28 and #21 installed in 2016 are part of phase 1 with the total rated capacity of 8 MW, and in phase 2, additional 20 turbines were installed in 2019 with the total rated capacity of 120 MW (6 MW each). FP: Long Feng fishing port; ES: Estuary of Zhonggang creek; B(*) and A(+): the approximate location and direction in which the PAM recorders were deployed to measure the pile driving events in 2016 and windfarm operational noise in 2017–2018 respectively. (Photograph taken by S.S on 14 January 2021).

Table 1. Location, starting, ending, and duration of the pile driving, total pile driving strikes, and the distance of pile driving from the recorder for installing turbines #21 and #28.

Pile driving distance from recorder (m)	Pile driving done to install turbine	Location	Pile driving start and end time (DD Mon HH:mm), 2016	Actual drilling duration (hours)	Number of strikes
1500	#21	24°41.27.45′N, 120°48.242′E	03 Sep 20:00–04 Sep 10:00	1.9	4757
230	#28	24°41.35.75′N, 120°49.1.54′E	07 Sep 12:00–15:00	1.4	3778

construction stage before, during, and after pile driving (2016) and during operational phases (2017 and 2018) (Fig. 1, Label A,B). Table 2 shows the details on the recording system, monitoring period, depth, and distance from turbines #28 and #21. The recorder was secured to a bottom-mounted steel frame with the hydrophone at ~1–2 m from the seabed (Fig. 2A and B). The timeline of events during the recording period is shown in Table 3. In all 3 years, recording was conducted during summer (i.e., August–September) to ensure that the fish chorusing behavior was not affected by seasonality or varying temperature (mean sea surface temperature: 28.9 ± 0.6°C) (see Fig. S1). The absence of typhoons, sediment transportation, or turbidity triggered by flooding (common in the area) was also assured.

During the windfarm operation phase in 2017 and 2018, the recorder was deployed at 10 m from turbine #28 (Fig. 1, Label A). In 2016 was placed at ~230 m from the pile driving site, carried out to install turbine #28 (Fig. 1, Label B); due to the construction site hazard and the risk of damaging to the recorder, the recorder was not therefore deployed too close. There is a difference of ~200 m in the recorder placement in 2016 and during windfarm operation in 2017 and 2018. However, we can assure that geographical and ecological features are readily comparable among sites.

Acoustic analysis and statistics

All sound spectral analyses were carried out in Matlab using scripts from PAMGuide (Merchant et al., 2015).

Table 2. At turbine #28, from 2016 to 2018 tabulated are the type of PAM recorder, starting and ending date of recordings, sampling frequency, sensitivity, gain, the distance of deployment from the turbine, depth of deployment, and acoustic file format.

Year	PAM recorder	Start date	End date	Sampling frequency (kHz)	Sensitivity (dB re V/μPa)	Gain (dB)	Distance from #28 turbine (m)	Deployed depth (m)	Acoustic file format
2016	SM3M	24 Aug	10 Sep	44.1	-165	2	230	20	.wav
2017	SM4M	31 Jul	16 Aug	96			10	18	
2018	SM4M	27 Aug	05 Sep	48			10	18	

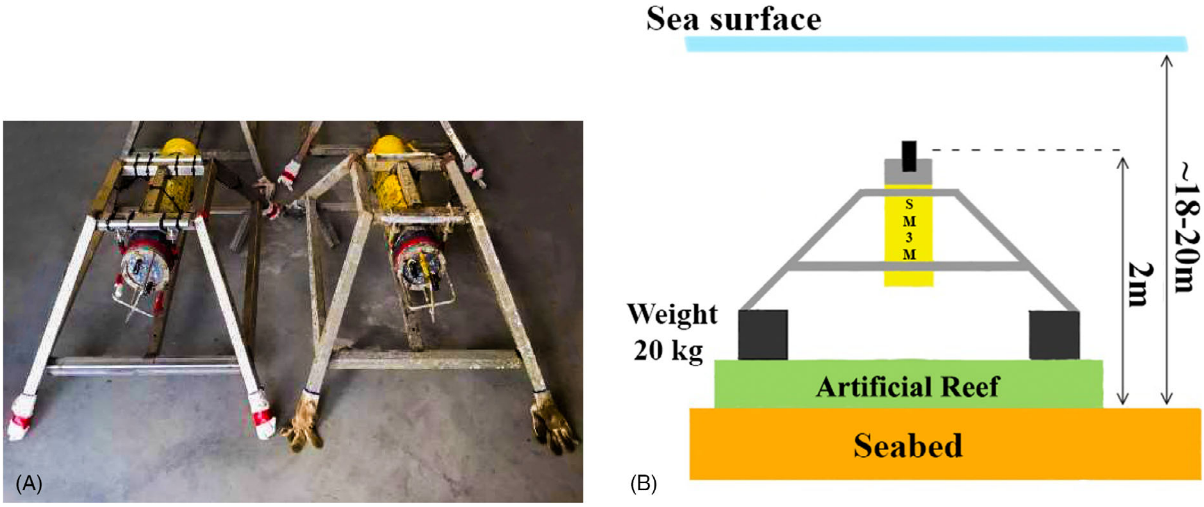


Figure 2. (A) Setup of the two SM3M submersible recorders attached to the metal frame prior to the deployment at sea. (B) Illustration sketch of the remote deployment of the recorder setup.

Table 3. Timeline of events during the monitoring period at recorder with corresponding mean peak intensity (PSD in units of dB re 1 μPa^2 Hz^{-1}) and duration of choruses types 1 and 2.

Year	Event (number of replicates)	Monitored period (start date – end date) (day month)	Type 1 chorusing		Type 2 Chorusing	
			Duration (hours) (mean ± SE)	Intensity (PSD) (mean ± SE)	Duration (hours) (mean ± SE)	Intensity (PSD) (mean ± SE)
2016	Before pile driving (n = 6)	24 Aug–29 Aug	5.1 ± 0.1	105.5 ± 1.2	2.07 ± 0.13	112.4 ± 2.3
	Construction activities (n = 7)	30 Aug–02 Sep 04 Sep–06 Sep	5.83 ± 0.11	109.2 ± 1.5	1.9 ± 0.12	112.8 ± 2.3
	Pile driving (n = 2)	03 Sep and 07 Sep	5 and 5	108 and 101	1.8 on 03 Sep	108 and 101
	After pile driving (n = 2)	08 Sep–09 Sep	7 ± 0	98.9 ± 3	2 ± 0	118.5 ± 1.2
2017	Windfarm operation (2017: n = 17) (2018: n = 10)	31 Jul–16 Aug	8.45 ± 0.11	115 ± 1.2	2.4 ± 0.24	110.5 ± 0.9
2018		27 Aug–05 Sep	7.5 ± 0.15	107.3 ± 1.2	2.4 ± 0.12	111.2 ± 0.8

PSD, power spectral density.

