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Biological perspectives on complexities of fisheries co-management: A case study of Newfoundland and Labrador snow crab

Darrell R.J. Mullowney*, Krista D. Baker, Sana Zabihi-Seissan, Corey Morris

Fisheries and Oceans Canada, Northwest Atlantic Fisheries Centre, 80 East Whitehills Road, St. John's, Newfoundland and Labrador, A1C 5X1, Canada

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ABSTRACT

A thrust toward fisheries co-management systems occurred globally throughout the 1990s. This was partially influenced by the collapse of groundfish stocks including the iconic northern cod and other fisheries resources in Newfoundland and Labrador (NL). The management system for NL snow crab burgeoned during this period, largely in the absence of biological information for the resource. There is a high volume of theoretical literature advocating for the benefits of fisheries co-management, but little documented perspectives from fisheries scientists actively engaged in such management systems, nor literature detailing how co-management regimes could affect scientific research or assessment programs. In this paper, in context of a large fishery, we provide specific examples of how co-management processes can influence scientific research and monitoring programs and the biological functioning of important marine resources. We undertake critical evaluation on topics including spatial scales of management, fishery timing, fishery closures, collaborative research, and harvester perceptions of stock size. We conclude there are both scientific advantages and disadvantages to operating within co-management systems, but that the NL snow crab management system has evolved to promote processes problematic to provision of the best possible science advice. We conclude that adaptive co-management measures are required to address several current challenges in order to maximize scientific value within this system. In general, the paper demonstrates how flexibility is needed by all partners involved in resource co-management systems to adapt to fundamental scientific principles inherent in changing methodologies and the generation of knowledge.

1. Introduction

1.1. Resource Co-management

An underlying philosophy of potential socio-ecological gains of decentralized resource management for common property resources is that secured user rights reduce abuses of the commons and promote improved stewardship (Hardin, 1968). Co-management then becomes a knowledge partnership mutually beneficial to resource users and other vested interests (Berkes, 2009). Co-management is broadly defined as the involvement of resource users in management (Linke and Bruckmeier, 2014). Guiding principles of co-management include empowerment of resource users and shared responsibilities and risks among parties.

Surprisingly, the term co-management only has a short history of being used in scientific literature related to natural resources management, with earliest explicit use of the term traced back to the late 1970s (Pinkerton, 2003; Berkes, 2009). Co-management can be an ambiguous concept due to the different levels at which co-operative resource management arrangements may be enacted. For example long-standing partnership arrangements such as Indigenous land and resource claims can be regarded as historical co-management agreements, even in the absence of modernized legislative or legal processes (Berkes, 2009). There are documented government-community partnerships spanning back as far as the 1920 s–1930 s in forestry management systems in India and formal terrestrial wildlife co-management agreements in Canada, Alaska, and Africa dating back to the 1980s (Berkes, 2009). However, the longest history of formalized resource co-management appears to be associated with fisheries, specifically in the case of cod (*Gadus morhua*) fisheries in Norway in the 1890s (Jentoft and McCay, 1995). The evolution of resource co-management systems demonstrates an increasing understanding and acceptance that humans are an integral part of biological ecosystems and that social capital is necessary to effectively manage natural resources impacted by human use

* Corresponding author.
E-mail addresses: Darrell.Mullowney@dfo-mpo.gc.ca (D.R.J. Mullowney), Krista.Baker@dfo-mpo.gc.ca (K.D. Baker), Sanaollah.Zabihi-Seissan@dfo-mpo.gc.ca (S. Zabihi-Seissan), Corey.Morris@dfo-mpo.gc.ca (C. Morris).

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(Plummer and Fitzgibbon, 2004).

In fisheries resource management, there are numerous theoretical and qualitative reviews on co-management initiatives from around the globe (e.g., Jentoft, 1989, 2005; Sen and Raakjaer Nielsen, 1996; Pomeroy et al., 2001; Wilson et al., 2003; Berkes, 2009; Linke and Jentoft, 2013 2014; d'Armengol et al., 2018). This body of literature typically advocates for inherent benefits of bringing multiple stakeholder and regulatory groups together in fisheries management, particularly with respect to inclusion of fish harvesters, who are most directly affected by the state of fish stocks. Advocates for fisheries co-management cite the fact that traditional top-down, bureaucratic, and science-based management approaches have been generally unsuccessful and associated with a global depletion of fish stocks (Jentoft et al., 1998). Interestingly, the Atlantic Canadian Province of Newfoundland and Labrador (NL), where this study occurs, has been highlighted as a key region helping to strengthen a global thrust toward fisheries co-management following the collapse of cod (*Gadus morhua*) and other major finfish stocks in the early 1990s (Neis, 1992; Finlayson, 1994; Linke and Bruckmeier, 2014).

