Title: Seismic survey noise disrupted fish use of a temperate reef

Authors: Avery B. Paxton,[1,2]* J. Christopher Taylor,[3] Douglas P. Nowacek,[4,5] Julian Dale,[4] Elijah Cole[5], Christine M. Voss,[1] Charles H. Peterson[1,2]

Affiliations:

[1]Institute of Marine Sciences, University of North Carolina at Chapel Hill, Morehead City, NC, United States of America.

[2]Department of Biology, University of North Carolina at Chapel Hill, Chapel Hill, NC, United States of America.

[3]National Ocean Service, National Centers for Coastal Ocean Science, National Oceanic and Atmospheric Administration, Beaufort NC, United States of America.

[4]Nicholas School of the Environment, Duke University Marine Laboratory, Beaufort, NC, United States of America.

[5]Pratt School of Engineering, Duke University, Durham, NC, United States of America.

***Corresponding Author:** abpaxton@live.unc.edu

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Abstract

Marine seismic surveying discerns subsurface seafloor geology, indicative of, for example, petroleum deposits, by emitting high-intensity, low-frequency impulsive sounds. Impacts on fish are uncertain. Opportunistic monitoring of acoustic signatures from a seismic survey on the inner continental shelf of North Carolina, USA, revealed noise exceeding 170 dB re 1μ Pa peak on two temperate reefs federally designated as Essential Fish Habitat 0.7 and 6.5 km from the survey ship path. Videos recorded fish abundance and behavior on a nearby third reef 7.9 km from the seismic track. During seismic surveying, reef-fish abundance declined by 78% during evening hours when fish habitat use was highest on the previous three days without seismic noise. Despite absence of videos documenting fish returns after seismic surveying, the significant reduction in fish occupation of the reef represents disruption to daily pattern. This numerical response confirms that conservation concerns associated with seismic surveying are realistic.

Keywords: reef fish, airgun, oil and gas exploration, fish abundance, marine conservation

1. Introduction

Marine seismic surveys emit high-intensity (up to 260 dB re 1μ Pa rms @ 1m), low-frequency (5-300 Hz peak spectral levels) sounds from airgun arrays downward into the water column [1]. The resultant sound waves penetrate the seafloor to provide imagery of the underlying geology. These surveys can detect reservoirs of oil and natural gas, determine site-specific suitability for installation of offshore renewable energy infrastructure, evaluate sources of minerals for commercial extraction or sand for use in beach nourishment, and/or provide information on the continental substructure for geological research. Noise from seismic surveying can alter marine mammal vocalizations and foraging rates, and can lead to marine mammal displacement [2–4]; however, there remain unanswered questions regarding how wild fish respond to seismic survey noise. Understanding whether fish are affected through alterations in behaviors associated with feeding, growth and survival has conservation and management implications.

Acute impacts to individual fish from seismic noise, including damage to sensory ear hair cells, can occur with close-range exposure to low-frequency, high-intensity sounds in laboratory settings [5,6]. Impulsive sounds similar to those from seismic surveys, such as noise made by pile driving, can cause mild to lethal injuries ranging from swim bladder rupture to hematoma and hemorrhaging [7–9]. Behavioral responses of fish to impulsive noise are more difficult to quantify but may include changes in abundance in particular habitats [10], changes in swimming patterns or feeding [11,12], as well as physiological stress even leading to mortality [7]. In contrast, in two studies that were specific to noise associated with seismic surveying, there were no marked changes in fish physiology or behavior [6,13]. Reductions in fish catches can persist for up to five days after seismic activity [10,14,15]. Aside from those mentioned previously, most studies testing fish response to seismic noise occurred in laboratory settings; underwater observations of fish in their natural environment during seismic surveys are rare [7]. Wardle et al. (2001) experimentally exposed fish *in situ* to noise from three synchronized airguns and observed startle responses in some fish but did not detect other changes in behavior or abundance. Although fish in their natural environment may be expected to respond to seismic surveys based on laboratory experiments and reduction in fisheries catch [17], no previous study has documented such an *in situ* behavioral response.

