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About the Cover	An acoustically tagged red snapper caught and released on the Tarantula platform, Gulf of America. Photo credit: Brett Falterman.

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Technical Summary

Abstract

Seismic airgun surveys produce intense low-frequency sound that may influence fish behavior. This study presents the first in situ assessment of behavioral responses of adult, free-swimming reef-associated fishes to seismic airgun sound in the northern Gulf of America (Gulf). Using acoustic telemetry and passive acoustic monitoring at an offshore oil and gas platform, we tracked 30 tagged individuals from four reef-associated species—red snapper, red porgy, almaco jack, and greater amberjack—across pre-, during-, and post-close-pass survey periods of a commercial-scale seismic vessel. Red snapper exhibited a significant decline in detections during the close-pass period followed by a significant increase afterward, indicating short-term avoidance or sheltering behavior and a return toward baseline conditions despite continued elevated sound levels. Detection responses for red porgy and greater amberjack were not significant across survey periods, and almaco jack results were descriptive due to low sample sizes. Overall, the findings indicate species-specific and individual-level variation in behavioral responses to elevated sound, though small sample sizes and mixed response patterns limit broader inference and warrant cautious interpretation.

Background

Sound is an important ecological cue for fishes, shaping navigation, predator avoidance, communication, and habitat selection. Natural reef soundscapes contribute to fish behavior and distribution, while anthropogenic noise, including seismic airgun sound, can alter fish behavior and physiology. Seismic airgun arrays used in offshore energy exploration generate powerful low-frequency impulses that overlap with auditory ranges of many marine fishes. Previous research has shown mixed results regarding behavioral and physiological responses to seismic sound, potentially influenced in part by the reliance of many studies on laboratory or caged conditions that differ from natural environments.

The Gulf experiences extensive seismic survey activity, yet no prior studies have evaluated in situ behavioral responses of free-swimming fishes in this region. This study addresses that gap by assessing behavioral patterns of reef-associated fishes exposed to seismic airgun sound under realistic field conditions.

Objectives

The objective of this study was to assess whether commercial-scale seismic airgun sound influences the behavior of adult, free-swimming reef-associated fishes in the Gulf.

Methods

The study was conducted at the South Timbalier 308 A (Tarantula) oil and gas platform in the northern Gulf. An array of five acoustic receivers and multiple passive acoustic recorders was deployed around the platform to monitor fish presence and characterize the acoustic environment. Thirty adult individuals representing four reef-associated species were captured and tagged with acoustic transmitters before the seismic survey.

Detection data were analyzed across three five-day periods: pre-close pass, close-pass, and post-close pass, defined relative to the seismic vessel's closest approach. Behavioral responses were inferred from changes in detection rates between periods. Broadband sound pressure levels and low-frequency spectral energy were examined for each period to relate behavioral patterns to acoustic conditions.

Results

The recovered receivers recorded 464,419 detections from 28 of the 30 tagged fish. Twenty-three fish were detected in both the pre- and during close-pass periods, each with more than 1,000 detections.

Red snapper showed significant differences across survey periods (N = 5), with reduced detections during the close-pass period followed by increased detections afterward. Two individuals were excluded from analysis due to mortality indicators. Red porgy did not show statistically significant differences across periods, though most individuals declined at the onset of the close-pass and then varied thereafter. Greater amberjack showed no significant differences in detection rates across periods. Individual fish exhibited variable changes in detection frequency, with some decreasing during the close-pass period and others showing stable or increased detections. Almaco jack results were descriptive because only two individuals exhibited adequate detection rates.

Mean broadband sound levels (50–1000 Hz) were elevated throughout the study. Pre-close-pass levels averaged 117 dB re 1 µPa, increasing slightly in the post-close-pass period. During the close pass, peak sound levels exceeded recorder limits (>175 dB re 1 µPa). Sound level distributions differed significantly among the three periods, with the pre-close-pass period being quieter than the close-pass and post-close-pass periods. However, close-pass and post-close-pass distributions did not differ significantly, though clipping during the close-pass period may have contributed to the lack of a detected difference between these two periods.

Conclusions

Low-frequency sound levels were elevated across all survey periods, with median broadband levels (50–1000 Hz) ranging from 115 to 116 dB re 1 µPa. Peak received levels during the close-pass period exceeded the recorder's dynamic range (>175 dB re 1 µPa), indicating exposure to very high-intensity impulses. The pre-close-pass period was quieter than the close-pass and post-close-pass periods, while close-pass and post-close-pass sound level distributions were not significantly different, reflecting sustained elevated sound after the vessel's closest approach.

Species responses differed. Red snapper exhibited a temporary decline in detections during the close-pass period followed by a significant increase afterward, consistent with short-term avoidance or sheltering. Red porgy and greater amberjack exhibited non-significant changes across survey periods, though individual variability was common. Almaco jack patterns suggested potential increases in detections for individuals with adequate data, but low sample sizes prevented statistical evaluation.

Overall, the findings show evidence of a short-term behavioral response for red snapper, with no significant detection changes observed for the other species. Variability among individuals and species reflects differences in how fish responded under elevated sound conditions. However, small sample sizes and incomplete detection histories limit the ability to draw definitive conclusions about the broader prevalence or consistency of these responses across taxa.

Future work should increase sample sizes, incorporate particle-motion measurements, evaluate physiological impacts, establish controlled comparisons, and ensure sufficient recorder dynamic range to avoid clipping during high-intensity events. These improvements will strengthen species-specific impact assessments and inform mitigation strategies for acoustically sensitive Gulf fish populations.

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List of Abbreviations and Acronyms

Short Form	Long Form
μPa	micropascal
AP	acoustic pressure
BOEM	Bureau of Ocean Energy Management
dB	decibel
dBrms	decibels calculated from root-mean-squared of pressure
Hz	Hertz
KW	Kruskal-Wallis test
m	meter
m/s2	meters per second squared
N	number of individuals
NOAA	National Oceanic and Atmospheric Administration
OCS	Outer Continental Shelf
PAM	passive acoustic monitoring
RM ANOVA	repeated measures analysis of variance
rms	root-mean-square
SPL	sound pressure level
ST	Sound Traps from Ocean Instruments
ST	South Timbalier
TTS	temporary threshold shifts

1 Background

Teleost fishes detect and respond to acoustic signals from a variety of sources, including conspecifics, predators, prey, anthropogenic activities, and ambient environmental sounds (Tavolga 1971, Lindseth and Lobel 2018). In reef environments, soundscapes are important cues for navigation and settlement; numerous fish larvae actively swim toward reef-associated sounds, demonstrating both directional hearing and attraction to specific acoustic cues (Leis et al. 2003, Tolimieri et al. 2004; Simpson et al. 2010; Huijbers et al. 2012; Barth et al. 2015). Many fish species also produce sound during a range of behaviors, including agonistic interactions (Ladich 1997, Bertucci et al. 2010, Tricas and Boyle 2014), courtship and mate selection (Mann and Lobel 1997, Amorim et al. 2003, Boyle and Cox 2009, Parmentier and Fine 2016), spawning (Lobel 2002, Rowell et al. 2015, Locascio and Burton 2016, Rowell et al. 2020, Wilson et al. 2020), and when startled or disturbed (Brawn 1961, Ladich 1997, Fine and Parmentier 2015). Understanding the importance of sound to fish across all life stages, including the extent to which anthropogenic noise alters behavior, is critical as the oceans become increasingly affected by human-generated acoustic inputs.

Teleost fishes detect the acoustic particle motion component of sound—the movement of water caused by sound waves—primarily through otoliths. Otoliths are calcium carbonate structures located within the otolithic organs (i.e., lagena, saccule, and utricle) and are the main auditory structures for sensing particle motion (Popper and Lu 2000; Popper et al. 2005; Popper et al. 2014, Carroll et al. 2017). Some teleosts also detect sound through the swim bladder (a gas-filled organ present in many, but not all, species), which responds to acoustic pressure waves (Popper et al. 2014). In species with specialized anatomical connections between the swim bladder and the inner ear, these pressure-induced vibrations can stimulate the otolith organs, enhancing hearing sensitivity across a broader frequency range.

Prolonged or excessive exposure to high-intensity, low-frequency sounds, such as those produced by seismic surveys using airguns, can lead to temporary threshold shifts (TTS, i.e., reduced hearing sensitivity) and barotraumatic injuries (e.g., swim bladder ruptures) (Carroll et al. 2017). Seismic surveys, which are conducted to detect potential oil and natural gas deposits below the seafloor, use airguns to generate impulsive sounds at regular intervals, typically ranging from below 10 to 300 Hz (Carroll et al. 2017). Importantly, the frequency bandwidth of seismic airgun sounds overlaps with the hearing ranges of most marine fishes: teleosts with swim bladders (~200 Hz to 3 kHz), teleosts without swim bladders (~100 Hz to 1 kHz), and elasmobranchs (~200 Hz to 1500 Hz) (Lucke et al. 2024). Consequently, airguns—and other anthropogenic sound sources—increase ambient sound levels in the ocean, which can result in physiological or behavioral effects (Kunc et al. 2016, Wright et al. 2007, Erbe et al. 2018).

