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Perspective

Effects of closing bottom trawling on fisheries, biodiversity and fishing communities in a boreal marine ecosystem: the Hawke Box off Labrador, Canada.

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Keywords: Hawke Channel, boreal marine ecosystem, closed area, fishery management, cod, bottom trawling, snow crab.

Abstract

The Hawke Box is an offshore area (8610km²) of the boreal Northwest Atlantic that at the request of local fishers was closed to trawling and gillnetting in 2003, but remained open to seasonal snow crab (*Chionocetes opilio*) pot fishing. Closure was a precautionary management measure primarily to sustain the crab fishery and secondarily to conserve cod known to aggregate there. Fall (1996-2013) and spring (1996-2003, 2015) surveys indicated that biological community assemblages changed significantly before-after and inside-outside the closure (Permanova $P_s < 0.01$). Crab fishery data (1996-2013) indicated that landings and relative production declined throughout the region post-closure, but significantly more outside than inside. Atlantic cod (*Gadus morhua*) increased inside and outside the closure and several other demersal species increased significantly more inside. The Hawke Box provides a unique boreal area for the study of restrictions on trawling and gillnetting in an area with historically strong fisheries, restrictions that are strongly supported by local fishers. The overall evidence suggests that within a decade the Hawke Box has benefited fisheries communities, fisheries production and biodiversity conservation.

Introduction

Closures to fisheries have been a management tool for centuries (Johannes 1978; Johannes 2002; Cinner et al. 2005), typically to protect spawning or juvenile fish and in some cases to benefit broader conservation concerns (Gell and Roberts 2002; Kaunda-Arara and Rose 2004; McClanahan 2010). Closures have also become a tool to conserve biodiversity, often as marine protected areas (MPAs). More recently, conservation and fisheries management goals have been converging (Gaines et al. 2010; Rice et al. 2012) under more inclusive ecosystem-based management (EBM) regimes (Salomon et al.

2011). Implementing such closed areas remains controversial (Gell and Roberts 2003; Abbott and Hayne 2012), particularly in temperate seas where evidence of their effectiveness in meeting management objectives is often lacking (Auster and Shackell 2000).

Closures in temperate seas may be less effective than in tropical reef systems. Temperate regions tend to have wider ranging and migratory species which limits spatial coverage of entire life cycles (Le Quesne and Codling 2008; Link et al. 2011; Breen et al. 2015). In addition, response times to closures may be longer (Fisher and Frank 2002) as a consequence of relatively slow individual and population growth rates. Some positive outcomes of closures have been documented in temperate ecosystems (Murawaki et al. 2000), but there are few examples in higher latitude boreal regions where many of the world's largest fisheries occur (Caveen et al. 2012).

Analyses of the potential impacts of fishery closures are made complex by several factors. Control areas are often problematic to assign, and in particular, untrawled areas in trawlable habitat are rare (Atkinson et al. 2011), perhaps absent in boreal seas. In addition, few studies have long term multi-species data from before – after the closure needed to examine spatial and temporal ecosystem changes (Sweeting and Polunin 2005; Horta e Costa et al. 2013). Moreover, information is scarce on heavily fished boreal regions with soft sediments, and studies on similar areas in temperate seas have tended to focus on invertebrates and not on species assemblages or mobile species (Caveen et al. 2012). Adding to the complexity, fisheries and biodiversity studies often ignore the impacts of closures on fishing communities, which must occur if the tenets of EBM are to be followed (FAO 2005).

The boreal marine ecosystem of the Labrador continental shelf has supported major fisheries for hundreds of years (Rose 2007). Numerous coastal communities are highly dependent on these adjacent

67 fisheries. In early 2000s, the local fishing industry requested that the federal regulatory authority, the
68 Department of Fisheries and Oceans Canada (DFO), implement an area closed to bottom trawling and
69 gill netting within the Hawke Channel fishing area with the objective of the conservation of snow crab
70 fishing grounds (*Chionocetes opilio*), (DFO 2007; Kincaid and Rose 2014) (Fig. 1). Many of the fishermen
71 advocating the closure fished snow crab in the Hawke Channel, but also bottom-trawled for shrimp
72 (primarily *Pandalus borealis*), thus were requesting to exclude themselves. This advocacy was supported
73 by the then Fisheries Resource Conservation Council (FRCC), which advised the Minister of Fisheries on
74 groundfish, as it was thought that such a closure might also assist the rebuilding of highly depleted
75 spawning and juvenile cod (*Gadus morhua*) and other groundfish (Anderson and Rose 2001; FRCC 2003;
76 DFO 2007). Following recommendations from the Labrador fishing industry, a small area (1370km²) was
77 closed to bottom trawling and gillnets by DFO management in 2002 and expanded to 8610km² in 2003
78 (Mullowney et al. 2012)(Fig 1). This area is referred to as the “Hawke Box”. Since the closure, trap
79 fishing for snow crab is the primary fishery and is permitted seasonally inside the Hawke Box, under
80 license and quotas (approximately May-Sept depending on ice conditions) (Mullowney et al. 2012). In
81 2013, the crab fishery was certified by the MSC (Marine Stewardship Council). The fishery is based on
82 catches of larger male crabs (legal size limit 95 mm, MSC 2016).

83
84 The Hawke Box is the only known relatively long-term (14 years) closure of large area of an Atlantic
85 boreal continental shelf within a heavily fished area. Analyses of the impacts of the Hawke Box since the
86 closure have been limited to stock assessments of shrimp and snow crab (DFO 2013a, 2014).
87 Mullowney et al. (2012) conducted a Before-After-Control-Impact design, using fisheries data,
88 concluding that the partial closure had limited benefits for snow crab, largely as an unintended
89 consequence of increased snow crab fishing effort within the Hawke Box. Nonetheless, local fishers and
90 communities remained supportive of the closure as the basis for their fishery (Kincaid and Rose 2014)

that takes place inside and outside (mainly shrimp fishing) the Hawke Box. Thus, guidance on the broader effectiveness of the closure was needed for management. The present study was the first to address the effects of the closure on fishing communities, fisheries and biodiversity beyond the commercial crustaceans.

As a direct consequence of differing views on the effectiveness of Hawke Box management, this study was advocated for and supported by the DFO, the Newfoundland Department of Fisheries and Aquaculture (DFA), industry, communities and fishers to address the impacts of closed areas within a wider EBM approach as part of the Natural Sciences and Engineering Research Council of Canada (NSERC) Canadian Fisheries Research Network (CFRN). The study embodied the CFRN focus on integrating and utilizing cross-institutional expertise and knowledge with that of industry, fishers and communities, with the objective of enhancing ocean management in terms of both fisheries production and Canadian commitments to conserve biodiversity (Government of Canada 2011; Link et al. 2011).

The overall objectives of this study were to examine spatial and temporal changes in the communities and abundance of a range of fish and crustacean species after closure of the Hawke Box to bottom trawling and gill netting. To address the initial goals of protecting snow crab and cod and ongoing concerns of both industry and management, particular attention is paid to changes in the production and abundance of these species. In keeping with EBM policies, we discuss the impacts of the closure on adjacent fishing communities (Kincaid and Rose 2014).

Materials and methods

Hawke Channel

The Hawke Channel is located on the boreal northern Newfoundland-Labrador shelf (NAFO Subdivision 2J) (Fig. 1). The Channel reaches depths of over 500m but shallows to a basin with depths of 200-400m as it approaches the Labrador coast (Brown and Anderson 1999). The oceanography of the region is complex, but is dominated by the southward flowing cold and relatively fresh Labrador Current (to -2C and 35 psu) that is seasonally variable but blankets the area to depths of over 100m year-round (Colbourne et al. 1994). There is seasonal heating of near-surface waters. The Channel depths contain warmer and more saline Atlantic Ocean waters contiguous with the Labrador Sea year-round (2-4.5C and 32-33 psu) that reach shoreward to the interception of the Labrador Current with the seafloor providing a biologically rich area (Rose 1993).