The duration, peak power spectral density (PSD), and type of the chorusing were quantified by careful manual scrolling of audio recordings along with the visual examination of the spectrograms. The visual and aural categorization of the fish call types are extensively utilized in bioacoustics studies (Di Iorio et al., 2018; Radford, Kerridge, & Simpson, 2014). Spectrograms based on PSD were obtained by setting a 1-s Hanning window, 50% overlap, and 10-s time-averaging. The two chorusing types at the ETS lie in the 500–2500 Hz and last for 2–8 h a day (Siddagangaiah et al., 2021; Siddagangaiah et al., 2019). Consequently, they are easily distinguishable from any low-frequency (10–500 Hz) noise such as shipping and windfarm operation noise. However, there were moments where the chorusing duration and peak PSD could not be determined since the construction noise during pile driving overlapped in time and frequency with the fish chorusing (i.e., 6 September and 7 September 2016). Sound pressure levels (SPLs) were computed in the frequency band 50–200 Hz (1-s Hanning window and 50% overlap, 24-h time averaging) to compare the sound levels during the monitored period (before/during/after pile-driving and operational noise in 2017–2018). Similarly, 1/3-octave band SPLs were calculated from 25 to 3150 Hz to compare the noise produced during the wind-turbine operation stage (in 2017 and 2018) with the noise recorded in 2016 prior to turbine installation. The logarithmic mean and the standard deviation of the peak PSD of the two chorusing types were evaluated by using the command *meandB* and *sddB* included in the R package *seewave* (Sueur, 2018). Further, the standard error was evaluated by dividing the standard deviation by the square root of the sample size.

Statistical calculations were performed using R (version 3.6.2) package *agricolae* (de Mendiburu & de Mendiburu, 2019). The nonparametric Kruskal-Wallis test followed by *post hoc* Bonferroni's multiple comparisons was applied to assess differences in daily choruses intensity and duration at different stages (i.e., before pile-driving vs. operational noise in 2017 and 2018). This statistical test was also used to compare SPLs at the frequency band 50–200 Hz (before pile driving, during construction and pile driving; operational noise in 2017 and 2018) and 1/3-octave band SPLs from 2016–2018 (prior to construction and pile driving in 2016, windfarm operational noise in 2017 and 2018). Since only 2 days of chorusing data were available, the statistical analysis did not take into account the post-pile driving period.

Results

Fish choruses recorded

There are almost 100 species of sciaenid fishes in the Indo-West Pacific region (Trewavas, 1977). The Sciaenid family of fishes are commonly found in shallow coastal waters of the ETS (Lin, Mok, & Huang, 2007) and are soniferous by nature (Mok & Gilmore, 1983). Throughout the recording duration, underwater noise levels in the frequency range 500–2500 Hz were significantly influenced by two types of fish choruses (Types 1 and 2; Fig. 3). A description of their acoustic features is provided in Table S1. Both choruses were recorded to cyclically repeat over a diurnal pattern (Figs. 4–6, Label FC). The acoustic features of chorus Type 2 resemble the *Johnius macrorhynus* (family Sciaenidae), as documented by Lin, Mok, & Huang (2007), which was recently renamed as *Johnius taiwanensis* by Chao et al. (2019) and previously documented to live in the waters of the ETS. Type 2 chorusing typically occurred during dusk hours and fluctuated according to the season and day length. Unfortunately, the acoustics characteristics of chorus Type 1 did not match with any of the recognized calls attributed to species in the region. Because chorus Type 1 is characterized by sustained chorusing activity occurring from dusk to dawn, with the length and intensity of chorusing being seasonally controlled, we hypothesize that they might belong to the family Sciaenidae as well. The 5-year fish chorusing trends derived at the ETS showed that these two chorusing types exhibited consistent seasonal chorusing patterns, without large variations in intensity and duration of the chorusing during summers (Siddagangaiah et al., 2021). The annual seasonal variation of the fish chorusing at the ETS is shown in Figure S2.

Fish choruses prior to pile driving

Sound levels from 24 to 29 August 2016, were mostly influenced by consistent low-frequency noise (50–200 Hz) caused by vessel movement (Fig. 4a, Label BP) and fish chorusing in the band 300–2500 Hz (Fig. 4a, Label FC). During these days, Type 1 chorus had a mean peak intensity of 105.5 dB re 1 $\mu Pa^2\ Hz^{-1}$, and the mean duration was 5.1 h, whereas the mean duration of Type 2 chorusing was 2 h with a mean peak intensity at 112.4 dB re 1 $\mu Pa^2\ Hz^{-1}$ (Fig. 4b and c, Table 3).

Fish choruses during construction activities prior to pile driving

In 2016, prior to pile driving (30 August–2 September), sound levels were affected by the ongoing movement of vessels transporting the construction equipment coupled with other anthropogenic activities (e.g., dredging, offshore barging of heavy cranes and monopiles). During this period, sound levels reached ~120–135 dB re 1 $\mu Pa^2\ Hz^{-1}$ in the frequency band 50–3000 Hz (Fig. 4a, Label C). The mean duration of Type 1 chorusing was 5.83 h, registering a mean peak intensity of 109.2 dB re 1 $\mu Pa^2\ Hz^{-1}$. Type 2 chorused for 1.9 h (mean), with the mean peak intensity reaching 112.8 dB re 1 $\mu Pa^2\ Hz^{-1}$ (Fig. 4b and c, Table 3).