Studies that have investigated the effects of seismic airgun sound on fish survival, physiology, reproduction, and behavior, have shown mixed results suggesting species-specific and context-dependent responses (e.g., McCauley et al. 2003; Carroll et al. 2017; Hubert et al. 2020; Meekan et al. 2021; McQueen et al. 2022). Captive studies have shown behavioral changes, such as altered swimming patterns and shifts in activity states (Fewtrell and McCauley 2012; Hubert et al. 2020), as well as damage to hair cells in the inner ear (McCauley et al. 2003) and swim bladders (Falk and Lawrence 1973) at close range, though some injuries, such as damage to sensory hair cells, may be recoverable (Monroe et al.

2015; Smith and Monroe 2016). Other studies found no lethal impacts (Weinhold and Weaver 1972; Turnpenny and Nedwell 1994), and recent in situ experiments have reported minimal effects on free-swimming individuals. For example, Meekan et al. (2021) and McQueen et al. (2022) observed minor behavioral disruptions and no changes in abundance or distribution during seismic surveys. A recent BOEM-funded study (BOEM 2024-056) found short-term behavioral responses in tagged, free-swimming rockfish during survey days, which reversed shortly afterward. In contrast, Engås et al. (1996) documented significant reductions in abundance and catch rates of cod and haddock during and after seismic shooting, with effects persisting for at least five days.

These contrasting results underscore the importance of species-specific and context-sensitive studies, because fish responses to seismic airgun exposure vary widely depending on auditory sensitivity, ecological traits, behavioral states, and experimental conditions. Factors such as proximity to the sound source, whether fish are caged or free-swimming, and the realism of the acoustic environment influence the ecological relevance of observed responses. In enclosed environments, such as tanks or pools, sound propagation is altered by reflective boundaries, leading to reverberation, standing waves, and spatially variable exposure levels that differ markedly from open-water conditions (Parvulescu 1967; Duncan et al. 2016; Jézéquel et al. 2022; Jones et al. 2019). These acoustic distortions can confound results. In contrast, field studies with free-swimming fish exposed to seismic airguns under natural conditions offer greater behavioral and environmental authenticity, capturing realistic sound propagation and allowing unrestricted movement that is important for assessing ecologically meaningful responses (Carroll et al. 2017).

This study is the first in situ experiment in the Gulf of America (Gulf; formerly the Gulf of Mexico) to evaluate behavioral responses of adult, free-swimming reef-associated fishes to seismic airgun exposure under realistic environmental conditions. The Gulf is one of the most fossil fuel-rich regions globally; seismic airguns are a dominant source of low-frequency anthropogenic noise (Rankin and Evans 1998; Estabrook et al. 2016; Wiggins et al. 2016; HDR 2022). Despite the intensity and prevalence of seismic activity in the region, no previous research has assessed fish behavior in response to seismic surveys using field-based telemetry methods. Such in situ experiments are essential for capturing ecologically relevant responses and improving impact assessments, enabling the Bureau of Ocean Energy Management (BOEM) to better evaluate the consequences of Outer Continental Shelf (OCS) seismic surveys and fulfill its statutory obligations to stakeholders, including fishing and scientific communities.

2 Objectives and Approach

The objective of this study was to assess whether seismic airgun activity influenced the behavior of adult, free-swimming fishes in the Gulf using an integrated approach that combined acoustic telemetry and passive acoustic monitoring. Behavioral effects were inferred from changes in detection frequency of acoustically tagged individuals. Specifically, the analysis focused on presence or absence at the monitoring site; changes in detections aggregated across receivers were the primary behavioral metric. This metric enabled inference of spatiotemporal distribution patterns, site fidelity, habitat use, and potential behavioral disruption or avoidance in relation to the passing seismic airgun survey. Telemetry data were collected via an array of receivers deployed around an offshore platform, and detection patterns were compared across three defined time periods—before, during, and after a close pass of the seismic survey vessel. Although some fish carried tags capable of recording fine-scale acceleration and depth, these data did not coincide with the survey period and were excluded from the impact analysis. The results from these tags are reported separately, as they may be of interest to other researchers or stakeholders (**Appendix A**). Ambient acoustic conditions were characterized by using data from a single recovered passive acoustic recorder, focusing on broadband sound levels and low-frequency spectral energy. This approach enabled assessment of fish responses in relation to variations in the acoustic environment during seismic survey activity.

3 Methods

The study was conducted at the South Timbalier (ST) 308 A (Tarantula) oil and gas production platform in the northern Gulf (**Figure 1**). Tarantula is an active, fixed four-legged platform located at a water depth of approximately 150 m (~492 ft). It is situated approximately 101 km (63 miles) from shore and was installed in 2004. The platform is supported by a jacketed foundation and is isolated, with no other platforms located within several miles. The surrounding seafloor is smooth and composed of fine-textured, silty clay sediments.

Fixed oil and gas platforms are known to concentrate high densities of reef-associated fish species within a relatively small area, making them ideal sites for efficient capture and monitoring using acoustic telemetry techniques. This specific study site was selected in coordination with BOEM because of its proximity to the planned track lines of a seismic airgun survey vessel operating in the north-central Gulf during the proposed study period.

The seismic survey was conducted using a commercial-scale, conventional airgun array consisting of 28 airguns with a total volume of 5,200 cubic inches. The array produced a sound pressure level (SPL) source level of 242 dB re: 1 μPa·m and peak source level of 268 dB re: 1 μPa·m, with frequencies reaching up to 240 Hz and a ping rate of one pulse every eight seconds.

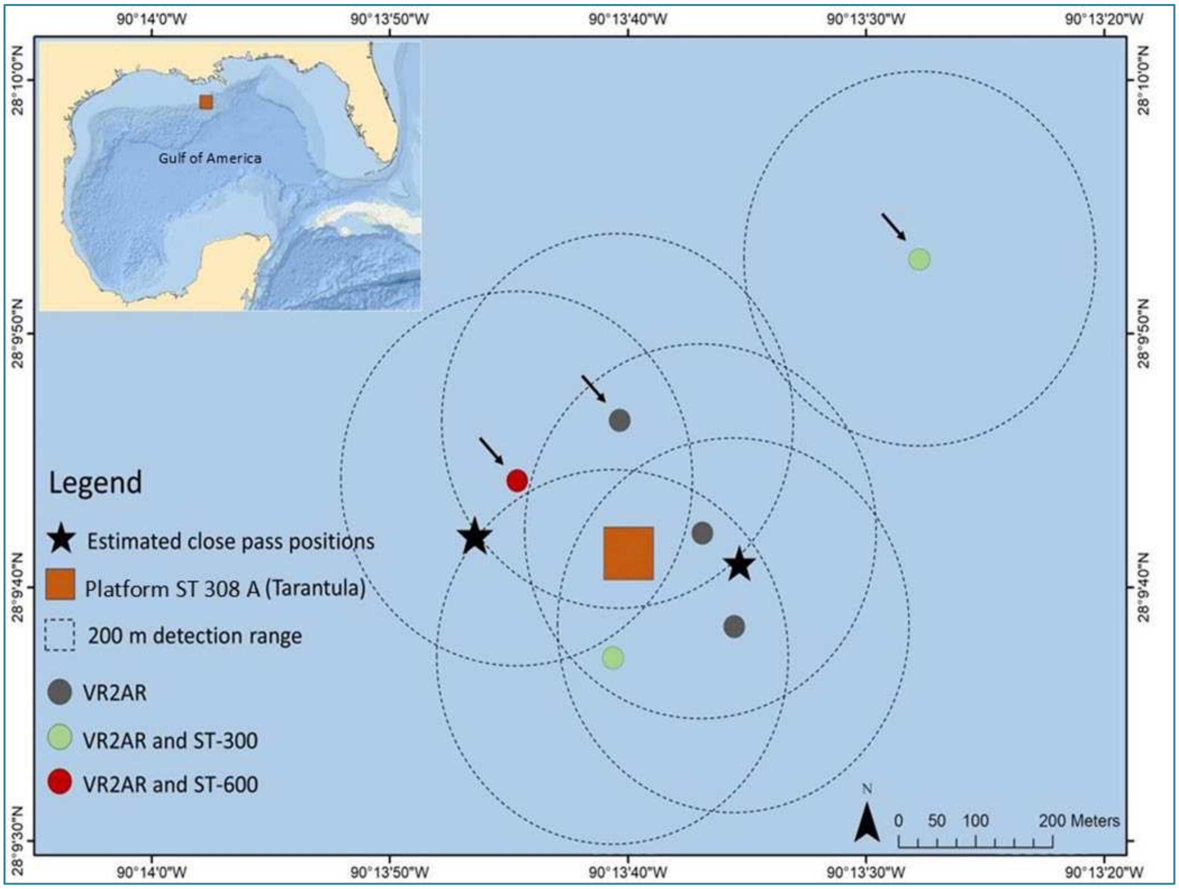

Figure 1. Locations of Innovasea VR2AR receivers and Sound Trap units deployed at platform ST-308 A (Tarantula) in the Gulf.

Black arrows indicate the three recovered receivers. Black stars mark the estimated close-pass locations of the survey vessel: 113 m (370 ft) east of the platform and 187 m (613 ft) west. Dashed 200-m detection-range circles around each receiver overlap, showing the combined spatial coverage of the acoustic monitoring array.