The biota of the region is characterized by relatively few species that can reach high abundance but have the slow growth rates typical of boreal ecosystems (Rose 2007). Post-1950, this region was one of the most important cod fishing grounds in the world (Rose 2007), but since the decline of cod in the early 1990s the region has supported large fisheries for shrimp and snow crab (DFO 2013a, 2014). Also of economic and ecological importance in this region are redfish (*Sebastes* spp), Greenland halibut (also known as Turbot) (*Reinhardtius hippoglossoides*) and capelin (*Mallotus villosus*). Little was known of other species. The importance of the snow crab fishery in the Hawke Channel led directly to local fishing industry advocating closing the area to bottom trawling, primarily targeted at shrimp. In the Hawke Channel region, shrimp are trawled commercially year-round (occasional trawls are recorded inside the closure) (see Mullaney et al. 2012 for a spatial representation). Within the Hawke Box, prior to the closure, 500-2,500 shrimp trawls of varying duration occurred each year; post-closure crab pot fishing occurred for 3 months each year (Mullaney et al. 2012). Outside the closure, commercial bottom trawling for shrimp and gillnetting for Greenland halibut has continued, in addition to crab fisheries.

Data

Multispecies bottom trawl data from NAFO Subdivision 2J were compiled from the Department for Fisheries and Oceans (DFO) annual fall surveys from 1996-2013 ("fall surveys"). Surveys followed standardised protocols using a Campelen 1800 Shrimp trawl and random-stratified survey design (Walsh et al. 2009; Chadwick et al. 2007). All catches were standardised to 15-minute tows. Catch data from the Hawke Box (inside) and a reference area (outside) that surrounds the Hawke Box were used, following a similar method to Jaworski et al (2006) to identify the outside area. The "outside" area sets were limited to NAFO 2J below 54 degrees latitude, within similar depths (150-550m) and habitat types (soft mud and sand) as the Hawke Box (NL Seabed Atlas 2016). Survey indices were: biomass (calculated as kg per tow, per species) and abundance (calculated as number per tow, per species).

In addition, targeted acoustic-trawl fishing sets using the same vessel and gear as the DFO fall surveys have been conducted in the spring ("spring surveys") (between March-June) by the NSERC Industrial Chair in Fisheries Conservation, Memorial University of Newfoundland, Canada (1996-2003) and the same gear and sample methodology but different vessel in 2015. These previously unpublished data were part of research to locate the distribution of cod overwintering and spawning in and around the Hawke Channel, and provided information of potential seasonality of changes in the area (Fig.2) (see Anderson and Rose 2001 and Rose and Rowe 2015 for additional detail). Sets were targeted at areas identified using a scientific echosounder (EK500 or EK60; 38 kHz) where the acoustic signal indicated that cod and other species were present. Catches were disaggregated by species and weighed. Not all species were sampled across all years therefore the main species sampled (n=10) were retained for multispecies analysis. Spring survey analyses were based on 123 individual targeted fishing sets between 1996-2015 (Table 1). No sets were included in the analysis from 2004 - 2014 (a few sets conducted in 2007 and 2008 had inadequate coverage for a comparison inside-outside). For temporal

comparisons, surveys were separated into 3 groups: B1 – before closure, n=60 (1996-1999), B2 – before closure, n=47 (2000-2003) and A – after closure, n=16 (2015).

Snow crab fisheries data for the 2J region between 1995-2014, including catch per unit effort from the trap fisheries (kg/trap) and landings, were available from DFO. Scaled landings data were used (logbook captured landings to dockside monitored landings for totals) because logbooks were incomplete (Darrell Mullowney, DFO Newfoundland, personal communication). Capture efficiency of snow crab in the multispecies trawl surveys is unknown, but is thought to be higher, and possibly more consistent, in soft mud habitat (Dawe et al. 2010; DFO 2014). For snow crab analyses, although the study nominally covers the NAFO 2J region, snow crab and their fisheries are concentrated in the Hawke and the Cartwright Channels (Fig. 1) therefore inside-outside comparisons are essentially between two similar channels with soft sediments, one with a trawl and gillnet closure, and one without a closure.

Analysis

Multivariate analysis for fall and spring survey data were performed separately using PRIMER (Plymouth Routines in Multivariate Ecological Research v6, Clarke and Gorley 2006) with the PERMANOVA (permutational multivariate analysis of variance) + add on (Anderson et al. 2008) on species level data. PERMANOVA uses a Pseudo-F test statistic, a multivariate analogue of Fishers F ratio (Martin et al. 2012). Data from the spring and fall surveys were not directly comparable due to potential seasonal differences and different survey designs, random (fall) and targeted (spring). Multivariate techniques were deemed appropriate for ecological data at this scale; PRIMER uses permutation techniques that do not require parametric assumptions and are able to handle unbalanced designs (Clarke and Warwick, 2001).

Mean abundance and biomass for each species per year inside and outside the closed area were treated as individual samples and used to create a Bray-Curtis similarity matrix, with the coefficient used to define similarity/dissimilarity. Abundances and biomass for each year was 4th root transformed prior to analysis to down-weight highly abundant species in the samples and increase the relative influence of rare species. The effects of year (before-after) and location (inside-outside) were considered as factors.

To test for relationships between community structure and the environmental variables of temperature and depth, a RELATE test (comparative test on similarity matrices) and PERMANOVA distLM (regression) tests were performed (Anderson et al. 2008). RELATE tests for relationships between the abundance/biomass of the taxa and environmental variables, based on Spearmans rank correlation. A PERMANOVA distLM distance-based linear model was used to assess the amount of variation in abundance-biomass explained by temperature and depth.

Hypotheses about differences in community structure were analysed at the species level using PERMANOVA. A three-way PERMANOVA was used to test for spatial and temporal differences. This allows analysis of a wide range of data distributions and factors to be tested using permutations (Anderson et al. 2008). PERMANOVA was used to test for significance of the following factors: Before_After = BA, In_Out = IO, Year = YR (nested in BA). Abundance and biomass were modelled as functions of the factors. Canonical analysis of principal coordinates (CAP) was applied to visualise the groupings from PERMANOVA as a measure of the distinctiveness amongst the groups in multivariate space, to characterise the groups and assess how distinct they are from one another (Anderson et al. 2008). To identify characteristic species within the assemblage, significant differences in the assemblage structure were analysed using similarity of percentages (PRIMER SIMPER). The SIMPER routine determines the contribution of each species in the assemblage by computing the average Bray-Curtis

similarities and dissimilarities between each sample before and after the closure. A one-way design was conducted with before-after closure as the factor inside and outside the closed area.

Species abundance (fall surveys only) and biomass changes over time were represented as the percent change post-closure relative to pre-closure: (Fall surveys: 2004-2013) (Spring surveys: 2015) and represented as a fold change.

For snow crab analysis, a normalized index of relative annual production (0-1 scale) was estimated from the sum of annual landings and change in trawl exploitable biomass estimates after completion of annual crab fisheries:

$$X_{new} = \frac{X - X_{min}}{X_{max} - X_{min}}$$

These indices represent comparable and bounded trends in total biomass of exploitable crab in the respective areas. The index does not account for the source of recruits.

Results

Environmental variables

Biological community composition and environmental variables temperature and depth were related in both spring and fall surveys (RELATE test), with depth and temperature explaining 23% (fall) and 24% (spring) of the variation in the data (PERMANOVA distLM distance based linear model). Nonetheless, neither variable explained a significant portion of the inter-annual variability, and hence were deemed to be constant over time for the purposes of this study.

Fall surveys

Nine hundred and fourteen fall fishing sets were used in this study, 763 before closure and 151 after (Table 1). The species level assemblage was comprised of 32 species from 24 genera, 16 families, 9 orders, 6 superorders, 3 subclasses and 3 classes (See Table A1 for a taxonomic list of the species assemblage). Species assemblages differed before and after and inside and outside the Hawke Box closure and by year (Permanovas, $P<0.0001$; Table 2A). Inside the Hawke Box, abundance increased significantly 6-10 years post-closure ($P<0.0077$) (Table 2c, Fig. 3). Outside the Hawke Box, overall biomass increased 6-10 years post-closure ($P<0.0228$), and abundance increased both 1-5 years ($P<0.0087$) and 6-10 years post-closure ($P<0.008$). There were notable differences inside and outside and before and after closure across 2 axes (CAP analysis, Fig. 4).

