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Effects of 2D seismic on the snow crab fishery

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ABSTRACT

Sound is used by a variety of marine taxa for feeding, reproduction, navigation and predator avoidance and therefore alterations to the soundscape from industrial noise have the potential to negatively affect an animal's fitness. Furthermore, responses to industrial noise would also have the potential to negatively influence commercial fishing interests. Unfortunately marine invertebrates are generally underrepresented in the seismic effects literature. Snow crab harvesters in Atlantic Canada contend that seismic noise from widespread hydrocarbon exploration has strong negative effects on catch rates. We repeated a Before-After-Control-Impact study over two years to assess the effects of industry scale seismic exposure on catch rates of snow crab along the continental slope of the Grand Banks of Newfoundland. Our results did not support the contention that seismic activity negatively affects catch rates in shorter term (i.e. within days) or longer time frames (weeks). However, significant differences in catches were observed across study areas and years. While the inherent variability of the CPUE data limited the statistical power of this study, our results do suggest that if seismic effects on snow crab harvests do exist, they are smaller than changes related to natural spatial and temporal variation.

1. Introduction

Sound is a key environmental feature that is used by a wide variety of marine taxa in many life activities such as navigation, foraging, predator avoidance and communication (Carroll et al., 2016; Edmonds et al., 2016). Noise from marine industries (e.g. seismic exploration, ship activities etc.) alters the soundscape (acoustics scene), and the associated effects on organisms and their responses can influence their physiology and fitness. Moreover, anthropogenic noise may have broader consequences, including the potential to influence important ecological processes (e.g. Solan et al., 2016) and commercial fishing interests (Skalski et al., 1992; Løkkeborg and Soldal, 1993; Engås et al., 1996; Slotte et al., 2004).

Marine environments have experienced increases in exposure to industrial noise in recent decades (Slabbekoorn, 2016). Noise has considerable potential to negatively affect marine organisms both physically and behaviourally and the range of potential effects include death, physical and physiological effects, masking of natural sound, and behavioural responses (Hirst and Roadhouse, 2000; Mooney et al., 2010; Edmonds et al., 2016; Hawkins and Popper 2017; McCauley et al., 2017). Measuring and demonstrating disruptions caused as a result of noise, however, has been challenging (Edmonds et al., 2016).

While the science documenting the implications of anthropogenic noise on marine wildlife is expanding, it remains heavily biased to marine mammals and fishes, whereas other ecologically and commercially important taxa like invertebrates are under-represented (Hawkins et al., 2015; Williams et al., 2015; Carroll et al., 2016). Furthermore, the logistical challenges of conducting marine field studies mean that much of what is known is based on lab studies where realism is difficult to achieve (Popper and Hastings 2009; Hawkins and Popper 2017; Slabbekoorn 2016). Field studies typically lack adequate control sites and/or pre-impact conditions and typically fail to quantify the degree of exposure experienced by the study animals (Edmunds et al., 2016). These complexities and related scientific shortcomings make it difficult to resolve/mitigate resource management conflicts.

Such a situation occurs along the shelf and slope marine habitats of Atlantic Canada where active seismic exploration overlaps extensively with an important snow crab fishery. Since the collapse of the groundfish fishery in Atlantic Canada, snow crab has been the highest valued fishery in Newfoundland and Labrador, with a landed value worth in excess of 273 million dollars (CAD) in 2016 (DFA, 2017). Many snow crab harvesters are concerned about seismic exploration and contend that seismic noise has strong negative effects on catch rates (FFAW personal communication; Christian et al., 2003; Mullowney

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et al., 2014); an issue that is likely to become more acute given that the species is currently experiencing unfavourable environmental conditions in many harvesting areas (DFO, 2016).

Two previous studies (Christian et al., 2003; Christian et al., 2004) attempted to assess the effects of seismic activity on snow crab behaviour, physiology, mortality and catchability and found no effects except for delayed development of embryos. Interpretation of these studies (Christian et al., 2003; Courtenay et al., 2009) note however, that they were challenged by equipment failures (Christian et al., 2003), study design limitations, confounding factors (e.g. delays in embryo development may have been caused by differences in water temperature at the study sites rather than seismic) and questions about the relevance of laboratory studies and field manipulations (Courtenay et al., 2009). Consequently, and not surprisingly, the resource conflict remains unresolved. Recent subject reviews of seismic impacts (Courtenay et al., 2009; Carroll et al., 2016; Hawkins and Popper 2017) have suggested potential ways in which study design, metrics, and topics of interest could improve the confidence in conclusions related to the effects of seismic exploration on marine animals. This study attempts to incorporate these recommendations and improve upon snow crab − seismic investigations by 1) using an enhanced study design with a multi-year BACI approach; 2) improving study realism by recreating seismic/fishery interactions using authentic platforms and methods from the respective industries; and 3) measuring exposures of snow crab to seismic-induced pressure and particle motion using recommended exposure metrics.

2. Methods

To ensure study realism, both industry-based snow crab harvesting and seismic surveying industries were consulted during the study design phase to identify an appropriate study area and methodology that aligned with industry standards. The study sites selected during these consultations were Lilly (control site) and Carson (treatment site) canyons − located on the eastern slope of the Grand Banks (Fig. 1). The sites were selected as they serve as important harvesting areas for snow crab and were within areas that were being actively surveyed by commercial seismic vessels. They were also both characterized by bathymetric relief, enabling an evaluation of potential flight responses to deeper water; a snow crab reaction that harvesters believed to occur following exposure to seismic noise.

The selected study sites were separated by a sufficient distance (70 km) such that Lilly Canyon would be unaffected by seismic air-gun exposures at Carson Canyon. Cumulative noise levels at the control site were similar to or less than the noise level generated by fishing vessels. In each year, all seismic operations were prohibited by the Canada-Newfoundland Offshore Petroleum Board within a 70 km radius of each of our sites for a 1 month period before our controlled seismic exposure and for an additional month at the control site only. This period of quiet-time is based on general observations from the fishing industry which indicate that catch rates are affected for days to weeks but not months. These restrictions were implemented consistently across each study site and used to mark beginning and end points for data analysis.

2.1. Snow crab collections

Catch surveys were conducted by industry harvesters across three trips in each of 2015 (Trip 1: Aug 26–28; Trip 2: Sep 13–16; and Trip 3: Oct 9–12; Fig. 1) and 2016 (Trip 1: Sep 2–5; Trip 2: Sep 18–25; and Trip 3: Oct 17–21) using standard industry survey methods, the Fish Food and Allied Workers (FFAW's) Post-Season Snow Crab Pot Survey (Stansbury et al., 2013). Only one vessel was used for all harvesting activities in each of the years. In 2015, seismic exposure occurred between Trip 2 and Trip 3, whereas in 2016, a scheduled seismic exposure occurred during Trip 2 on September 22. The planned exposure in 2016 enabled an equal distribution of trap sets in "Before" and "After" exposure categories ($n_{Carson} = 20$, $n_{Lilly} = 10$; Fig. 2) for each sampling area within the trip (Fig. 1). Sampling intensity in 2016 was guided by power analyses that followed collections of 2015 data (see methods below). Sampling areas were restricted to the area bound by the control and test areas (Fig. 2). Within those areas, trap placement was not random but reflected actual commercial fishing practices. Each sampling location was typically sampled using a string of 10 baited commercial crab traps (5.5 inch mesh) spaced at 25 fathom intervals. Coordinates and depth of water were collected for each deployment and strings were soaked for a minimum of 12 h. All snow crab were counted and crab from the third pot in each string was measured by trained sampling personnel from the Observer Program of the FFAW. Only male crabs were caught during commercial fishing activities.