Opportunistic monitoring of a seismic survey offshore of North Carolina (NC) during September 2014 determined whether reef-associated fishes in their natural environment respond to marine seismic surveying. The academic objective of the seismic survey was to study the formation and evolution of the Eastern North American Margin [18], which involved use of an airgun array of similar volume to those used during oil and gas exploration. The majority of the survey occurred in deep (> 1000 m) waters off the continental shelf, although it continued across the shelf and into shallow (< 35 m) inner continental shelf waters of northeastern Onslow Bay, NC (Fig. 1).

[Fig. 1 here]

This area supports hardbottom reefs that sustain an abundance of fish representing a diverse community, including tropical, subtropical, and warm-temperate species [19–21]. Fish use the temperate reefs for spawning and foraging, as well as for nurseries and refugia, qualifying them as Essential Fish Habitat under the Magnuson-Stevens Fishery Conservation and Management Act (2007).

2. Materials and Methods

As an empirical test of whether noise from seismic surveying can elicit a response from reef-associated fishes, such as a change in abundance, passive underwater monitoring stations were opportunistically established on three temperate reefs during September 2014 (Fig. 1). The reefs, ranging from 25 to 33 m deep, were located 0.7, 6.5, and 7.9 km from the path of the vessel continuously conducting the seismic survey. The reefs were selected based on their proximity to the seismic survey track and because they have been the focus of various marine fisheries and ecological studies for several decades and have been documented to have notable abundances of fish in the federally-managed snapper-grouper complex and other commercially and recreationally important fishery species [20,21].

The two reefs located closest to the survey track, a natural rocky reef and an artificial reef, were equipped with hydrophones (SoundTrap 202 recorders, Ocean Instruments, New Zealand) that documented the acoustic signatures of the surveying noise (Audio S1-S2). Hydrophones sampled continuously at 16-bit, 96 kHz. A video camera recorded fish abundance and behavior on the third reef, a naturally occurring rocky reef, farthest from the survey path (Video S1-S2). The video camera (GoPro, USA) was outfitted with an intervalometer (cam-do, USA) to record 10-sec videos every 20 min. These monitoring instruments were mounted on conical metal frames (0.5 m high, 0.3 m base diameter), anchored with 60-80 kg of lead, and deployed on each reef on September 17, 2014 so that the instruments could record before and during seismic surveying. Video cameras deployed at the two reefs outfitted with hydrophones malfunctioned. Logistical constraints prevented collection of data following seismic surveying.

Acoustic data from the two hydrophones were processed and then five shots were aggregated for each of nine selected time points. Shots were processed in groups of five to obtain a 'local average' to smooth fine scale variation that occurs in the propagation conditions. The time points were chosen relative to the closest point of approach (CPA) on both the landward and seaward components of the survey path. The five shots closest to the CPA that were not clipped were processed, and other locations were chosen to compare the received signals from the reefs, e.g., the more distant sampling locations gave similar propagation paths to the reefs, while the closer locations were subject to very different parts of the non-uniform source beam pattern [22]. On acoustic recordings from the reef located 0.7 km from the path of the seismic surveying vessel, the noise of the seismic shots overloaded the recorders when the ship was at its CPA. Using the known source sound level of the survey vessel's airgun array [22], the anticipated broadband level of received sound at the reef was calculated based on two models, spherical spreading and cylindrical spreading [23]. All acoustic values reported are in dB re 1µ Pa peak-peak.

Each 10-sec video recording from daylight hours was used to identify fish to the lowest taxonomic level possible, count the maximum number of fish in the frame by species, and document their behaviors as feeding, resting, schooling, or swimming. Noises from seismic surveying were audible as discrete airgun shots in video recordings, allowing us to associate any observed behavioral responses with timing of individual shots. To prevent observer bias, fish were first counted with video sound turned off; then sound was turned back on to detect whether shots were present.

Fish data obtained from video recordings were analyzed in R [24]. The time series of hourly untransformed fish abundance was plotted for each of three days before and the following day during seismic surveying to visualize daily abundance patterns. The smoothed conditional mean of the hourly fish abundance for the combined three days before seismic activity and the accompanying standard error, as well as the smoothed conditional mean of hourly fish abundance on the day with seismic activity, was also calculated. The resulting two curves and the standard error were compared to determine whether the temporal pattern of fish abundance differed from before to during seismic surveying.