3.1 Array Design and Sound Trap Deployment

An array of five Innovasea VR2AR acoustic release receivers were deployed near the Tarantula platform on December 8, 2022 (**Table 1**). The receivers were positioned with overlapping detection ranges to enhance the probability of simultaneous fish detections by multiple units. Four receivers were positioned 120 to 170 m (393 to 558 ft) from the platform in the N, NW, SW, and SE directions. A fifth receiver was installed in a central location approximately 80 m (262 ft) from the platform. Each receiver was secured to a mooring line using plastic cable ties and was elevated about 4 m (13 ft) above the seafloor. The mooring line was anchored to a concrete block placed on the substrate and equipped with submerged trawl net floats at the upper end to maintain vertical alignment (**Figure 2**). An additional receiver was deployed on April 2, 2024, approximately 0.5 km (0.3 miles) northeast of the platform.

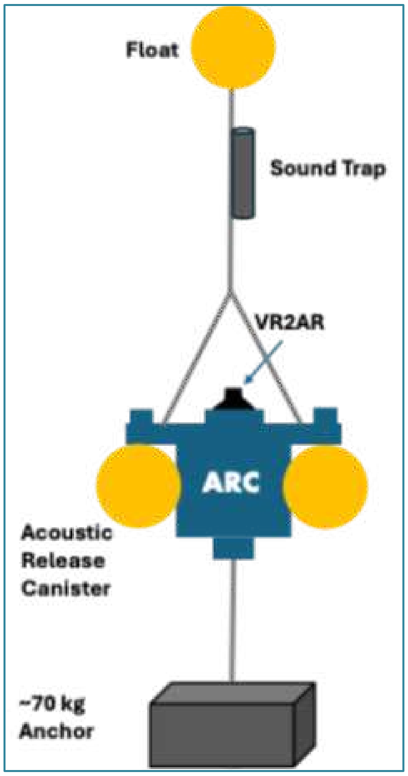

Figure 2. Schematic illustrating an acoustic-release mooring system.
Components are arranged vertically from bottom to top, beginning with a 70-kg anchor at the base. Above the anchor is an acoustic-release canister connected to a VR2AR receiver equipped with flotation. A SoundTrap acoustic recorder is positioned higher in the water column, and an additional float is located at the top of the mooring line.

Three Sound Traps from Ocean Instruments (models ST300 and ST600) were deployed alongside VR2AR acoustic receivers at NW, SW, and NE locations and were set to sample continuously at 48,000 samples per second. The Sound Traps were attached to the mooring lines between the receivers and floats using cable ties. These passive acoustic recorders have a flat frequency response from approximately 50 Hz and extending across the recording bandwidth used here (24 kHz) with a sensitivity of 175 dB re 1 μPa.

Two VR2AR receivers (located N and NW) and one Sound Trap ST600 were successfully recovered on June 24, 2023, using a remote acoustic release system. The VR2AR release mechanism was triggered using a VR100 receiver connected to a transponding hydrophone, which emitted a coded acoustic signal to prompt the release and allow the receiver to float to the surface for retrieval. The NE receiver and its associated Sound Trap ST300 were recovered on May 30, 2024, using a remotely operated vehicle, after communication issues prevented recovery during the first attempt. Unfortunately, due to a communication failure with the three receivers installed at the SW, SE, and Center locations, along with one Sound Trap (ST300), these devices could not be retrieved despite multiple recovery attempts. They were ultimately considered lost.

Table 1. Summary of Locations, Deployment Details, and Recovery Status for VR2AR Receivers and Sound Trap Recorders at Platform ST-308 A (Tarantula)

Receiver ID	Deployed	Location	Latitude	Longitude	Depth (m)	Sound Trap	Recovered
551089	12/8/2022	NW	28.16227	-90.22905	150	ST600	6/24/2023
551090	12/8/2022	N	28.16293	-90.22785	150	-	6/24/2023
551091	12/8/2022	SW	28.16037	-90.22793	150	ST300	Lost
552252	12/8/2022	SE	28.1607	-90.22652	150	-	Lost
552259	12/8/2022	Center	28.16173	-90.22688	150	-	Lost
552251	4/2/2023	NE	28.1647	-90.22435	142	ST300	5/30/2024

3.2 Study Species Selection and Acoustic Tagging

The four reef-associated teleosts selected for this study—red snapper, red porgy, almaco jack, greater amberjack—were chosen based on their high abundance and ease of capture around oil and gas platforms, and for their fisheries relevance. Species were selected to assess whether behavioral responses differ between benthic and pelagic reef-associated taxa. Red snapper is a medium-sized, demersal species with strong associations to artificial structures and high site fidelity (Strelcheck et al. 2012; Williams-Grove & Szedlmayer 2016). Red porgy is also medium-sized and bottom-dwelling, with expected site fidelity to structured habitats, though this has not been characterized in the Gulf. Almaco jack is a medium-sized pelagic, structure-associated species with limited life history data in the region, but is presumed to share reproductive, growth, movement, and feeding traits with greater amberjack due to their ecological and phylogenetic similarity. Greater amberjack are large, mobile pelagic species that occupy the water column and can exhibit moderately broad spatial movements across offshore, structured habitats, though tagging studies in the Gulf have shown that most individuals exhibit zero net movement, with a smaller proportion displaying net movements within 25 nautical miles of release sites (McClelland and Cummings 1997).

To evaluate potential behavioral responses to seismic airgun exposure, 30 individuals were caught using traditional hook-and-line gear, jigging, and electric reels between December 8, 2022 and April 2, 2023: red snapper (N = 11, mean total length = 780mm, range 575-880), almaco jack (N = 6, mean total length = 831mm, range 790-885), greater amberjack (N = 6, mean total length = 1328mm, range 1035-1445) and red porgy (N = 7, mean total length = 476mm, range 445-530) (**Table 2**). Of these, 20 individuals were fitted with Innovasea V9 acoustic transmitters to identify potential changes in detection rates and presence/absence around the platform in response to seismic survey activity. The remaining 10 individuals (five red snappers and five red porgies) were tagged with V9 accelerometer and pressure acoustic transmitters (V9AP) to assess fine-scale behavioral metrics such as depth changes and acceleration, which may indicate shelter-seeking, elevated activity levels, or displacements is response to seismic airgun sound. Acoustic tags were externally attached to the dorsal musculature just below the anterior portion of the dorsal fin using stainless steel wires.

Table 2. Detection Summary for 30 Acoustically Tagged Individuals at Platform ST-308 A (Tarantula)

Fish ID	Species	Transmitter Type	Date Tagged	Last Day Detected	Detection Span (Days Detected)	Number of Detections
Almaco Jack #01	*Seriola rivoliana*	V9	12/8/2022	5/5/2024	515 (337)	34148
Almaco Jack #02	*Seriola rivoliana*	V9	12/8/2022	6/18/2023	193 (165)	24283
Almaco Jack #03	*Seriola rivoliana*	V9	12/8/2022	1/24/2024	413 (253)	25805
Almaco Jack #04	*Seriola rivoliana*	V9	12/8/2022	6/11/2023	186 (133)	48202
Red Snapper #01	*Lutjanus campechanus*	V9	12/8/2022	4/30/2024	510 (203)	38018
Red Snapper #02	*Lutjanus campechanus*	V9AP	12/8/2022	6/24/2023	199 (175)	71566
Red Snapper #03	*Lutjanus campechanus*	V9AP	12/8/2022	12/8/2022	1 (1)	3
Red Snapper #04	*Lutjanus campechanus*	V9AP	12/8/2022	12/9/2022	2 (2)	40
Red Snapper #05	*Lutjanus campechanus*	V9AP	12/8/2022	N/A	N/A	N/A
Almaco Jack #05	*Seriola rivoliana*	V9	4/2/2023	4/17/2024	382 (263)	34750
Almaco Jack #06	*Seriola rivoliana*	V9	4/2/2023	6/22/2023	82 (82)	26498
Greater Amberjack #01	*Seriola dumerili*	V9	4/2/2023	4/17/2023	16 (13)	3964
Greater Amberjack #02	*Seriola dumerili*	V9	4/2/2023	5/12/2023	41 (41)	6047
Greater Amberjack #03	*Seriola dumerili*	V9	4/2/2023	4/13/2023	12 (12)	2575
Greater Amberjack #04	*Seriola dumerili*	V9	4/2/2023	4/22/2023	21 (21)	5410
Greater Amberjack #05	*Seriola dumerili*	V9	4/2/2023	6/24/2023	84 (84)	23967
Greater Amberjack #06	*Seriola dumerili*	V9	4/2/2023	5/4/2023	33 (33)	8378
Red Porgy #01	*Pagrus pagrus*	V9	4/2/2023	5/30/2024	425 (137)	29122

Fish ID	Species	Transmitter Type	Date Tagged	Last Day Detected	Detection Span (Days Detected)	Number of Detections
Red Porgy #02	*Pagrus pagrus*	V9	4/2/2023	N/A	N/A	N/A
Red Porgy #03	*Pagrus pagrus*	V9AP	4/2/2023	4/2/2023	1 (1)	2
Red Porgy #04	*Pagrus pagrus*	V9AP	4/2/2023	6/24/2023	84 (84)	11127
Red Porgy #05	*Pagrus pagrus*	V9AP	4/2/2023	12/24/2023	266 (94)	17101
Red Porgy #06	*Pagrus pagrus*	V9AP	4/2/2023	6/21/2023	80 (59)	3780
Red Porgy #07	*Pagrus pagrus*	V9AP	4/2/2023	12/14/2023	256 (70)	991
Red Snapper #06	*Lutjanus campechanus*	V9	4/2/2023	5/1/2024	396 (100)	3756
Red Snapper #07	*Lutjanus campechanus*	V9	4/2/2023	6/24/2023	84 (79)	14173
Red Snapper #08	*Lutjanus campechanus*	V9	4/2/2023	4/4/2023	3 (3)	475
Red Snapper #09	*Lutjanus campechanus*	V9	4/2/2023	6/18/2023	78 (34)	3557
Red Snapper #10	*Lutjanus campechanus*	V9	4/2/2023	6/7/2023	67 (35)	3646
Red Snapper #11	*Lutjanus campechanus*	V9AP	4/2/2023	3/24/2024	358 (341)	23035

*Detection span represents the number of days between the date tagged and the last day detected. Days detected indicates the total number of days the fish was detected. Number of detections is the combined total from the three recovered receivers.