Fish chorusing behavior during and post-pile driving

On 3 September at 20:00, pile-driving activity took place 1.5 km from the recording station. The pile-driving activity intermittently continued until the following day 10:00, 4 September (Fig. 4a, Label A), totaling an overall

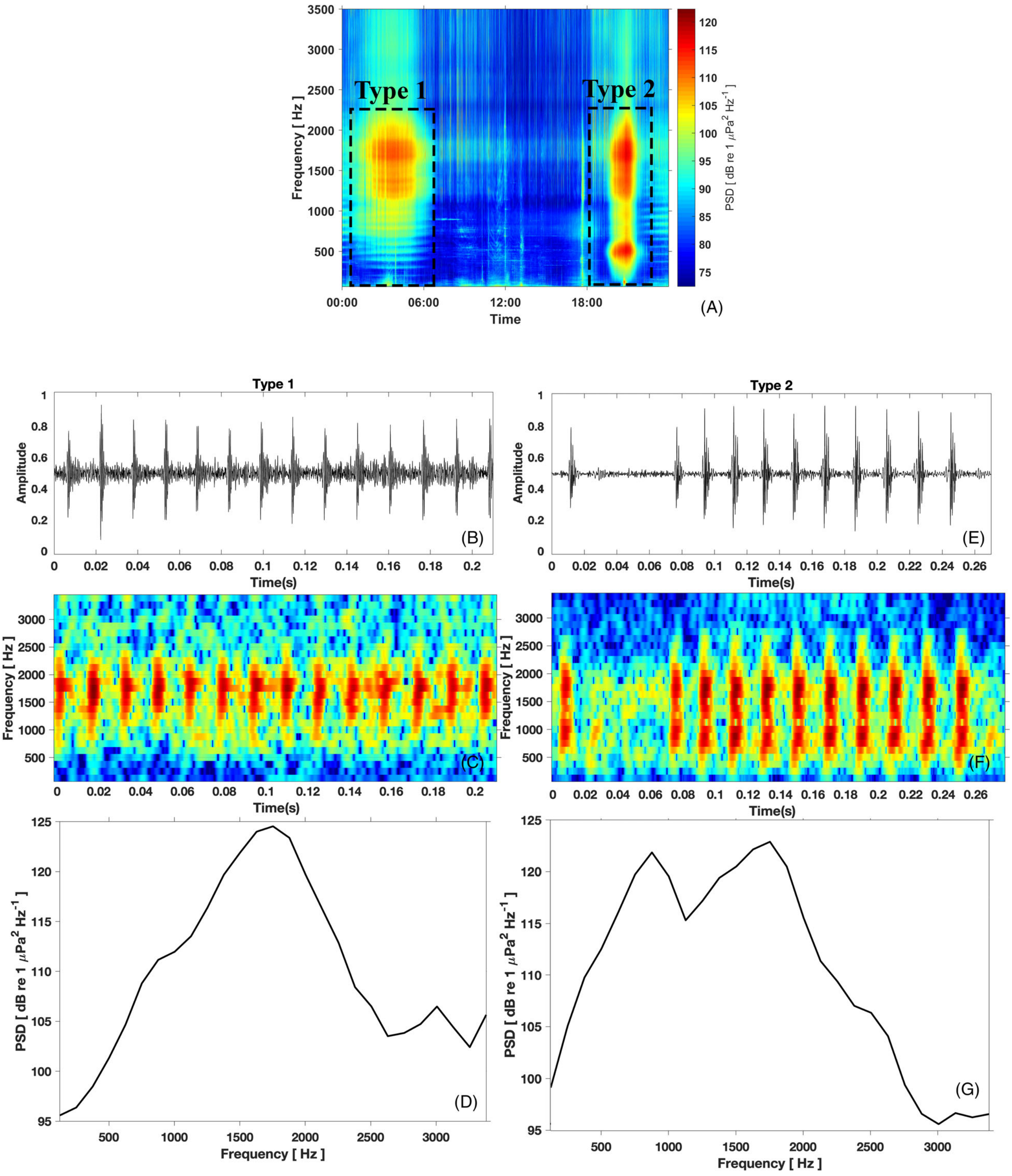


Figure 3. (A) Spectrogram depicting the chorus types occurring at dawn (Type 1) and dusk (Type 2) hours; color label represents PSD in units of dB re 1 μPa^2 Hz^{-1}. (B and E) Waveform of individual fish calls of Types 1 and 2. (C and F) Spectrogram of individual fish calls of chorus Types 1 and 2, respectively. (D and G) PSD of individual fish calls of chorus Types 1 and 2, respectively. PSD, power spectral density.

duration of *c.* 2 h. During pile driving, the peak noise intensity reached 150–160 dB re 1 μPa^2 Hz^{-1}. Successively (4–6 September), other anthropogenic activities produced a high-intensity noise (~120–135 dB re 1 μPa^2 Hz^{-1}) similar to that documented prior to pile driving on 3 September (Fig. 4a, Label DP).

