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Effects of 3D seismic surveying on snow crab fishery

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ABSTRACT

Commercial Snow Crab (*Chionoecetes opilio*) harvesters believe marine noise from seismic surveys reduces commercial Snow Crab catch rates. Depending on the type of seismic survey used, animals living in a particular area could be exposed to loud noise (e.g. daily Sound Exposure Level (SEL) > 165 dB re 1 $\mu Pa^2 \cdot s$) for periods ranging from hours (typical 2D survey) to months (detailed 3D survey). This field experiment applied a series of comparisons conducted within a Before-After-Control-Impact study design to investigate the effect of prolonged industrial 3D seismic exposure on the catch rates of Snow Crab over nine weeks in 2017 and five weeks in 2018. Changes in catch rates at 3D seismic surveying sites were inconsistent across years, with reduced catches in 2017 and increased catches in 2018. Catch rates were similar at experimental and control sites within two weeks after exposure, and the potential effect of seismic surveying was not measured at a distance of 30 km. The large variation in catch rates across small temporal and spatial scales coupled with the absence of notable mechanistic responses of Snow Crab in past studies to seismic in associated snow crab movement behavior, gene expression and physiology, we conclude that the observed differences owing to seismic surveying in our study design are likely a result of stochastic processes external to our manipulation.

1. Introduction

Marine industries continue to expand (e.g. shipping, fishing, oil and gas development among many others) and as a result oceans are becoming increasingly noisy (Hildebrand, 2009; Martin et al., 2019). The potential impact of marine noise is a growing concern, particularly for harvesters of commercial species. Unfortunately, there is a general absence of field data to evaluate these concerns, even for valuable invertebrate fisheries (Carroll et al., 2017; Popper and Hawkins, 2019).

Compounding the general lack of information of the effects of seismic surveys on marine species is the issue that the sound exposure associated with seismic surveys is very much context dependent (e.g. depth, bathymetry, bottom type, weather etc.) (Jensen et al., 2011,Matthews and MacGillivray, 2013). Additionally, industry can apply both 2D and 3D survey designs in which the former is typically designed for broad spatial coverage with widely-spaced transects (e.g. Morris et al., 2018) and the latter in a localized area with more closely-spaced transects to achieve high spatial resolution (Caldwell and Dragoset, 2000; Gisiner, 2016). Consequently, despite similar noise sources used in both survey approaches, exposure profiles to biota can be very different across time and space. Specifically, resident or low mobility animals within 3D survey grids will experience more sustained exposures (Hirst and Rodhouse, 2000), which could in turn result in effects that would not occur after exposure to 2D surveys.

In Atlantic Canada, invertebrates such as Snow Crab (Chionoecetes opilio) support the highest valued fisheries (http://www.dfo-mpo.gc.ca/stats/commercial/sea-maritimes-eng.htm). Harvesters in the Newfoundland and Labrador region of Canada believe that noise created during seismic surveying on offshore commercial fishing grounds negatively affects catch rates of Snow Crab despite results of field studies to the contrary (Morris et al., 2018). However, since existing research was evaluated using 2D surveys, there remains a possibility that the longer duration exposures from 3D surveys might illicit different or more pronounced behavioral responses that might affect catch rates. The objective of this study is to examine whether long duration/locally intense 3D seismic surveying alters commercial Snow Crab catch rates.

2. Methods

2.1. Study areas

This study was conducted opportunistically in association with two industry 3D seismic surveys that took place on important commercial Snow Crab fishing grounds along the continental slope edge of the

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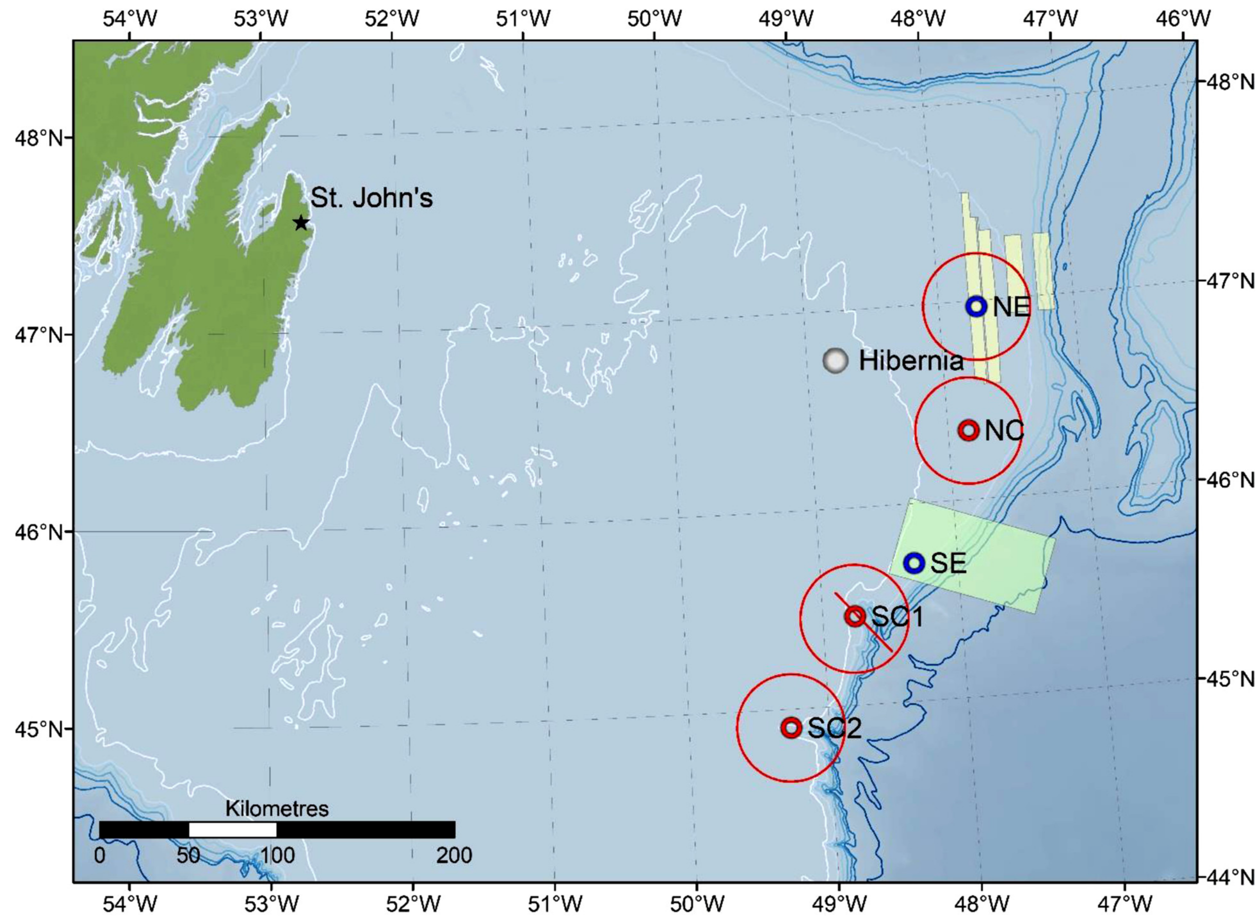