3.3 Data Analysis

Potential changes in fish behavior associated with seismic airgun exposure were assessed across three 5-day observation periods: pre–, during–, and post-close pass. These periods were defined based on the highest recorded sound levels on April 13, 2023, and the shortest reported survey distance from the platform—113 m (370 ft) to the east and 187 m (613 ft) to the west—on April 14, 2023. The date April 13, 2023, was used to define the "during-close pass" period (April 13–17). Five-day windows on either side of this period were designated as the pre– and post-close pass periods.

Most tagged fish (21 out of 30) were tagged on April 2, 2023, shortly before the close pass by the seismic airguns. To minimize the influence of handling and tagging stress on fish behavior, the initial six-day post-tagging period was excluded from the analysis. The subsequent five-day period (April 8–12) was designated as the pre-close pass period. The during-close pass period was defined as April 13–17, for reasons described above. The five-day period that followed (April 18–22) was designated as the post-close pass period to ensure temporal consistency and analytical balance across the three observation periods. To assess potential behavioral responses, a repeated measures analysis of variance (RM ANOVA) was performed to compare the mean number of daily fish detections across the pre-, during-, and post-close pass periods.

Broadband sound pressure level data and power spectral density across the low-frequency band (50–1000 Hz) were calculated for the same three five-day observation periods. Spectra were averaged over 1-minute intervals with 1 Hz frequency resolution using the PAMGuide package for MATLAB. Summary statistics (median, 1st, 10th, 90th and 99th percentiles) of these one-minute spectra were calculated for each five-day observation period. Maximum received levels were also calculated for the closest approach. Differences among broadband sound level distributions across the three five-day periods were tested using the Kruskal-Wallis non-parametric test.

4 Results

A total of 464,419 detections from 28 of the 30 tagged fish were recorded by the recovered receivers (**Table 2**). Most tagged fish (70%) were monitored for durations ranging from approximately 30 to 515 days. Four fish were detected fewer than three days, and two were never detected (**Figure 3**). Twenty-three fish were detected before and during the close pass of the survey vessel, with each individual having more than 1,000 detections. Eleven tagged fish (6 almaco, 3 red snappers, 1 red porgy, 1 greater amberjack) had more than 20,000 detections each.

The Sound Trap ST600, deployed in the NW receiver location, did not record any data. However, the Sound Trap ST300, deployed in the NE corner of the study area, recorded continuously from April 3 to July 8, 2023, including the close pass of the survey vessel (**Figure 4**). The highest received levels recorded on the ST300 occurred at 20:11:32 on April 13, 2023, with SPLs exceeding 175 dBrms re 1μPa, surpassing the recorder’s dynamic range and resulting in periods when data were clipped and the actual maximum SPL could not be measured. Ship noise was detectable across all three time periods, particularly at frequencies below 200 Hz. Air gun pulses were detected more sporadically during the pre-close pass but became more pronounced during and after the close pass.

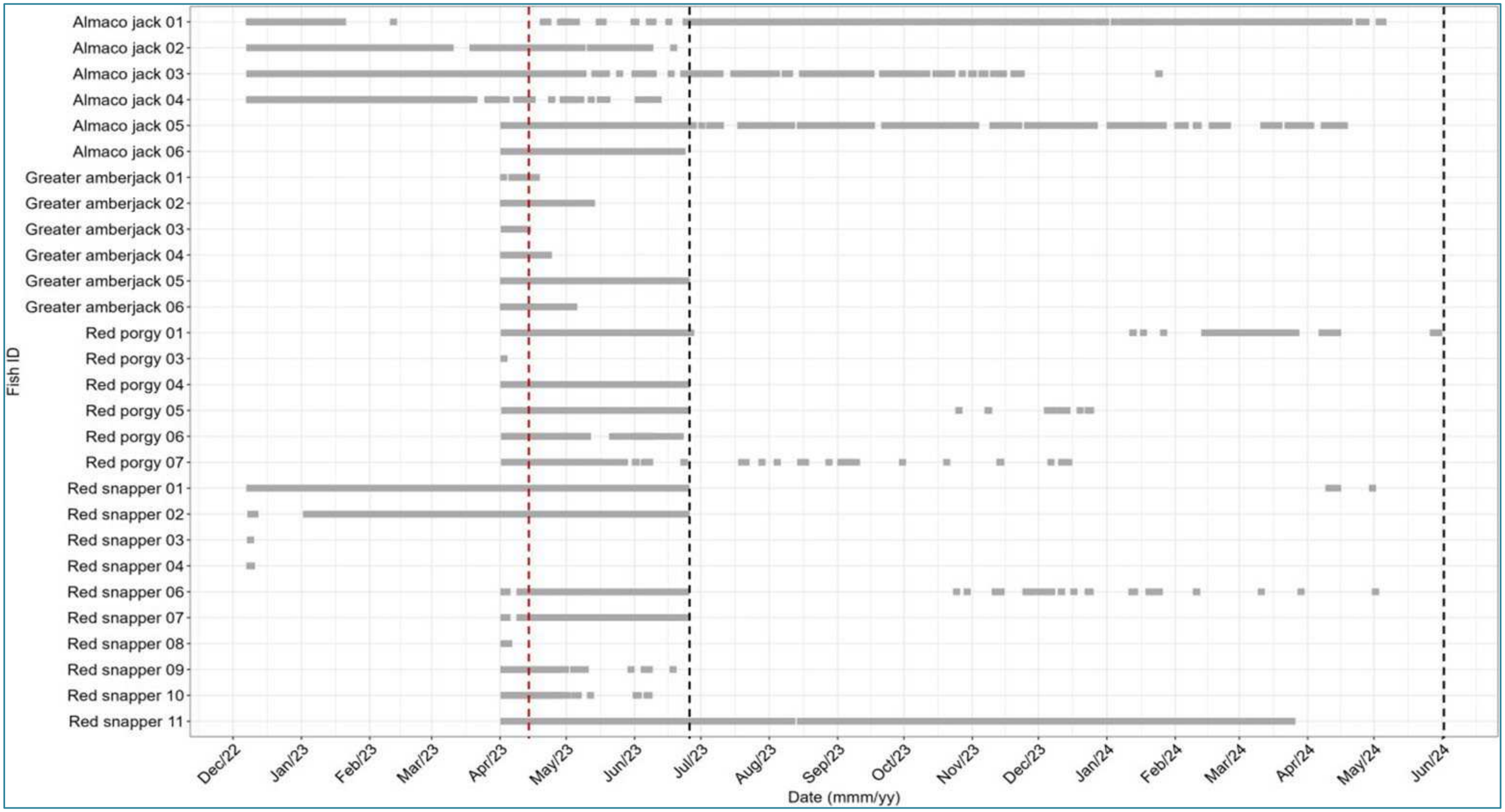

Figure 3. Abacus plot showing the daily presence of tagged fish within the array.

The red dashed line indicates the date of the close pass (April 13, 2023), and the dashed black lines represent the receiver recovery dates (N and NW receivers on June 24, 2023, and NE receiver on May 30, 2024).

