

## Research



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## Marine biology

## A sound worth saving: acoustic characteristics of a massive fish spawning aggregation

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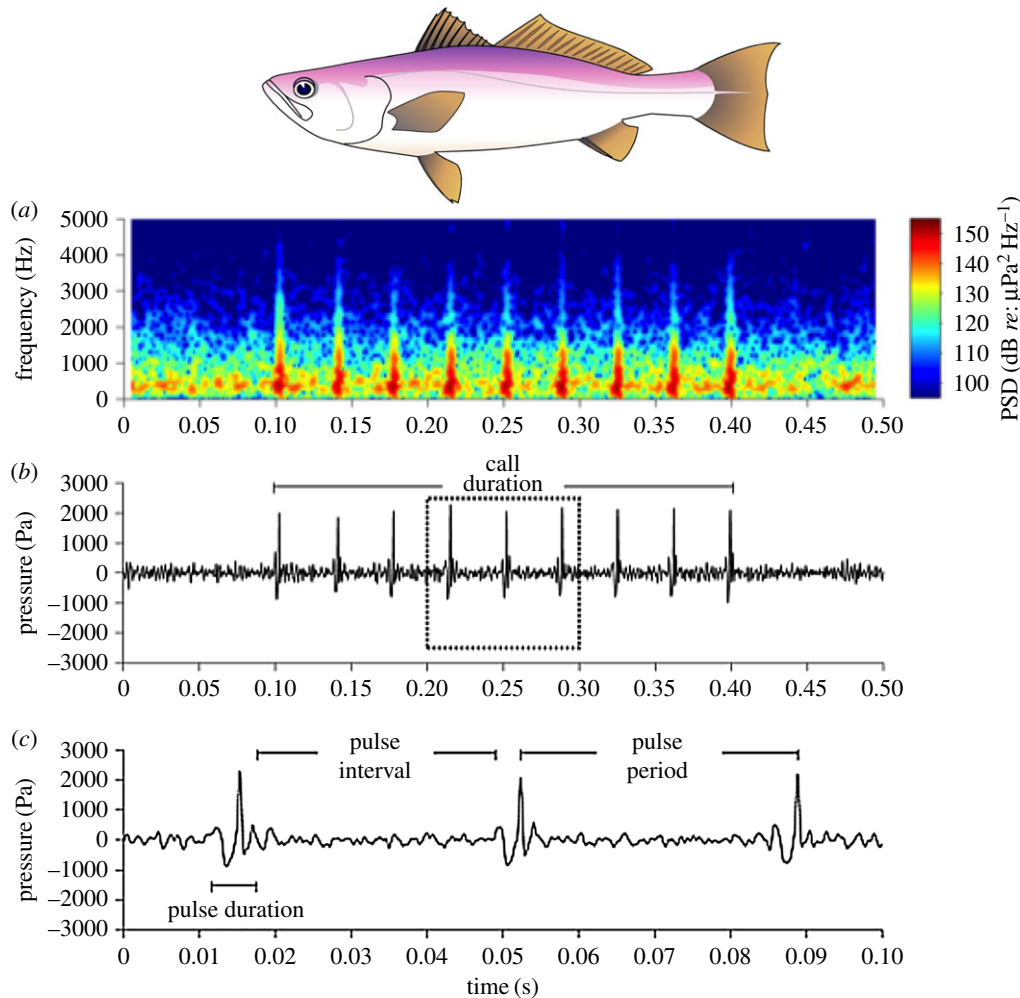
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Group choruses of marine animals can produce extraordinarily loud sounds that markedly elevate levels of the ambient soundscape. We investigated sound production in the Gulf corvina (*Cynoscion othonopterus*), a soniferous marine fish with a unique reproductive behaviour threatened by overfishing, to compare with sounds produced by other marine animals. We coupled echosounder and hydrophone surveys to estimate the magnitude of the aggregation and sounds produced during spawning. We characterized individual calls and documented changes in the soundscape generated by the presence of as many as 1.5 million corvina within a spawning aggregation spanning distances up to 27 km. We show that calls by male corvina represent the loudest sounds recorded in a marine fish, and the spatio-temporal magnitude of their collective choruses are among the loudest animal sounds recorded in aquatic environments. While this wildlife spectacle is at great risk of disappearing due to overfishing, regional conservation efforts are focused on other endangered marine animals.