Fig. 1. Locations of the sorthern study area (including the Northern Experimental site (NE), the Northern Control site (NC)), and the southern study area (including the Southern Experimental site (SE) and the Southern Control sites (SC1 and SC2)). SC1 is also the location of the 2D seismic exposure. The 2D seismic survey line is indicated by the line passing across SC1. Red circles (30 km radius) indicate the distance beyond which siesmic noise would attenuate to a level that is less than a fishing vessel. . The 3D survey areas are located at the NE and SE areas, indicated by the light shaded rectangles. The location of the Hibernia oil platform is included for reference (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Grand Bank off Newfoundland, Canada (Fig. 1). Across this area, large male Snow Crab are known to move tens to hundreds of kilometres and exhibit an ontogenetic movement to deeper water over the course of their lives (Mullowney et al., 2018). Commercial Snow Crab also exhibit different behavioral patterns over shorter time scales, potentially associated with feeding and foraging, however recent research suggests that these short-term movement patterns are not strongly affected by 2D seismic surveying (Cote et al., 2020).

Field experiments were conducted at our southern study area in 2017 and northern study area in 2018. Each area had a control and exposure site, and sites within each area were selected for similar bathymetric and oceanographic conditions. During the study period, water temperatures at our median fishing depth of 155 m was very similar in both 2017 and 2018 for all study sites; with mean temperatures at each site ranging from 0.2–1.2 ˚C (range: -0.4˚C to 2.4˚C) (CMEMS Global Reanalysis, http://navigator.oceansdata.ca, 2020).

The southern study area, assessed in 2017, included three sampling sites; two control sites (SC1 at Carson Canyon and SC2 at Lilly Canyon) and a 3D exposure site (SE ~30 km north of SC1-Carson Canyon). The northern study area was assessed in 2018 and included a site (NE) that was exposed to 3D seismic and a single control site (NC). Control sites in each study year were placed at least 30 km from exposure sites to ensure that daily sound exposure levels from seismic sound did not exceed that of a fishing vessel. This sound threshold was selected based on the assumption that fishing vessel noise is not considered to be detrimental to Snow Crab catch rates by harvesters.

2.2. Seismic noise exposure

The 3D seismic exposures in both 2017 and 2018 were conduced from the *Ramform Titan* (2017) and *Ramform Stirling* (2018); industry vessels operated under similar seismic protocols, and using the same sound source specifications and array configuration. The energy source used by the vessels included a source volume of 4130 in^3, operated at 2000 psi, with a 25 m shot spacing (~10 s sec) towed at a depth of 7 m. In 2017 the seismic survey was conducted at SE from August 2 to October 4, and progressed from east to west, having parallel vessel transect survey lines spaced 800 m apart. During 2018, the survey at NE occurred from July 8–24 and from August 7–26, and also progressed from east to west, using transect lines spaced at 700 m. The east-west progression used in both surveys meant that sound exposure was intensifying in the experimental exposure areas during the survey.

In addition to 3D exposures, a single vessel pass (2D seismic exposure) was conduced by the seismic survey vessel *Atlantic Explorer* at site SC1 on September 12, 2017 to differentiate potential 2D and 3D exposure effects. This 2D exposure replicated seismic exposures described by Morris et al. (2018) and utilized the same vessel, seismic array (4880 in^3 seismic source array, −10 s shot interval), and vessel path as that study.

2.3. Acoustic measurements and soundscape

Acoustic recordings were taken for the duration of the study using Autonomous Multichannel Acoustic Recorders (AMARs, JASCO Applied

Sciences) located on the seabed. One AMAR was deployed at each study site, with the exception of SE, and were affixed to frames that held the hydrophones -0.6 m above the seafloor. Each AMAR was equipped with Geospectrum M36-V0−100 hydrophones with a nominal sensitivity of -200 dB re 1 V/μPa and sampled at 16 or 32 kHz. The recorder at SC1 in 2017 was directly below the 2D exposure track line (September 12, 2017), whereas the NE recorder in 2018 was 100 m from the track line on August 24, and 400 m from the track line on August 21, 2018. The recorders sampled a range of sound exposures over several weeks as seismic surveying approached from the east and as transect lines were surveyed in northerly and southerly directions. The daily sound exposure level (SEL) was used to quantify sound energy since this metric is generally regarded as the best predictor of hearing threshold shift as a result of long-term sound exposure on marine life (e.g. Popper et al., 2014; NMFS, 2018). The SEL is the arithmetic sum of each second's sound pressure level (SPL) in the frequency band $10-7000$ Hz over each 24-h period (UTC). Seismic surveys in this study ranged from 0.1–152 km from a sound recorder and SEL was estimated for all relevant distances. For locally intense exposures to seismic survey sound, the daily SEL is also a relevant metric since the SEL accumulates almost entirely from the local exposure (Martin et al., 2019). Daily SEL also facilitated comparison between the long-term sound exposures over a day from a distant seismic survey and our baseline for normal noise levels - the local operation of a fishing vessel (Morris et al., 2018).

2.4. Snow crab catch rates

Commercial Snow Crab harvesters conducted all fishing operations for this experiment, using typical industry fishing methods and gear (i.e., crab traps). Sampling methods in this study followed that of Morris et al. (2018) who used an established fishing-industry based survey (Stansbury et al., 2013). Sampling included 10–20 long-line type fishing fleets per site, with each fleet consisting of 10 commercial Snow Crab traps along the line (45 m spacing). Each pot was baited with approximately 1.5 kg of squid and set for $12-18$ hours. Commercial-sized Snow Crab (>95 mm carapace width) were counted from all traps.

During 2017, experimental fishing was conducted at the southern area, and included the exposure site (SE) and two control areas (SC1 and SC2). Harvesting in this year started at each site six weeks after 3D seismic surveying was initiated in the region. Therefore no pre-seismic experimental sampling data were available in 2017. Consequently the experimental design was During-After-Control-Impact (DACI). The catch data collected "During" seismic represented crabs that were experiencing seismic exposures that increased as the vessel progressively approached the fishing location; fishing was conducted when the seismic survey was closest to the sampling location. Sampling was conducted again two weeks "After" all seismic exposure ended in the region. Concurrent Snow Crab sampling was also conducted at the southern control sites (SC1 and SC2).