Effective interaction between scientists and resource users is a critical element of success in fisheries co-management (Berkes, 2009; Linke and Jentoft, 2013). Theoretically, scientists and fish harvesters can produce complementary relevant knowledge superior to what either party can produce alone (Arnold and Fernandez-Gimenez, 2007; Berkes, 2008). Combining science and harvester knowledge can be a difficult process; although harvester knowledge is now generally valued in management systems, there remain questions and challenges on how to implement it (Reid et al., 2006; Berkes, 2009; Linke and Jentoft, 2013). For European fisheries, uncertainties in how to effectively combine harvester perspectives with scientific information is a major issue affecting further advancement of co-management regimes (Linke and Bruckmeier, 2014). Particular challenges revolve around how parties communicate, as well as how to deal with scientific uncertainty and anecdotal information.

Despite a high level of advocacy to bring scientist and harvester knowledge together in co-management systems, there is limited evidence that stocks are better-protected (Bavington, 2010). There is also potential for science to be distorted or dismissed (Wilson, 2009) or for politics to override science in determining direction of decision-making processes (Stöhr and Chabay, 2010). Little literature exists explicitly detailing biological experiences on how attempts to operate within co-management regimes have fared, particularly in regard to first-hand perspectives from scientists.

Co-management inevitably requires a lot of patience and flexibility from scientists (Linke and Jentoft, 2013). In traditional fisheries management systems, scientists predominately directly service the needs of institutional decision-making bodies, but newer co-management systems necessitate them to assume more direct and frequent horizontal integration with stakeholder groups, such as harvesters. Effective communication can be challenging for scientists, particularly as harvesters often base their views on localized areas or anecdotal reports, as opposed to population-structure views and rigid statistical methods (Linke and Jentoft, 2013).

1.2. The Newfoundland and Labrador snow crab fishery

The NL snow crab (*Chionoecetes opilio*) resource and fishery grew rapidly following an ecological marine regime shift in the early 1990s that in association with overfishing collapsed most components of the finfish community (DFO, 2014). From limited levels of fishery participation and interest in snow crab during the 1980s, this fishery grew to a level of over 3,300 enterprises by 1998 (Taylor and O'Keefe, 1999). The federal government was seeking to implement a 'modern fisheries model' for the snow crab industry in the aftermath of the finfish industry collapse, characterized by collaborative management and decision-making processes (Davis and Korneski, 2012). With so many interests seeking entry into the new focal fishery for the Province, arguments over access rights characterized the early years of fishery expansion and the management system evolved to accommodate collaborative and democratic governance at progressively smaller spatial scales as successive groups entered the fishery. The rapid fishery expansion out-paced the accumulation of biological knowledge of the resource, thus management measures were often instituted in the absence of or with limited scientific information.

Fisheries and Oceans Canada (DFO), the federal government management agency of fisheries management, formally sets objectives for the management of the NL snow crab resource, including the following:

> *"promote a co-management approach, providing licence holders with an effective sharing of responsibility, accountability and decision making, within the constraints of the Fisheries Act" and for "improved management of the fishery through co-management (*DFO, 2019 [Section 5]*)".*

So, although the NL snow crab resource is not fully co-managed, with the Federal Government maintaining exclusive decision-making power, the current management system entails extensive collaboration between fisheries scientists, harvesters, and managers.

In this paper, as a group of fisheries scientists, we provide biological and statistical perspectives on experiences associated with the development and growth phases of a co-management-type system in the context of a large fishery resource. We focus analyses on how intricacies of the management regime affect various aspects of our research and assessment program, as well as the health of the snow crab resource. We provide context and perspectives on how complexities associated with collaborative research and extensive consultation affect our ability to provide the best possible scientific advice in both positive and negative ways. Topics covered include spatial scales of management, fishery timing, fishery closures, collaborative research, and perception of stock size.