## 1. Introduction

Many animals in aquatic environments produce loud sounds in association with reproduction, social interactions and other behaviours [1,2]. In many circumstances, numerous individuals within a particular area produce sounds simultaneously, and these group choruses can greatly alter the acoustic environment (soundscape) through marked, ephemeral amplifications in ambient noise levels [3–5]. The intensity, duration and other characteristics of these sounds are evolutionary products of the specific function they serve and the soundscape within which they have evolved [6,7]. Moreover, species-specific characteristics of sound production are useful and practical for monitoring the presence, abundance and activity patterns of aquatic animals for research, management and conservation [8,9].

The Gulf corvina (*Cynoscion othonopterus*) is a species of croaker (family: Sciaenidae) endemic to the Northern Gulf of California, Mexico. It is one of many marine fishes known to produce sounds in association with spawning [10,11], but their common acoustic behaviour is tightly linked to a unique reproductive pattern threatened by overfishing [12]. Each spring, all adults of the species migrate to one site, the Colorado River Delta in the uppermost portion of the Gulf to form one spawning aggregation of several million fish [13]. Spawning is synchronized with tidal and lunar cycles, occurring during the outgoing tides over a 3- to 4-day period before the new and full moons [11,13]. Male corvina produce sounds during spawning, and their collective mating choruses reverberate through the hulls of small, fibreglass fishing boats (pangas) and are audible to the naked ear. The intense sound levels can mask and overwhelm concurrent engine noise from fishing activity, enabling fishers to use the sound to easily locate and harvest fish



**Figure 1.** A single Gulf corvina call comprised nine pulses. The frequency composition of calls and choruses are depicted in a spectrogram (a), where the nine individual pulses overlay continuous background chorusing at frequencies below 2000 Hz. Oscillograms of the entire call (b) and a close-up of three pulses (c; boxed area shown in (b)) show the structure and high pressure levels (Pa) of pulses recorded. PSD, pressure spectral density. Fish illustration by L. G. Allen.

during spawning [11]. A single panga with one net can catch 2 tons of corvina within minutes, and the local fleet of 500 pangas harvests up to 5900 tons (2 million corvina) in 20 days of fishing each year, placing the species at great risk of collapsing [12,13].

We investigated the dynamics of sound production associated with corvina spawning to compare with the magnitude of noise produced by other marine animals. Our results identify the spawning sounds of male corvina as the loudest sounds recorded for a marine fish, loud enough to harm the hearing of other marine animals. The levels and spatial dimensions of sound produced by the entire aggregation coupled with the migration of an entire adult population to a single location constitutes a wildlife spectacle that merits increased protection.

## 2. Material and methods

We conducted 4 days of acoustic surveys of the corvina aggregation in the Delta during peak spawning periods in March and April 2014. Active acoustic (split-beam echosounder) surveys were comprised of transects across the Delta channel from a panga. Echosounder data were analysed to estimate the distribution and abundance of fish for each survey (electronic supplementary material). Passive acoustic (hydrophone) surveys of corvina sound production were conducted from a second vessel, in

synchrony with the timing and location of echosounder transects, to estimate the magnitude and spatial distribution of received sound pressure levels (SPL;  $\text{dB}_{\text{rms}}$  *re*:  $1 \mu\text{Pa}$ ) attributable to spawning corvina (electronic supplementary material). Additional sound measurements were made outside of the spawning period to document the mean ambient SPL in the absence of corvina sound production.

We isolated audio recordings of calls with high signal to noise ratios and choruses exceeding  $150 \text{ dB}_{\text{rms}}$  to characterize the individual calls and collective choruses of male corvina. Oscillograms of calls were generated to estimate call duration, pulses per call, pulse duration, pulse interval and pulse period. We isolated single pulses from calls to calculate three measurements of individual sound levels (dB measured as 0-to-peak (0-p), peak-to-peak (p-p) and rms) and estimate source levels (dB at 1 m) based on the maximum levels recorded. Pressure spectral density (dB *re*:  $1 \mu\text{Pa}^2 \text{Hz}^{-1}$ ) curves of calls and choruses were generated to estimate their peak frequencies and 3 dB and 6 dB bandwidths (Hz), which describe the distribution of acoustic pressure as a function of frequency.