2.2. Seismic exposure

Each year seismic noise was introduced to the Carson Canyon area from the Atlantic Explorer; an industry seismic survey vessel that is typical of those that operate off Atlantic Canada. The exposure lasted for five days in 2015 (September 25 through the 29th; Fig. 3) when an industrial seismic exploration survey was conducted in and near the study area. The closest approach of the vessel to the sound recorders at the treatment site in 2015 was 1465 m. During 2015, more seismic exploration on the Grand Banks was conducted during our study period outside our 70 km radius buffer zones than in 2016. Seismic exposure on September 22nd 2016 at the Carson Canyon experimental site occurred for a duration of 2 h, and the vessel passed within 100 m from the acoustic recorder. Exposure was also conducted while the fishing vessel was on-site, which enabled experimental fishing immediately before and after exposure. In both years, the seismic source was an airgun array with a total volume of 4880 cubic inches, with shots at 10 s intervals, operated at 2000 psi and deployed at 9 m of depth. The seismic source was modeled using the Airgun Array Sound Model (AASM, JASCO Applied Sciences, MacGillivray 2006). The horizontal zero-to-peak sound pressure level was 251 dB re 1 μPa @ 1 m and the source sound exposure level was 229 dB re 1 $\mu Pa^2 \cdot s$ @ 1m. The full recorded sound spectrum for 2016, including natural sources such wind, waves and marine mammals is provided in Fig. 4.

2.3. Acoustic measurements

Acoustic recordings were taken at the treatment and control sites from early September until mid-October in both years to 1) ensure that ambient conditions were quiet relative to seismic surveys and 2) confirm that seismic exploration activity at the treatment site was not greater than fishing vessel noise at the control site. The daily sound exposure level was used to compare the sites because it is believed to best capture the effects of long-term sound exposure on marine life (e.g. Popper et al., 2014, [NMFS] National Marine Fisheries Service 2016). The reported sound exposure level is the arithmetic sum of the sound pressure level in the frequency band of 10–7000 Hz over each 24-h period.

Data were collected using an AMAR acoustic recorder (JASCO Applied Sciences), sampling at 16 kHz. The recorders were located on the seabed (105–115 m deep) on frames that held the hydrophones ~0.6 m above the seafloor. In 2015 a Geospectrum M36-V35-100 hydrophone with sensitivity of −165 dB re 1 V/μPa was used; in 2016 an M36-V0-100 hydrophone with sensitivity of −200 dB re 1 V/μPa was used. In 2016 particle motion was also measured. A Geospectrum M20-101 particle acceleration sensor was suspended 0.5 m above the seabed and a PCB-356B18 micro-electrical-mechanical-system (MEMS) accelerometer was coupled to the seabed mooring plate. The close pass of the seismic vessel in 2015 was not planned before the hydrophones were deployed, and the high levels of received sound caused the hydrophone to reach its maximum signal output when the seismic vessel was 8 km from the recorder while operating over the shallow Grand Banks and

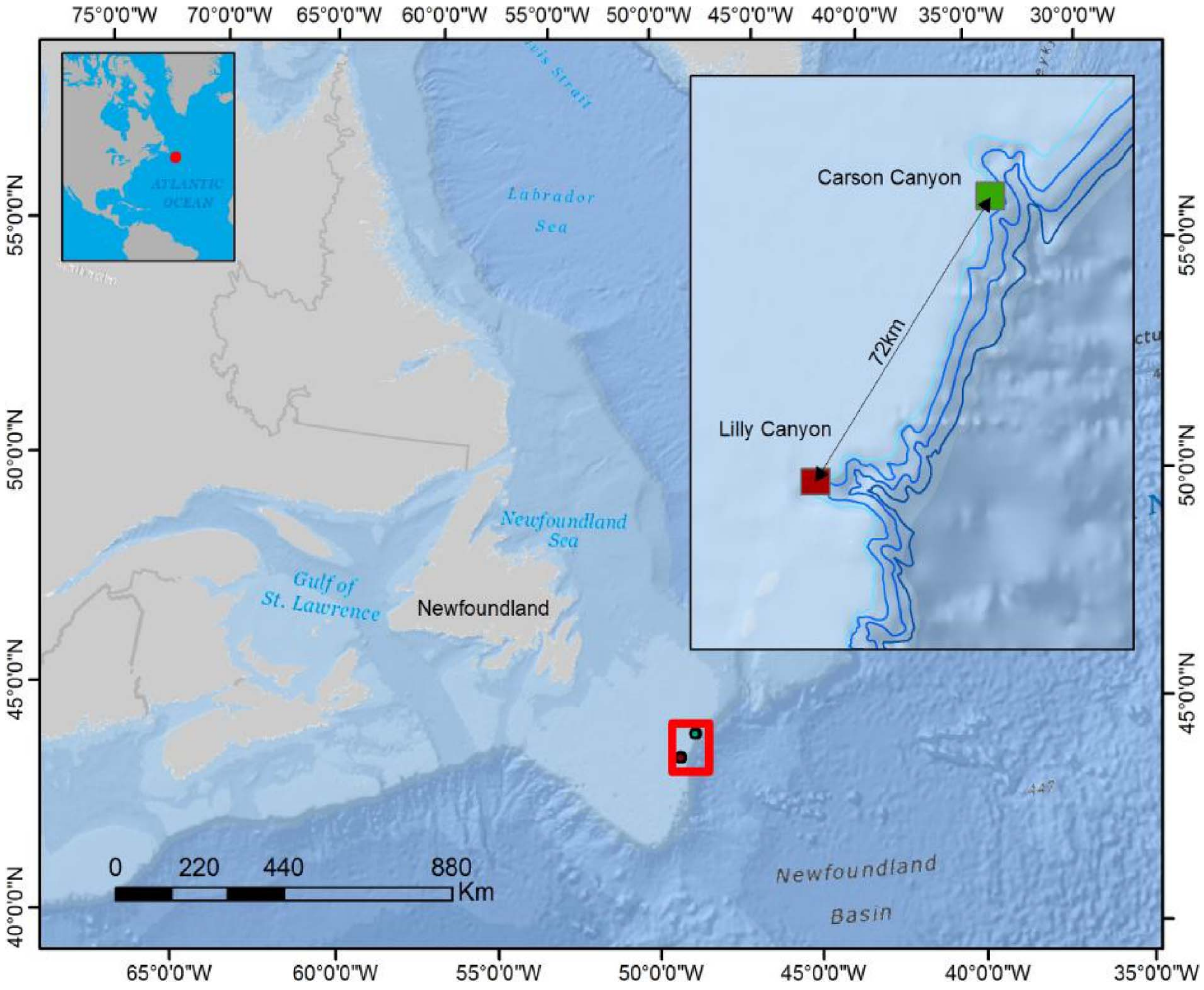

Fig. 1. Geographic location of the control (Lilly Canyon, lower red square) and test (Carson Canyon, upper green square) sites on the slope of the Grand Banks. The configuration of the acoustic receivers is shown in the inset.