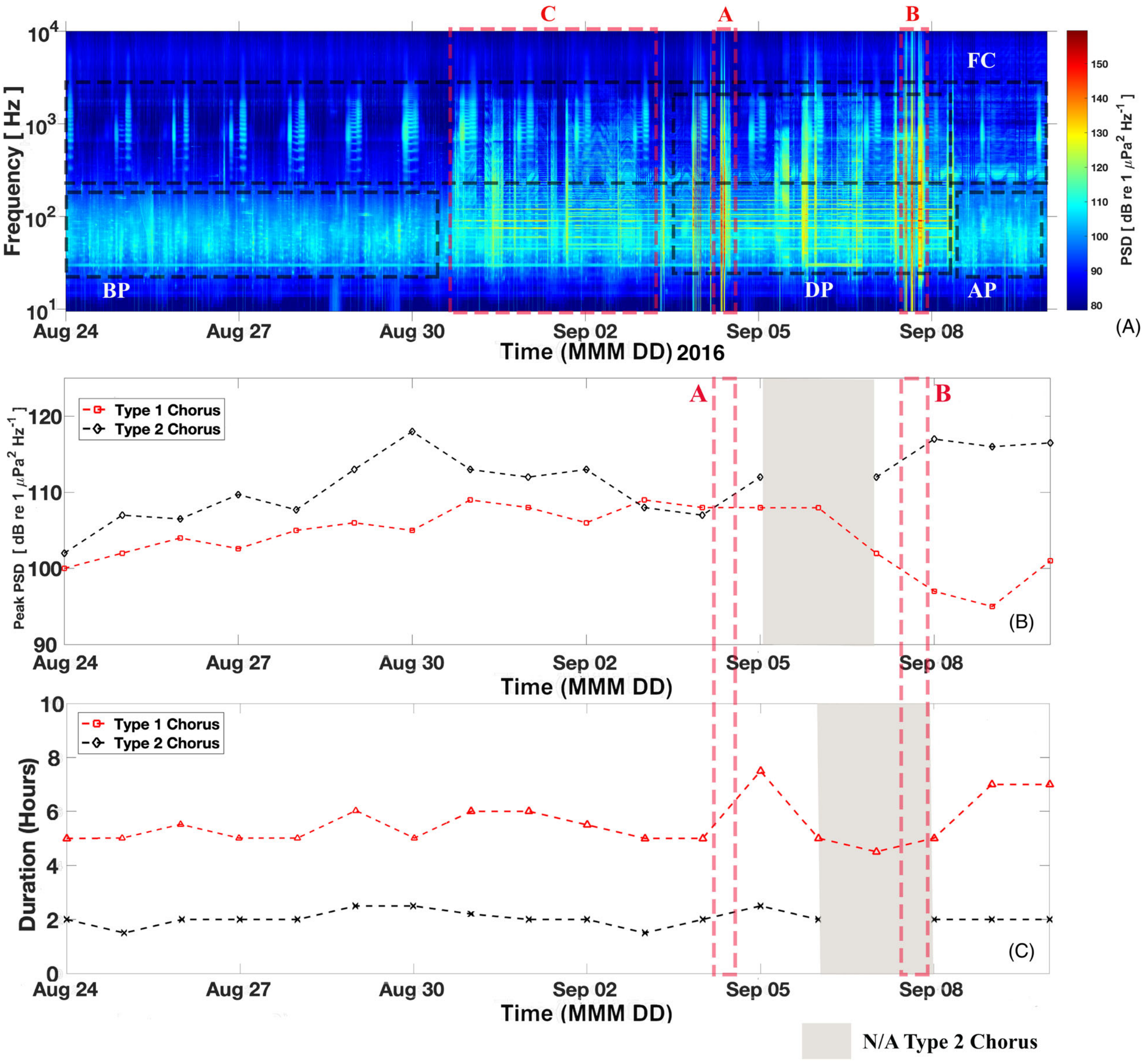


Figure 4. (A) Spectrogram showing the Types 1 and 2 chorusing activity diurnally in the frequency band 500–2500 Hz (Label FC: Fish chorusing) with sustained low-frequency noise in the range 50–200 Hz. A and B represent the two pile driving events; C represents the construction activities prior to pile driving; BP, DP, AP: low frequency (50–200 Hz) noise before, during, and after pile driving, respectively. Color label represents PSD in units of dB re 1 μPa^2 Hz^{-1}. (B and C) Peak PSD and duration of Types 1 and 2 for corresponding days in the spectrogram. The color label N/A represents the day on which the Type 2 chorus peak PSD and duration was not able to determine due to overlapping noise. PSD, power spectral density.

During the post-pile driving (5 September), chorus Types 1 and 2 had a peak intensity of 110 and 105 dB re 1 μPa^2 Hz^{-1} and duration of 8 and 2 h, respectively (Fig. 4b and c). On 6 September, Type 1 chorused for 5.5 h with a peak intensity of 110 dB re 1 μPa^2 Hz^{-1}. When pile-driving noise and other related activities occurred in the same frequency band occupied by chorus Type 2, it was not possible to determine precisely the peak intensity (in 6 September) and duration (in 7 September) of chorusing.

On 7 September, a second pile-driving period took place intermittently from ~12:00 to 17:00 at *c.* 230 m from the recorder (Fig. 4a, Label B). The peak intensity of the pile driving reached ~150–160 dB re 1 μPa^2 Hz^{-1} in the frequency range 10–3000 Hz. Post pile driving (8–10 September), the sound levels were influenced by frequent vessel transits (Fig. 4a, Label AP). During this period, the mean peak Type 1 chorusing intensity and duration was 98.9 dB re 1 μPa^2 Hz^{-1} and 7 h. Type 2 chorusing peaked at