2. Context & methods

2.1. Assessment and consultation processes

The snow crab fishery is the largest fishery in the Province of NL and one of the largest fisheries in Canada. In 2017, there were about 2,200 active snow crab enterprises, with industry rationalization occurring since approximately 3,000 enterprises were active in 2008 (DFO, 2019). Despite a shrinking fishing fleet size for over a decade, the snow crab fishery is normally the most valuable in the Province, with landings valued at $325 million in 2017. Most NL fishing fleets are vitally dependent on snow crab, with the fishery comprising 25–90 % of annual revenue for fishing fleets throughout the Province (DFO, 2019). Although the NL marine region and snow crab stock range is large, the scale of fishery management is small, with 42 Crab Management Areas (CMAs) (Fig. 1) and 51 separate allocations of quotas given to individual fleets (information taken from DFO quota reports).

The scientific snow crab stock assessment occurs in late February each year. Among other metrics, the assessment quantifies trends in exploitable biomass, recruitment and pre-recruitment, fishing and total mortality, reproductive capacity, and fishery performance (Mullowney et al., 2019; Baker et al., in press). The primary biomass estimation tool is multi-species bottom trawl survey data. These surveys are conducted during fall (Sep.-Dec.) in Northwest Atlantic Fisheries Organization (NAFO) Divisions 2H, 2J, 3K, 3L, 3N, and 3O (Fig. 1) and in spring in Divisions 3L, 3N, 3O, and 3P. The trawl is a Campelen 1800 shrimp trawl featuring 46 cm rockhopper footgear, a 17 m wingspread, and a 3 mm mesh codend liner (Walsh et al., 2009). The trawl is towed at a speed of 3 knots for 15 min. wherever possible, with all individual tows subsequently converted to swept-area based on bottom contact time. The survey time series spans 1995–2018 for fall surveys and 1996–2018 for spring surveys, with the survey design following a random-stratified approach based on depth.

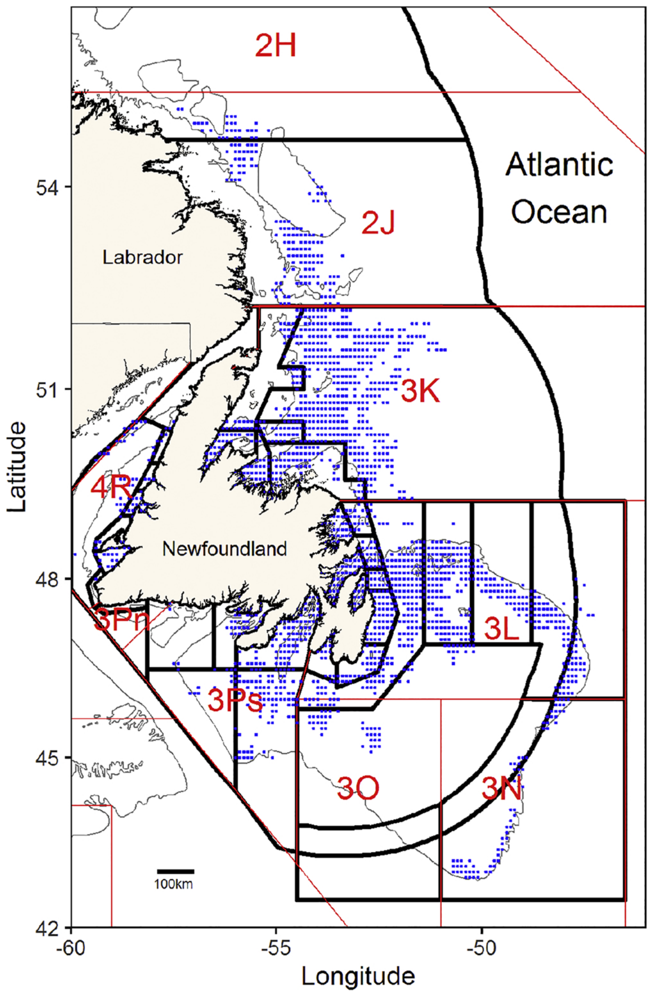

Fig. 1. Map of Newfoundland and Labrador, NAFO Divisions (red), CMAs (black) and 2018 fishing positions (blue dots). Grey underlay is 200 m depth contour (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

Dedicated snow crab trap surveys also occur throughout the region, conducted both solely by DFO as well as in collaboration with crab harvesters. However, the various trap surveys are typically of shorter time series, with only a few localized bays having time series spanning more than twenty-five years. Commercial logbooks and at-sea observer coverage information are used to assess aspects of fishery performance including catch per unit effort (CPUE) and discard rates. The stock assessment is conducted at spatial scales closely conforming to the NAFO Divisions (Fig. 1). The Assessment Divisions (ADs) include 2HJ, 3K, 3LNO Offshore, 3L Inshore, 3Ps, and 4R3Pn. Further details on the stock assessment are available in Mullowney et al. (2019). ADs 3LNO Offshore and 3L Inshore have been combined in analyses herein as their partitioning for stock assessments does not have a biological basis (Mullowney et al., 2019; Baker et al., in press).