16 km while operating over deep water east of the treatment site. Therefore, the reported daily sound exposure levels at the treatment area are less than the actual exposures during the five days of seismic survey. In 2016 only of 16 of the closest seismic pulses (+/− 200 m) caused the M36-V0-100 hydrophone to exceed its maximum levels, which likely reduced the recorded sound exposure level by 3–6 dB.

For comparison, the sound exposure levels measured at the control and treatment sites are compared to the median of the daily sound exposure level measured over the period of 24 August − 13 October 2015 at 45.70N, 51.23W as part of a separate research project. This location, also on the Grand Banks, was not exposed to significant seismic survey or vessel activity during the measurement period.

2.4. Statistical approach

Several previous seismic effect studies have been criticized for lacking adequate controls (Payne et al., 2008; Courtenay et al., 2009; Hawkins and Popper 2017). Consequently, this study employed a multi-year Before-After-Control-Impact (BACI) approach, which safeguarded against Type I errors caused by naturally occurring spatial and temporal variation

The catch data being examined in this document have inherent characteristics that need to be accounted for during statistical analysis. First, count data are bounded by zero and generally do not satisfy the statistical assumptions used in conventional approaches (e.g. ANOVA). Techniques such as generalized linear models can better approximate the underlying data distributions (e.g. Poisson or negative binomial distributions) and should be used in such circumstances (Zuur et al., 2009). Second, the field methods require that the traps are deployed in strings of 10. Since each trap within a string shares a localized sampling area, traps on the same string are not likely to be independent in a statistical sense and this violates the assumptions of most conventional models. Mixed effects models account for such dependence in the model and are recommended over averaging catches within a string (Zuur et al., 2009). Based on these characteristics, a negative binomial generalized linear mixed effects model and associated likelihood ratio tests were selected to analyze the data.

The generalized linear mixed effects model (lme4 extension of R; R Core Team, 2015) used total counts of snow crab within a trap as the response variable, temporal (Before/After Exposure) and spatial (Reference/Treatment) categorical variables as the fixed effects and the string's identity as a random effect. For a BACI study design, the statistical interaction between spatial and temporal fixed effects is also included since to detect a treatment effect we look to see if catch rates responded similarly over time across the two areas.

Graphical examination of the data also indicated that depth may influence catch rates of snow crab. Therefore, to reduce unexplained variance and improve statistical power, depth was also included as a continuous explanatory variable in the statistical model.

In 2016, the planned seismic exposure enabled the evaluation of more immediate effects on catch rates within Trip 2 of 2016. The model structure for that short-term evaluation was as follows:

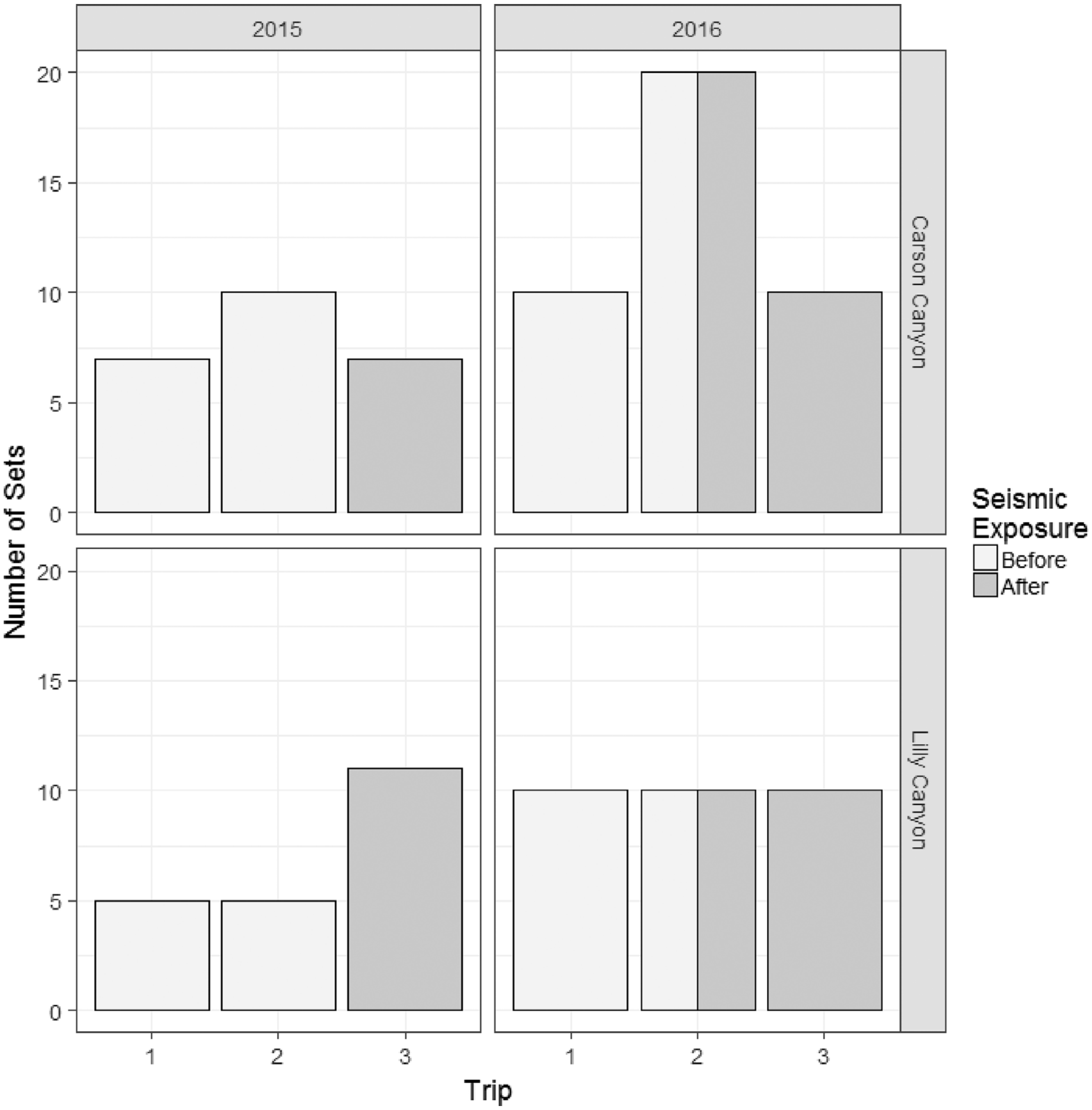

Fig. 2. Sampling effort allocated to the control (Lilly Canyon) and treatment (Carson Canyon) areas before and after exposure to seismic activity in 2015 and 2016. No seismic activity occurred in the control area; shading is provided for comparison purposes only.