Two different statistical tests determined if the pattern in daily fish abundance differed before versus during seismic surveying. First, an analysis of means for variance (ANOMV) with a Levene transformation [25,26] tested the equality of variance in fish counts on three days pre-seismic surveying and one day during seismic surveying. ANOMV determined whether daily means for variance in fish counts were significantly different than the grand mean for variance. Second, ANOVA followed by post-hoc pairwise t-test on box-cox transformed fish counts [27] tested for daily differences in fish abundance during the four-hour evening period (1600-2000) of typically greatest fish occupation. The percent change in fish occupation of the reef based on the average evening fish abundance on three days without seismic surveying and the evening fish abundance on the following day with seismic noise was also computed.

3. Results and Discussion

Noise levels on the two reefs designated as Essential Fish Habitat and located closest to the seismic survey track, 0.7 and 6.5 km away, exceeded 170 dB re 1μ Pa (Fig. 2).

[Fig. 2 here]

The peak levels that actually occurred at the sites are unknown because the noise overloaded the recorders. Using a sound source level of 258.6 dB re 1μ Pa [22], the received sound was estimated using two different models, spherical spreading and cylindrical spreading [23]. Based on a spherical spreading model, the corresponding received sound level on the closest reef would have been 202 dB re 1μ Pa, whereas based on the cylindrical spreading model, the received level would have been 230 dB re 1μ Pa. Realized peak sound levels likely fall between those predicted by spherical and cylindrical spreading models [28]. The high intensity of this low-frequency sound is consistent with previous measurements [29,30]. The intensity of the noise is of significant concern because laboratory experiments indicate that fish experience recoverable injuries and/or potentially mortal injuries at noise levels > 207 dB re 1μ Pa peak [9].

Ten-second videos were recorded every 20 min for three days before and through the day with seismic surveying on a 33-m-deep reef located 7.9 km from the closest approach of the seismic survey vessel. Although a hydrophone did not record sound on this reef, based on spherical spreading and a source sound of 258.6 dB re 1μ Pa the estimated noise experienced on this reef was 181 dB re 1μ Pa when the survey vessel was closest. Using a second model based on cylindrical spreading, the received sound level was 220 dB re 1μ Pa on the reef. Realized peak sound levels probably lie between the predictions of these two spreading models [28]. The resulting 140 videos from daylight hours were used to identify and count maximum number of fish in frame by species and document their behaviors. During the four days of monitoring this temperate reef, 32 species belonging to 17 families (Table S1), including many federally managed as part of the snapper-grouper complex, were observed.

On the reef monitored by video camera, fish occupation during three days prior to the seismic survey exhibited a daily pattern of increasing abundance during the evening, as compared to morning and afternoon (Fig. 3).

[Fig. 3 here]

On the following day with airgun noise, this pattern in fish use did not emerge from observations across periods of the day. Fish abundance remained low for the entire day, with the exception of one outlying observation during evening (Fig. S1). The outliers were predominately comprised of *Haemulon aurolineatum* (tomtate), a grunt that consumes benthic invertebrates and zooplankton, and *Decapterus* spp. (scad), a forage fish that eats zooplankton. Reductions in fish abundances during seismic surveying proved statistically significant using two different statistical tests. First, the mean variance in fish counts on each of the three days without seismic noise was greater than the corresponding mean variance on the day with seismic surveying (via analysis of means for variance (ANOMV) with Levene transformation, $p = 0.047$; Fig. S2). The statistically significant differences in fish abundance between the single day with and the three days without seismic noise were driven by data from a four-hour evening period (1600-2000 local time). Whether fish occupation of the reef differed during the evening across all days was further tested. The total number of fish occupying the reef during evening declined by 78% when exposed to seismic noise (ANOVA followed by post-hoc pairwise t-test with Box-Cox transformation, $F_{3,36} = 4.74$, $p = 0.007$).