Following the annual stock assessment, harvester consultation meetings occur in communities throughout the Province, normally during the first two weeks of March. Separate consultations also occur with Indigenous groups and processing sector interests. At consultation meetings, scientists lead a presentation and discussion on stock status, enforcement officials lead a regulatory compliance piece, and managers overview strengths and weaknesses of current management approaches. Harvesters are represented by Fleet Committees, comprised of panels of elected individuals to voice opinions and concerns on behalf of members within their respective CMAs. The Fleet Committees are elected from individuals represented by the Fish, Food, and Allied Workers (FFAW-Unifor, herein 'FFAW') Union, the labour bargaining agent for fish harvesters in the Province. The Fleet Committees are of different sizes, ranging from one to two individuals in small CMAs to dozens of individuals in large CMAs.

Two focal items discussed at harvester consultations are quotas and seasonality, with Fleet Committees making formal recommendations on both. A myriad of other issues are discussed depending on local, national, or international circumstances affecting the fishery, with associated recommendations on best courses of action for any given issue similarly put forth by the Fleet Committees. DFO maintains exclusive decision-making authority, with no formal obligation to follow Fleet Committee recommendations on any given issue. However, in the spirit of co-management, assurances are given that recommendations will be taken seriously upon final decision making in developing the annual fishery management plan. Science is tasked to provide impartial information to the two parties involved in decision-making. The fishery management plan is released as soon as possible (normally by the end of March or early April) and the fishery opens almost immediately thereafter.

2.2. Spatial scales of management

Most CMAs were developed in the 1990s when there was little long-term or broad-based biological information on NL snow crab upon which to base delineation of management units. The limited information available on movement dynamics, from localized tagging studies, suggested movements were small (Taylor, 1992), consistent with studies from the neighbouring Gulf of St. Lawrence (Powles, 1968; Watson, 1970; Watson and Wells, 1972). Nothing was known on larval movement dynamics or genetic stock structure. The CMAs progressively developed as successive harvester groups entered the fishery after the collapse of the groundfish stocks (Davis, 2012). The fisheries management plan (DFO, 2019 [Section 6.2.3]) states that:

> *"The use of separate CMAs is a management tool to spread fishing effort over a wide area. Increasing the number of CMAs was used as a mechanism to explore areas that had not been fished in the past. There is no scientific reason to have a large number of CMAs…"*

In fisheries in general, to the extent possible, common biological attributes used to delineate management areas include known stock ranges, larval drift dynamics, recruitment patterns, spatiotemporal synchrony of resource trends, and scales of individual movements. Since most of the CMAs were developed, improved information on most of these attributes has emerged.

Over the past decade, a genetic study has shown connectivity throughout all NL waters and more broadly into other regions of Atlantic Canada (Puebla et al., 2008). Movements and migrations have been shown to be larger than indicated by early tagging studies, with conservative downslope ontogenetic movements estimated to average 54–72 km over the course of life and annual upslope mating migrations to average about 43–46 km for both males and females in offshore portions of the NL shelf (Mullowney et al., 2018a). With respect to larval drift, no studies on snow crab have occurred, although a recent study on Northern Shrimp (*Pandalus borealis*) in NAFO Divisions 2GHJ3KLNO found a high level of north-south connectivity associated with downstream flow of the Labrador Current and questioned the efficacy of just three management areas for that stock (LeCorre et al., 2019).