$$\text{Total Snow Crab} \sim \text{Study Area*Temporal Period} + \text{Depth} + (1|\text{String})$$

For both years, longer term effects of seismic on catch rates were compared (i.e. comparison of Trip 2 "Before" data to Trip 3 "After" data). This evaluation was conducted using the same model as described for short term effects with the exception that a variable was included to account for year effects.

$$\text{Total Snow Crab} \sim \text{Study Area*Temporal Period} + \text{Depth} + \text{Year} + (1|\text{String})$$

2.5. Power analysis methods

We used power analysis on the 2015 data to guide the 2016 sampling intensity. Statistical power was assessed for a variety of scenarios using a data simulation approach that was informed with pilot data collected at the study site in 2015. Specifically, scenarios that included a variety of sample sizes (6–18 strings) and effect sizes (CPUE reductions of 0–70% of baseline) were assessed by simulating scenario-specific data based on the observed variability in within-string catches and across-string catches during the baseline condition (Trip 2 of Carson Canyon) (Supplementary Fig. 1). The scenarios described above were tested using a more simple design using Before-After or Control-Impact, in which the parameter of interest was either sampling period or site. A final set of scenarios was also conducted using a more complete BACI study design, in which the parameter of interest was the interaction between sites and sampling period. None of the simulations incorporated variance related to depth, since the effect of depth was reflected in the model that was used to generate the input values for the power analysis.

Within a given scenario, 500 simulated data sets were generated; each of which was assessed for significance within a negative binomial generalized linear mixed effects model framework (lme4 extension of R; R Core Team, 2015), where total counts of snow crab were the response variable. In the more simple Before/After simulations, the Before/After condition was the fixed effect and the string was the random effect, whereas the BACI simulations also included a Control-Impact fixed effect and an interaction term. As with the analysis described above, traps within a string were not considered independent, hence the need for a random effect. All "Before", "Before-Impact", "Before-Control" and "After-Control" datasets were generated from the same sampling distribution parameters derived from Trip 2 of Carson Canyon. The "After" or "After-Impact" datasets were similarly created but only after the sampling distribution mean was adjusted to the scenario-specific effect

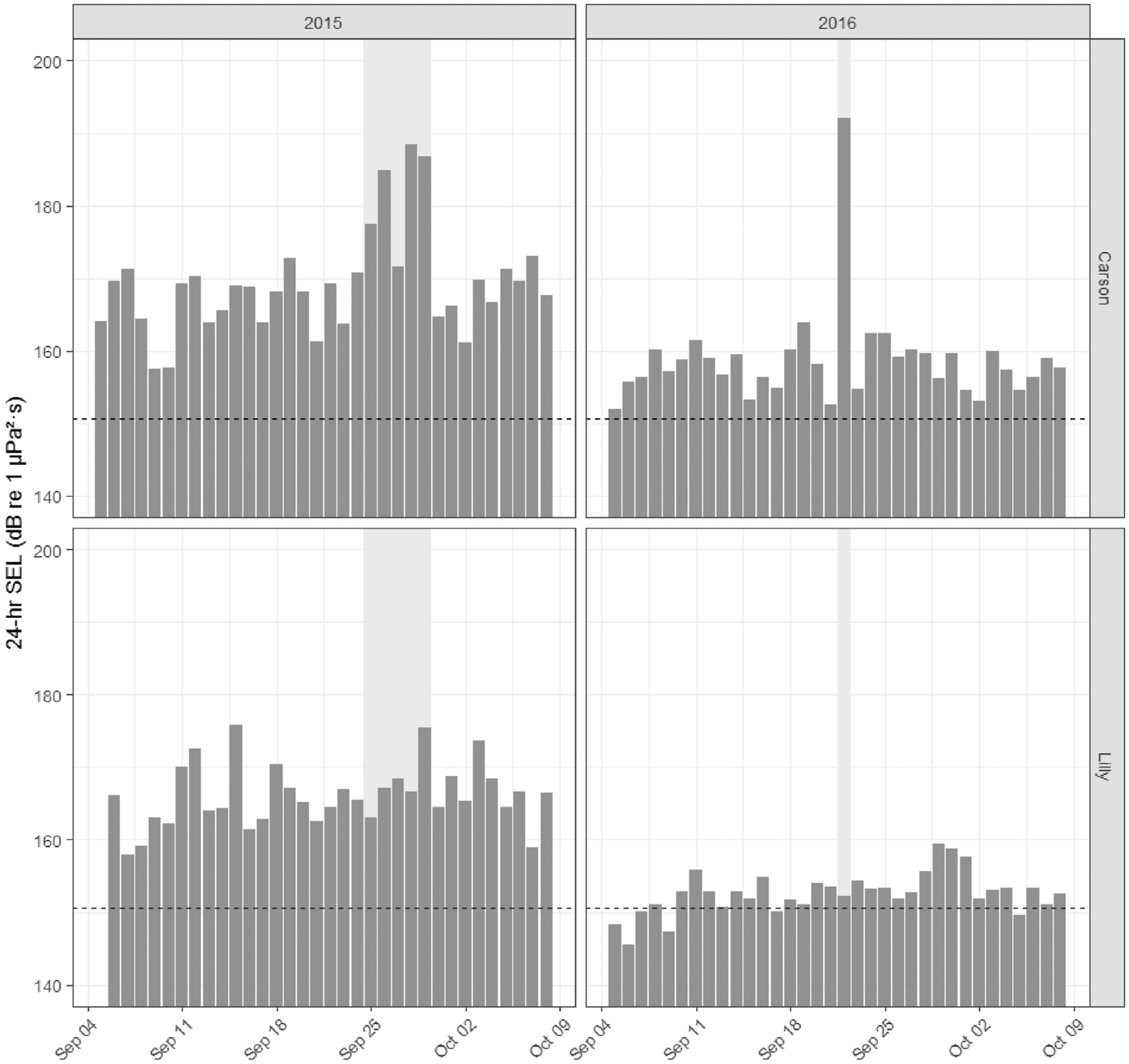

Fig. 3. Daily sound exposure levels measured at the control and treatment sites in 2015 and 2016. The gray-shaded areas are the days that the Atlantic Explorer performed exposures near the treatment site. The dashed line is the median sound level measured at a different Grand Banks location less affected by anthropogenic noise during the same period in 2015. The sound exposure levels for 26 Sep 2015, 28 Sep 2015, 29 Sep 2015 and 22 Sep 2016 are underestimates due to hydrophone saturation.

size. The proportion of significant likelihood ratio test results across these iterations represented the scenario's statistical power.