Abundance changes after the closure were similar inside and outside the Hawke Box (Fig. 3). Cod, the wolffishes, capelin and redfish all increased in abundance, with Arctic cod, snow crab, shrimp and turbot decreasing. Biomass changes were more striking. Capelin (*Mallotus villosus*) biomass increased 6-fold inside (+622%) but 0.9-fold outside (+94%) (SIMPER analysis, Table 3). In addition, biomass of smooth skate (*Raja senta*) (+531% in, +167% out), American plaice (*Hippoglossoides platessoides*) (+39% in, +8% out), thorny skate (*Raja raidata*) (+35% in, +14% out) and turbot (*Reinhardtius hippoglossoides*) (+31% in, -28% out) all increased more within the closure than outside. Biomass declined across the region but less so within the closure for snow crab (-36% inside, -71% outside) and northern shrimp spp. (northern shrimp -11% inside, -24% outside). Atlantic cod increased in biomass with a 0.1-fold increase inside (+14.53%) and 0.6-fold increase outside (+61.44%) the closed area. Redfish biomass also increased across the region, both inside (+50%) and outside (+284%) the closed area, as did marlin-spike grenadier

(*Nezumia bairdii*) (+48% in, +124% out). A few species showed opposing biomass trends, notably northern wolffish (*Anarhichas denticulatus*) (-21% in, +214% out).

Spring surveys

Species assemblages assessed during the spring surveys differed before and after and inside and outside the Hawke Box and by year (Permanovas, $P < 0.001$; Table 4). There were some noticeable separations in assemblages before and after the closure (CAP analysis, Fig.5). Inside-outside the closure patterns were less distinct. Overall, 7 species were responsible for the changes in community structure (SIMPER analysis). Species with the highest similarity and the principle contributor's before-closure were turbot, snow crab and shrimp. Post-closure the principle contributor was Atlantic cod (Table 5). The differences between inside and outside the closed area detected in the PERMANOVA test are represented in the biomass change plot (Fig. 6) with higher increases in biomass inside relative to outside the closed area. Atlantic cod displayed the largest biomass change with higher biomass inside than outside (see next section for further results). In addition, redfish increased 5-fold (+551.97%) inside relative to 0.08-fold (+8.57%) outside, American plaice increased 4-fold (+474.31%) inside and declined outside (-2.67%), thorny skate increased inside (+139.92%) more than outside (+5.46%), and roughhead grenadier (*Macrourus berglax*) increased inside 9-fold (+928.07%), but decreased outside the closed area (-99.32%). The 5 other species all had declining biomass (turbot, shrimp, capelin, arctic cod and snow crab) and this pattern was similar both inside and outside the closed area.

Cod changes

Spring surveys indicate that Atlantic cod underwent a dramatic 110-fold increase in biomass (+10,909%) in the 2J region, in 2015, after the closure (Fig. 6, 7). Mean biomass was 13.4 kg (Std.Dev. 14.7; 95% CI. 3.71) in 1996-1999 increasing to 25.9 kg (Std.Dev. 30.4; 95% CI. 4.4) in 2000-2003. Mean biomass

increased to 2065.7 kg (Std.Dev. 4319.55; 95% CI. 2116.54) in 2015, 12 years after the closure. Biomass increase was slightly greater inside the closed area with a 139 –fold increase (+13,908%) than outside with a 117-fold increase (+11,703%).

Snow crab fishery

Snow crab landings fluctuated between 1995-2014 with decreased landings post closure. Prior to the closure (1995-2003) landings were higher outside (22,576t) than inside the closure (9,998t); post-closure (2004-2014) total landings were higher inside the closed area (11,010t outside; 10,870t inside). In general, despite fluctuations, landings are relatively stable inside the closed area but show a decreasing trend outside (Fig. 8a). Post closure, fishing effort remained relatively stable in the closed area, but decreased outside (Fig. 8b). CPUE remained similar inside and outside the closed area over the entire period of study with a decreasing trend pre-closure, and an increasing trend post closure (Fig. 8c). The annual index of production was similar inside and outside prior to the closure, but beginning in 2005 became higher inside than outside the closed area in each year, on average by a factor of 2 (Fig. 8d).

Discussion

The primary objective of the Hawke Box was to enhance the likelihood of a sustainable snow crab fishery by eliminating what were thought by local fishers to be detrimental fishing practices for other species. Despite evidence that the density of snow crab of exploitable size had not increased within the closed area, nor had CPUE (Mullowney et al. 2012); local fishers believed that this objective had been met (Kincaid and Rose 2014). The present analyses indicate that although landings and relative production have declined throughout the region post-closure, largely as a consequence of a warming oceanographic trend (DFO 2014), they have not declined nearly as much inside the box as outside. This

suggests that the removal of trawling and gillnetting has resulted in an increase in the relative production of snow crab. Increased production is consistent with the lesser decline in landings despite an increase in effort within the closure relative to a decline outside. Of note here, our CPUE and landings data do not include what could be substantial discards of soft-shell crabs (Mullowney et al. 2012). The impact of discarding, if diverse among areas, could bias the present results although it is not clear in what direction. For example, if discarding was relatively higher within the Hawke Box, as suggested by one reviewer, it would lead to even higher production estimates within the closure relative to outside. With further data the impacts of discarding could be addressed in future studies. The mechanism by which trawling or gill-netting may have led to a decrease in relative production is not known, but Nguyen et al. (2014) reported that 54% of snow crabs had a direct encounter with an experimental shrimp trawl. Whether or not such encounters result in increased mortality is unclear but it is likely that moulting and soft-shelled crabs may be particularly susceptible. We note, however, that several studies have concluded that there is no significant impact of trawling on snow crab (FDP 2002; Dawe et al. 2007; Mullowney et al. 2014). There is little information on the impacts of gillnets on snow crab, but there is little doubt that they will be entangled if gillnets are encountered (G.A. Rose, personal observations).

A secondary objective of the Hawke Box closure was to enhance the survival of juvenile and spawning cod known to utilize this area (Anderson and Rose 2001; Rose 2007). Spring surveys in 2015 in the Hawke Channel region recorded a dramatic increase in cod biomass over the past decade (Rose and Rowe 2015). This biomass increase was slightly greater inside than outside the Hawke Box but the sparse data and wide ranging migratory nature of cod in the region (Rose 1993) impose difficulties in determining the impact of the closed area on this increase (Breen et al. 2015), and may be insufficient to have impact at the population level (Laurel and Bradbury 2006; Le Quesne and Codling 2008).

Nonetheless, an impact of the Hawke Box on cod should not be dismissed out of hand (Lester et al. 2009). The abundance of cod increased post-closure in both surveys, but the fall survey showed increased abundance post-closure but declines in biomass, which is consistent with an increase in younger juveniles (DFO 2015), while the increase in the spring survey represented an increase in the spawning population (Rose and Rowe 2015). The Hawke Box closure could have enhanced the survival of juvenile cod spawned in that region (Anderson and Rose 2001) that would be expected to increase their range as they matured (Anderson and Dalley 1997) and perhaps home back to their natal grounds (Robichaud and Rose 2001). Such behaviour could have led to an increase in spawning biomass inside the closure and nearby. Closed areas (in the right locations) have been shown to protect juvenile cod (Schopka et al. 2009), and even relatively small area closures (Jaworski et al. 2006) can protect spawning sites, migration routes and potential nursery and productive areas like the Hawke Channel (Gell and Roberts 2003). We note that relatively small closures have been used as a management tool to protect spawning cod populations in Maine, USA (Armstrong et al 2013) and gear restrictions banning trawling have been in place on cod spawning areas in Norway for many years (Nakken 2008). Overall, although it is uncertain if the Hawke Box has played a role in the rebuilding of the northern cod, the evidence is that at a minimum it has done no harm.

Data from the fall surveys show abundance increases in 11 species inside and 10 species outside the Box post-closure (8 species increased in biomass in both areas). Data from spring surveys detected a large biomass increase in the 2015 survey inside and outside the box 12 years post-closure but this was largely a function of the increase in cod. It is important that several species declined across the region, as evident in both spring and fall surveys. These included snow crab, shrimp, and arctic cod, all species expected to decline with the warming oceanographic conditions (Mullowney et al. 2014). On the other hand, increases in redfish, American plaice, roughhead grenadier and thorny skate evident in the spring

surveys within the closure relative to outside may have resulted from the elimination of bottom trawling and gillnetting, although the fall data did not show these trends as strongly.