In addition to counting fish, video recordings were examined to assess whether fish exhibited behaviors that could help understand the change in reef use. Noises from seismic surveying were audible as discrete airgun shots in video recordings, allowing association of any observed behavioral responses with timing of individual shots. Eight shots were audible on video. The other shots occurred at 30 to 90-s intervals and did not coincide with the recording schedule. Only one observed fish, a *H. aurolineatum*, exhibited an apparent behavioral response to an airgun shot by swimming away from a ledge. From the lack of abundant fish observed during evening when repeatedly exposed to seismic noise, it is presumed that at least some reef-associated fishes left the reef.

4. Conclusion

Although working with limited data, this study provides evidence that during exposure to seismic noise, the prevailing pattern of heavy fish use of reefs during the evening was suppressed. The finding is notable because it goes well beyond detection of a startle response from individual fish [16], instead suggesting a multi-species response to airgun noise and/or particle acceleration, validating expectations [17] that fish respond to seismic surveying in their natural environments. The Magnuson-Stevens Fishery Conservation and Management Act (2007) mandates protection of reefs, including those studied here, as Essential Fish Habitat. Reducing opportunities for fish to aggregate causes concern as this could reduce options for foraging, mating, or other important life history functions. Though there are no observations to indicate the duration of the observed effect, these research results augment and confirm issues raised by marine mammal experts [31] and suggest that concerns associated with marine seismic surveys appear to be realistic and well-founded.

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videos, and analyzed fish data. D.P.N., J.D., E.C. processed and analyzed hydrophone data. A.B.P. and C.H.P. wrote the manuscript.

References

[1] J. Hildebrand, Anthropogenic and natural sources of ambient noise in the ocean, Mar. Ecol. Prog. Ser. 395 (2009) 5–20. doi:10.3354/meps08353.

[2] P.J.O. Miller, M.P. Johnson, P.T. Madsen, N. Biassoni, M. Quero, P.L. Tyack, Using at-sea experiments to study the effects of airguns on the foraging behavior of sperm whales in the Gulf of Mexico, Deep Sea Res. I. 56 (2009) 1168–1181. doi:10.1016/j.dsr.2009.02.008.

[3] E. Pirotta, K.L. Brookes, I.M. Graham, P.M. Thompson, Variation in harbour porpoise activity in response to seismic survey noise, Biol. Lett. 10 (2014) 20131090. doi:10.1098/rsbl.2013.1090.

[4] S.B. Blackwell, C.S. Nations, T.L. McDonald, A.M. Thode, D. Mathias, K.H. Kim, C.R. Greene, A.M. Macrander, Effects of airgun sounds on bowhead whale calling rates: evidence for two behavioral thresholds, PLoS One. 10 (2015) e0125720. doi:10.1371/journal.pone.0125720.

[5] R.D. McCauley, J. Fewtrell, A.N. Popper, High intensity anthropogenic sound damages fish ears, J. Acoust. Soc. Am. 113 (2003) 638–642. doi:10.1121/1.1527962.

[6] A.N. Popper, M.E. Smith, P.A. Cott, B.W. Hanna, A.O. MacGillivray, M.E. Austin, D.A. Mann, Effects of exposure to seismic airgun use on hearing of three fish species, J. Acoust. Soc. Am. 117 (2005) 3958–3971. doi:10.1121/1.1904386.

[7] A.N. Popper, M.C. Hastings, The effects of human-generated sound on fish, Integr. Zool. 4 (2009) 43–52. doi:10.1111/j.1749-4877.2008.00134.x.

[8] M.B. Halvorsen, B.M. Casper, F. Matthews, T.J. Carlson, A.N. Popper, Effects of exposure to pile-driving sounds on the lake sturgeon, Nile tilapia and hogchoker, Proc. R. Soc. B Biol. Sci. 279 (2012) 4705–4714. doi:10.1098/rspb.2012.1544.