During 2018, experimental fishing was conducted in the northern area. Sampling included four periods; before-seismic (July 5–7), after-distant seismic (15–40 km from sound source; August 4–7), immediately after close-proximity seismic (at least one seismic pass within 5 km each day August 23–26), and two weeks after all seismic surveying ended in the region (September $10-12$). Catch data during these time periods were collected at both the exposure (NE) and control (NC) sites.

2.5. Commercial fisheries log book data comparison

A key assumption of BACI designs is that control and impact areas are similar in nature and thus control for environmental variables beyond the experimental manipulation. We evaluated this assumption by examining naturally occurring spatiotemporal variability in commercial catch rates (CPUE) for two Crab Management Areas (CMAs 3LEX and 3N200) in which our seismic experiments were located (see Mullowney et al., 2019 for details). Commercial fishing data did not coincide with our experimental data since the commercial harvesting was completed earlier in the season. To examine variability in commercial catch rates, data on catch and effort were binned to 5-day increments and CPUE medians were plotted for visual assessment. In both CMAs, excluding the fishery start (i.e. days $105-120$) and end (i.e. days 195–215) periods, sample sizes of both catch and effort were consistently large ranging from $5-250$ t and 1,000–20,000 trap hauls per 5-day time units in each CMA. Synchrony of CPUE trends across CMAs were examined using linear regression models of mean CPUE for each 5-day time bins. This analysis was done for each year.

Sampling in this study is also meant to represent the commercial fishing in the region. We evaluated this by comparing our experimental catch rates with commercial catch rates using fisheries log book data, and tested for differences in catch rate slopes across the two data series (fishery versus experimental) using the following linear mixed model (LMM, lme4 extension, R Core Development Team 2015).

CPUEdiff = ln(CPUE) ~ year*source + site:source + site + 1|site:year:source

The model regressed the response variable of natural log-transformed CPUE against the main effects of year, site, and source (logbooks versus experimental) and the interactions of source with both year and site. Catch rate data from July were included in the analysis because it was temporally closest to our experimental sampling period. A random intercept of the interaction of site, year, and source was included. Significance across data series was interpreted by the relative magnitude of the effect size of the year*source interaction and model fit was assessed by visual assessment of the residuals.

2.6. Analysis of seismic effects on catch rates

This study incorporated a similar design, sampling methodology, and statistical analysis as that described by Morris et al. (2018). Generalized linear models using negative binomial error structures were applied to these count data. Mixed effects models and associated likelihood ratio tests were used to meet model assumptions related to sample independence and to assess differences of effect. The generalized linear mixed effects model (lme4 package in R 3.3.3; R Core Development Team 2015) used total counts of Snow Crab within a trap as the response variable, Temporal Period (Before/During/After in 2017 for 2D seismic; During/After Exposure in 2017 for 3D seismic; Before/During Distant Seismic/During Seismic/After Seismic in 2018 for 3D seismic) and Exposure Treatment (Control/Exposure) categorical variables as the fixed effects and the fleet of traps as a random effect. For the 3D seismic experiment in 2017, two control sites were monitored so a second random effect was fitted for the study area to account for potential dependencies of catch rates within the two control sites. Depth was also included as a continuous explanatory variable in the statistical model (Morris et al., 2018).

Thus the following three models were applied:

2.6.1. 2-D experiment

Total Snow Crab ~ Exposure Treatment*Temporal Period + Depth + (1|Fleet ID)

2.6.2. 3-D experiment

Total Snow Crab ~ Exposure Treatment*Temporal Period + Depth + (1|Fleet ID) + (1|Study Area)

2.6.3. 3 -D experiment

Total Snow Crab ~ Exposure Treatment*Temporal Period + Depth + (1|Fleet ID)

For both years, the statistical interaction between spatial and temporal fixed effects was the key model term to isolate seismic-related

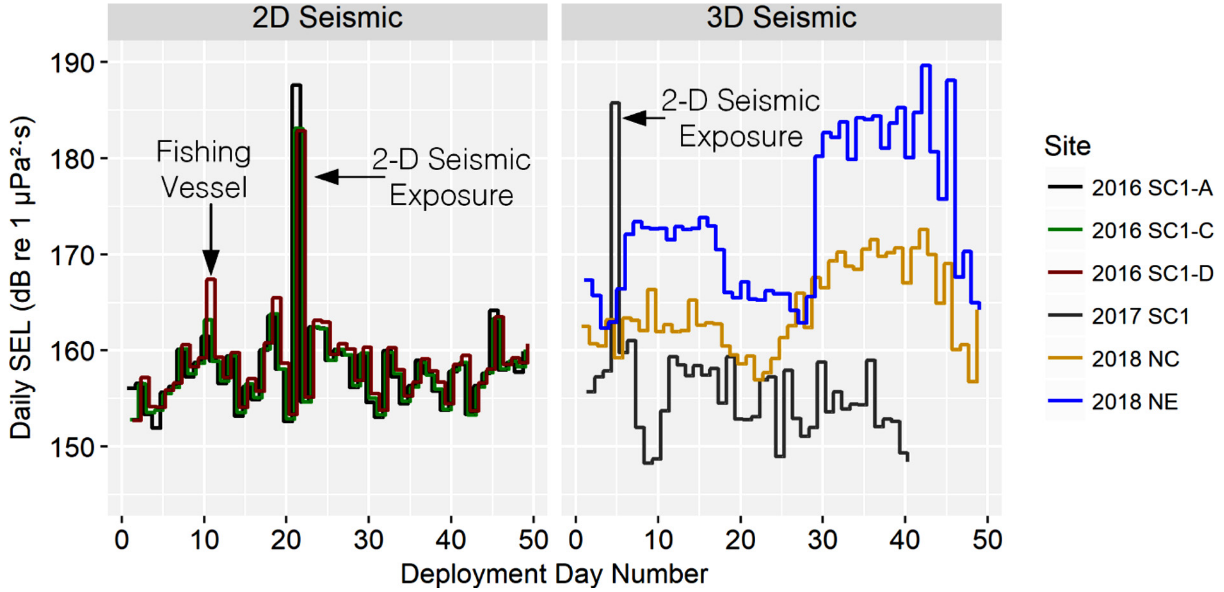

Fig. 2. Comparison of the daily SEL (10-7000 Hz) measured during 2D and 3D seismic surveys. 2D data from 2016 is from Morris et al. (2018) and is included here for comparison. The 2017 SC1 site was exposed to the experimental 2D seismic survey on 12 Sep 17 (day 4 of the 3D Seismic Panel), as well as a 3D seismic survey to the North-East that had a closest point of approach to SC1 of −38 km when the recorders were present (see Fig. 1). No seismic vessels approached closer than 70 km to the 2016 SC1 sites except the 2D experimental exposure on 22 Sept (day 21 in the 2D Seismic panel). A fishing vessel that was not part of the experiment passed almost directly over recorder SC1-D on 12 Sep 16 (day 11 in the 2D Seismic Panel).