All assessments of the changes observed in marine ecosystems and fishes, including those of closed areas, should be made in light of the ecological and climate dynamics that influence distributions and abundances. In effect, all measures are made against what is essentially a moving background that is independent of closures. In terms of the biological community under study here, it was expected that cod and perhaps other demersal fishes would increase, and crustaceans decline, over the period under study (Mullowney et al. 2014; Rose and Rowe 2015), independent of the closure, largely as a result of changing production (e.g., Pastoors et al. 2000). Both changes were observed, and against that background we measured significant differences in response between the closed and open areas. Of note, temperature and depth as expected explained some of the variability in the overall biological community data, because Atlantic cod, shrimp and snow crab occur within known temperature and depth ranges at the times of both surveys (the designs of both are based on this (e.g., Walsh et al. 2009, Rose and Rowe 2015, and references therein). Consistent with this, depth and temperature did not contribute significantly to inter-annual variation in the inside-onside comparisons made in this study, although statistical power is acknowledged to be limited.

The use of a quasi-control area, with similar oceanographic conditions, bathymetry and seafloor characteristics was thought to provide a measure against which to judge any changes attributable to the closure in Hawke Channel. Shrimp trawling and gillnetting occurred in the outside area, not inside, allowing the comparison for this and other studies in temperate environments (e.g., Deehr et al. 2014; Sherwood and Grabowski 2015). In our study, compared areas had similar temperatures, depths and

oceanographic conditions. Nonetheless, we acknowledge that no oceanic control area for such studies can be perfect and it would be beneficial in future studies to make comparisons with additional areas. For example, the outside area did not have the same crab fishing effort (Mullowney et al., 2012), and the Hawke box could be more naturally productive than the control (Hilborn 2002; Halpern et al 2004). Siting the closure in a productive area likely increases the likelihood of increased abundance, and this factor may have impacted some of the present results, but for snow crab at least, this appears unlikely, as the bulk of the control data came from the Cartwright Channel, which although not as well studied at the Hawke Channel, may be similarly productive, and furthermore, the landings, effort and production data pre-closure offer no support that the Hawke is naturally more productive than the Cartwright Channel. That our data using a quasi-control (e.g., Edgar and Barrett 1997) suggest that differences did occur against that moving background is evidence that the closure did influence both commercial and non-fished species. Perhaps the most important dynamics were the maintenance of catches and relative production of snow crab against a background of decline outside the closure – meeting the primary objective of the closure.

The Hawke Box was implemented solely as a fishery management tool. Over the past 14 years, a strong sense of ownership among local fishers has developed. Fishers asked for the closure to protect the snow crab fishery through eliminating bottom trawl and gill net fishing gears, thus eliminating themselves from fishing for shrimp and turbot within the closure. Doing so resulted in increased travel time and costs, particularly in their shrimp fishery; increases that fishers believed were worthwhile to ensure a sustainable crab fishery. Despite evidence that the crab fishery (particularly CPUE) had not improved (Mullowney et al. 2012), fishers continued to value the closure as a management tool and understood that increased effort within the closure had negated some potential gains. A sentiment expressed one respondent was “If that box wasn’t closed for the crab we wouldn’t have a fishery today, that’s all that’s

keeping us going” (Kincaid and Rose 2014). Local fishers were aware of the need to reduce their fishing effort and collectively agreed to reduce their crab quota under advice from DFO (DFO 2013b). Fishers were also aware of conservation related indicators including spillover effects and habitat protection for all species, and discussed the importance of the area as a nursery, moulting and spawning ground. Overall, from the standpoint of the local community and fishers, the Hawke Box has been a large success and thought to be fundamental to the future of their communities and livelihoods.

One of the often understated goals of fisheries management is to contribute to the viability and sustainability not only of the fish but of the fisheries and fishing communities. This goal is particularly important in EBM. The commitment of local fishers and communities has only increased recently with the overall decline in snow crab and shrimp primarily as a result of oceanographic warming (DFO 2014; Mullowney et al. 2014). An important aspect of this commitment is the ownership taken not only of the area but also of inevitable changes that are necessary for management, including reducing their own quotas and effort to maintain a sustainable fishery. The Hawke Box in many ways exemplifies how closures can and should be implemented in prime fishing areas, based on the knowledge and involvement of local fishing communities. Such implementations will almost certainly be more effective in achieving both fisheries and biodiversity conservation goals – they will be better supported, with higher rates of compliance, than those that do not have such characteristics (Agardy et al. 2011; Arias et al. 2015)

The Hawke Channel provides a unique reference site of no trawling (or gillnetting) in the boreal northwest Atlantic. Globally, there is a lack of representative unfished areas to compare with trawled fishing grounds and untrawled areas in trawable habitat for comparative studies are rare (Kaiser and Spencer 1996; Atkinson et al. 2011). Although positive results have been reported from closures in the

temperate North Atlantic (Murawski et al. 2000; Fisher and Frank 2002), the Hawke Box provides a rare boreal closure with soft mud sediments, a seafloor type for which the impacts of trawling are contentious (Kaiser et al. 2003; Caveen et al. 2012). In the Gulf of Maine, seasonal shrimp trawling on mud bottom fishing areas created only short-term changes (Simpson and Waitling 2006). However, in the Mediterranean, meiofauna biodiversity, abundance and biomass decreased by 80% in deep trawled vs. untrawled soft mud bottom areas (Pusceddu et al. 2014). This conflicting evidence supports the importance of the Hawke Box as a reference site for an “untrawled” area in a region of highly trawled fishing grounds.

The Hawke Box closure was closed as a precautionary management measure for the conservation of snow crab fishing grounds and to conserve cod concentrations (DFO 2007). Although changing oceanic regimes and increased effort led to declines in crab landings, there is evidence that production has been maintained relative to trawled and gillnetted areas outside the closure. There has also been a dramatic increase in cod, although it is more difficult to relate this directly to the closure. Nonetheless, other demersal species appear to have benefitted and this may apply to cod. Perhaps of importance, the Hawke Box provides a unique boreal area for the study of restrictions on trawling and gillnetting in an area with historically strong finfish and crustacean fisheries, restrictions that are strongly supported by local fishers and their communities. The overall evidence suggests that within a decade of closure the Hawke Box has benefitted fisheries communities, fisheries production and biodiversity conservation.

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References

- Abbott, J.K., and Hayne, A.C. 2012. What are we protecting? Fisher behaviour and the unintended consequences of spatial closures as a fishery management tool. *Ecological Applications*. 22(3): 762-777.
- Agardy, T., Di Sciara, G.N. and Christie, P., 2011. Mind the gap: addressing the shortcomings of marine protected areas through large scale marine spatial planning. *Marine Policy*. 35(2): 226-232.
- Anderson, J.T., and E.L. Dalley. 1997. Spawning and year-class strength of northern cod (*Gadus morhua*) as measured by pelagic juvenile cod surveys, 1991-1994. *Can. J. Fish. Aquat. Sci. Spec. Publ.* 54 (Suppl. 1): 158-167.

- 469 Anderson, J.T., and Rose, G.A. 2001. Offshore spawning and year-class strength of northern cod (2J3KL)
470 during the fishing moratorium, 1994-1996. Canadian Journal of Fisheries and Aquatic
471 Sciences. 58(7): 1386-1394.
- 472 Anderson, M., Gorley, R. and Clarke, K.P., 2008. for PRIMER: guide to software and statistical
473 methods. PRIMER-E, Plymouth, UK.
- 474 Arias, A., Cinner, J.E., Jones, R.E. and Pressey, R.L., 2015. Levels and drivers of fishers' compliance with
475 marine protected areas. Ecology and Society. 20(4): 1-14.
- 476 Armstrong, M.P., Dean, M.J., Hoffman, W.S., Zemeckis, D.R., Nies, T.A., Pierce, D.E., Diodati, P.J. and
477 McKiernan, D.J., 2013. The application of small scale fishery closures to protect Atlantic cod
478 spawning aggregations in the inshore Gulf of Maine. Fisheries Research. 141: 62-69.
- 479 Atkinson, L.J., Field, J.G., and Hutchings, L. 2011. Effects of demersal trawling along the west coast of
480 southern Africa: multivariate analysis of benthic assemblages. Marine Ecology Progress
481 Series. 430: 241-255.
- 482 Auster, P.J., and Shackell, N.L. 2000. Marine protected areas for the temperate and boreal Northwest
483 Atlantic: the potential for sustainable fisheries and conservation of biodiversity. Northeastern
484 Naturalist. 7(4): 419-434.
- 485 Breen, P., Posen, P., and Righton, D. 2015. Temperate Marine Protected Areas and highly mobile fish: A
486 review. Ocean & Coastal Management. 105: 75-83.
- 487 Brown, T. and Anderson, T. 1999. The Hamilton Bank-Hawke Channel Region: Potential as an Offshore
488 Marine Protected Area? A study to examine the physical, biological, economic, and social
489 characteristics of an offshore fishing area. 258078. Fisheries and Oceans, St. John's, Canada.
- 490 Caveen, A.J., Sweeting, C.J., Willis, T.J., and Polunin, N.V.C. 2012. Are the scientific foundations of
491 temperate marine reserves too warm and hard? Environmental Conservation. 39(03): 199-203.