3. Results

3.1. Sound exposure

The median daily sound exposure level was 13 dB higher in 2015 than 2016 at the control site and 11 dB higher at the treatment site, likely as a result of differences in seismic surveying activities between years (Fig. 3). Despite the louder environment at both sites during 2015, the seismic exposure included as part of this study was approximately 20 dB higher than other recorded sound levels. Sound levels at the control site did not increase while seismic activity occurred at the test site in 2015. Similarly, the sound exposure level at the control site in 2016 did not increase during the 2-h exposure experiment at the treatment site 70 km away. The median of the sound exposures in 2016 were 2 dB higher at the control site than our separate sound measure representing quiet Grand Banks in 2015, indicating that it was representative of offshore Newfoundland. During the periods of time that the commercial fishing vessel, Royal Venture, was working near the sound recorders in 2016 the maximum measured sound exposure levels were typically 155–163 dB (Fig. 3). Thus, the sound exposure level near the seabed due to the seismic vessel was at least 30 dB higher (1000-fold increase) when the seismic vessel passed over the recorders on September 22, 2016 than during a day's fishing.

The particle acceleration and velocities increased during the seismic CPA proportionally to the pressure levels (Fig. 5). No interface waves that would increase particle motion at the seabed (i.e. ground roll) were detected.

3.2. Power analysis

The BACI study design was slightly less powerful approach to detect change than the Before-After approach. The Before-After study design could reliably detect change at the highest sample sizes (n = 18 per group; i.e. the number of samples used in the longer term comparison) when declines reached 50% of baseline while the BACI approach could only do so for declines of 60% or more (n = 18) (Supplementary Fig. 1.). For the smaller sample sizes associated with the short term effects assessment, a BACI design was expected to be able to reliably detect a decline of 70% whereas a Before-After design would be able to detect declines of 60%.

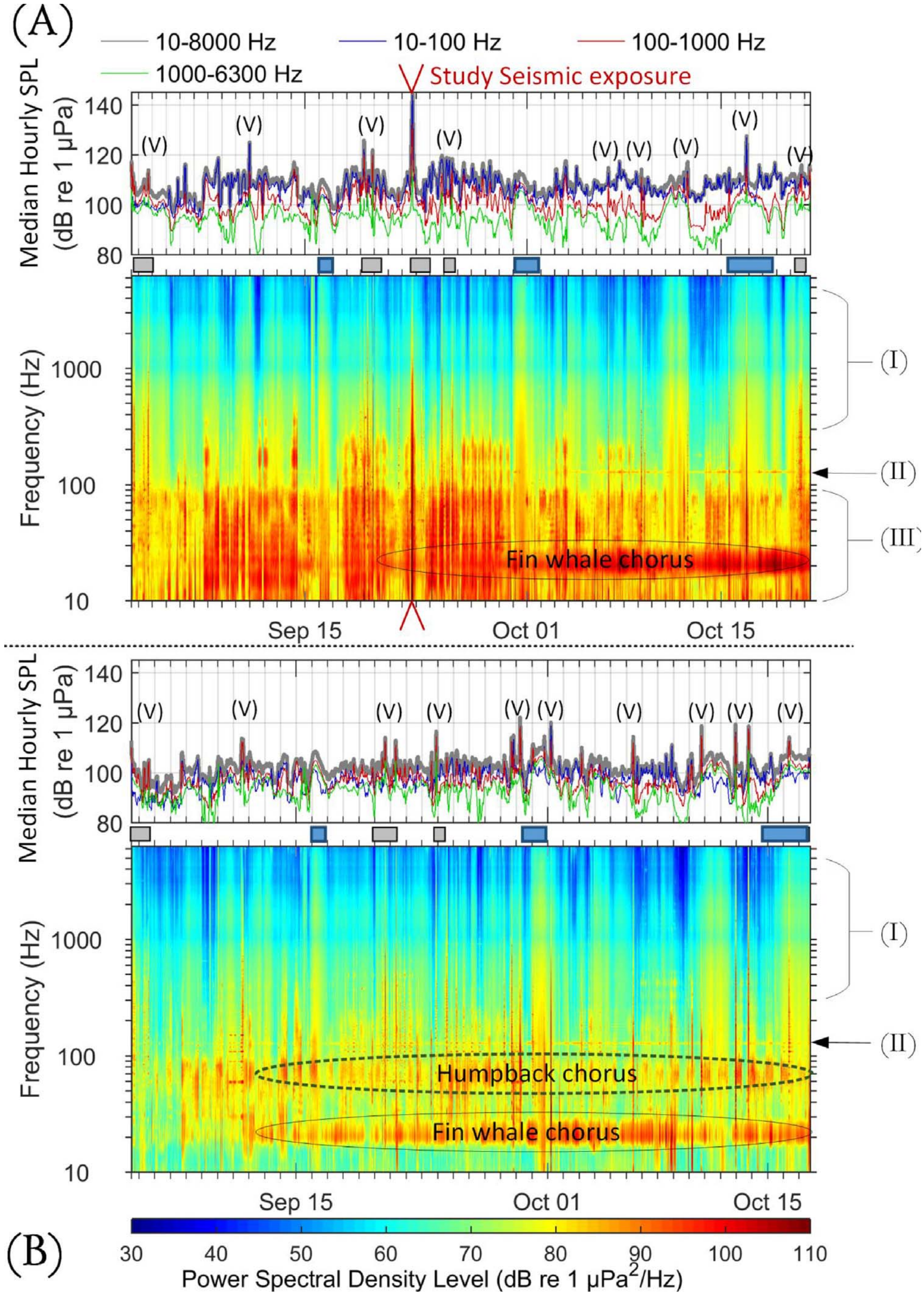

Fig. 4. Acoustic summary at the (A) treatment site (Carson Canyon) and (B) control site (Lilly Canyon) in 2016. For each site the top panel is the median hourly in-band SPL and bottom is the long-term spectral average of the measured sound. Named tropical storms that passed the area are identified by the blue bars (from left-right: Ian, Karl, Nicole). Days when the study's fishing effort occurred within 5 km of the recorders are shown by the gray bars. The study seismic exposure on 22 Sept 2016 at Carson Canyon is framed by the red-arrows. (V) indicatesnotable passages of vessels. Frequency bands with notable sound sources: (I) wind and wave noise; (II) 130 Hz fin whale top note; (III) distant seismic surveys affecting Carson Canyon's sound levels.

3.3. *Short term effects of seismic activity on 2016 snow crab catch rates*

In Carson Canyon, catch rates dropped from 5.29 ind/pot (range 0–44) to 5.03 ind/pot (range 0–33; a decline of 4.9%), whereas in Lilly Canyon, catch rates increased from 10.2 ind/pot (range 0–60) to 13.9 ind/pot (range 0–65; an increase of 36%) (Fig. 6). BACI interactions between site and exposure category were not significant ($P = 0.838$) and therefore did not provide evidence to suggest that seismic exposure was affecting catch rates. The remaining terms of the model indicate that Lilly Canyon has significantly higher catches ($P < 0.001$) and depth was a significant variable in catch rates ($P < 0.001$; Fig. 7). In light of the increased ability of Before-After comparisons to detect change (described above), the short term effects model was re-run for just Carson Canyon data. The comparison yielded a non-significant result ($P = 0.345$) for the Before-After variable.