[9] A.N. Popper, A.D. Hawkins, R.R. Fay, D.A. Mann, S. Bartol, T.J. Carlson, S. Coombs, W.T. Ellison, R.L. Gentry, M.B. Halvorsen, S. Løkkeborg, P.H. Rogers, B.L. Southal, D.G. Zeddies, W.N. Tavolga, Sound Exposure Guidelines for Fishes and Sea Turtles: A Technical Report prepared by ANSI-Accredited Standards Committe S3/SC1 and registered with ANSI, Springer Briefs in Oceanography, ASA Press and Springer, London, 2014.

[10] A. Slotte, K. Hansen, J. Dalen, E. Ona, Acoustic mapping of pelagic fish distribution and abundance in relation to a seismic shooting area off the Norwegian west coast, Fish. Res. 67 (2004) 143–150. doi:10.1016/j.fishres.2003.09.046.

[11] J. Purser, A.N. Radford, Acoustic noise induces attention shifts and reduces foraging performance in three-spined sticklebacks (*Gasterosteus aculeatus*), PLoS One. 6 (2011) e17478. doi:10.1371/journal.pone.0017478.

[12] A.D. Hawkins, L. Roberts, S. Cheesman, Responses of free-living coastal pelagic fish to impulsive sounds, J. Acoust. Soc. Am. 135 (2014) 3101–3116. doi:10.1121/1.4870697.

[13] J. Song, D.A. Mann, P.A. Cott, B.W. Hanna, A.N. Popper, The inner ears of Northern Canadian freshwater fishes following exposure to seismic air gun sounds, J. Acoust. Soc. Am. 124 (2008) 1360–1366. doi:10.1121/1.2946702.

[14] J.R. Skalski, W.H. Pearson, C.I. Malme, Effects of sounds from a geophysical survey

device on catch-per-unit-effort in a hook-and-line fishery for rockfish (Sebastes spp.), Can. J. Fish. Aquat. Sci. 49 (1992) 1357–1365.

[15] S. Løkkeborg, E. Ona, A. Vold, A. Salthaug, Sounds from seismic air guns: gear- and species-specific effects on catch rates and fish distribution, Can. J. Fish. Aquat. Sci. 69 (2012) 1278–1291. doi:10.1139/F2012-059.

[16] C.S. Wardle, T.J. Carter, G.G. Urquhart, A.D.F. Johnstone, A.M. Ziolkowski, G. Hampson, D. Mackie, Effects of seismic air guns on marine fish, Cont. Shelf Res. 21 (2001) 1005–1027.

[17] H. Slabbekoorn, N. Bouton, I. van Opzeeland, A. Coers, C. ten Cate, A.N. Popper, A noisy spring: the impact of globally rising underwater sound levels on fish, Trends Ecol. Evol. 25 (2010) 419–427. doi:10.1016/j.tree.2010.04.005.

[18] Cruise Report: Eastern North American Margin Community Seismic Experiment, Cruise MGL1408, R/V Marcus G Langseth, 2014. www.marine-geo.org/tools/search/data/field/Langseth/MGL1408/docs/MGL1408_cruise_report_v2_with_appendices.pdf.

[19] R.O. Parker Jr., Tagging studies and diver observations of fish populations on live-bottom reefs of the U.S. southeastern coast, Bull. Mar. Sci. 46 (1990) 749–760.

[20] R.O. Parker Jr., R.L. Dixon, Changes in a North Carolina reef fish community after 15 years of intense fishing — global warming implications, Trans. Am. Fish. Soc. 127 (1998) 908–920. doi:10.1577/1548-8659(1998)127<0908.

[21] P.E. Whitfield, R.C. Muñoz, C.A. Buckel, B.P. Degan, D.W. Freshwater, J.A. Hare, Native fish community structure and Indo-Pacific lionfish *Pterois volitans* densities along a depth-temperature gradient in Onslow Bay, North Carolina, USA, Mar. Ecol. Prog. Ser.

509 (2014) 241–254. doi:10.3354/meps10882.

[22] M. Tolstoy, J. Diebold, L. Doermann, S. Nooner, S.C. Webb, D.R. Bohnenstiehl, T.J. Crone, R.C. Holmes, Broadband calibration of the R/V *Marcus G. Langseth* four-string seismic sources, Geochem. Geophys. Geosystems. 10 (2009) 1–15. doi:10.1029/2009GC002451.