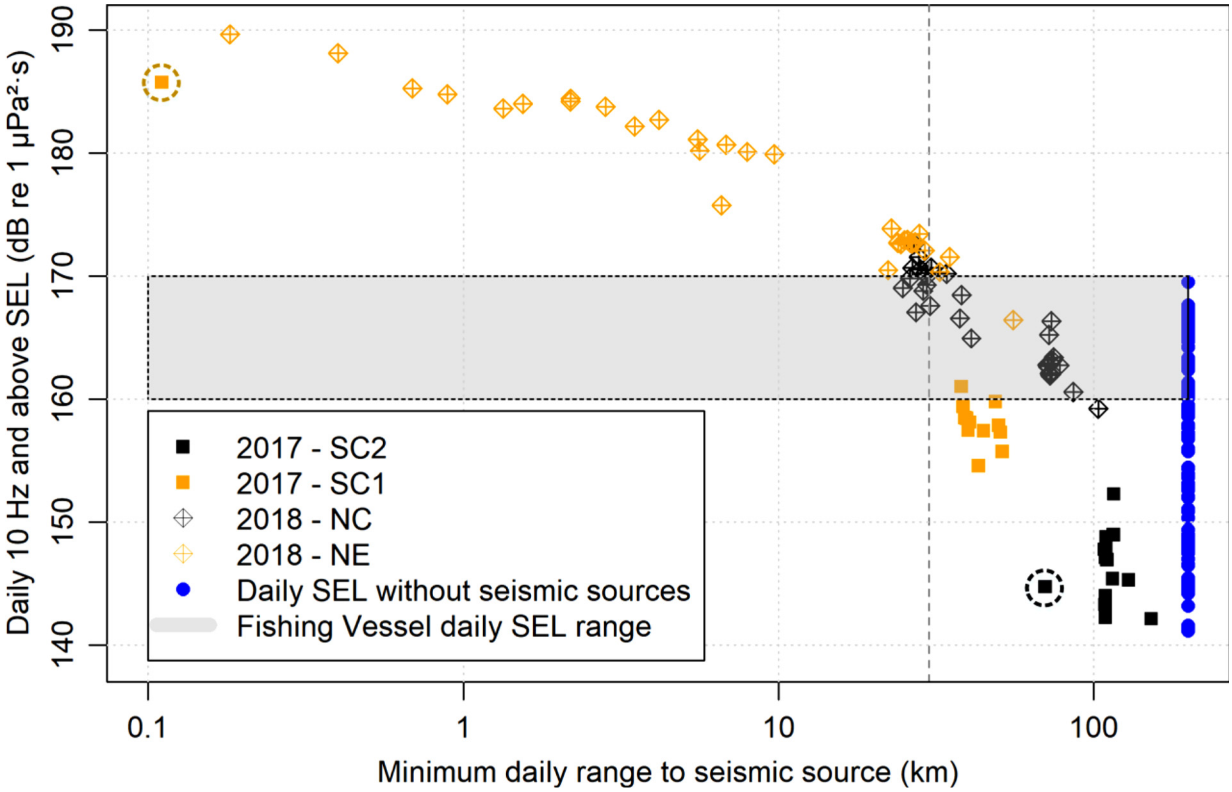

Fig. 3. Daily SEL vs minimum range to the seismic source. The vertical dashed line is drawn at 30 km range. The gray box indicates the values of daily SEL expected at the seabed when a fishing vessel is operating near a recorder (0-1 km distances). The dashed circles around one of the 2017 SC1 and SC2 markers indicate the levels associated with the 2D seismic survey. The remainder are associated with the 2017 3D seismic survey. The 2017 SC1 2D data point is lower than the actual daily SEL because the hydrophone was overloaded when the source was directly over the recorder.

effects within this Before-After-Control-Impact (or During-After-Control-Impact) study design. Accordingly, each year's full model was compared (Chi-square test) to a reduced model that excluded the interaction term, to determine if the model performance was significantly degraded by the exclusion of the interaction term. Model assumptions were evaluated by examining residuals.