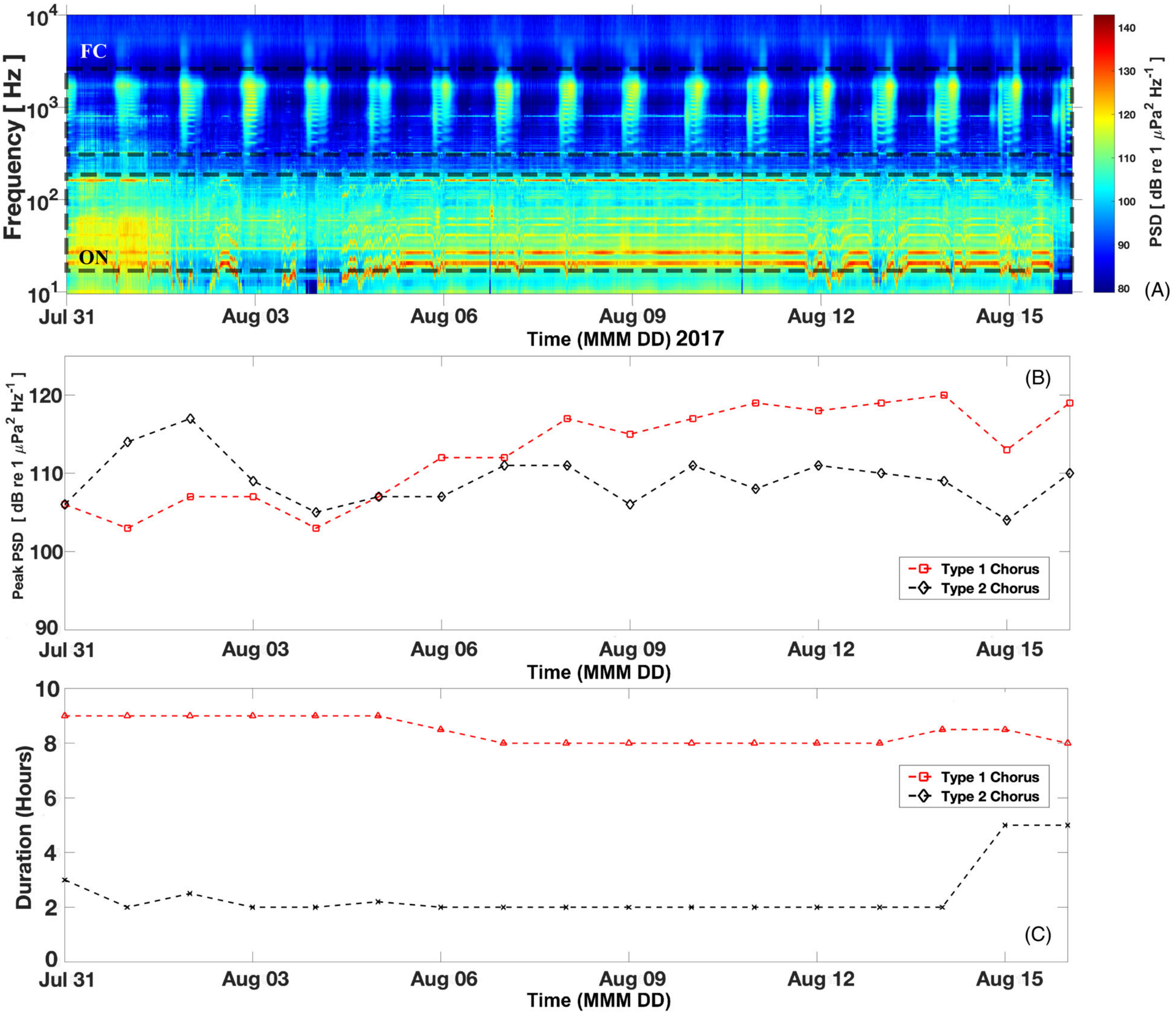


Figure 5. (A) Spectrogram showing Types 1 and 2 chorusing activity diurnally in the frequency band 500–2500 Hz (FC: Fish chorusing) with sustained operational noise from the wind turbine (ON: Operational noise); Color label represents PSD in units of dB re 1 μPa^2 Hz^{-1}. (B and C) Peak PSD and duration of Types 1 and 2 for corresponding days in the spectrogram. PSD, power spectral density.

118.5 dB re 1 μPa^2 Hz^{-1} (mean) registering a mean duration of 2 h (Fig. 4b and c, Table 3).

Fish chorusing behavior in the presence of operation noise

During the operational phase of the windfarm (31 July to 16 August 2017, and 27 August to 5 September 2018), a sustained noise due to the turbine rotation was recorded. The rotation of the turbine blades produces harmonic noise components at several low frequencies varying from ~25 to 200 Hz, with sound levels reaching up to ~130–150 dB re 1 μPa^2 Hz^{-1} (Figs. 5A and 6A, Label ON). During 2017 and 2018, the mean peak chorusing intensity of Type 1 was 115 and 107.3 dB re 1 μPa^2 Hz^{-1}, and that of Type 2 was 110.5 and 111.2 dB re 1 μPa^2 Hz^{-1}, and the mean chorusing duration of Type 1 was 8.4 and 7.5 h, and that of Type 2 was 2.4 h on both years (Figs. 5 and 6, Table 3).

Comparison of noise levels and fish chorusing variations

When compared to the before pile driving, the median SPL in the frequency band 50–200 Hz during pile driving and construction activities significantly increased by 10 dB re 1 μPa ($P < 0.001$) (Fig. 7A, Table 4).

In the two post-pile driving days, the Type 1 chorusing showed a median decrease of 7 dB re 1 μPa^2 Hz^{-1} in

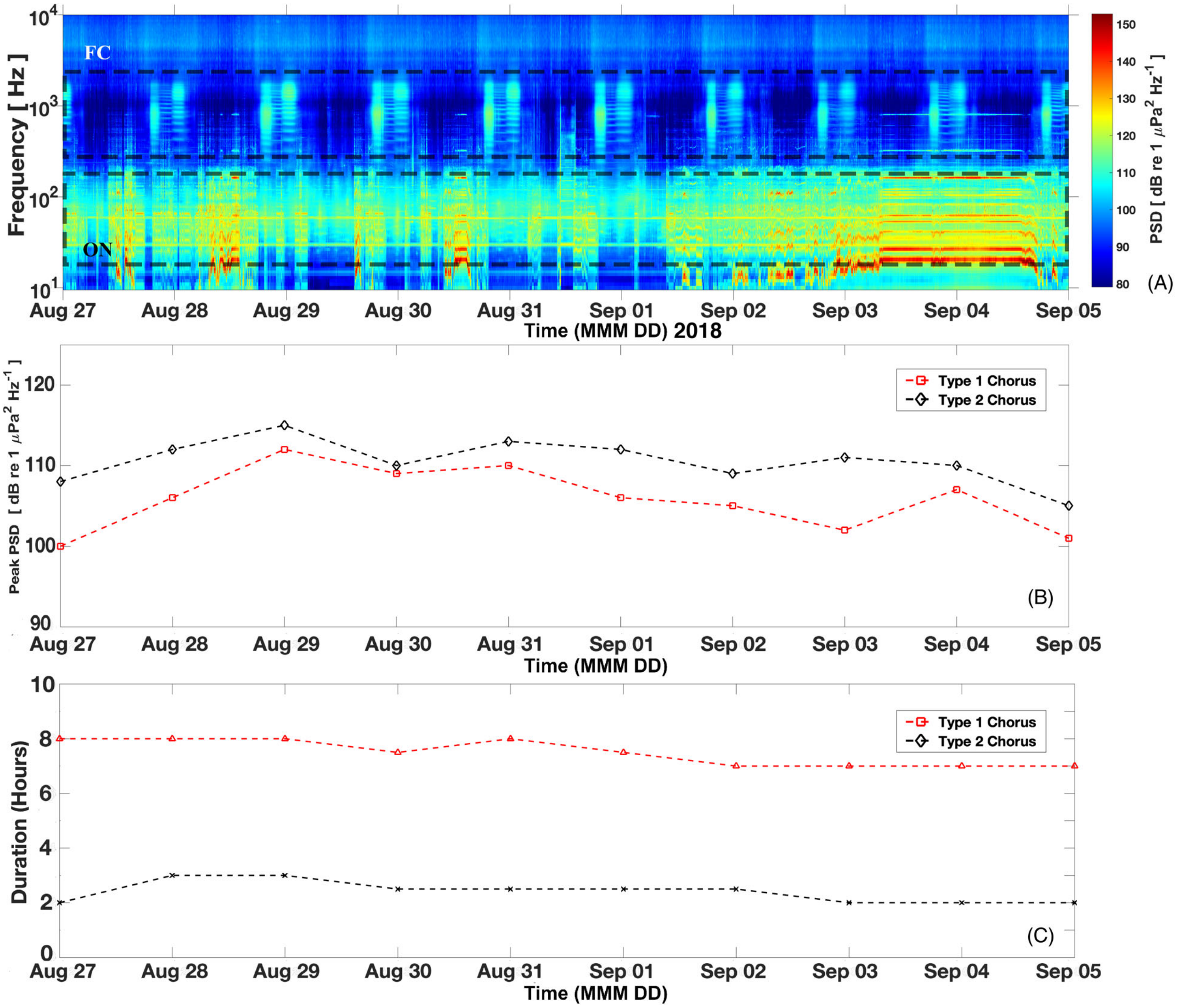
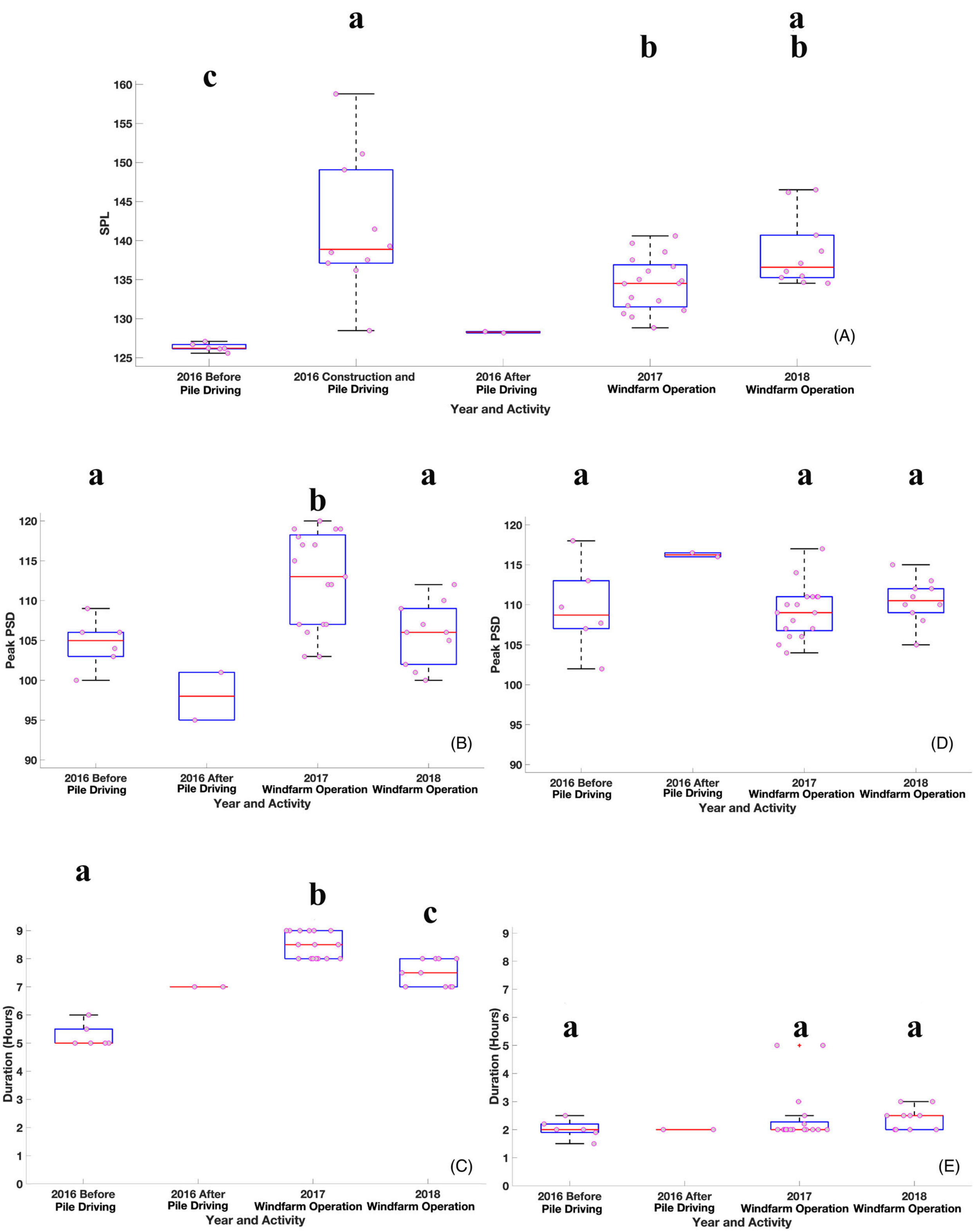