[23] R.J. Urick, Principles of Underwater Sound, 3rd Ed., Peninsula Publishing, Westport, CT, 1983.

[24] R Development Core Team, R: A language and environment for statistical computing, (2015). http://www.r-project.org/.

[25] P.S. Wludyka, P.R. Nelson, An analysis-of-means-type test for variances from normal populations, Technometrics. 39 (1997) 274–285. doi:10.1080/00401706.1997.10485119.

[26] P. Pallmann, ANOM: Analysis of Means. R package version 0.4.2, (2015).

[27] M.N. Venables, B.D. Ripley, Modern Applied Statistics with S, 4th Ed., Springer, New York, 2002.

[28] D.P. Nowacek, K. Bröker, G. Donovan, G. Gailey, R. Racca, R.R. Reeves, A.I. Vedenev, D.W. Weller, B.L. Southall, Responsible practices for minimizing and monitoring environmental impacts of marine seismic surveys with an emphasis on marine mammals, Aquat. Mamm. 39 (2013) 356–377. doi:10.1578/AM.39.4.2013.356.

[29] M. Guerra, A.M. Thode, S.B. Blackwell, A.M. Macrander, Quantifying seismic survey reverberation off the Alaskan North Slope, J. Acoust. Soc. Am. 130 (2011) 3046–3058. doi:10.1121/1.3628326.

[30] R. Racca, M. Austin, A. Rutenko, K. Bröker, Monitoring the gray whale sound exposure mitigation zone and estimating acoustic transmission during a 4-D seismic survey,

Sakhalin Island, Russia, Endanger. Species Res. 29 (2015) 131–146. doi:10.3354/esr00703.

[31] D.P. Nowacek, C.W. Clark, D. Mann, P.J.O. Miller, H.C. Rosenbaum, J.S. Golden, M. Jasny, J. Kraska, B.L. Southall, Marine seismic surveys and ocean noise: time for coordinated and prudent planning, Front. Ecol. Environ. 13 (2015) 378–386. doi:10.1890/130286.

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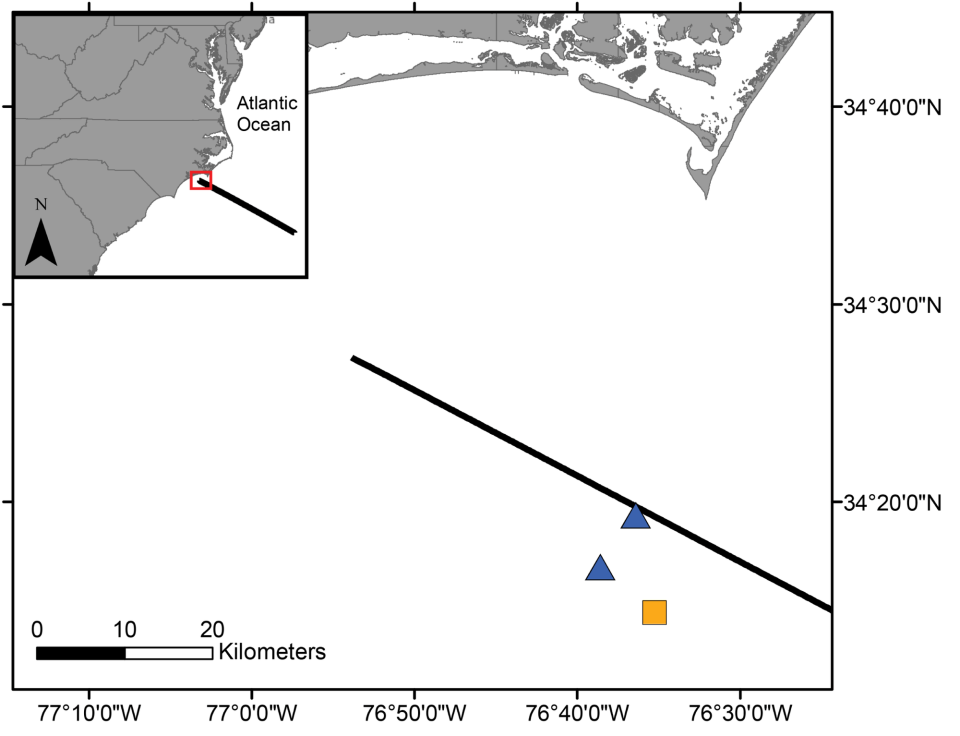
Figure Captions:

Fig. 1. Track of seismic survey vessel (black line) relative to three monitoring reefs on the inner continental shelf of NC: two outfitted with hydrophones (blue triangles) and one with video camera (orange square).