To investigate the newest biological information relevant to spatial scales of management and assessment, we examined data from a tagging study carried out on snow crab along the eastern slope edge of the Grand Bank (NAFO Divisions 3L & 3N) from 2015 to 2018. These data were originally presented in Mullowney et al. (2018a) but have since been updated. This experiment, part of a larger suite of investigations into potential effects of seismic noise on snow crab, tagged large terminally molted males with acoustic transmitters during August-

September in 2015–2017 with recaptures occurring in subsequent spring and summer fisheries. We mapped movement distances of recaptured crab in relation to CMAs to assess the regularity with which snow crab cross CMA boundaries, and plotted histograms of movement distances (km) and rates (km/day) to assess overall movement dynamics.

To investigate synchrony of resource trends across the stock range, we compared time-series (1996–2018) trends of exploitable biomass indices across ADs using simple Pearson Correlations, with biomass indices taken from the most recent stock assessment (Baker et al., in press). The data used to derive biomass indices were restricted to the longest available time series from the multi-species trawl surveys, with 1995 and 2006 omitted from correlation analysis because there was a lack of surveys in AD 3Ps during those years.

2.3. Fishery timing

Fishery timing is an issue of high importance to both harvesters and managers as it affects annual planning processes for both groups. Fishery timing can also affect the quality of the catch and subsequently markets. Fishery timing does not directly affect research and assessment work per se, but can and does directly affect the biological well-being of the stock for which scientists are tasked to provide advice on health and best fishing practices. An aspect of fishery timing particularly important in management is the incidence of soft-shelled (recently molted) crab in the catch (DFO, 2019). Capture and subsequent release of these crab, representing incoming recruits into the fishery, constitutes resource wastage as low meat content renders them unmarketable. Also, a high proportion of soft-shelled crab are believed to die after being handled and released (Mullowney et al., 2019).

The prevalence of soft-shelled crab in the catch is a function of both seasonality and relative strength of the residual biomass (legal-sized, hard-shelled crab). Circumstantial evidence suggests that a depleted residual biomass enables recently molted crab to increase their competitive ability to enter baited traps (Mullowney et al., 2019; Baker et al., in press). Maintaining a high ratio of residual to pre-recruit crab in the population has long been advised as a best practice to minimize the catch of soft-shelled crab in the fishery.

There are two main periods of molting in adolescent male snow crab, one following over-winter mating of first-time spawning (primiparous) females (Sainte-Marie and Hazel, 1992,1999), which predominantly occurs in shallow water, and one during spring, which is more typical in deep water (Mullowney et al., 2018a). Beyond the mating process, other intrinsic factors such as condition and extrinsic factors such as temperature affect the molting schedule (Dutil et al., 2010). With specific respect to temperature, snow crab in warm areas tend to have earlier molting schedules and reduced post-molt recovery times than those in colder areas (Dutil et al., 2010). Along the NL marine shelf, warmest conditions are found in the northern NAFO Divisions (2J, 3K), where bathymetric features are more dynamic and the bottom is typically deeper and less directly influenced by the presence of the Cold Intermediate Layer (a body of < 0 °C water that sits at intermediate depths in the water column) than the southern Divisions (3LNOP) (Mullowney et al., 2019; Baker et al., in press). Nonetheless, despite potential for spatiotemporal variability in the timing of molting, long-term observations show that soft-shelled incidence in the fishery consistently increases in most areas during late spring as recently molted crab become increasingly mobile, particularly in circumstances where the residual biomass is low (Mullowney et al., 2019; Baker et al., in press).

The NL snow crab fishery is prosecuted by small vessels. The three main fleet sectors are < 40' (feet) vessels that operate in inshore CMAs, a mid-distance 40 – 89'11" vessel fleet, and a ≥ 90' fleet that fishes in farthest offshore CMAs in AD 3LNO, although there are not many of these largest vessels. The small vessels make fishing during extreme weather periods such as winter particularly dangerous. Accordingly, with a safety-based preference to fish in calmer conditions, there inevitably exists a high potential to encounter soft-shelled crab in the fishery in any given year, particularly if the residual biomass becomes depleted.

We examined temporal fishing patterns from commercial logbooks (1995–2018) to interpret the extent to which the seasonality of the fishery has changed over time. Accurate completion and timely return of logbooks detailing time and space of fishing along with catch (kilograms) and effort (number of pots fished) is a requirement of license. In most ADs and years, a high percentage of logbooks are returned (Baker et al., in press). For the analysis, we constructed bubble plots of annual percentages of effort (number of trap hauls) by month and year within each AD.