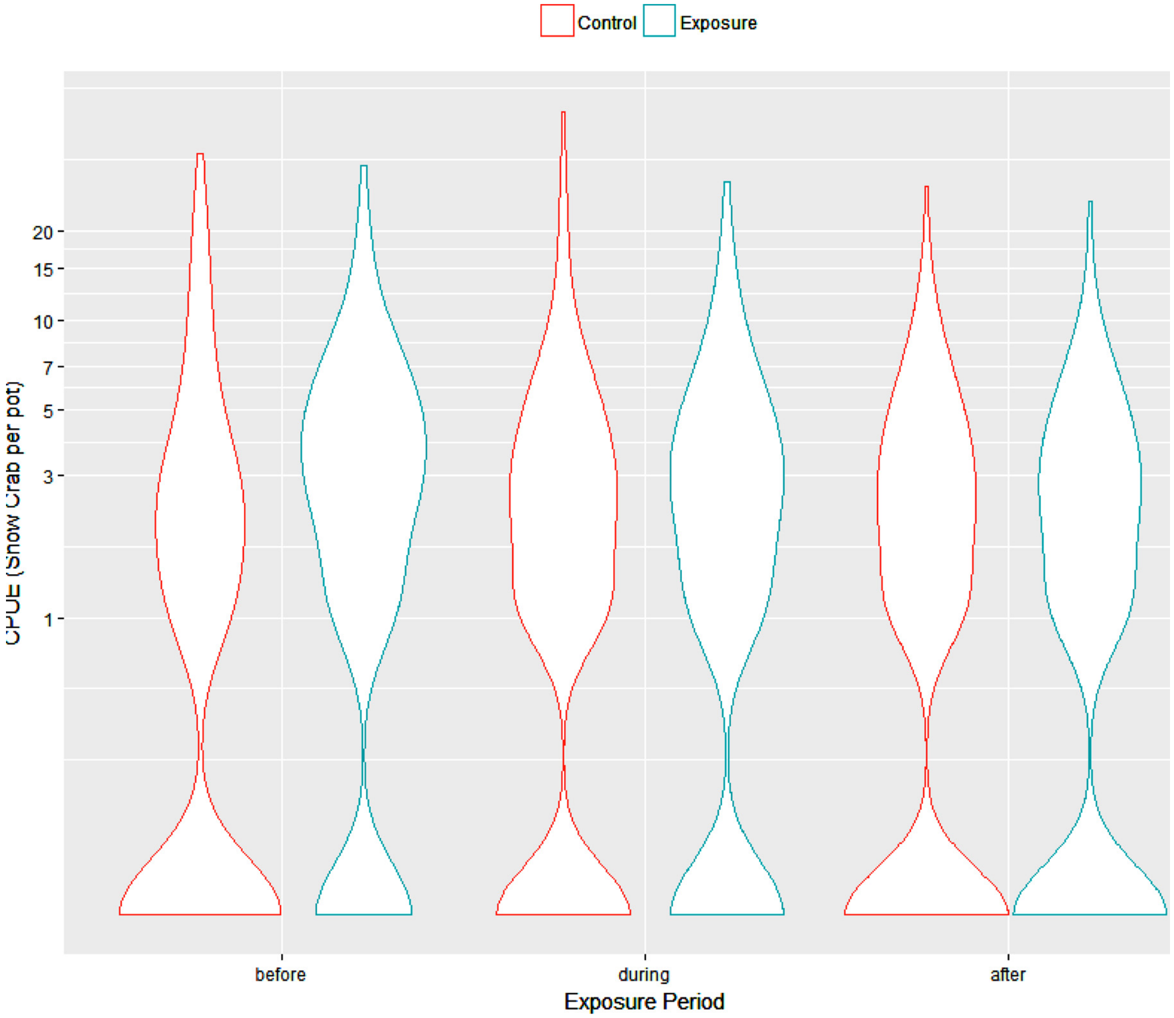

Fig. 4. Catch rates (CPUE) of snow crab Before Seismic, During 2D Seismic and After Seismic at control and exposure sites on the Grand Banks of 2017. Violin plots represent frequency distributions of catch rates across pots. Catch rates did not differ across exposure or temporal treatments.

Table 1

Sampling study design, 3D seismic exposure periods, fishing periods and average catch per pot during 2017 and 2018.

Year	Area	Study design	Site	Seismic period	Fishing dates	Avg. CPUE
2017	Southern	During seismic	Control 1 (SC1)	Sept 12 (2D-7.5 h)	Sept 9 – 10 and 12 – 13	3.8
			Control 2 (SC2)		Sept 7 – 9	6.3
			Experimental (SE)	Aug 2-Oct 4	Sept 14 – 15	1.5
		After seismic	Control 1 (SC1)		Oct 16 – 18	2.9
			Control 2 (SC 2)		Oct 19 – 20	3.8
			Experimental (SE)		Oct 20 – 21	2.9
2018	Northern	Before seismic	Northern Experiment (NE)		Jul 5 – 6	0.6
			Northern Control (NC)		Jul 7 – 8	0.8
		During seismic (15 – 40 km)	Northern Experiment (NE)	Jul 8-Jul 30	Aug 4 – 5	1.5
			Northern Control (NC)		Aug 6 – 7	0.8
		During seismic (0–5 km)	Northern Experiment (NE)	Aug 8 – 24	Aug 25 – 26	1.8
			Northern Control (NC)		Aug 23 – 24	0.5
		After seismic	Northern Experiment (NE)		Sept 11 – 12	0.8
			Northern Control (NC)		Sept 9 – 10	0.6

3. Results

3.1. Sound exposures

Sound levels in the ocean, in the absence of human generated sound, depends largely on the wind speed, which controls wave height and by extension the sound generated by breaking waves (Carey and Evans, 2011). Changes in wind speed resulted in daily SEL in the range of 145 – 165 dB re 1 μPa^2·s that are within −1 dB of each other when measured in the same area (e.g. sites SC1-A, SC1-C and SC1-D in the 2D Seismic panel of Fig. 2). Human activities add sound sources to the environment that can raise the daily SEL in a location-specific manner;

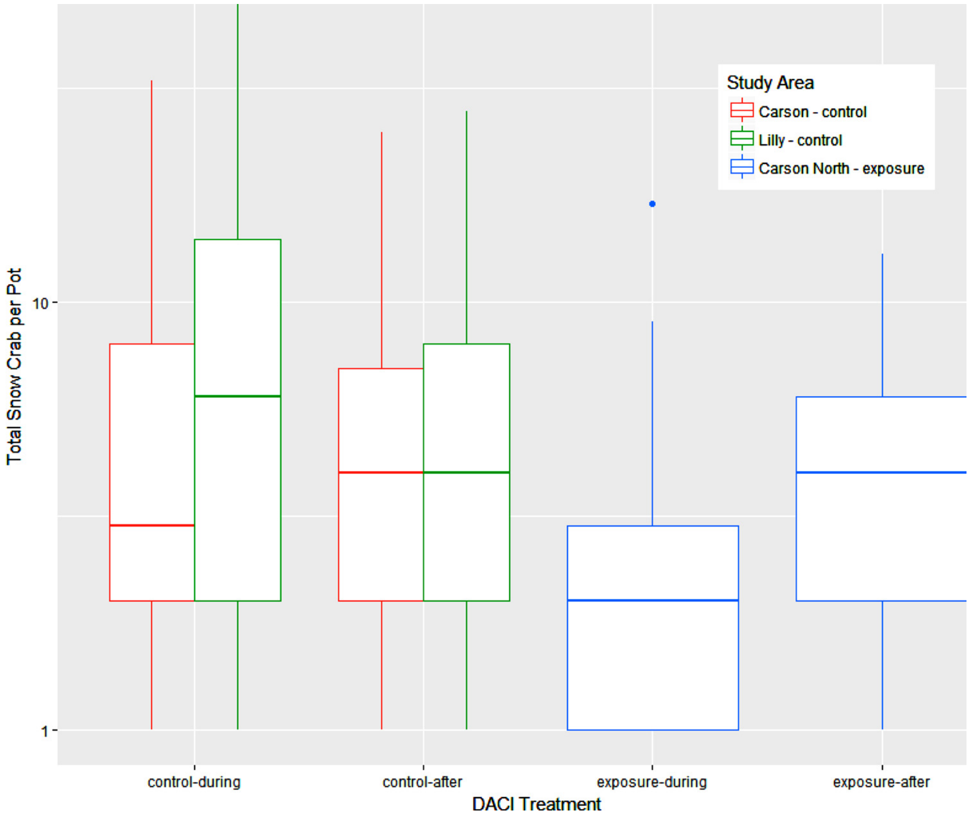

Fig. 5. Catch rates (CPUE) of snow crab during 2017, at the southern area control sites (30 and 100 km away from 3D survey) and 3D seismic survey exposure site. Sampling was conducted during 3D seismic survey exposure period and 2 weeks after the seismic survey was completed.