- 492 Cinner, J.E., Marnane, M.J., and McClanahan, T. R. 2005. Conservation and community benefits from
493 traditional coral reef management at Ahus Island, Papua New Guinea. *Conservation*
494 *Biology*. 19(6): 1714-1723.
- 495 Chadwick, E.M.P., Brodie, W., Colbourne, E., Clark, D., Gascon, D. and Hurlbut, T., 2007. History of
496 annual multi-species trawl surveys on the Atlantic coast of Canada. *Atlantic Zonal Monitoring*
497 *Program Bulletin*, 6: 25-42.
- 498 Clarke, K.R., and Warwick, R.M. 2001. Change in marine communities: an approach to statistical analysis
499 and interpretation, 2nd edition. PRIMER-E, Plymouth, UK.
- 500 Clarke, K.R., and Gorley, R.N. 2006. PRIMER v6: user manual. Primer-E Ltd, Plymouth, UK
- 501 Colbourne, E., Narayanan, S., and Prinsenber, N.S. 1994. Climatic changes and environmental
502 conditions in the Northwest Atlantic, 1970-1993. *ICES Marine Science Symposia*. 198: 311-315.
- 503 Dawe, E.G., Gilkinson, K.D., Walsh, S.J., Hickey, W., Mullowney, D.R, Orr, D.C., Forward, R.N. 2007. A
504 study of the effect of trawling in the Newfoundland and Labrador shrimp (*Pandalus borealis*)
505 fishery on mortality and damage to snow crab (*Chionoecetes opilio*). Canadian Technical Report
506 of Fisheries and Aquatic Sciences; 2752: v + 43p
- 507 Dawe, E.G., Walsh, S.J., Hynick, E.M. 2010. Capture efficiency of a multi-species survey trawl for Snow
508 Crab (*Chionoecetes opilio*) in the Newfoundland region. *Fisheries Research*. 101 (1): 70-79.
- 509 Deehr, R.A., Luczkovich, J.J., Hart, K.J., Clough, L.M., Johnson, B.J. and Johnson, J.C., 2014. Using stable
510 isotope analysis to validate effective trophic levels from Ecopath models of areas closed and
511 open to shrimp trawling in Core Sound, NC, USA. *Ecological Modelling*, 282: 1-17.
- 512 DFO. 2007 Northern shrimp (SFAs) 0-7 and the Flemish Cap. Integrated Fisheries Management Plan.
513 Resource Management Operations – Fisheries and Oceans Canada.
- 514 DFO. 2013a. Assessment of Divisions 2G-3K (Shrimp Fishing Areas 4-6) Northern Shrimp. DFO Can. Sci.
515 Advis. Sec. Sci. Advis. Rep. 2013/012.

- 516 DFO. 2013b. Fisheries and Oceans Canada Snow Crab Fishing Areas [online]. Available from:
517 <http://www.dfo-mpo.gc.ca/decisions/fm-2013-gp/atl-003-eng.htm> [Accessed 28th October
518 2013].
- 519 DFO. 2014. Assessment of Newfoundland and Labrador Snow Crab. DFO Can. Sci. Advis. Sec. Sci. Advis.
520 Rep. 2014/037.
- 521 DFO. 2015. Northern (NAFO divs. 2J3KL) cod stock update. DFO Can. Sci. Advis. Sec. Sci. Res. 2015/018.
- 522 Edgar, G.J., and Barrett, N.S. 1997. Short term monitoring of biotic change in Tasmanian marine
523 reserves. *Journal of Experimental Marine Biology and Ecology*. 213(2): 261-279.
- 524 FAO. 2005. The ecosystem approach to fisheries management. Fisheries and Resources Monitoring
525 System [online]. Available from: www.fao.org/fishery/topic/13261/en [Accessed 10th December
526 2015].
- 527 FDP. 2002. Fisheries diversification program report on the interaction between shrimp trawling and the
528 snow crab resource—phase II (revised). Project report; EACT-4.2002.DFO(FDP 281): 26pp
- 529 Fisher, J. A., and Frank, K.T. 2002. Changes in finfish community structure associated with an offshore
530 fishery closed area on the Scotian Shelf. *Marine ecology progress series*. 240: 249-265.
- 531 FRCC. 2003. Conservation Requirements for 2J3KL Cod Stocks 2003/2004. Report to the Minister of
532 Fisheries and Oceans. Fisheries Resource Conservation Council. Minister of Public Works and
533 Government Services, Ottawa, Canada.
- 534 Gaines, S.D., White, C., Carr, M.H., and Palumbi, S.R. 2010. Designing marine reserve networks for both
535 conservation and fisheries management. *Proceedings of the National Academy of*
536 *Sciences*. 107(43): 18286-18293.
- 537 Gell, F.R., and Roberts, C.M. 2003. Benefits beyond boundaries: the fishery effects of marine
538 reserves. *Trends in Ecology and Evolution*. 18(9): 448-455.

- 539 Government of Canada. 2011. National Framework for Canada's Network of Marine Protected Areas.
540 Fisheries and Oceans Canada, Ottawa, Canada.
- 541 Halpern, B.S., Gaines, S.D. and Warner, R.R., 2004. Confounding effects of the export of production and
542 the displacement of fishing effort from marine reserves. *Ecological Applications*, 14(4): 1248-
543 1256.
- 544 Hilborn, R. 2002. Measuring the effects of marine reserves of fisheries: the dilemmas of experimental
545 programs. *MPA News* 4: 1-3.
- 546 Horta e Costa, B.H., Erzini, K., Caselle, J.E., Folhas, H., and Gonçalves, E. J. 2013. 'Reserve effect' within a
547 temperate marine protected area in the north-eastern Atlantic (Arrábida Marine Park,
548 Portugal). *Mar Ecol Prog Ser.* 481: 11-24.
- 549 Jaworski, A., Solmundsson, J., and Ragnarsson, S.A. 2006. The effect of area closures on the demersal
550 fish community off the east coast of Iceland. *ICES Journal of Marine Science.* 63(5): 897-911.
- 551 Johannes, R.E. 1978. Traditional marine conservation methods in Oceania and their demise. *Annual*
552 *Review of Ecology and Systematics.* 349-364.
- 553 Johannes, R.E. 2002. The renaissance of community-based marine resource management in
554 Oceania. *Annual Review of Ecology and Systematics:* 317-340.
- 555 Kaiser, M.J., Collie, J.S., Hall, S.J., Jennings, S., and Poiner, I.R. 2003. 12 Impacts of Fishing Gear on
556 Marine Benthic Habitats. *Responsible fisheries in the marine ecosystem.* 57(3): 197.
- 557 Kaiser, M.J., and Spencer, B.E. 1996. The effects of beam-trawl disturbance on infaunal communities in
558 different habitats. *Journal of Animal Ecology.* 348-358.
- 559 Kaunda-Arara, B., and Rose, G.A. 2004. Effects of marine reef National Parks on fishery CPUE in coastal
560 Kenya. *Biological Conservation.* 118(1): 1-13.