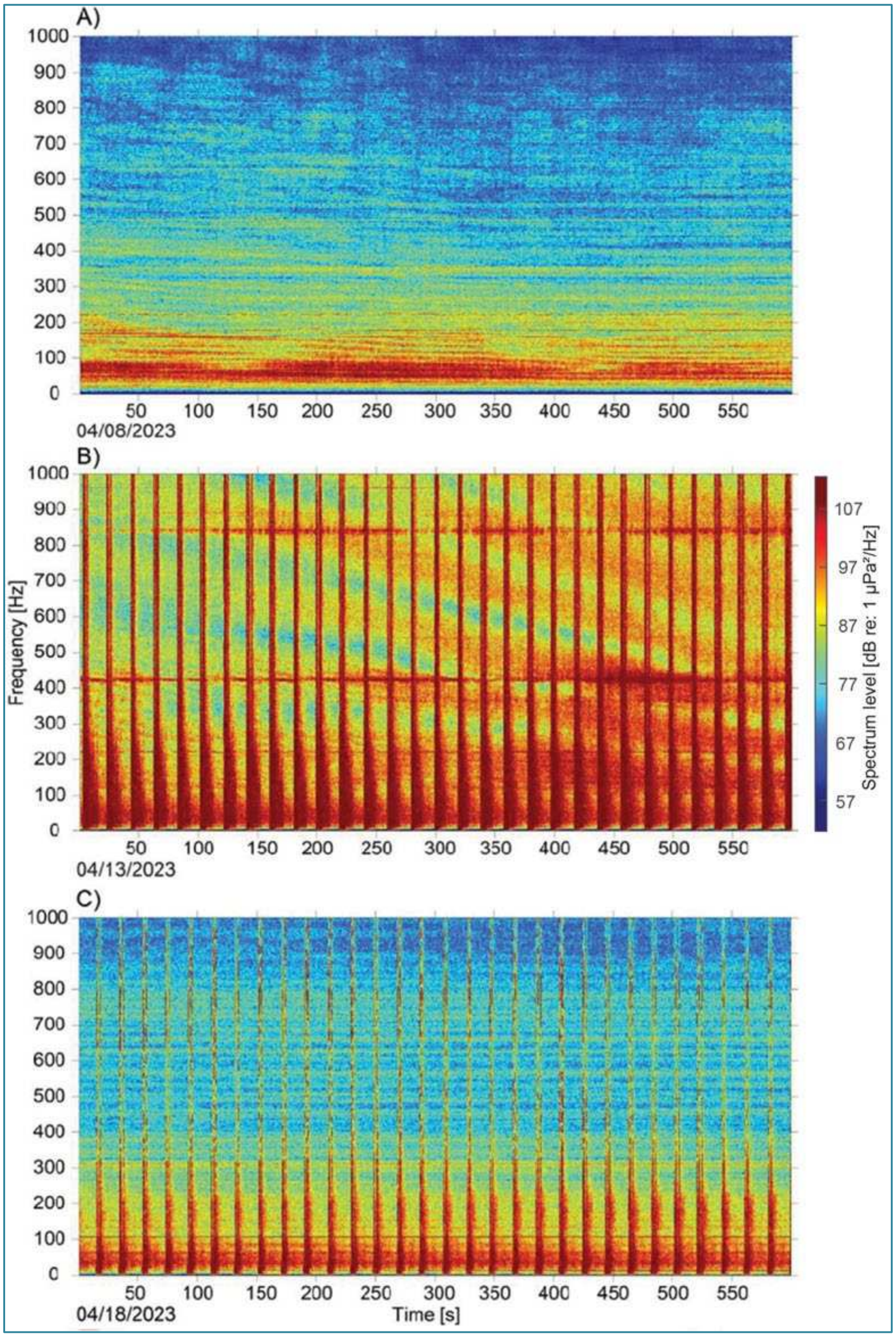

Figure 4. Spectrograms showing 10-minute segments of underwater acoustic recordings.

Recordings are from the A) pre-close pass (April 8, 2023), B) during-close pass (April 13, 2023), and C) post-close pass (April 18, 2023) periods. Ship noise, visible as continuous horizontal bands below 200 Hz, is present during all recordings and is most distinct in panel A. Broadband air-gun pulses, shown as vertical lines spanning 0–1000 Hz, dominate the during-close pass period (panel B) and continue into the post-close pass period (panel C), though at lower intensity. Some sporadic pulses are also visible early in the study period.

Significant differences in acoustic detections were observed among pre-, during-, and post-close pass periods for red snapper (N=5; RM ANOVA, $F = 9.9$, $p < 0.01$; **Figure 5A**). Red snapper showed a significant reduction in the number of detections for the 5-day "during" period of the close pass (Tukey's post-hoc, $p < 0.01$), with all individuals detected pre-, during-, and post-surveys (n=5) showing clear declines in detections on the exact day (April 13, 2023) of the close pass by the survey ship. These reductions in detections may indicate behavioral responses to seismic airgun exposure, such as fish temporarily moving away from the platform beyond the detection range of the receivers, or seeking shelter within the platform's interior, where structural interference may block transmitter emissions. A significant increase in the number of detections of red snapper was observed during the post-close pass period (Tukey's post-hoc, $p < 0.05$), suggesting that fish returned to the platform and may have resumed spatial behaviors consistent with pre-disturbance conditions within a few days after the close pass. Two red snappers (2 and #11) were removed from the analysis, as these fish were considered dead during the airgun survey period, based on the acceleration and depth results (see **Appendix A**).

Red porgy did not exhibit statistically significant differences in detection rates across the pre-, during-, and post-close pass periods (N = 4; RM ANOVA, $F = 2.1$, $p = 0.09$). Although all four individuals showed a decline in detections at the onset of the close pass (**Figure 5B**), their responses varied thereafter, with some individuals exhibiting increased detections later in the close-pass or post-close pass periods; overall, these fluctuations were not statistically significant. Red porgy #7 was excluded from the analysis due to the low detection rate (fewer than 10 detections/day).

Two of the six greater amberjack ceased being detected during the close-pass period, which could indicate possible mortality or permanent displacement from the platform. In contrast, the remaining four tagged greater amberjack remained within the vicinity of the platform and did not exhibit significant differences in detection rates across the pre-, during- and post-close pass period (N=4; RM ANOVA, $F = 1.12$, $p = 0.35$). As shown in **Figure 5C**, detections for these individuals were variable throughout the pre- and close-pass periods, with several individuals showing increases during the post-close pass period; however, these differences were not statistically significant, indicating no measurable effect of the close pass on their detection rates. Thus, while the seismic survey remains a possible factor, the detection interruptions in these two individuals cannot be clearly linked to the close pass based on the available data.

Almaco jacks #1, # 2, #3, and #4 were detected throughout the seismic airgun survey period but exhibited low detection rates, averaging fewer than four detections per day, and were therefore excluded from analysis. In contrast, the other two monitored almaco jacks (#5 and #6) with high detection rates (over 150 detections per day) appeared to show increased detections from the pre- to post-close pass periods (**Figure 5D**). However, due to low sample size, no formal statistical analysis was conducted for these almaco jacks; therefore, this observation should be interpreted descriptively rather than as evidence of a significant effect.

While it is possible that intense underwater sound can interfere with acoustic telemetry detection efficiency (Long et al., 2023), the detection patterns observed here are likely more consistent with behavioral responses rather than technical limitations. Red porgy and greater amberjack did not show significant reductions in detections during or after the close-pass period, which may be expected if seismic noise had disrupted receiver performance. Red snapper showed a statistically significant increase in detections post-close pass, while red porgy and greater amberjack exhibited non-significant increases, suggesting individual variability in behavior rather than systemic detection failure. For almaco jack, two individuals were consistently detected during the close pass, and both showed a steady increase in detections throughout the study period, peaking in the post-close pass period. Taken together, these results suggest that receivers retained sufficient functionality to detect tagged fish during seismic activity, though further analysis would be needed to fully separate behavioral effects from potential technical interference.

The study area experienced elevated sound levels over the entire duration of the study. Mean (and median) SPLs over the 50–1000 Hz band were 117 (115) and 119 (115) dBrms re 1μPa during the pre and post-close pass, respectively. The clipping of airgun pulses over the "during" portion of the survey, which can be seen in the fact that the whisker of the box plot of during data extends to the clipping value of 175, while outliers for the two other periods mostly do not reach 175 (**Figure 6**), precludes us from measuring the true mean SPL. However, the clipped, hence low-biased mean (and median) SPL during this period was 120 (116) dBrms re 1μPa. By comparison, median SPLs in June, after the survey was completed, were 107 dB re 1μPa, with a maximum of 114 dB re 1μPa over the same frequency range. The June period provides a better baseline of ambient noise in the area than the "pre" period, as it is clear that even before the survey reached its closest point of approach, sound levels were much higher at this site than they are during non-survey periods.

Despite the skew to lower levels in the during-close pass period, a significant difference was observed in the distributions of SPLs recorded across the three five-day periods (Kruskal-Wallis test, $\chi 2 = 204.07$, $p<0.001$; **Figure 6**), with lower levels recorded during the pre-close pass period compared to the other two. SPLs during the during– and post-close pass periods were not significantly different from each other (Kruskal-Wallis test, $\chi 2 = 438.53$, $p=0.075$), which may be attributed to the continued presence of high-intensity air gun activity in the vicinity of the study area throughout the post-close pass period. Additionally, clipping of the signal during very close passes caused the sound levels to appear lower than they actually were during parts of the study period. Had we been able to measure the full range of the high-intensity signal, it is possible we would have detected a difference between these two time periods.