for example the daily SEL differed by 5−8 dB at sound recorder-sites SC1-A, -C and -D depending on whether the seismic source or the fishing vessel passed close to the recorder (for more on the effects of distance to sources on daily SEL see Morris et al. (2018) or Martin et al. (2019)). 2D seismic surveys increased the daily SEL by −30 dB in the project area only on the day that the seismic vessel passed over the site. 3D seismic surveys, which remain in an area for weeks to months, increase the daily SEL for the survey period (Fig. 2, 3D Seismic panel). Within the survey period however, the received sound level near a 3D seismic survey increases and decreases as the vessel approaches and then departs an area (e.g. Fig. 4 of Martin et al., 2017). The minimum distance from the survey is the primary determinant of the daily SEL (e.g. NC compared to NE), however, multiple passes in one 24 -h period can also increase the daily SEL compared to a 2D survey.

Daily SEL is very dependant on the distance from the seismic source (Fig. 3). For example, the daily SELs from 2017 at SC1 were −10 dB lower than those from 2018 at NC when the seismic source was at the same distance from the recorder (Fig. 3). This was due to the effects of increased attenuation at the 2017 seismic survey location, where the sound from the source travelled upslope from deep water, compared to the 2018 seismic survey conducted on the shelf (Fig. 1; see Jensen et al. (2011) for a discussion of upslope propagation). The use of SEL as the sound metric allowed comparison between the exposure to seismic surveys and a fishing vessel (Fig. 3). At a distance of 30 km from the seismic survey, 40 of 43 daily SEL results associated with the 3D seismic surveys were below the daily SEL of a fishing vessel, and all seismic SEL exposures at a distance of more than 38 km from the survey were below the fishing vessel daily SEL.

3.2. 2017 2-D seismic study

The interaction between exposure treatment and time period was not significant ($\text{Chi-square}_{d.f.=2} = 3.25$; $P = 0.197$) indicating that 2D seismic exposure did not influence catch rates of Snow Crab (see Fig. 4). Water depth, however was a significant factor in explaining catch rate variability ($\text{Chi-square}_{d.f.=1} = 88.8$; $P < 0.001$).

3.3. 2017 3-D seismic study

The DACI trial in 2017 revealed a significant interaction between exposure site and exposure period ($\text{Chi-square}_{d.f.=1} = 6.87$; $P = 0.009$), indicating the temporal response to seismic exposure differed across control and exposure treatments. Specifically, CPUE of Snow Crab was greater two weeks After Seismic surveying exposure than it was During Seismic surveying exposure at the Exposure Site (Table 1; Fig. 5).

3.4. 2018 3-D seismic study

In 2018, the full model that included the interaction term between exposure period and site was significantly better than the reduced model that excluded the interaction term ($\text{Chi-square}_{d.f.=3} = 17$; $P = 0.001$). The importance of the interaction term signified an apparent effect of seismic. Model results indicate that the catch rates at the control site during 3D exposure did not differ from any other time period ($P > 0.05$ for all comparisons; Table 1; Fig. 6). In contrast, the catch rates During 3D exposure at the Exposure site was significantly higher than both the Before 3D Seismic ($P < 0.001$) and After 3D Seismic ($P < 0.001$) treatments but not the After Distant 3D Seismic treatment ($P = 0.145$; Table 1, Fig. 6).

3.5. Commercial and experimental catch rates

There was little difference in the CPUE trend over the time series between the commercial fishery and our experimental fishing (Fig. 7). The commercial fishery catch rates declined from a high in 2015,