Figure 6. (A) Spectrogram showing Types 1 and 2 chorusing activity diurnally in frequency band 500–2500 Hz (FC: Fish chorusing) with sustained operation noise from the wind turbine (ON: Operational noise); Color label represents PSD in units of dB re 1 μPa^2 Hz^{-1}. (B and C) Peak PSD and duration of Types 1 and 2 for corresponding days in the spectrogram. PSD, power spectral density.

intensity and a longer duration of *c.* 2 h when compared to the median levels recorded before pile driving (Fig. 7B and C). Indeed, before the pile driving, the Type 1 peak PSD lied in the range of 100–109 dB re 1 μPa^2 Hz^{-1} (median: 105 dB), while we recorded a peak PSD of 101 and 95 dB re 1 μPa^2 Hz^{-1} after the pile driving. The chorusing duration was between 5 and 6 h before the pile driving and 7 h on both days after the pile driving (Fig. 7B and C).

After the pile driving, the Type 2 chorusing showed peak PSD levels that resulted higher of 10 dB re 1 μPa^2 Hz^{-1} than the median before pile-driving period, although there was no change in chorusing duration (Fig. 7D and E). After the pile driving, the Type 2 chorusing peak PSD on both days was ~116 dB re 1 μPa^2 Hz^{-1}, while it ranged from 102 to 118 dB re 1 μPa^2 Hz^{-1} before the pile driving (Fig. 7D and E).

Compared to before pile driving and post-installation of the turbine, due to the windfarm's operational noise, the median SPL in the frequency band 50–200 Hz was significantly higher by 8 and 10 dB re 1 μPa in 2017 and 2018 ($P < 0.01$ and $P < 0.001$), respectively (Fig. 7A, Table 4). This significant increase in the SPL is also evident from the 1/3 octave bands (25–200 Hz), with the SPL being significantly higher in 2017 and 2018 ($P < 0.05$) than 2016 (Fig. 8). The median duration of chorus Type 1 was significantly increased by 3 h in 2017 and 2 h and 2018 ($P < 0.001$) compared to before pile



driving (Fig. 7B and C, Table 5). The median peak intensity of Type 1 significantly increased by 10 dB re 1 μPa^2 Hz^{-1} in 2017 ($P < 0.001$) (Fig. 7B and C, Table 5). The significant increase in the SPL due to the chorusing activity was also evidenced in the 1/3 octave band (1600–3150 Hz) ($P < 0.05$) (Fig. 8). Type 2

Figure 7. (A) Variation of low frequency (50–200 Hz) SPL (in units of dB re 1 μPa) from the year 2016 to 2018. Variation of Types 1 and 2 (B and D) chorusing intensity (PSD in units of dB re 1 μPa^2 Hz^{-1}) and chorusing duration (C and E), during 2018 (n = 10), 2017 (n = 17), before (n = 6) and after pile driving (n = 2) in 2016. On each box, the central red mark represents the median, and the top and bottom edges of the box represent the 25th and 75th percentiles. The black mark at the extreme ends are the maximum and minimum values. The symbol '+' represents outliers. The data points superimposed on the boxplot are represented as filled circle dots. Each box with a common superscript letter represents results from *post hoc* multiple comparison test; different superscript letters indicates significant differences ($P < 0.05$), with letter 'a' at the top and subsequent statistical differences are represented a level lower it. NOTE: After pile driving event is excluded from statistical comparison since it just has n = 2 days of chorusing replicates. SPL, Sound pressure level; PSD, power spectral density.

chorusing showed no significant increase in its peak intensity and duration compared to 2016 (Fig. 7D and E, Table 5).