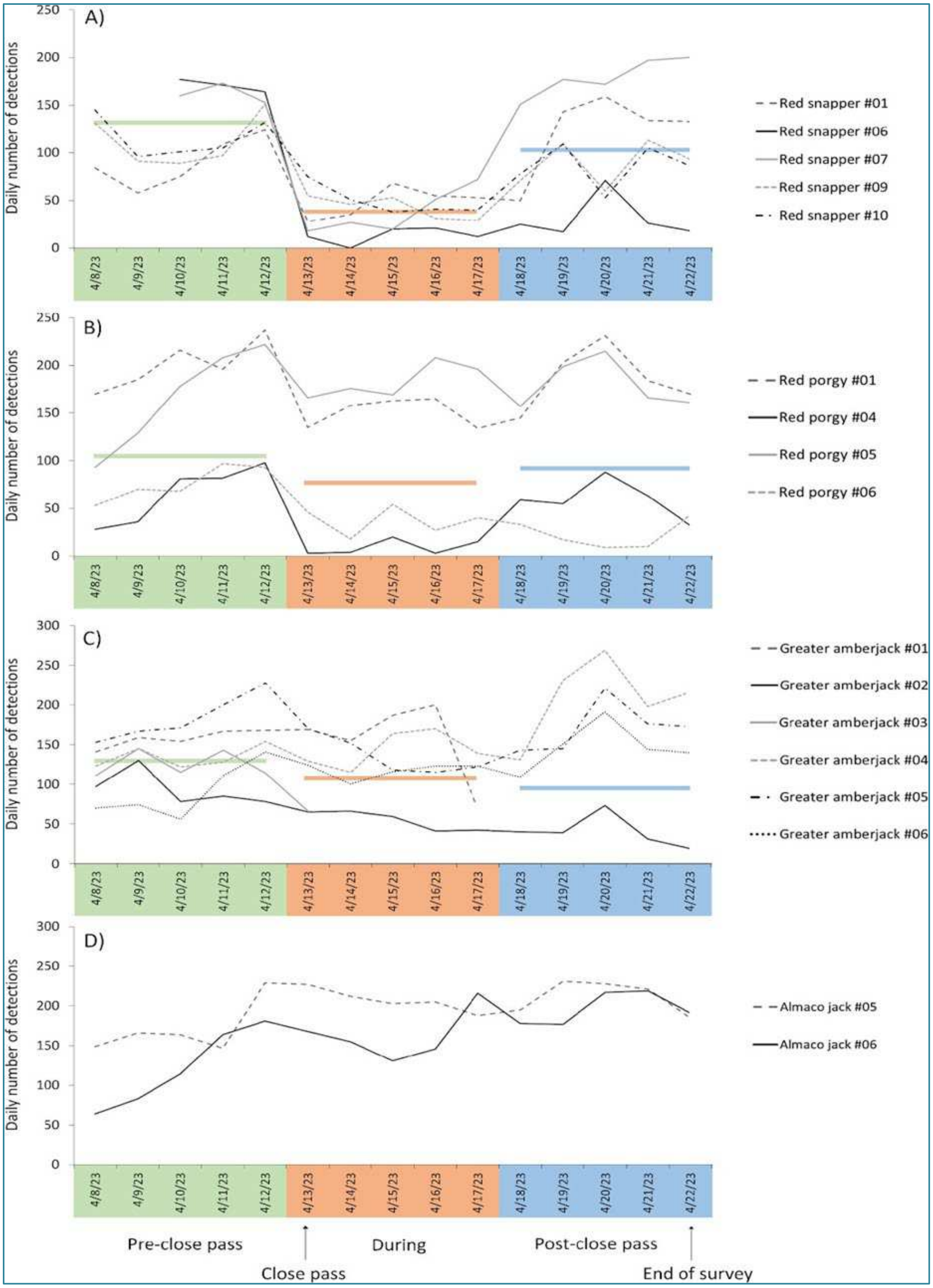

Figure 5. Daily number of acoustic detections.

Detections for A) red snapper, B) red porgy, C) greater amberjack, and D) almaco jack across three five-day periods: pre-close pass (green background), during-close pass (orange), and post-close pass (blue). Each line represents an individually tagged fish of that species. Horizontal colored bars in panels A–C indicate the mean number of detections for each period. Mean bars are omitted in panel D because no formal statistical analysis was conducted for almaco jack. The x-axis spans late March through early May 2023, with the close-pass date marking the transition between the pre- and during-close-pass periods.

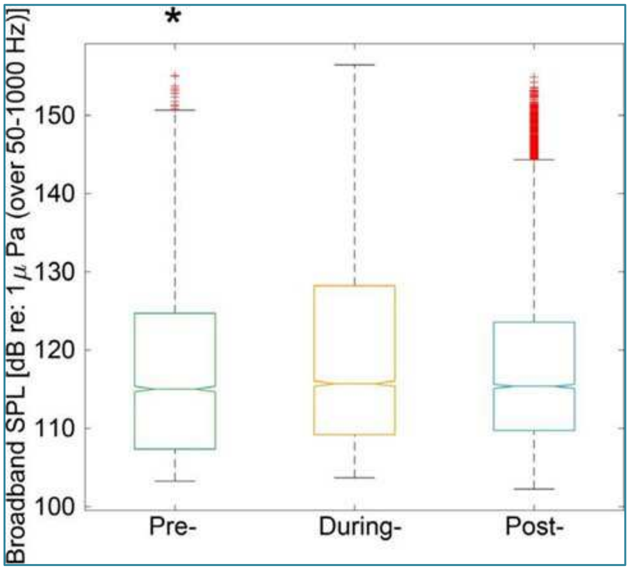

Figure 6. Boxplot of broadband sound pressure levels (SPL; dB re 1 μPa, 50–1000 Hz) recorded during the pre-close pass (green), during-close pass (orange), and post-close pass (blue) periods.
For each distribution, the central horizontal line shows the median, the box bounds represent the 25th and 75th percentiles, and the whiskers extend to the most extreme non-outlier values. Outliers are shown as small red plus symbols. The asterisk above the pre-close pass category indicates that this condition differed significantly from the others. SPL values during the close-pass period were clipped, so true received levels during this interval could not be fully resolved.

Elevated spectral levels (>90 dB re 1 μPa2/Hz at frequencies below 100 Hz) were recorded at the study site over the entire duration of the experiment, including pre–, during–, and post-close pass periods (**Figure 7**). The persistence of airguns is evident in the long tail at high sound intensity level distributions over the during-close pass period, with 10th and 1st percentile exceedance levels exceeding 110 and 120 dB re 1 μPa2/Hz at frequencies below 100 Hz, respectively. This pattern persisted into the post-close pass period, where 1st percentile exceedance levels also remained largely above 120 dB, indicating that sound levels associated with the survey vessel remained elevated at times after the close pass.

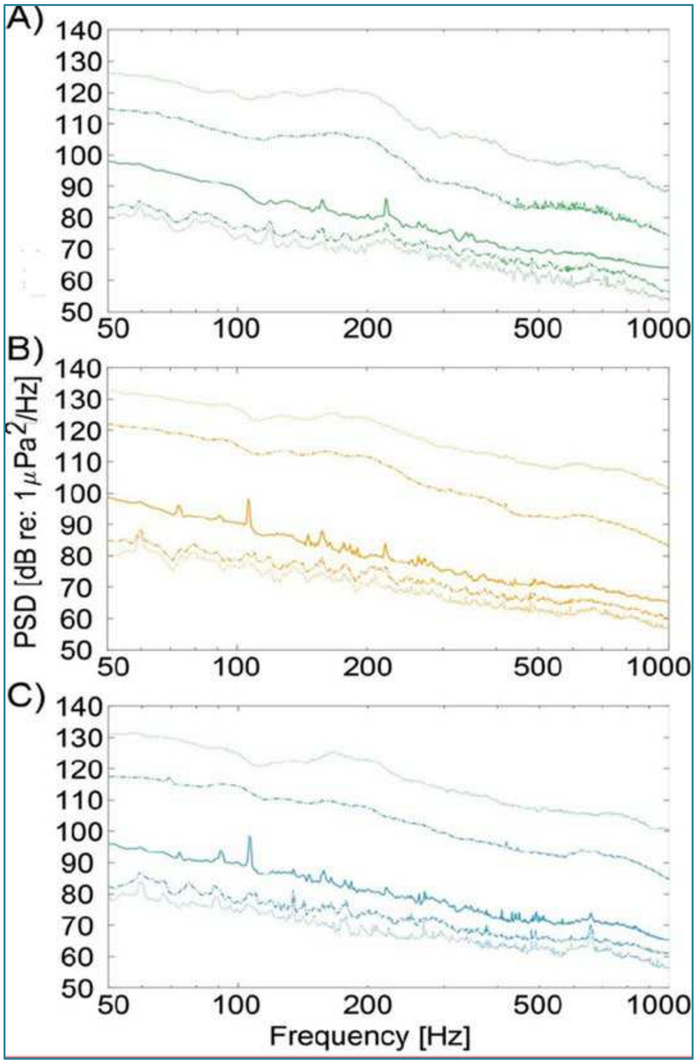

Figure 7. Power spectral density (PSD; dB re 1 μPa²/Hz) of underwater sound recorded over the 50–1000 Hz frequency band.

During the A) pre-close pass, B) during-close pass, and C) post-close pass periods. Each panel shows the median spectral level (solid line), the 10th and 90th percentiles (dash-dotted lines), and the 1st and 99th percentile exceedances (dotted lines).

Results from one red snapper tagged with an accelerometer and pressure sensor (i.e., A9AP tag) are presented in **Appendix A**, as the data collection period (January 3–April 1, 2023) did not overlap with the primary study period (April 8–22, 2023). Although outside the main analysis window, these data offer valuable insights into depth use and activity patterns. Other fish tagged with similar sensors did not provide usable data due to short detection durations, presumed mortality, or sensor failure.

5 Conclusions

This study provides the first in situ assessment of potential behavioral responses to seismic airgun sound in adult, free-swimming fishes in the northern Gulf. Using a combination of acoustic telemetry and passive acoustic monitoring, we evaluated species-specific changes in detection frequency of acoustically tagged individuals near an offshore oil and gas production platform during a close pass of a commercial-scale seismic survey. Detection patterns, aggregated across receivers and compared across pre-, during, and post-survey periods, served as a proxy for inferred behavioral effects.