- 561 Kincaid, K.B., and Rose, G.A. 2014. Why fishers want a closed area in their fishing grounds: Exploring
562 perceptions and attitudes to sustainable fisheries and conservation 10 years post-closure in
563 Labrador, Canada. *Marine Policy*. 46: 84-90.
- 564 Laurel, B.J., and Bradbury, I.R. 2006. "Big" concerns with high latitude marine protected areas (MPAs):
565 trends in connectivity and MPA size. *Canadian Journal of Fisheries and Aquatic Sciences*. 63(12):
566 2603-2607.
- 567 Le Quesne, W.J., and Codling, E.A. 2009. Managing mobile species with MPAs: the effects of mobility,
568 larval dispersal, and fishing mortality on closure size. *ICES Journal of Marine Science: Journal du*
569 *Conseil*. 66(1): 122-131.
- 570 Lester, S.E., Halpern, B.S., Grorud-Colvert, K., Lubchenco, J., Ruttenberg, B.I., Gaines, S.D., and Warner,
571 R.R. 2009. Biological effects within no-take marine reserves: a global synthesis. *Marine Ecology*
572 *Progress Series*. 384(2): 33-46.
- 573 Link, J.S., Bundy, A., Overholtz, W.J., Shackell, N., Manderson, J., Duplisea, D., and Friedland, K.D. 2011.
574 Ecosystem-based fisheries management in the Northwest Atlantic. *Fish and Fisheries*. 12(2):
575 152-170.
- 576 Martin, C.J., Allen, B.J., and Lowe, C.G. 2012. Environmental Impact Assessment: Detecting Changes in
577 Fish Community Structure in Response to Disturbance with an Asymmetric Multivariate BACI
578 Sampling Design. *Bulletin, Southern California Academy of Sciences*. 111(2): 119-131.
- 579 McClanahan, T.R. 2010. Effects of fisheries closures and gear restrictions on fishing income in a Kenyan
580 coral reef. *Conservation Biology*. 24(6): 1519-1528.
- 581 MSC (2016) Newfoundland and Labrador Snow Crab. Marine Stewardship Council. Available from:
582 www.fisheries.msc.org/en/fisheries/newfoundland-labrador-snow-crab [accessed 23rd
583 November 2016].

- 584 Mullowney, D.R., Morris, C.J., Dawe, E.G., and Skanes, K.R. 2012. Impacts of a bottom trawling exclusion
585 zone on Snow Crab abundance and fish harvester behavior in the Labrador Sea, Canada. *Marine*
586 *Policy*. 36(3): 567-575.
- 587 Mullowney, D.R., Dawe, E.G., Colbourne, E.B., Rose, G. 2014. A review of factors contributing to the
588 decline of Newfoundland and Labrador snow crab (*Chionoecetes opilio*). *Reviews in Fish Biology*
589 *and Fisheries*, 24 (2): 639-657.
- 590 Murawski, S.A., Brown, R., Lai, H.L., Rago, P.J., and Hendrickson, L. 2000. Large-scale closed areas as a
591 fishery-management tool in temperate marine systems: the Georges Bank experience. *Bulletin*
592 *of Marine Science*. 66(3): 775-798.
- 593 Nakken, O. 2008. Northeast Arctic cod, In *Norwegian spring spawning herring and Northeast Arctic cod:*
594 *100 years of research and management*, edited by O. Nakken. Fagbokforlaget, Norway.
- 595 Nguyen, T.X., Winger, P.D., Legge, G., Dawe, E.G., and Mullowney, D. R. 2014. Underwater observations
596 of the behaviour of snow crab (*Chionoecetes opilio*) encountering a shrimp trawl off northeast
597 Newfoundland. *Fisheries Research*. 156: 9-13.
- 598 Pastoors, M.A., Rijnsdorp, A.D., and Van Beek, F.A. 2000. Effects of a partially closed area in the North
599 Sea ("plaice box") on stock development of plaice. *ICES Journal of Marine Science: Journal du*
600 *Conseil*. 57(4): 1014-1022.
- 601 Pusceddu, A., Bianchelli, S., Martín, J., Puig, P., Palanques, A., Masqué, P., and Danovaro, R. 2014.
602 Chronic and intensive bottom trawling impairs deep-sea biodiversity and ecosystem
603 functioning. *Proceedings of the National Academy of Sciences*. 111(24): 8861-8866.
- 604 Rice, J., Moksness, E., Attwood, C., Brown, S.K., Dahle, G., Gjerde, K.M., and Westlund, L. 2012. The role
605 of MPAs in reconciling fisheries management with conservation of biological diversity. *Ocean &*
606 *Coastal Management*. 69: 217-230.

- 607 Robichaud, D. and Rose, G.A., 2001. Multiyear homing of Atlantic cod to a spawning ground. Canadian
608 Journal of Fisheries and Aquatic Sciences. 58(12):.2325-2329.
- 609 Rose, G.A. 1993. Cod spawning on a migration highway in the north-west Atlantic. Nature. 366 (6454):
610 45 8-461.
- 611 Rose, G.A. 2007. Cod: The ecological history of the North Atlantic fisheries. Breakwater books, Canada.
- 612 Rose, G.A. and Rowe, S., 2015. Northern cod comeback. Canadian Journal of Fisheries and Aquatic
613 Sciences. 72(12): 1789-1798.
- 614 Salomon, A.K., Gaichas, S.K., Jensen, O.P., Agostini, V.N., Sloan, N.A., Rice, J., McClanahan, T.R;
615 Ruckelshaus, M H; Levin, P.S; Dulvy, N K; and Babcock, E.A. 2011. Bridging the divide between
616 fisheries and marine conservation science. Bulletin of Marine Science. 87(2): 251-274.
- 617 Schopka, S.A., Solmundsson, J., Ragnarsson, S.A., and Thorsteinsson, V. 2010. Using tagging experiments
618 to evaluate the potential of closed areas in protecting migratory Atlantic cod (*Gadus*
619 *morhua*). ICES Journal of Marine Science: Journal du Conseil. 67(5): 1024-1035.
- 620 Sherwood, G.D. and Grabowski, J.H., 2015. A comparison of cod life-history parameters inside and
621 outside of four year-round groundfish closed areas in New England, USA. ICES Journal of Marine
622 Science: Journal du Conseil, p.fsv215.
- 623 Simpson, A.W., and Watling, L. 2006. An investigation of the cumulative impacts of shrimp trawling on
624 mud-bottom fishing grounds in the Gulf of Maine: effects on habitat and macrofaunal
625 community structure. ICES Journal of Marine Science: Journal du Conseil. 63(9):1616-1630.
- 626 Sweeting, C.J. and Polunin, N.V.C., 2005. Marine protected areas for management of temperate north
627 Atlantic fisheries. Lessons learned in MPA use for sustainable fisheries exploitation and stock
628 recovery. Report to DEFRA, UK [www document]. URL [http://archive.defra.gov.](http://archive.defra.gov.uk/environment/marine/documents/science/mpareport-northatlantic.pdf)
629 [uk/environment/marine/documents/science/mpareport-northatlantic.pdf](http://archive.defra.gov.uk/environment/marine/documents/science/mpareport-northatlantic.pdf).

630 Walsh, S.J., Hickey, W.H., Porter, J., Delouche, H., and McCallum, B.R. 2009. NAFC Survey Trawl
631 Operations Manual: Version 1.0. Fisheries and Oceans, Northwest Atlantic Fisheries Centre,
632 Newfoundland Region, St. John's, Canada.

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634 Tables
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636 Table 1: Number of sets inside and outside the Hawke Box closed area for fall and spring data.