Fig. 2. Acoustic signatures of A) ambient noise and B-D) noise from seismic airgun shots on reef 0.7 km from closest approach of seismic surveying vessel: B) 22.2 km from reef before closest approach; C) 0.7 km from reef showing the seismic shots just prior to shots that overloaded our instruments; D) 19.6 km from reef following closest approach. Insets depict 10 Hz – 5 kHz range of low frequency.

Fig. 3. Hourly fish abundance on the reef 7.9 km from the closest approach of the seismic survey ship during three days before (solid black line) and on one day during the height of seismic activity near the reef (red line). The solid black line is the smoothed conditional mean and the black dotted lines are standard error of the hourly fish abundance for three days before seismic

surveying. The red line is the smoothed conditional mean of hourly fish abundance on the day with seismic activity.



Atlantic
Ocean
N
34°40'0"N
34°30'0"N
34°20'0"N
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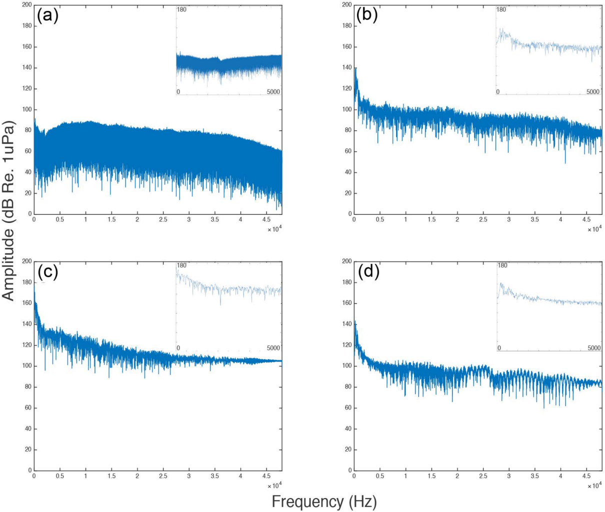
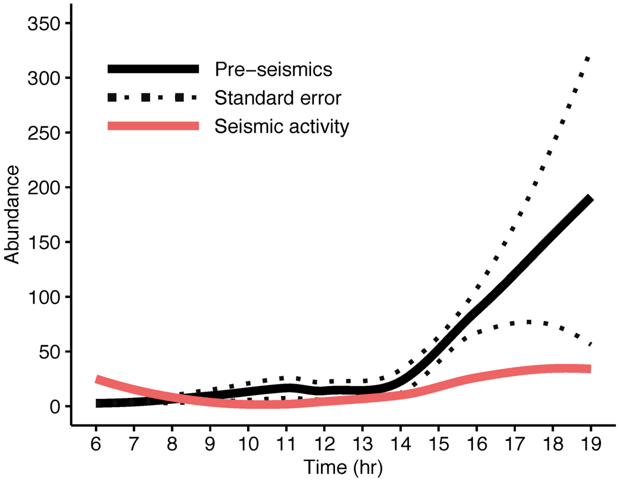
20
Kilometers
77°10'0"W
77°0'0"W
76°50'0"W
76°40'0"W
76°30'0"W



(a)
(b)
(c)
(d)
Amplitude (dB Re. 1uPa)
Frequency (Hz)
× 10^4
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
0
20
40
60
80
100
120
140
160
180
200
180
0
5000



Pre–seismics
Standard error
Seismic activity
Abundance
0
50
100
150
200
250
300
350
6
7
8
9
10
11
12
13
14
15
16
17
18
19
Time (hr)