Median SPLs recorded during the study ranged from 115 to 116 dB re 1 μPa over the 50–1000 Hz band, exceeding both the June post-survey median (107 dB re 1 μPa) and typical ambient levels reported for offshore environments, which generally range from 90 to 110 dB re 1 μPa over the 10–1000 Hz band (Wenz, 1962; Urick, 1984; Veeriayan & Rajendran, 2020). These elevated levels are consistent with regional soundscape data from the Gulf, where seismic airguns have been shown to dominate low-frequency acoustic energy at deep-water sites (1000–1500 m; 3280–4920 ft), with average spectrum levels exceeding 90 dB re 1 $\mu Pa^2/Hz$ below 40 Hz (Wiggins et al., 2016). Notably, peak SPLs recorded during the close pass of the seismic survey vessel exceeded 175 dBrms re 1 μPa, surpassing the dynamic range of the recorder and indicating transient exposure to extremely high-intensity impulses. In addition, some of the highest recorded levels during the during-close pass and post-close pass periods remained above 120 dB re 1 $\mu Pa^2/Hz$ at frequencies below 100 Hz, reflecting sustained acoustic elevation beyond median conditions.

Among the four species examined, only red snapper exhibited statistically significant changes in detection frequency across the pre-, during-, and post-close pass periods. All red snapper present in the array showed marked declines in detections on the day of the seismic vessel's closest approach, followed by a significant increase in detections during the post-close pass period. This pattern may indicate a short-term behavioral response to the seismic activity, such as temporary avoidance or sheltering within the platform structure, followed by a return to the site and resumption of detectable, pre-disturbance movement behaviors. Red porgy did not show significant differences between survey periods; although, three of the four individuals displayed reduced detections during the close pass and increased detections afterward.

Two greater amberjack individuals ceased detections during the close pass period and appeared to have left the area, while the remaining four showed no significant changes across periods. It is unclear why only these two individuals became undetectable while the others remained, making it difficult to determine whether their absence was due to mortality, permanent displacement, or unrelated factors. The two monitored almaco jacks with high detection rates appeared to show generally increasing detections from the pre- to post-close pass periods, which may suggest minimal to no apparent disturbance, although no formal statistical analysis was conducted for this species.

The increase in detections observed during the post-close pass period for red snapper, and the non-significant changes in red porgy and greater amberjack, may reflect a degree of behavioral tolerance or acclimation to the elevated acoustic environment. Similar patterns of behavioral adjustment to repeated or chronic sound exposure have been documented in other taxa exposed to low-frequency noise, such as vessel traffic (Nedelec, 2015; Bruintjes et al., 2016; Staaterman et al., 2020; Rojas et al., 2021). Taken together, these findings suggest that while some individuals may exhibit short-term avoidance or displacement, others may remain in or return to the area, potentially indicating that both species and individual differences play a role in sensitivity to seismic disturbance. However, the small sample sizes for each species limit the strength of these conclusions, and results should be interpreted with caution.

This study did not directly assess physiological impacts, but the proximity of the seismic source to the study site (113–187 m; 370–613 ft) and the intensity of recorded sound levels fall within ranges previously associated with TTS and inner ear damage in fishes; although, such effects are typically non-lethal (Turnpenny & Nedwell, 1994). Popper et al. (2005) observed up to 20 dB of TTS at 13–17 m (43–56 ft) from a 730 in^3 airgun, with peak levels near 207 dB re 1 μPa. As noted above, in our study peak SPLs exceeded 175 dB RMS during the closest point of approach, which is lower than Popper et al. (2005) recorded but presumably loud enough for fish to hear. McCauley et al. (2003) reported inner ear damage at 5–800 m (16–2,625 ft) from a 20 in^3 array, with received levels of 160–180 dB re 1 μPa. In contrast, Hastings et al. (2008) found no hearing loss in reef fishes exposed to a 2,055 in^3 array at up to 2,743 m (8,999 ft), despite SELs reaching 190 dB re 1 $\mu Pa^2 \cdot s$. While mortality is unlikely, secondary effects of TTS may still influence individual fitness and behavior. For example, a fish experiencing reduced auditory function for several days may be more vulnerable to predation, less likely to find a mate, or unable to locate food while its hearing recovers. The severity of these impacts likely depends on species-specific sensitivity, life stage, exposure distance, and site-specific acoustic conditions.

In summary, this study demonstrates that seismic airgun activity may elicit short-term behavioral responses in Gulf fishes, depending on the taxa, as observed in this study for the demersal, reef-associated fish species red snapper. These responses occurred under sound levels that exceeded typical ambient conditions. Although detection counts are sufficient to support statistical analyses for certain individuals, the low number of tagged fish may constrain inference and limit confidence in broader conclusions about species-specific responses to seismic airgun exposure. Future research should aim to increase sample sizes, incorporate particle motion measurements (given that most fish detect sound primarily through particle motion rather than acoustic pressure), evaluate physiological impacts and the potential for recovery, and establish controlled comparisons. Studies should also minimize the risk of acoustic clipping by ensuring that recording systems have sufficient dynamic range for expected sound levels. These efforts will improve confidence in species-specific response assessments and support the development of effective management strategies for acoustically sensitive fish populations in the Gulf.

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Appendix A: Accelerometer and Pressure Sensor Data

Apart from shifts in the number of detections from pre- to post-close pass periods, one red snapper tagged with a V9AP accelerometer and pressure tag provided high-quality acceleration and depth data. Red snapper #02 transmitted sensor data from January 3 to April 1, 2023 (88 days). The fish was assumed dead after that period (6 days before the pre-close pass period) based on continuous depth readings matching the site's maximum depth (~150 m; ~492 ft) and the absence of acceleration (**Figure 8**). While alive, this individual spent over 70% of its time at depths between 90 and 105 m (~295 to 344 ft; range: 68 to 149 m or ~ 223 to 489 ft).

Red snapper #02 generally occupied shallower depths during daylight hours and moved to greater depths at night (**Figure 9**). Over the course of several months, its daily depth use varied, alternating between periods of consistent depth and periods with pronounced diel shifts (**Figure 10**). Average acceleration was low (1.03 ± 0.4 m/s2) consistent with expectations for the species, with slightly higher values during daylight hours (**Figure 8**). Although the acceleration and depth data did not overlap with the primary study period (April 8–22), they are reported here due to their potential relevance to the scientific and fisheries management communities. To our knowledge, few studies have deployed accelerometer and pressure tags on reef-associated fish at comparable depths in the Gulf, making these data unique contributions to the scientific literature.

The remaining fish tagged with V9AP tags did not provide useful data. Red snapper #03, #04, and #05 were detected for less than two days, and red snapper #11 was assumed dead shortly after release based on acceleration and depth data (**Figure 8**). V9AP tags were also deployed on red porgy; however, individual #3 was never detected, and tags on individuals #04 through #07 showed sensor failures (Figure 11). These failures might have been caused by the fish exceeding the sensor's maximum depth threshold of 136 m (446 ft).

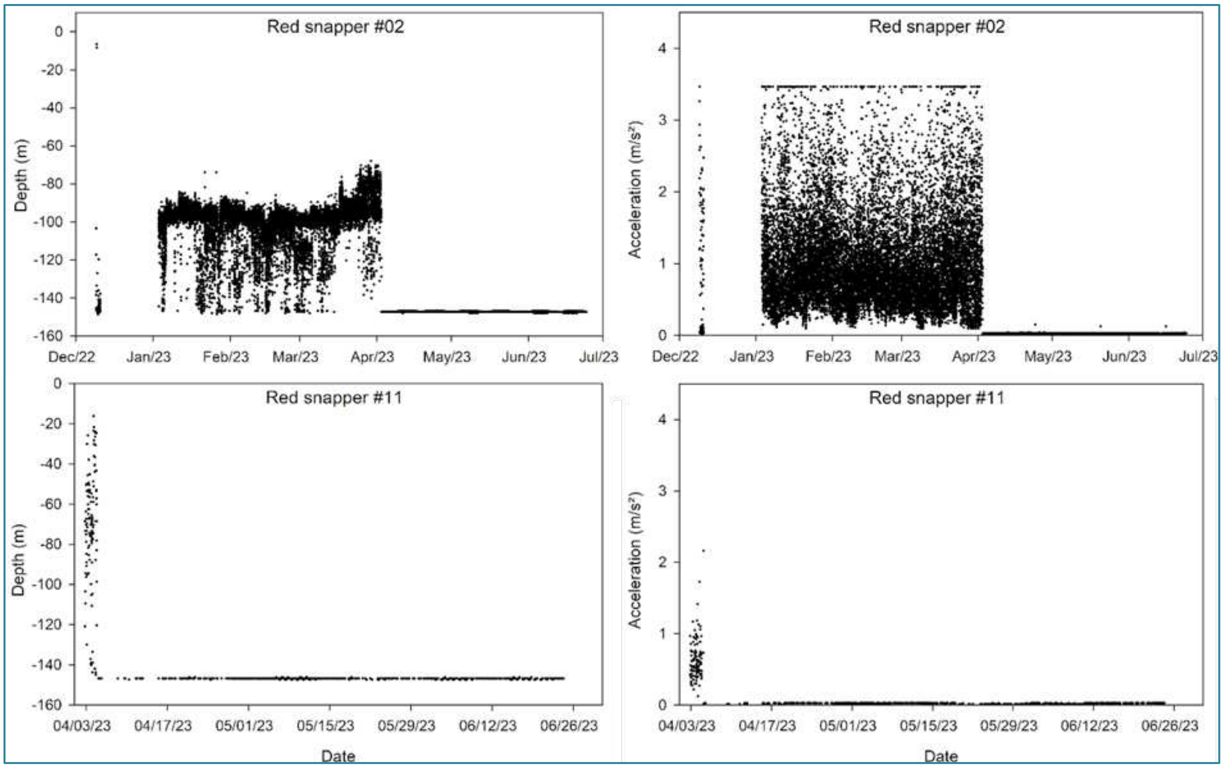

Figure 8. Depth (m) and acceleration (m/s²) time series for two red snapper tagged with V9AP accelerometer-pressure transmitters.