3.4. *Longer term effects of seismic activity on 2015 and 2016 snow crab catch rates*

Combined across both years, average catch rates declined in Carson Canyon by 38%, whereas they increased in Lilly Canyon (control) by 1.7%. However, the BACI interaction term of the model was not significant ($P = 0.450$); indicating that the observed longer term seismic-related differences in catch rates could have occurred by chance. The remaining terms of this model were significant with Lilly Canyon showing elevated catch rates versus Carson Canyon ($P < 0.001$), Before Exposure catch rates (across all sites) were significantly higher than After Exposure ($P = 0.025$), 2016 catch rates were lower than 2015 ($P < 0.001$) and depth remained as a significant predictor variable ($P < 0.001$). As for short term effects, we assessed the more simple Before-After model with only Carson Canyon for Trip 2 and Trip 3 data.

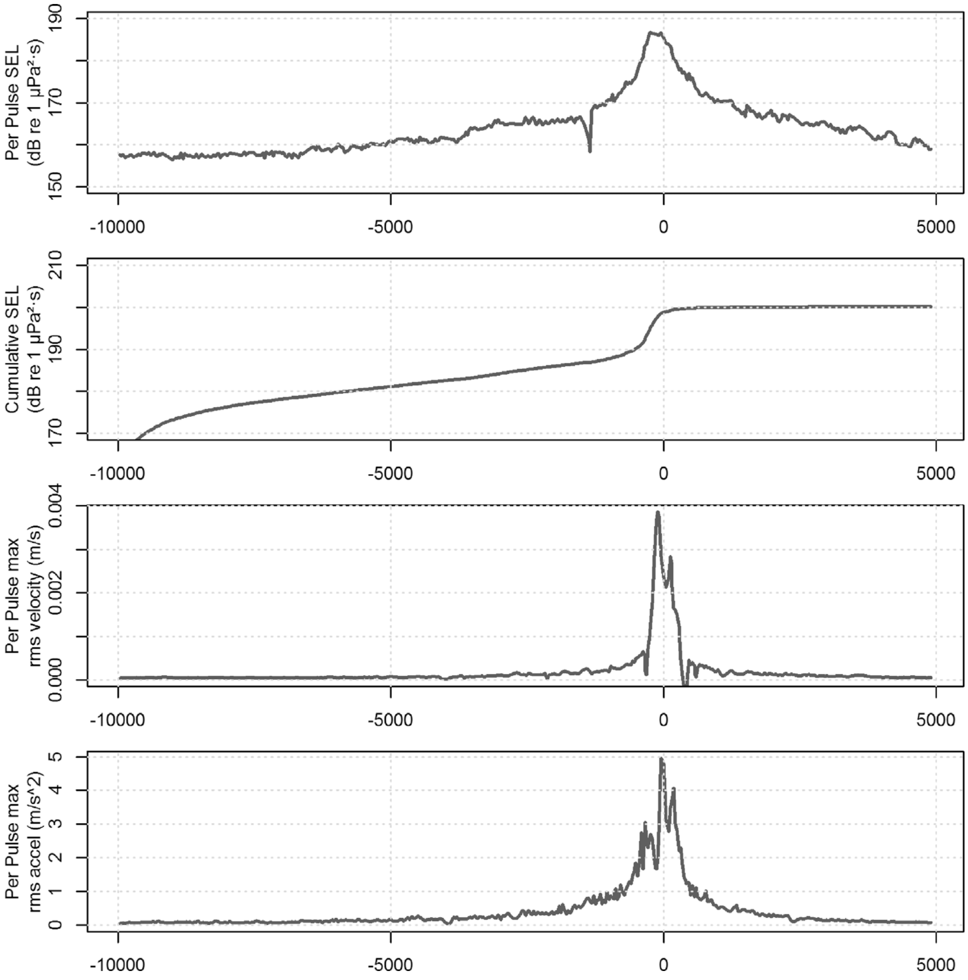

Fig. 5. Sound metrics of the 2D seismic exploration vessel used for this experiment measured near the sea-floor, representing the per-pulse sound exposure of a snow crab directly under the source. The particle acceleration measurements are from the MEMS sensor coupled to the seafloor.

The result was significant (P = 0.014).

For interest, we also compared Trip 1 (Before) vs. Trip 3 (After). The results were qualitatively consistent with the initial longer term model in that Carson Canyon catch rates declined by 18% post-exposure, whereas the control site increased by 16% post-exposure. As with the previous comparison, the interaction term was not significant (P = 0.270) and the remaining main effects were highly significant (i.e. catches were higher in 2015 at both sites and catches were higher in Lilly Canyon in both years; all P < 0.001).

4. Discussion

The experimental manipulations conducted in this study, which featured both spatial and temporal controls, did not support the idea that seismic exploration affects commercial catch rates of snow crab over the shorter (days) or longer (weeks) term examined. If seismic-related declines occurred that were too small for our study design to detect, they were secondary to more important natural spatial (i.e. Control-Impact) and temporal influences (Before-After effects).

Seismic exploration effects on catch rates could be manifested through a variety of mechanisms ranging across death, injury, stress or altering the sensory environment, which influence the individual's physical capacity and/or motivation to enter a trap. Vulnerable taxa only suffer mortality in close proximity to seismic guns (i.e. within meters) (Hawkins and Popper 2017; Slabbekoorn 2016 but see McCauley et al., 2017). The depths that snow crab are commercially harvested put the benthic life stages well beyond the kill zone of seismic arrays (Christian et al., 2003; DFO, 2004) with apparently limited long term impacts on survival. One hundred and twenty snow crab that were captured and transferred to laboratory facilities at the Northwest Atlantic Fisheries Centre from Carson Canyon, after being exposed to seismic noise in the offshore during 2015 were held in captivity for 18 months, and although the total mortality over that time period was 40% (Morris, personal observation June 22, 2017) this is low compared to other mortality rates of snow crab measured in captivity (Siikavuopio et al., 2017).

Sound-related injury and physiological responses can occur farther from the source (Hawkins and Popper 2017). Snow crab and other invertebrates however, are generally considered less vulnerable to noise-related trauma than marine mammals and fishes because they lack gas-filled spaces (Edmonds et al., 2016; MacGregor et al., 2016). Gas-filled morphological features (e.g. swim bladders in fish) are typically the location of barotrauma for noise-exposed animals as sound-generated pressure waves cause rapid motion in these structures and can damage adjacent tissue (Hawkins and Popper, 2017). For example, comparative studies show greater physical trauma to impulsive sound by fishes with swim bladders relative to those that lack that structure (Casper et al., 2016). Instead, invertebrates like snow crab are considered to only be vulnerable to particle motion (Payne et al., 2007; Mooney et al., 2010; Casper et al., 2016; Edmonds et al., 2016; Hawkins and Popper, 2017). Particle motion effects are thought to only be of consequence in close proximity to the sound source (Casper et al., 2016). Accordingly, lab and cage exposures of snow crab (Christian et al., 2003; Courtenay et al., 2009) and American lobster (Payne et al., 2007) to seismic sound did not result in any conclusive physiological effects, beyond some non-lethal signs of organ stress in lobster.