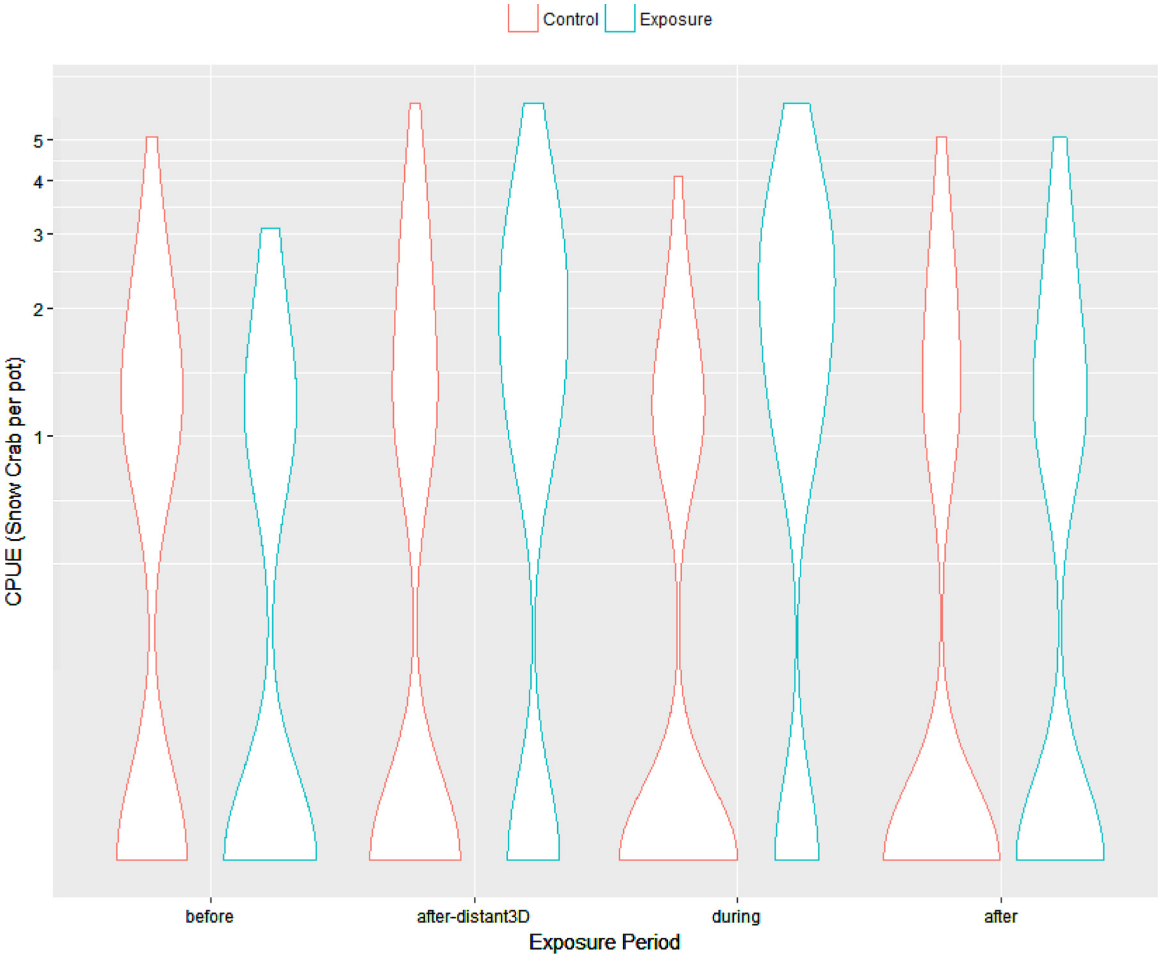

Fig. 6. Catch rates (CPUE) of snow crab during 2018 at the northern areas control site and seismic exposure site. Sampling included Before Seismic, immediately after Distant 3D Seismic, During close proximity 3D Seismic, and 2 weeks After Seismic surveying was completed. Violin plots represent frequency distributions of catch rates across pots. Control Site catch rates did not differ across temporal periods but Exposure Site catch rates During Seismic were significantly higher than Before or After periods.

generally averaging about 5 − 12 kg/trap across sites, to a low in 2017–2018, ranging from about 2 − 5 kg/trap on average. The LMM analysis did not detect a significant effect size of the year:source interaction (t = 0.626), confirming no difference in the slopes of catch rate trends over the time series between the two survey series.

Like the seismic exposure experiments, catch rates in the commercial fishery were variable over short time periods, in different years, and in different fishing areas (Fig. 8). In 2017, we measured a 95 % reduction in catch During seismic compared to two weeks After seismic. In 2018 with pre-seismic data, we measured an increase of 204 % after several weeks of seismic exposure, then a decrease to 43 % of the pre-seismic baseline two weeks after seismic surveying ended. Average commercial snow crab catch rates in the region conducted before any seismic surveying started, in both 2017 and 2018, showed similarly large variation in catch over short time periods (Fig. 8), for example, changing as much as 116 % and 236 % from one five day period to next in 2017 and 2018 respectively. There was also little congruence in temporal trends across commercial fishing areas (Fig. 8).

4. Discussion

Data analysis in this study show that catch rates of Snow Crab were altered upon exposure to 3D seismic, which was in contrast to observations associated with 2D seismic exposure (this paper, Morris et al., 2018). However, the direction of the effect was unpredictable; with lower catch rates observed one year and higher the next. In a multi-year 2D seismic study conducted at the same locations used in our southern study area, Morris et al. (2018) were unable to detect effects of 2D seismic on catch rates of Snow Crab over time periods that ranged from days to weeks. While high variability in catch rates limited statistical power in their study, catch rates were observed to change across time and space suggesting that if effects did exist they were smaller than natural fluctuations.

General responses of invertebrates to seismic exposure vary across studies, ranging from no effect to quite severe impacts (Andriguetto-Filho et al., 2005; Day et al., 2019; Carroll et al., 2017). In part these differing conclusions can result from species-specific sensitivities (Løkkeborg et al., 2012), environmental conditions (Przeslawski et al., 2018), study-design issues (McGaw and Nancollis, 2018; Hawkins and Popper, 2017; Popper and Hawkins, 2018), and poor ecological understanding regarding impacts of noise on invertebrates.

Experimental differences in sound exposures across the years of study do not seem a likely explanation for the divergent trends observed in this study. Indeed, the lower intensity sound exposures in 2017 were associated with the reduced catch rates. Generally however, several weeks of industrial seismic surveying at each of our study areas represents the upper-limits of sound exposure expected from realistic oil and gas exploration, and both surveys incorporated wide variation in sound exposure, that might impact Snow Crab. Alternatively, Snow Crab responses to seismic may be complex and modified by external environmental conditions. Unfortunately, our ability to reconcile seemingly contradictory catch rate results across years is hampered by

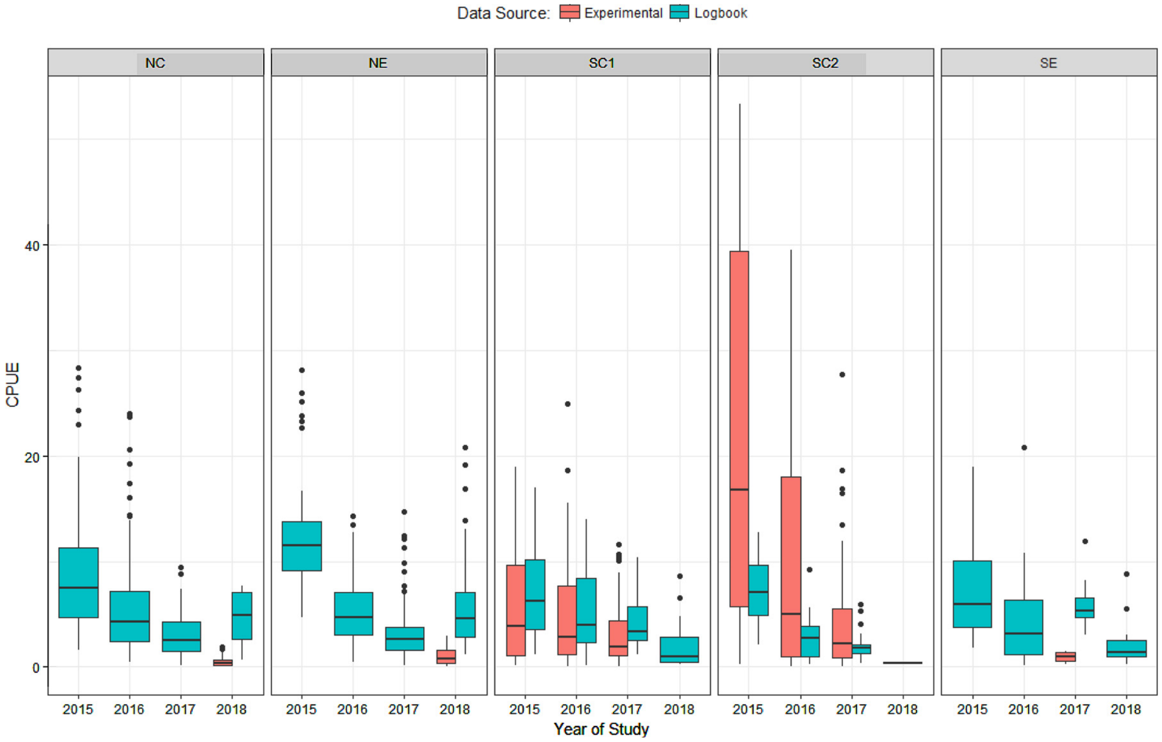

Fig. 7. Experimental and Commercial Snow Crab Catch Per unit Effort data. Commercial data was collected by at-sea fishery observers aboard commercial fishing vessel during the fishing season (July) in the vicinity (within 20 km) of our study area.