Fish densities and SPLs per transect were mapped to delineate the aggregation, spawning activity and chorusing. The spatial extent of each aggregation event was estimated by measuring the linear distance over which densities per transect were greater than two fish per  $1000 \text{ m}^3$ . The linear distance of SPLs exceeding  $150 \text{ dB}_{\text{rms}}$  was measured to estimate the spatial extent of pronounced spawning activity for each survey. As peak spawning and stable sound production rates occur over a predictable 2 h period [11], we calculated cumulative sound exposure levels

**Table 1.** Characterization statistics of Gulf corvina calls and choruses. Maximum values of pulse SPLs represent the minimum expected source levels (dB at 1 m) of Gulf corvina.

	mean	CI <sub>95</sub>	n	min	max
<b>calls</b>					
call duration (ms)	389.2	373.7, 404.7	139	103.3	655.0
pulses per call	11.1	10.7, 11.5	139	4	20
pulse duration (ms)	5.5	5.4, 5.6	1520	2.4	9.5
pulse interval (ms)	32.6	32.4, 32.8	1381	17.1	80.1
pulse period (ms)	37.9	37.7, 38.1	1367	29.8	60.2
pulse SPL (dB <sub>0-p</sub> re: 1 µPa)	176.3	176.1, 176.5	1530	164.3	187.2
pulse SPL (dB <sub>p-p</sub> re: 1 µPa)	179.6	179.4, 179.8	1530	167.4	190.0
pulse SPL (dB <sub>rms</sub> re: 1 µPa)	166.6	166.4, 166.8	1530	155.7	177.3
peak frequency (Hz)	384.3	372.8, 395.8	139	265	655
3 dB bandwidth (Hz)	4.9	4.5, 5.3	139	2	16
6 dB bandwidth (Hz)	7.6	7.0, 8.2	139	2	20
<b>choruses</b>					
peak frequency (Hz)	377.9	372.8, 383.0	182	314	475
3 dB bandwidth (Hz)	14.0	12.4, 15.6	182	3	64
6 dB bandwidth (Hz)	209.8	203.4, 216.2	182	27	322

(SEL<sub>cum</sub>; dB re: 1 µPa<sup>2</sup> s) throughout the aggregations by integrating received levels recorded during this period. We used SEL<sub>cum</sub> values, which estimate the total (i.e. additive) sound energy produced during the 2 h spawning event, to infer the potential impact of elevated acoustic exposure on marine mammals present at the site.

### 3. Results

Recorded calls consisted of a variable number of short, sequential pulses repeated over the duration of the call (figure 1; table 1). Pulses were comprised of low amplitude positive and negative peaks followed by a high amplitude positive peak and single-peak decay. The maximum SPLs of pulses recorded were 187.2 dB<sub>0-p</sub>, 190.0 dB<sub>p-p</sub> and 177.3 dB<sub>rms</sub>, which represent the minimum expected source levels of corvina given that the exact source range was not measured. The mean peak frequencies of calls and choruses were 384 Hz and 377 Hz, respectively.

The spawning aggregation and associated chorusing were distributed over distances of 9–27 km (mean = 16 km). Fish densities per transect ranged from 0.07 to 33.94 fish per 1000 m<sup>3</sup> (figure 2), and total abundance ranged from 522 201 (CI<sub>95</sub> 387 606–673 620) to 1 551 729 (CI<sub>95</sub> 1 253 025–1 988 297) fish per survey. Received sound levels ranged from 136.17 to 163.43 dB<sub>rms</sub> or 6.43 to 148.51 Pa<sub>rms</sub> ( $n = 117$ ; figure 2) during surveys of the aggregation compared to 99.34 (CI<sub>95</sub> 98.26–100.42) dB<sub>rms</sub> outside the spawning period, indicating that corvina choruses elevated levels of the soundscape by 64.09 dB<sub>rms</sub>. SEL<sub>cum</sub> ranged from 179.57 to 201.98 dB during the peak spawning period.