Fall data					Spring data			
	Year	Out	In	Total	Year	Out	In	Total
Before closure	1996	48	14	62	1996	9	9	18
	1997	42	9	51	1997	0	0	0
	1998	40	10	50	1998	15	16	31
	1999	37	9	46	1999	5	6	11
	2000	39	1	40	2000	4	9	13
	2001	38	10	48	2001	3	12	15
	2002	18	8	26	2002	2	7	9
	2003	56	9	65	2003	2	8	10
Total		318	70	388		40	67	107
After closure	2004	41	7	48				
	2005	40	5	45				
	2006	41	8	49				
	2007	40	6	46				
	2008	34	7	41				
	2009	36	6	42				
	2010	39	11	50				
	2011	50	12	62				
	2012	65	9	74				
	2013	59	10	69				
					2015	11	5	16
Total		445	81	526		11	5	16
Total sets (all years)		763	151	914		51	72	123

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638

639 Table 2: Fall survey PERMANOVA models.

A)All	Abundance				Biomass			
Factor	df	MS	Pseudo-F	P(MC)	df	MS	Pseudo-F	P(MC)
Before_After = BA	1	1037.4	13.877	0.0001	1	1184.1	9.216	0.0001
In_Out = IO	1	1591.5	21.288	0.0001	1	2524.9	19.652	0.0001
Year = YR (BA)	16	244.29	3.267	0.0001	16	569.02	4.428	0.0001
BA X IO	1	34.559	0.462	ns	1	42.494	0.331	ns
Residual	16	74.76			16	128.48		
Total	35				35			
B)Pair-wise comparisons								
Temporal effects (Abundance)								
a) Allb)Insidec)Outside								
tP (MC)tP (MC)tP (MC)								
Before-after 1 (2004-08)	1.6747	0.027	1.2926	ns	1.8382	0.0087		
Before-after 2 (2009-13)	2.6663	0.0002	2.0508	0.0077	2.2597	0.008		
After 1-after 2	1.8912	0.0162	1.5145	0.0403	1.4644	ns		
C)Pair-wise comparisons								
Temporal effects (Biomass)								
a) Allb)Insidec)Outside								
tP (MC)tP (MC)tP (MC)								
Before-after 1 (2004-08)	1.3927	ns	1.1095	ns	1.4923	ns		
Before-after 2 (2009-13)	2.2366	0.0027	1.5406	ns	1.9379	0.0228		
After 1-after 2	1.8141	0.0258	1.236	ns	1.4311	ns		

640 A) Three-way PERMANOVA analysis of spatial-temporal variation in community structure for
641 all species. Factors were fixed (before-after closure, inside-outside closure and year) with year
642 nested within Before_After. All analyses were carried out on abundance and biomass data using
643 permutations of residuals under a reduced model on normalised, fourth root transformed data and

644 9999 permutations and type III sums of squares. df, degrees of freedom; MS, mean square;
645 P(MC), probability level after Monte Carlo tests; pseudo-F, statistic F. * ns = not significant.
646 PERMANOVA Pair-wise comparisons of temporal effects before-after closure on the whole
647 area, inside only and outside only, unrestricted permutation of raw data for abundance (B) and
648 biomass (C).
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650 Table 3: Fall survey SIMPER routines on Bray-Curtis similarity, standardised and 4th root
651 transformed abundance and biomass data inside and outside the HC closed area showing species
652 with the highest contribution to the similarity per year and % dissimilarity before and after the
653 closed area.

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		Inside HC closure						Outside HC closure					
		Abundance			Biomass			Abundance			Biomass		
		%		Before-	%	Before-		%		Before-	%	Before-	
		Similarity		After %	Similarity	After %		Similarity		After %	Similarity	After %	
		Befo	Aft	dissimila	Befo	Aft	dissimil	Befo	Aft	dissimila	Befo	Aft	dissimil
		re	er	arity	re	er	arity	re	er	arity	re	er	arity
Average Similarity		83.4	80.9	19.7	79.9	67.7	27.2	88.4	81.5	17.7	86.2	76.1	20.8
Species	Common name												
Pandalus borealis	Northern shrimp	35.0	31.7	5.7	19.9	17.6	14.6	25.0	25.2	5.8	13.3	11.7	6.6
Pandalus montagui	Striped shrimp	11.7	12.7	6.8	6.7	7.5	3.1	10.8	11.7	6.2	5.7	5.7	*
R. hippoglossoides	Turbot	10.2	8.8	3.6	15.1	13.3	6.0	7.1	6.5	*	8.9	8.8	3.5
Sebastes mentella	Redfish (beaked)	5.8	8.4	6.6	7.4	8.5	5.4	5.8	8.8	7.0	6.7	8.0	7.8
Mallotus villosus	Capelin	5.7	4.9	13.2	5.3	4.6	7.4	5.4	4.1	9.0	4.1	3.3	5.5
Boreogadus saida	Polar/Arctic cod	5.7	3.0	10.0	4.6		5.9	7.1	3.5	8.0	5.4	*	5.9
Chionoecetes opilio	Snow crab	4.7	5.2	*	6.4	7.3	4.2	4.5	3.8	*	5.2	4.1	3.8
H. platessoides	American plaice	4.6	4.9	*	7.0	5.9	3.2	3.2	3.9	*	4.3	3.8	*
Gadus morhua	Atlantic cod	3.4	3.8	*	6.5	5.6	4.0	*	3.5	*	4.8	5.2	*
Nezumia bairdii	Marlin-spike grenadier	3.0	*	4.7	3.1	3.1	3.6						*
Raja radiata	Thorny skate	3.0	3.1	*	5.6	5.6	*				4.0	4.2	*
Icelus spatula	Spatulate sculpin			3.8									
Anarhicas minor	Spotted Wolffish			3.7		*	5.0					4.23	3.3
Raja senta	Smooth skate			3.4									*
Lycodes reticulatus	Arctic eelpout			3.2			3.9				3.5	*	3.2
Cyclopterus lumpus	Lumpfish				*	3.5	3.8				4.1	3.2	3.2
Anarhicas lupus	Atlantic Wolffish					3.0	*				3.1	4.3	

Glyptocephalus cynoglossus	Witch flounder	3.0	4.0			*
Anarchicas denticulatus	Northern Wolfish		3.9	*	5.4	3.7
Macrourus berlax	Roughhead grenadier		3.6	3.7	3.7	*
Coryphaenoides rupestris	Roundnose grenadier					4.09
Antimora rostrata	Blue hake					3.9

* = <3% similarity. Before: data collected before closure; After: data collected post-closure.

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Table 4: Spring surveys. Three-way PERMANOVA analysis of spatial-temporal variation in community structure for species (n=10) from spring surveys (targeted cod acoustic-trawls sets.

A) All		Biomass		
Factor	df	MS	Pseudo-F	P(MC)
Before_After = BA	2	10470	9.436	0.0001
In_Out = IO	1	5532	4.985	0.0007
Year = YR (BA)	5	5715.4	5.151	0.0001
BA X IO	2	2748.2	2.477	0.0082
Residual	107	1109.6		
Total	122			

B)Pair-wise comparisons	All		Inside		Outside	
	t	P(MC)	t	P(MC)	t	P(MC)
Before 1 - Before 2	1.816	ns	1.2634	ns	1.6009	ns
Before 1-After	3.9539	0.0001	2.4366	0.001	3.8928	0.001
Before 2- After	3.7383	0.0001	2.448	0.004	2.9546	0.001

(A)Temporal pair-wise comparisons (B). Factors were fixed (before-after closure, inside-outside closure and year) with year nested within Before_After. All analyses were carried out on biomass data using permutations of residuals under a reduced model on normalised, fourth root transformed data and 9999 permutations and type III sums of squares. df, degrees of freedom; MS, mean square; pseudo-F, statistic F; P(MC), probability level after Monte Carlo tests.

Table 5: Spring survey SIMPER routines on Bray-Curtis similarity, standardised and 4th root transformed biomass data for the 2J area showing species with the highest contribution to the similarity per year and % dissimilarity before and after the closed area.

ALL 2J	Before 1		Before 2		After		Before 1- After
Species	Mean biomas s per tow (kg)	% Similarit y	Mean biomas s per tow (kg)	% Similarit y	Mean biomass per tow (kg)	% Similarit y	% dissimilarit y
Turbot	48.48	24.28	47.18	18.65	10.53	15.82	11.6
Snow crab	11.63	16.11	13.40	13.17	0.19		12.39
Northern shrimp	61.43	15.00	77.65	23.13	2.91		15.06
Atlantic cod	13.17	12.95	25.90	15.05	2065.65	43.35	26.24
American plaice	3.43	11.83	3.64	12.24	8.87	9.69	7.36
Redfish	4.40	9.23	11.63	9.35	21.73	22.80	8.71
Thorny skate	1.50	5.70	2.61		2.89		8.42

Figures

Figure 1: Map of SE Labrador and NAFO 2J area showing the location of the Hawke Box closed area. To the north is the Cartwright channel, this and the Hawke Channel are the main fishing areas for snow crab pot fishery. All shelf area is commercial shrimp trawling areas. Solid line and arrows show predicted migration pathway for northern cod from offshore spawning areas to inshore feeding areas (Rose 1993). Dotted line represents the 500m shelf edge. Map reproduced and re-annotated from DFO.