Discussions

The results of this study show, for the first time, the short- and long-term behavior of two types of fish chorusing (Types 1 and 2) being exposed to noise originating from an offshore windfarm during pile-driving and operational activities at the ETS. After the pile driving, the two types of choruses showed a different pattern. In particular, the species producing the Type 1 chorus reduced the intensity and extended the duration of the chorusing (Fig. 7B and C), whereas chorus Type 2 increased its intensity with no change in its chorusing duration (Fig. 7D and E). During sustained turbine operational noise in 2017 and 2018, the Type 1 chorusing increased the duration of chorusing (2–3 h) and its intensity (by ~5–10 dB re 1 μPa^2 Hz^{-1} in 2017) compared to the pre-installment of the windfarm. However, the Type 2 species did not exhibit any significant change in its chorusing behavior (Fig. 7).

The change in the Type 1 chorusing behavior was clearly evident when the pile driving was at 230 m distance, but no significant shift was observed when pile driving was performed at 1.5 km from the recorder (Fig. 4). This observation might be due to the high-intensity noise affecting the chorusing species' social cohesion that might have promoted the dispersion, led to the low intensity of chorusing and, in a following effort of fishes to re-establish cohesion, it might have resulted in increased chorusing activity duration. Impulsive sounds originating from activities such as pile driving have been found to affect behavior in some fish species and may lead to social cohesion disruption (Casper et al., 2013; Halvorsen, Casper, Woodley, et al., 2012; Hawkins, Roberts, & Cheesman, 2014; McCauley, Fewtrell, & Popper, 2003; Neo et al., 2014). The study in (Mueller-Blenkle et al., 2010) showed reduced aggregation and increased mobility in cod and sole fishes when exposed to pile driving playback noise. Similar dispersion of schools was observed in sprats, which may result in metabolic changes, differential foraging efficiency, and spanning success (Hawkins, Roberts, & Cheesman, 2014). The high-intensity noise from pile driving events is known to induce severe behavioral changes in European seabass (Neo et al., 2014). Studies also showed that sustained exposure to noise may also cause fishes to exhibit Lombard effect by increasing the calling amplitude (Holt & Johnston, 2014, 2015).

After the pile driving, Type 2 chorusing duration did not exhibit any change when compared to the period recorded before the pile driving. However, this species may have been influenced in ways that we were not able

Table 4. Results of Kruskal–Wallis test and the post hoc Bonferroni's multiple comparisons test showing the significance of differences in the SPL measured during the different timelines of events occurring during the monitoring period.

	Kruskal–Wallis test				
Sound level	H	*P*	d.f.	Bonferroni's multiple comparison test	*P*
SPL (50–200 Hz)	21.89	0.0001	3	2016 Before pile driving – 2016 Construction and pile driving	***
				2016 Before pile driving – 2017 Windfarm operation	**
				2016 Before pile driving – 2018 Windfarm operation	***
				2016 Construction and pile driving – 2017 Windfarm operation	**
				2016 Construction and pile driving – 2018 Windfarm operation	ns
				2017–2018 Windfarm operation	ns

H, test value; ns, non-significant; d.f., degrees of freedom; *P*, significance level; SPL, sound pressure levels.
*$P \leq 0.05$.
**$P \leq 0.01$.
***$P \leq 0.001$.

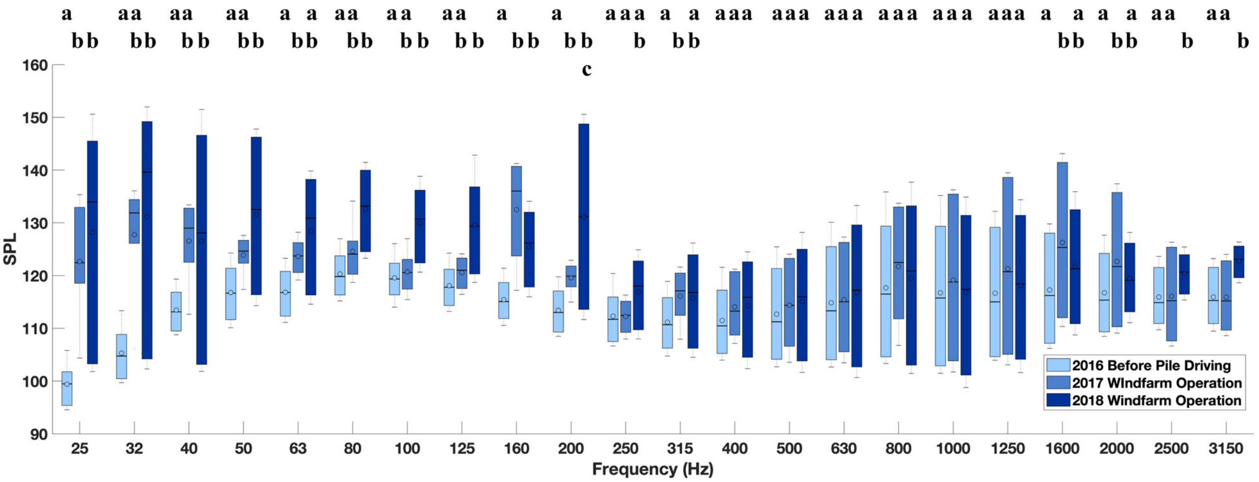


Figure 8. Variation of SPL (in units of dB re 1 μPa) from 2016–2018 (n = 6, 17, 10) at different 1/3-octave band frequencies. On each box, the central mark and marked circle represents the median and mean, and the top and bottom edges of the box represent the 25th and 75th percentiles. The black marks at the extreme ends are the maximum and minimum values. Each box with a common superscript letter represents results from *post hoc* multiple comparison test; different superscript letters indicates significant differences ($P < 0.05$), with letter 'a' at the top and subsequent statistical differences are represented a level lower it. SPL, Sound pressure level.

Table 5. Results of Kruskal–Wallis test and the post hoc Bonferroni's multiple comparisons test showing the significance of differences in the intensity and duration of two types of choruses measured during the different timelines of events occurring during the monitoring period.