The top row shows depth and acceleration for red snapper #02 from December 2022 through July 2023. The bottom row shows depth and acceleration for red snapper #11 from April through June 2023.

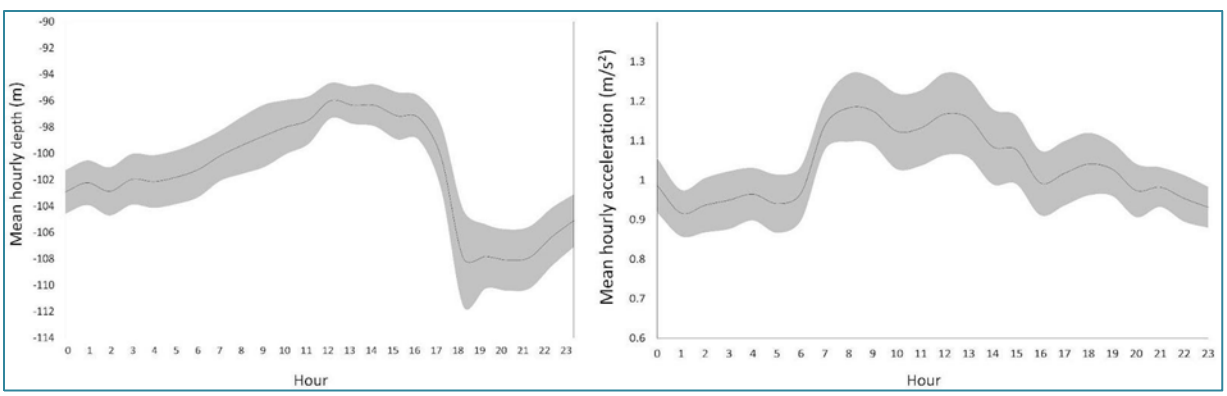

Figure 9. Mean hourly depth (m) and mean hourly acceleration (m/s²) for red snapper #02 from January 3 to April 1, 2023.

Each line represents the average value for a given hour of the day (0–23), and the gray shaded regions denote the 95% confidence intervals around the hourly means.

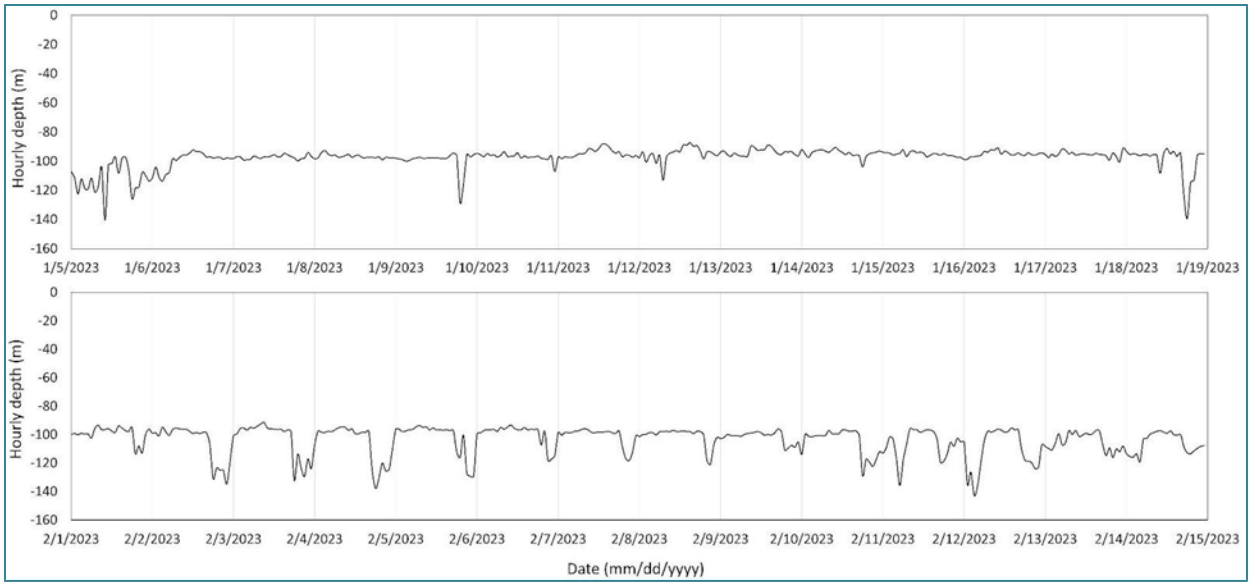

Figure 10. Hourly depth (m) time series for red snapper #02 recorded by a V9AP accelerometer-pressure tag over two separate two-week periods.

The upper plot shows data from January 5–19, 2023, during which no clear diel pattern was observed. The lower plot shows data from February 1–15, 2023, during which the fish exhibited a clear diel pattern characterized by repeated daily depth excursions.

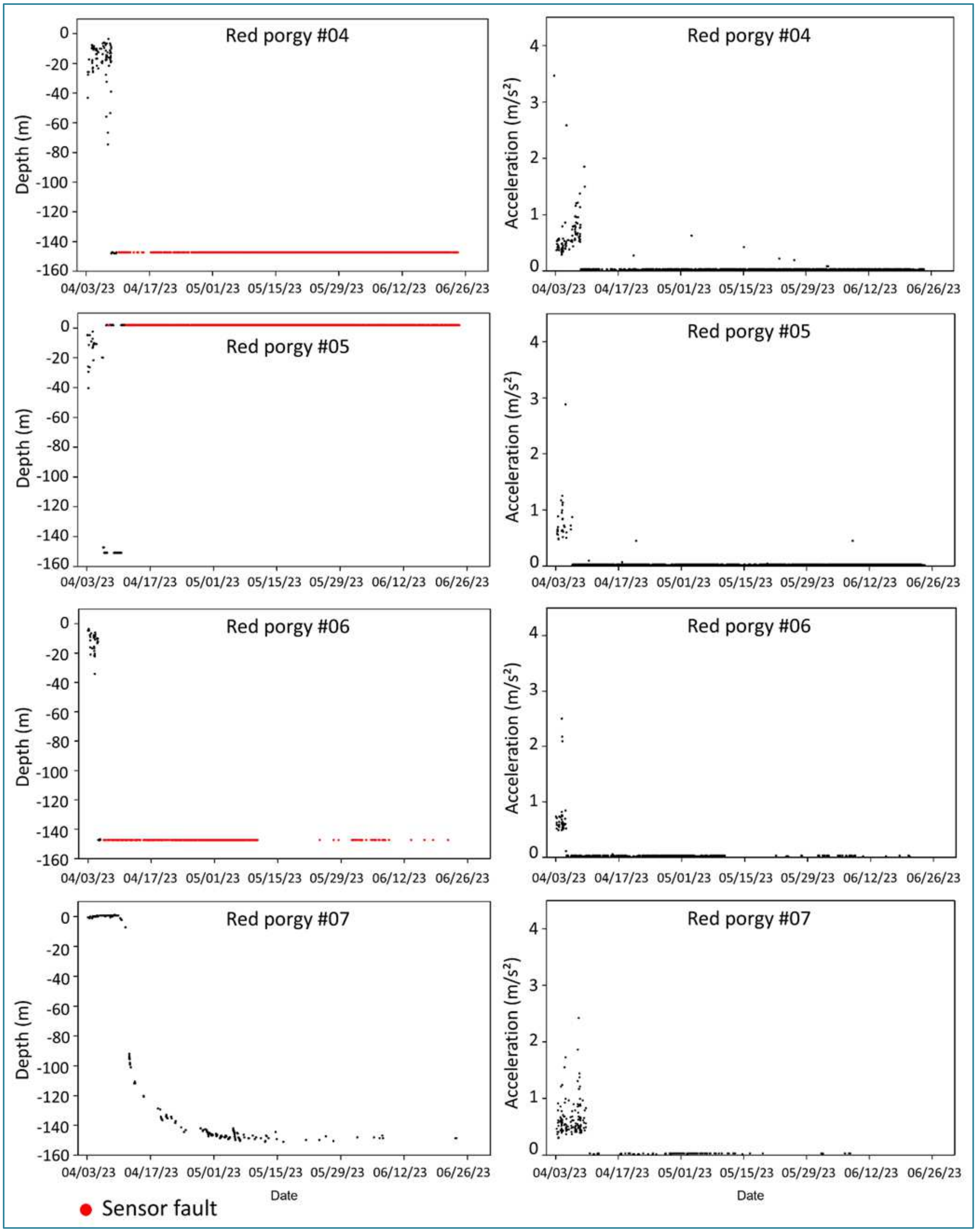

Figure 11. Depth (m) and acceleration (m/s²) time series for four red porgy individuals (#04, #05, #06, and #07) tagged with V9AP accelerometer-pressure transmitters.

Each row displays depth (left) and acceleration (right) for a single fish from April to June 2023. Red dots indicate values identified by the receivers as sensor-fault readings.

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