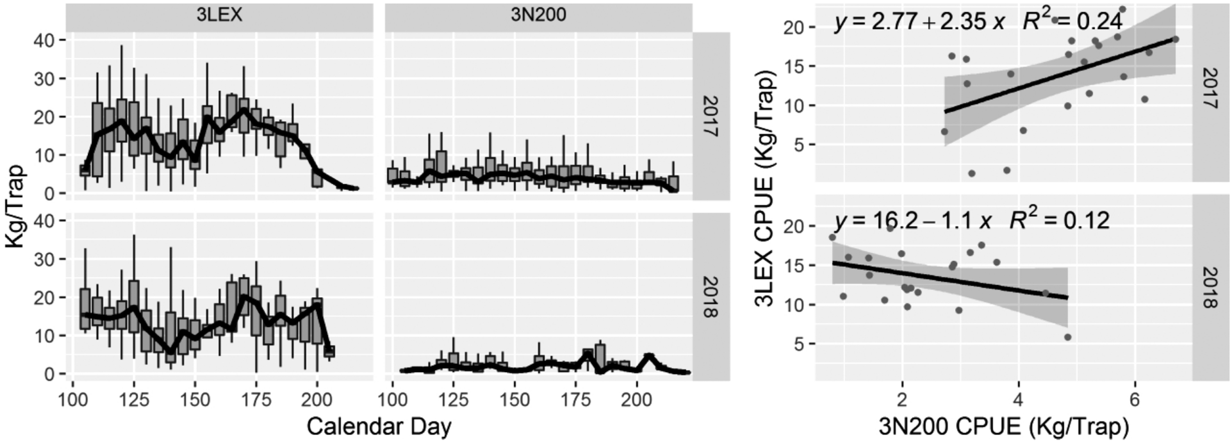

Fig. 8. Commercial Snow Crab catch rates in 2017 and 2018, before seismic surveying, for two management areas in which our experiments were conduced. Median catch rates by the commercial Snow Crab fleet is represented in 5 day intervals, each interval included 5-250 t of caught-crab and 1000-20,000 trap hauls. Areas with high (3LEX) and low (3N200) catch rates are represented.

limited knowledge of Snow Crab behavior. Although this knowledge has increased in recent years, behavior of this species is not well explained by typically important environmental variables such as light, temperature and water velocity (Cote et al., 2019, 2020). Snow Crab fisheries data indicate however, that our study region is in flux with Snow Crab abundance experiencing a pronounced multi-year decline. The stock has shown strong responses to both climatic forcing and chronically heavy exploitation (Mullowney et al., 2014; Mullowney et al., 2019). Total mortality estimates in commercial-size male crab routinely range from 50 to 90% per year in the absence of seismic interference (Baker et al., 2019). While seismic activity has not been implicated as the primary driver in these declines (Mullowney et al., 2014; Mullowney et al., 2020), such conditions leave the possibility of density-mediated responses to seismic exposure. The mechanism behind such a scenario is not obvious, however.

Since we cannot readily explain divergent responses in catch with respect to seismic survey exposure across years, we also accept the possibility that these results may have arose due to external drivers on catch rates (environmental or stochastic) that are unrelated to seismic exposure. While there has been a decline in Snow Crab abundance over time, as we showed in our examination of commercial fishing throughout the season, Snow Crab catch rates can be highly variable in nature, over small spatial and temporal scales similar to that measured in response to seismic exposure in this study. While BACI study designs are considered more robust than simple before-after designs, they still have limitations within such variable study systems, since controlling for environmental factors outside of the experimental manipulation may not be possible (Underwood, 1992). One solution to overcome such issues is to expand the replication of control sites to account for broad level variability (Underwood, 1992). We did this to some degree by including two control sites in 2017 but further replication is likely infeasible across the large spatial scales and given the complex logistics required for research incorporating realistic seismic oil and gas surveys over multiple years. Instead we suggest it is more prudent to utilize multiple lines of evidence in addition to catch; exploring behavioral and physiological mechanisms that might help to explain catchability changes under field conditions, and by supporting such field studies with controlled lab studies.

Like this study, the assessment of 2D seismic surveys on catch rates was challenged by high natural variability in catch rates (Morris et al., 2018). However, multiple lines of evidence were used to support the assessment of 2D seismic effects on Snow Crab, including animal movement behavior (Cote et al., 2020), physiology (Hanlon et al., 2020) and genomics (Hall et al., 2020), that indicated a similar result; i.e. any observed effects were subtle. Some of these results are instructive to the interpretation of our 3D survey results. For example, Snow Crab exposed to 2D surveys did not show strong behavioural responses, particularly when compared to other environmental variables (Cote et al., 2020). Since sound sources used in 2D and 3D surveys are similar, behavior would also not be expected to change after short-term exposure to 3D surveys. Any potential change in behavior would have to arise from the prolonged exposure associated with 3D surveys. However, the prolonged exposures of Snow Crab to seismic noise in the laboratory (Hanlon et al., 2020) did not result in physiological or morphological responses even though the exposures were considered unrealistically high (Hanlon et al., 2020). Collectively, these studies lend support to our supposition that the observed effects of seismic surveying on catch rates were driven by spatiotemporal variation external to the seismic exposures. Nevertheless, we cannot rule out the potential for 3D seismic surveying to affect commercial Snow Crab catch rates. If 3D seismic does indeed have an impact, the effect remains unpredictable, both in magnitude and direction, and occurs at modest temporal (i.e. within a 2 week period) and spatial scales (< 30 km radius).

CRediT authorship contribution statement

Corey J. Morris: Conceptualization, Methodology, Investigation, Validation, Resources, Writing - review & editing, Supervision, Project administration, Funding acquisition. **David Cote:** Investigtaion, Methodology, Formal analysis, Validation, Visualization, Writing - original draft, Writing - review & editing. **S. Bruce Martin:** Conceptualization, Methodology, Formal analysis, Validation, Software, Writing - review & editing. **Darrell Mullowney:** Investigation, Formal analysis, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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