Figure 2: Map of spring and fall survey sampling sites inside and outside the Hawke Box closed area.

Figure 3: Fall survey post-closure mean abundance and biomass change (relative to the mean abundance and biomass pre-closure) for the whole area and inside and outside the Hawke Box for key species and species of conservation interest. Method adapted from Fisher and Frank (2002).

Figure 4: Fall survey canonical CAP analysis of the principal coordinates for mean abundance (a) and biomass (b) per year, all species, for inside-outside, before-after the closed area.

Analysis on fourth root transformed, Bray-Curtis similarity resemblance data. Symbols: in: inside the closed area; out: outside the closure; B: data collected before closure; A: data collected post-closure. A miss-classification error of 2.78% (abundance) and 19.44% (biomass) indicated

a strong association. In addition, the permutation test in CAP of no difference was significant ($p < 0.001$).

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Figure 5: Spring survey canonical CAP analysis of the principal coordinates for targeted sets. Analysis on fourth root transformed, Bray-Curtis similarity resemblance data. Groups were defined by the ordination $P < 0.001$ based on the trace statistic. B1 - $n=60$ (1996-1999), B2 – before closure, $n=47$ (2000-2003) and A – after closure, $n=16$ (2015). I: Inside, O: outside the closed area.

Figure 6: Spring survey species biomass changes (relative to pre-closure biomass) for all of the area, inside the Hawke closure only, and outside the Hawke closure only for 2015 data, 12 years post-closure.

Figure 7: Spring survey mean annual cod catch per standardized 15 minute fishing set before-after, inside-outside the Hawke Channel closed area. Cod biomass increased 110-fold from 2003 to 2015 (no surveys in between) with 95% CI.

Figure 8: Snow Crab fishery data inside and outside the Hawke Box (NAFO 2J), pre (1995-2003) and post (2004-2014) closure. a) scaled landings*, b) fishing effort, c) catch per unit effort, CPUE (kg/trap) and d) normalized relative production. * Due to incomplete logbook data scaled landings capture landings to dockside monitored landings. Scaled landings provided by DFO. Note that data for CPUE and landings excludes discard data.

Common name	Species	Genus	Family	Order	Superorder	Subclass	Class
Phylum: Arthropoda; Subphylum: Crustacea							
Snow Crab	<i>Chionoecetes opilio</i>	<i>Chionoecetes</i>	Oregoniidae	Decapoda	Eucarida	Eumalacostraca	Malacostraca
Northern shrimp	<i>Pandalus borealis</i>	<i>Pandalus</i>	Pandaloidae	Decapoda	Eucarida	Eumalacostraca	Malacostraca
Striped shrimp	<i>Pandalus montagui</i>	<i>Pandalus</i>	Pandaloidae	Decapoda	Eucarida	Eumalacostraca	Malacostraca
	<i>Pandalus propinquus</i>	<i>Pandalus</i>	Pandaloidae	Decapoda	Eucarida	Eumalacostraca	Malacostraca
Phylum: Chordata; Subphylum: Vertebrata							
Northern Wolffish	<i>Anarhichas denticulatus</i>	<i>Anarhichas</i>	Anarhichidae	Perciformes	Acanthopterygii	Neopterygii	Actinopterygii
Atlantic Wolffish	<i>Anarhichas lupus</i>	<i>Anarhichas</i>	Anarhichidae	Perciformes	Acanthopterygii	Neopterygii	Actinopterygii
Spotted Wolffish	<i>Anarhichas minor</i>	<i>Anarhichas</i>	Anarhichidae	Perciformes	Acanthopterygii	Neopterygii	Actinopterygii
Blue Antimora, blue hake	<i>Antimora rostrata</i>	<i>Antimora</i>	Moridae	Gadiformes	Paracanthopterygii	Neopterygii	Actinopterygii
Polar cod/Arctic cod	<i>Boreogadus saida</i>	<i>Boreogadus</i>	Gadidae	Gadiformes	Paracanthopterygii	Neopterygii	Actinopterygii
Atlantic Herring	<i>Clupea harengus</i>	<i>Clupea</i>	Clupeidae	Clupeiformes	Clupeomorpha	Neopterygii	Actinopterygii
Roundnose Grenadier	<i>Coryphaenoides rupestris</i>	<i>Coryphaenoides</i>	Macrouridae	Gadiformes	Paracanthopterygii	Neopterygii	Actinopterygii
Polar Scupin	<i>Cottunculus microps</i>	<i>Cottunculus</i>	Cottidae	Scorpaeniformes	Acanthopterygii	Neopterygii	Actinopterygii
Lumpfish	<i>Cyclopterus lumpus</i>	<i>Cyclopterus</i>	Cyclopteridae	Scorpaeniformes	Acanthopterygii	Neopterygii	Actinopterygii
Fouline snakeblenny	<i>Eumesogrammus praecisus</i>	<i>Eumeogrammus</i>	Stichaeidae	Perciformes	Acanthopterygii	Neopterygii	Actinopterygii

Atlantic cod	Gadus morhua	Gadus	Gadidae	Gadiformes	Paracanthopterygii	Neopterygii	Actinopterygii
Greenland cod	Gadus ogac	Gadus	Gadidae	Gadiformes	Paracanthopterygii	Neopterygii	Actinopterygii
Witch flounder	Glyptocephalus cynoglossus	Glyptocephalus	Pleuronectidae	Pleuronectiformes	Acanthopterygii	Neopterygii	Actinopterygii
Fish doctor	Gymnelis viridis	Gymnelis	Zoarcidae	Perciformes	Acanthopterygii	Neopterygii	Actinopterygii
Arctic staghorn sculpin	Gymnocanthus tricuspid	Gymnocanthus	Cottidae	Scorpaeniformes	Acanthopterygii	Neopterygii	Actinopterygii
American plaice/dab	Hoppoglossoides platessoides	Hippoglossoides	Pleuronectidae	Pleuronectiformes	Acanthopterygii	Neopterygii	Actinopterygii
Spatulate sculpin	Icelus spatula	Icelus	Cottidae	Scorpaeniformes	Acanthopterygii	Neopterygii	Actinopterygii
Greater eelpout	Lycodes esmarki	Lycodes	Zoarcidae	Perciformes	Acanthopterygii	Neopterygii	Actinopterygii
Arctic eelpout	Lycodes reticulatus	Lycodes	Zoarcidae	Perciformes	Acanthopterygii	Neopterygii	Actinopterygii
Roughhead grenadier	Macrourus berglax	Macrourus	Macrouidae	Gadiformes	Paracanthopterygii	Neopterygii	Actinopterygii
Capelin	Mallotus villosus	Mallotus	Osmeridae	Osmeriformes	Protacanthopterygii	Neopterygii	Actinopterygii
Shorthorn sculpin	Myoxocephalus scorpius	Myoxocephalus	Cottidae	Scorpaeniformes	Acanthopterygii	Neopterygii	Actinopterygii
Marlin-spike grenadier	Nezumia bairdii	Nezumia	Macrouidae	Gadiformes	Paracanthopterygii	Neopterygii	Actinopterygii
Thorny skate	Raja radiata	Raja	Rajidae	Rajiformes	Euselachii	Elasmobranchii	Chondrichthyes
Smooth skate	Raja senta	Raja	Rajidae	Rajiformes	Euselachii	Elasmobranchii	Chondrichthyes
Turbot/Greenland halibut	Reinhardtius hippoglossoides	Reinhardtius	Pleuronectidae	Pleuronectiformes	Acanthopterygii	Neopterygii	Actinopterygii
Golden redfish	Sebastes marinus	Sebastes	Sebastidae	Scorpaeniformes	Acanthopterygii	Neopterygii	Actinopterygii

Beaked redfish	Sebastes mentella	Sebastes	Sebastidae	Scorpaeniformes	Acanthopterygii	Neopterygii	Actinopterygii
Boa dragonfish	Stomias boa ferox	Stomias	Stomiidae	Stomiiformes	Stenopterygii	Neopterygii	Actinopterygii

Appendix Table A1. Taxonomy of species caught within the NAFO 2J Hawke Channel survey area during Spring and Fall multispecies trawl surveys between 1996-2013.

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