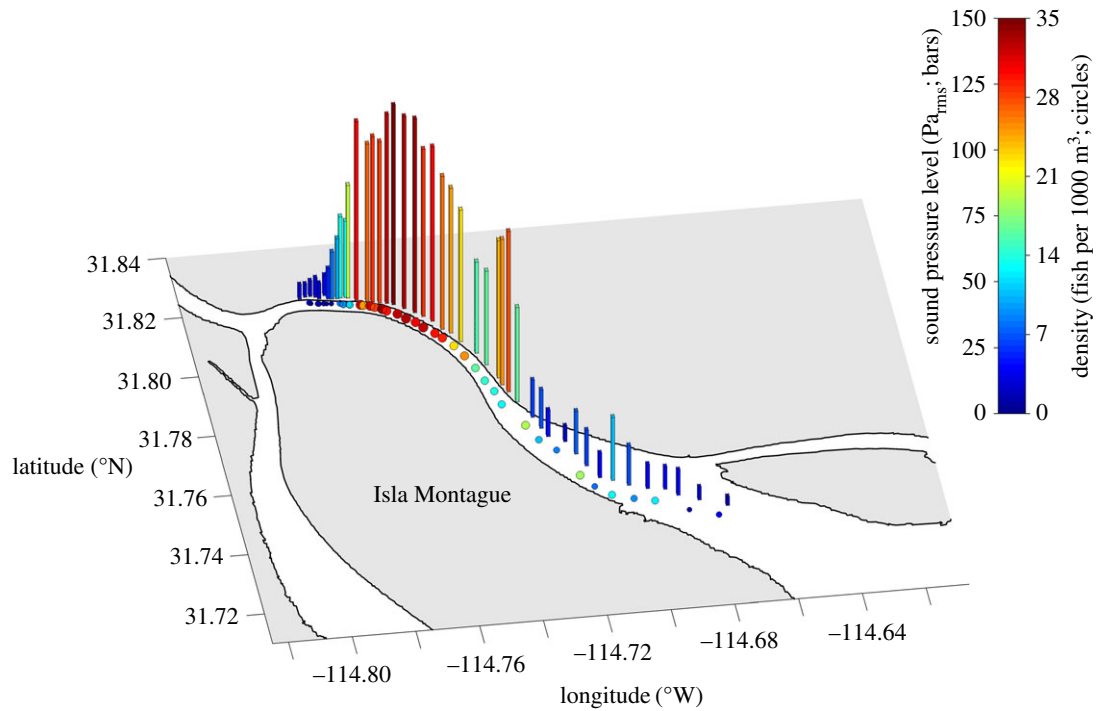
### 4. Discussion

Estimated source levels of calls by male corvina represent the loudest sounds recorded in a marine fish and among the

loudest animal sounds recorded in aquatic environments (table 2). However, the magnitude of the sounds produced by corvina are best described by the simultaneous chorusing of males within the larger spawning aggregation, which can extend up to 27 km in length along the main channel of the Delta and include 1.5 million individuals during a single spawning period. The chorus of the aggregation can elevate the local soundscape 21 times louder than ambient levels, making these unique acoustic behavioural events a true wildlife spectacle. Notably, our measurements likely underestimate the soundscape potential of the event, given the intense, persistent fishing activity that has greatly reduced the size of the adult population [12,13].

Hearing mechanisms and performance in animals can evolve in accordance with environmental acoustics, background noise and the range of detectable sounds that are biologically relevant [28]. Ambient noise levels in the Delta are known to be unusually high [29]. Therefore, the loud acoustic characteristics of corvina may represent an evolutionary adaptation that permits intraspecific communication in an inherently noisy environment, a phenomenon termed the Lombard effect [30]. Like other animals that engage in mass breeding choruses (e.g. crickets and frogs) [31], the loud sounds produced by male corvina during spawning may facilitate communication among potential mates in a noisy environment made even noisier by the synchronous chorusing of conspecifics (i.e. the ‘cocktail party problem’ [32]). We speculate that the magnitude of sound produced serves to coordinate the mass, brief, synchronous spawning activity of the entire adult population that occurs during the outgoing tide in highly turbid and turbulent waters that render visual cues much less effective.