		Kruskal–Wallis test			2016 Before pile driving	2016 Before pile driving	2017 Windfarm operation-
Chorus types	Parameters	H	*P*	d.f.	– 2017 Windfarm operation	– 2018 Windfarm operation	2018 Windfarm operation
Type 1	Intensity	11.16	0.001	2	**	ns	**
	Duration	23.75	0.001	2	***	***	***
Type 2	Intensity	1.55	0.46	2	ns	ns	ns
	Duration	3.72	0.15	2	ns	ns	ns

H, test value; ns, non-significant; d.f., degrees of freedom; *P*, significance level.
*$P \leq 0.05$.
**$P \leq 0.01$.
***$P \leq 0.001$.

to capture in this study or it may be the case that it could not alter its chorusing. These differential effects of high-intensity pile driving and construction noise on two types of chorusing show that different species may dissimilarly respond to the same disturbance, hence the results obtained in controlled environment (i.e., laboratory) or in the field cannot be simply extrapolated and generalized across all species. Species-specific impact analysis is therefore needed.

These two pile driving events were the first in Taiwan and served as demonstrational windfarm installation. However, the selected area for the windfarm project overlapped with the traditional fishing grounds, which are known to experience heavy fishing vessel traffic with fishing nets spanning 3–5 km^2 (Lin, Hsu, & Liu, 2019) (Fig. 1, Label FP, ES). In this challenging environment there exists a chance of loss or damage to the recorder. Being cautious of losing the data and the recorder, we retrieved the recorder soon after the pile driving activity and we were able to report only 2 days of chorusing behavior after the pile driving (n = 2). As a result, our study can be considered as a single-case investigation on the influence of a pile-driving event on two types of fish chorusing behavior. Additional data are necessary to consolidate results here found.

We recorded amidst windfarm operation noise reaching up to ~150 dB re 1 μPa^2 Hz^{-1} (2017 and 2018), which caused the Type 1 chorusing to significantly increase in duration (2–3 h) and peak intensity (~5–10 dB re 1 μPa^2 Hz^{-1}) in comparison to before the pile-driving phase (Fig. 7). The duration of Type 2 chorusing increased by ~0.5 h, which resulted in no significant difference. This increase in chorusing activity may be related to the presence of windfarm foundation structures providing an artificial reef effect with a consequent potential increase of the fish population (Ashley, Mangi, & Rodwell, 2014; Vandendriessche, Derweduwen, & Hostens, 2015; Vella et al., 2001; Wahlberg & Westerberg, 2005). Alternatively, the restrictions of commercial activities, including fishing, and the absence of transiting vessels that surround windfarm areas may provide a higher-quality habitat for these chorusing species (Reubens, Degraer, & Vincx, 2014; Stenberg et al., 2015; Van Hal, Griffioen, & van Keeken, 2017). A study in (De Troch et al., 2013) documented aggregations of Atlantic cod and pouting that chose to feed around windfarms' artificial reefs. A similar increase in abundance of fishes was observed in the vicinity of the monopile structure (Van Hal, Griffioen, & van Keeken, 2017). Studies have presented the possible masking and behavioral changes that may occur due to the particle motion caused during operation (Hawkins & Popper, 2018). However, there were no apparent negative effects observed on these two types of species in terms of their chorusing behavior. Similarly, a study in Langhamer, Dahlgren, and Rosenqvist (2018) showed no negative effects of windfarms on the individual health nor reproductive performances of the eelpout. No destructive effects of windmill noise on the hearing abilities of fish within ranges of a few meters were also documented (Vandendriessche, Derweduwen, & Hostens, 2015). It is, however, estimated that fishes are consistently scared away from windmills in ranges closer than 4 m (Wahlberg & Westerberg, 2005). This effect may be associated with the particle motion because fishes are sensitive to high levels of particle motion at low frequencies (Popper et al., 2014).

The Taiwan government's 'Thousand wind turbine project' plans to install *c.* 600 offshore turbines before 2030. The results here reported suggest that the mass installation of wind turbines involving pile driving may substantially affect the typical chorusing patterns of some soniferous species that chorus in a diurnal pattern to deviate from their normal chorusing behavior, which may affect these species' activities, such as spawning and foraging (Hawkins, 2005). Stakeholders should take these findings into account when establishing the construction calendar of windfarms and endeavor to avoid periods of the year when these species are known to spawn. However, the same chorusing species exhibited an increase in duration and intensity of chorusing post-installation of the wind turbine, even in the presence of sustained high-intensity operation noise. This result also reiterates the evidence of the artificial reef effect provided by the wind turbine foundation structures. Hence, if the high-intensity noise from the pile driving is mitigated with measures such as cofferdams, bubble curtain, or screens (Halvorsen et al., 2011; Lucke et al., 2011; Würsig, Greene Jr, & Jefferson, 2000), while making an effort to maintain vessel engine noise at a low level with various measures, including speed control (Pine et al., 2018), noise impacts on fishes could be mitigated to some extent. These strategies may help to avert any adverse impact of construction and pile driving noise, and the windfarm foundation structure may provide a new ecosystem for marine organisms.

Conclusions

This study provides an assessment of fish chorusing of a natural habitat exposed to windfarm construction and operation noise in the ETS. Passive monitoring from 2016 to 2018 revealed that two chorusing species (Types 1 and 2) cyclically repeating their chorus over a diurnal pattern at the windfarm site. When exposed to pile driving and operation noise, the two chorusing types behaved differently. The Type 1 chorusing showed a reduced intensity and an extended duration immediately after the pile driving, whereas it significantly increased both duration and intensity during operation noise. The Type 2 chorusing showed an increase in its intensity after the pile-driving (with no change in duration) but did not exhibit any significant change during the operational phases of the turbines. This study also suggests the need to provide site and species-specific impact analyses of the pile driving and operating windfarm noise. Accordingly, the conservation and noise mitigation measures can be taken up by policymakers. The results presented in this study could complement existing literature on offshore windfarms' influence on the effects of pile driving and wind turbine operational noise on marine mammals and fishes and serve as a baseline for future conservation measures.

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Experimental Techniques

Data were conducted in the sea by deploying autonomous passive recorder. The authors claim that this deployment did not cause any hindrance to any species and the environment. The experiments were approved by the National Taiwan University.

Data Availability Statement

The authors declare that the data supporting the findings of this study are available within the article and its Supplementary Information Files, or are available from the corresponding authors upon request.

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Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Figures S1-S2-Table S1