More likely to influence commercial catch rates are behavioural responses to sound (Hirst and Roadhouse, 2000). First, the potential

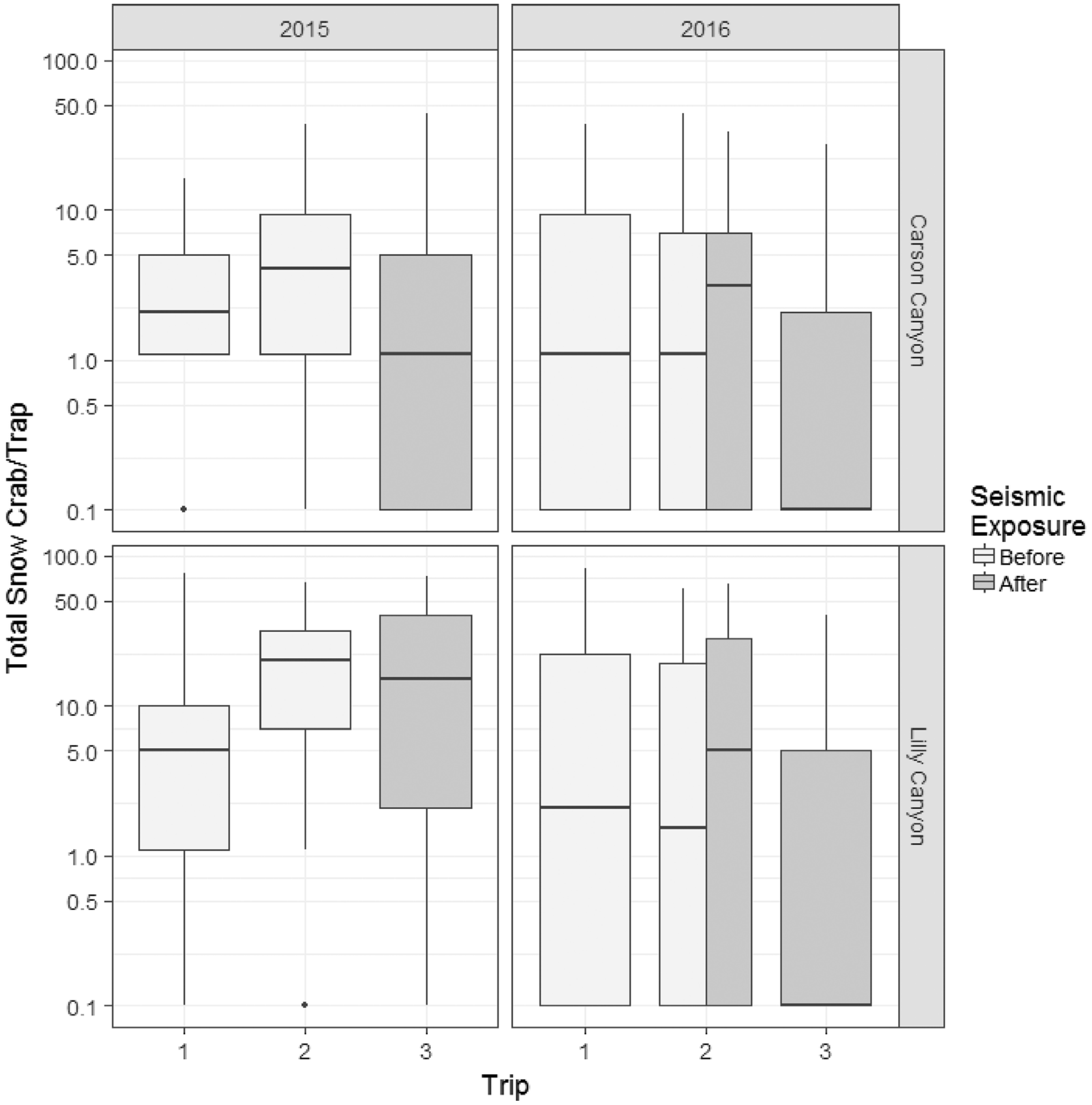

Fig. 6. Snow crab catch per trap in Lilly and Carson canyons on each of three trips. Horizontal lines represent median catch rates, boxes represent the middle quartiles and whiskers represent 1.5 times the interquartile range. Data beyond the whiskers are represented as individual data points.

area of influence is considerably larger (Hirst and Rodhouse 2000; Hawkins and Popper 2017; Slabbekoorn 2016), extending to 10 s of km for some fishes (Engås et al., 1996; Løkkeborg and Soldal,1993); a scale that better corresponds to those of commercial harvests. Second, some marine crustaceans are known to produce and respond to sound (Mooney et al., 2010; Edmonds et al., 2016) and therefore it is likely that the presence of anthropogenic sound could cause behavioural alterations to the likelihood that an individual encounters a trap and is motivated to enter it.

Foreign noises may illicit direct behavioural changes such as anti-predator responses, which may trigger cessation or alteration of feeding and/or mating behaviour, and movement away from the perceived threat to less suitable habitats (e.g. Wale et al., 2013a, 2013b; Day et al., 2016). They may also alter the soundscape; reducing the sensitivity at which organisms can perceive and react to their environment. While cage and laboratory exposures did not identify behavioural responses in snow crab (Christian et al., 2003; Christian et al., 2004) or American lobster (Payne et al., 2007), responses have been observed in other crustaceans (Edmonds et al., 2016). Even though crustaceans clearly use and respond to sound (Popper et al., 2001; Mooney et al., 2010), studies suggest that invertebrate commercial catches are usually not affected (Carroll et al., 2016). Snow crab catches actually increased after exposure to seismic sound (Christian et al., 2003), but the authors as well as Courtenay et al., 2009, conceded that the observed differences were likely the result of other phenomena. Certainly, a comparable time interval to Christian et al. (2003) study, between pre and post treatments in our study resulted in significant changes in catch rates even in our control area. Nevertheless, a similar absence of effect has also been observed for crustaceans such as shrimp (Southern Brown, Southern White and Atlantic Seabob, Andriguetto-Filho et al., 2005), rock lobster (Parry and Gason 2006), Norway lobster and mantis shrimp (La Bella et al., 1996) and reflects their reduced sensitivity of these taxa to anthropogenic noise.