The SEL<sub>cum</sub> produced in 2 h by the corvina aggregation ranged from 179 to 202 dB and was concurrent with a 21-fold (i.e. 64 dB) increase in ambient sound; increases of 3 dB equate to a doubling of sound intensity. SEL<sub>cum</sub> of 173–219 dB over a 24 h period can cause permanent hearing loss



**Figure 2.** Map showing the distribution of fish densities (circles) and courtship sound levels (vertical bars) from acoustic surveys of Gulf corvina in the Colorado River Delta.

**Table 2.** Sounds produced by marine animals ranked by estimated source levels. Bold text identifies estimations made during this study.

species	source level and type (dB <sub>rms</sub> re: 1 µPa)	reference
sperm whale ( <i>Physeter microcephalus</i> )	236, sonar click	Møhl <i>et al.</i> [14]
blue whale ( <i>Balaenoptera musculus</i> )	189, call	Širović <i>et al.</i> [15]
fin whale ( <i>Balaenoptera physalus</i> )	189, call	Širović <i>et al.</i> [15]; Weirathmueller <i>et al.</i> [16]
bowhead whale ( <i>Balaena mysticetus</i> )	185, song	Tervo <i>et al.</i> [17]
<b>Gulf corvina (<i>Cynoscion othonopterus</i>)</b>	<b>177, call</b>	<b>Erismán &amp; Rowell [18]</b>
humpback whale ( <i>Megaptera novaeangliae</i> )	169, song	Au <i>et al.</i> [19]
black drum ( <i>Pogonias cromis</i> )	165, call	Locascio & Mann [20]
humpback whale ( <i>Megaptera novaeangliae</i> )	158, call	Dunlop <i>et al.</i> [21]
Nassau grouper ( <i>Epinephelus striatus</i> )	143, call	Schärer <i>et al.</i> [22]
killer whale ( <i>Orcinus orca</i> )	140, whistle	Miller [23]
bottlenose dolphin ( <i>Tursiops truncatus</i> )	138, whistle	Frankel <i>et al.</i> [24]
silver perch ( <i>Bairdiella chrysoura</i> )	135, call	Sprague & Luczkovich [25]
oyster toadfish ( <i>Opsanus tau</i> )	126, call	Barimo & Fine [26]
Bocaccio rockfish ( <i>Sebastes paucispinis</i> )	113, call	Širović & Demer [27]

in cetaceans and pinnipeds, and temporary hearing loss in these animals can occur at SEL<sub>cum</sub> of 153–199 dB [33]. The frequency of sound produced by corvina falls within the range of hearing of pinnipeds and cetaceans, and SEL<sub>cum</sub> generated at the aggregation exceeded recommendations for daily (e.g. 24 h) exposure thresholds after only 2 h [33]. Therefore, it was surprising that adult California sea lions (*Zalophus californianus*) and dolphins were frequently observed concomitantly feeding in the area despite the potentially detrimental risk imposed by the elevated soundscape.

The corvina is endemic to the Northern Gulf of California, reproduces within an area that represents less than 1% of its

species range, and faces imminent risk of a fishery and species collapse due to overfishing of its spawning aggregation and regulations that allow overfishing to persist [12,13]. A regional ban on commercial gill nets was recently implemented to protect two other endemic and endangered species, the vaquita porpoise (*Phocoena sinus*) and the Totoaba (*Totoaba macdonaldi*), but allows gill net fishing for corvina during spawning to continue [34]. Ironically, while sound has long been used to exploit corvina, sound production is highly correlated with fish abundance and can be used as a practical tool to estimate the population size, monitor the spawning population and set sustainable harvest limits [11]. Fish sounds are increasingly

being valued for the information they convey about the biology, behaviour and population sizes of fishes, but the persistence of loud acoustic events, such as those created by corvina, into the future has intrinsic value worthy of conservation due to their uniqueness and warranted inclusion among wildlife spectacles.

**Ethics.** Research protocol was approved under UCSD IACUC ID no. S13240. Data were collected under CONANP permit no. CNANP-00-007.

**Data accessibility.** Data are available online at <https://inport.nmfs.noaa.gov/inport/item/27628>.

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