Pronounced seismic-induced changes to commercial catches are more common in fishes (Skalski et al., 1992; Løkkeborg and Soldal, 1993; Engås et al., 1996; Løkkeborg et al., 2012; Vold et al., 2012). Observed changes are typically attributed to avoidance responses that occur on both horizontal (Engås et al., 1996; Slotte et al., 2004) and vertical (Skalski et al., 1992; Pearson et al., 1992; Slotte et al., 2004) planes. The change to catch rates depends on gear type, with decreases

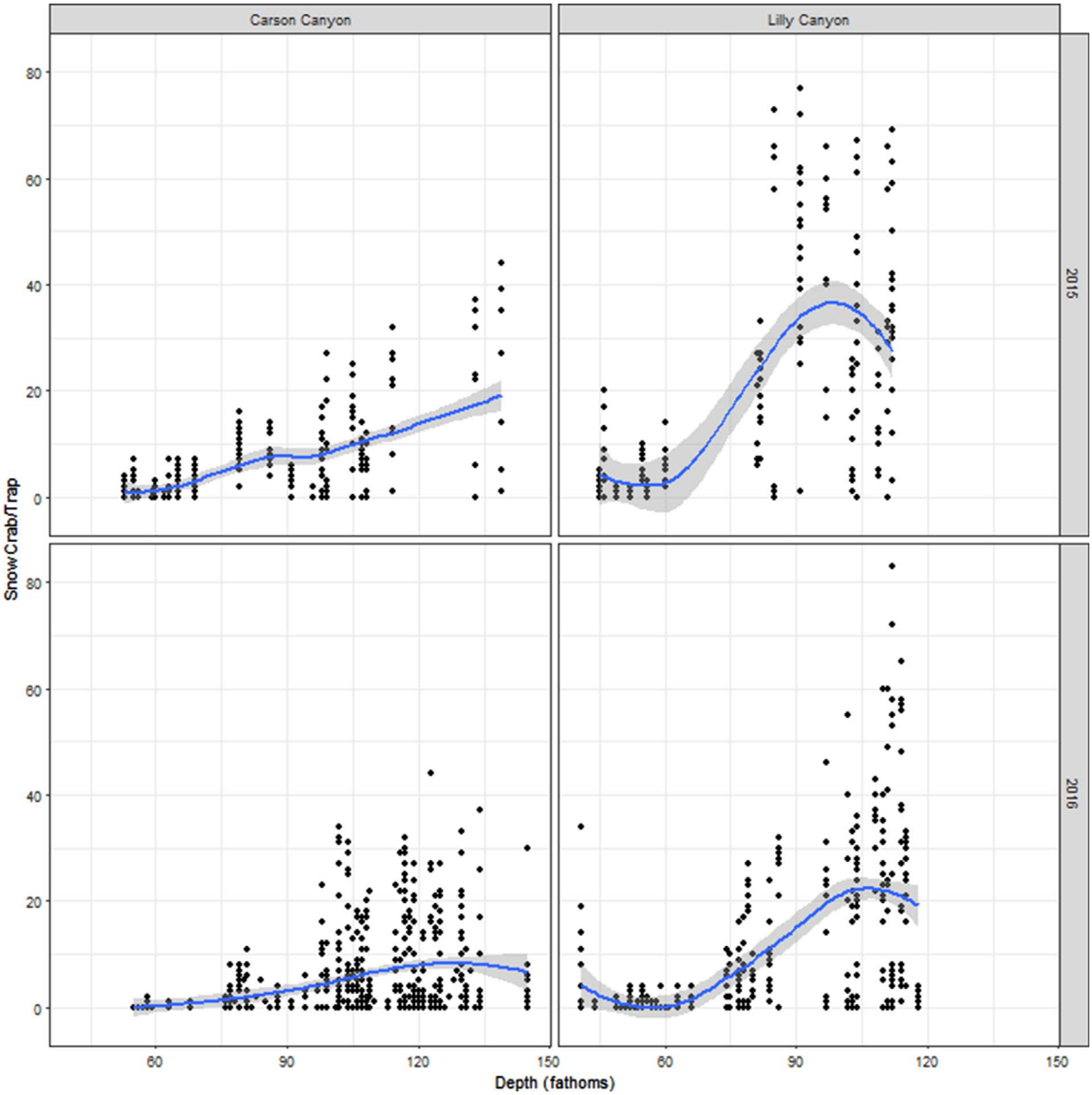

Fig. 7. The effects of depth on catch rates in Carson and Lilly canyons in 2015. A locally weighted smoother and associated 95% confidence interval envelope are superimposed on the data.

often associated with active gear methods (e.g. trawls; Engås et al., 1996) but increases are sometimes noted with passive methods such as gill nets, which initially benefit from the increased movement associated with the avoidance response (Løkkeborg et al., 2012). The avoidance response observed, however is context-dependent (Radford et al., 2016). For example, studies on fish species associated with local habitat features (e.g. sea mounts or reefs) often do not document latitudinal dispersal (Skalski et al., 1992; Wardle et al., 2001) but may still observe changes in depth use and/or a reduced willingness to take baited hooks (Skalski et al., 1992). In contrast, mobile demersal species may show an increased likelihood of horizontal displacement (e.g. Løkkeborg and Soldal, 1993; Løkkeborg et al.,2012). Some fish species may be undeterred by seismic activity when there is sufficient motivation (e.g. good feeding conditions; Peña et al., 2013). The variation of seismic effects, within and among populations, remains relatively unstudied however (Radford et al., 2014).

Studies of seismic effects on marine biota have been plagued by study design issues (Hawkins and Popper 2017); a result of the significant challenge related to isolating seismic effects while still maintaining study designs that provide biologically meaningful results (Slabbekoorn, 2016). Feasibility and experimental control encourage many researchers to use laboratory-based studies even though the resulting studies may have poor acoustic and behavioural validity (Popper and Hastings, 2009; Slabbekoorn, 2016). Similarly, field studies struggle to achieve adequate sample sizes needed to overcome the inherent variability associated with marine environments and consequently suffer from marginal statistical power (Slabbekoorn, 2016; Williams et al., 2015; Payne et al., 2007; Edmonds et al., 2016; e.g. Parry and Gason 2006; Courtenay et al., 2009). Logistical challenges may also cause many researchers to forego the suitable controls needed to effectively test for seismic effects (Hawkins and Popper, 2017) or to design studies opportunistically on existing seismic surveys; a compromise which can detract from the study's goals (Løkkeborg and Soldal, 1993; Parry and Gason, 2006; Vold et al., 2012). In this study, efforts were made to make the manipulations realistic from both a harvester and seismic operations perspective. This study is also a rare case where both spatial and temporal controls were implemented in a field environment. Interestingly, while BACI designs allow for greater confidence in positive (i.e. significant) results, they are not without detractors (e.g. Underwood, 1992). Our power analysis simulations indicate that they come with the penalty of having less statistical power to detect an effect than Before-After designs. Like previous seismic studies on invertebrate commercial catch rates (Parry and Gason 2006; Payne et al., 2007), we remain unable to distinguish small changes in catch rates. However, the use of the BACI design enabled us to place any potential effects in the context of other sources of variation (spatial and temporal); results which were aligned with temporal trends in biomass for the stock (DFO stock assessment). Conclusions regarding more subtle effects of seismic exposure will likely need to be inferred from supporting laboratory studies (Williams et al., 2015; Slabbekoorn, 2016) and complimentary field studies that look for mechanistic evidence of effects (e.g. changes to physiology, genomic expression, movement) that could influence catch rates.

A principal goal of this study was to provide information useful to resolving resource conflicts of two marine industries. To maximize the chance of acceptance of this knowledge and its incorporation to resolving resource conflicts, considerable effort was made to involve the affected industries. These collaborations were initiated at the project planning stages, addressed industry viewpoints, included regulatory support from the Canada-Newfoundland and Labrador Offshore Petroleum Board (C-NLOPB) and Fisheries and Oceans Canada (DFO) and incorporated feedback during the project. We believe that this approach enhanced the relevance and quality of this study and is worth considering for other industry-related studies.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.fishres.2017.09.012.

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