To investigate the relationship between soft-shelled prevalence and fishery timing, we regressed the observed percentage of soft-shelled crab in the catch against the median fishing day (calendar day) for each AD using simple linear regression. The analysis was restricted to 2000–2018 due to data availability on soft-shelled crab observations, which came from the at-sea observer program. Observers are randomly deployed to fishing vessels during the fishery to sample the catch. Typically, 2–5% of fishing trips are observed in any given AD and year, although coverage levels have been near the low end of that range in all ADs in recent years (Mullowney et al., 2018b). Beginning in 2000, observers instituted a subjective shell classification system into their measurements, using a three-stage index: soft (1), new (2), and old (3). Percentages of soft-shelled crab in the catch were calculated at the AD-year level with no finer standardization for time or space, invoking an assumption that a representative sampling scheme was employed in observer monitoring throughout the fishery in any given year. The median fishing day was calculated from commercial logbooks based on reported calendar days for set hauls. Loess regression curves were also fit to the time series data on soft-shell incidence versus fishery timing to assess the degree to which temporal differences in timing of soft-shell incidence occurred across ADs.

To investigate the seasonality of meat yield from soft-shelled crab, we present novel data from a meat yield study undertaken in 2017. The primary purpose of the study was to investigate how fast snow crab shells become filled with meat after molting. This is relevant to optimal fishery timing, particularly in circumstances where the residual biomass is depleted. For the investigation, crab were taken from various inshore and offshore trap and trawl surveys around the Province. Sets where collections were obtained were opportunistic. Wherever time allowed, the first five soft- or new-shelled male crab of legal-size (≥ 95 mm carapace width [CW]) in a given set were examined, to a maximum of 20 crab per survey trip. The right centre leg was removed from the animal and sliced horizontally to assess shell fullness. Six fullness groupings were used for assessment (0%, 1–25 %, 26–50 %, 51–75 %, 76–99 %, 100 %). In total, 2,530 crab were examined encompassing specimens from all ADs over the May to December period. To control for spatiotemporal collection bias, and in consideration of the proportional structure of the response variable, we analyzed the data using a beta regression model (with a logit link function) defined in [1] to predict shell fullness as a function of month and latitude (and their interaction). The model was run using the *betareg* package, according to Cribari-Neto and Zeileis (2010), in R version 3.4 (R Core Team, 2017). As a result of poor sample sizes in May, data from May were removed from the model analysis.

$$\text{logit}(\text{fullness}_{ij}) = \text{month}_i + \text{latitude}_j + (\text{month}_i * \text{latitude}_j), \text{ where logit } (x) = \log(x/1\text{-}x) \quad (1)$$

Finally, to qualitatively assess potential risks of encountering a high incidence of soft-shelled crab in the fishery, we plotted size-specific compositions of shell conditions from measurements taken by DFO Biologists and Technicians (using a five stage index ranging from soft- to very-old shell) during the broad suite of annual trawl and trap surveys by AD and year. Ultimately, the analysis is intended to examine how the presence or absence of a residual biomass (large intermediate to very-old shell crab) in the population relates to soft-shell incidence in the fishery. DFO data were used rather than observer data due to increased sample sizes and more consistency in shell-condition staging. Sizes were binned to 3 mm CW measurements and years were grouped into two-year periods for this analysis. Soft- and new-shelled crab would have most likely molted in winter-spring of the current year (Mullowney et al., 2018a), while older-shelled crab would have last molted more than a year ago, and possibly as long as 5 years or more for very-old shelled individuals (Mullowney et al., 2019). The soft and new-shelled crab are analogous to the crab examined in the meat yield study.

2.4. Fishing closures

To address concerns for high incidence of soft-shelled encounters in the fishery by all partners, a soft-shell protocol was implemented in 2005 in an attempt to protect pre-recruit crab from handling mortality (DFO, 2013).

The soft-shell protocol has evolved over time. Initially, it aimed to close 7 × 10 nautical miles grids for the remainder of the fishing season when 20 % of the catch was observed to be soft-shelled. However, over time harvesters in many areas expressed concerns that the scale of closures was too large and too prohibitive in affecting their ability to find suitable fishing grounds. Accordingly, the grid sizes in these areas (inshore CMAs in all ADs as well as all CMAs in ADs 3Ps and 4R3Pn) became quartered into 3.5 × 5 M sizes. Furthermore, harvester groups in AD 3LNO wished to reduce the closure threshold from 20 % to 15 % observed soft-shelled crab, and this reduction became implemented in various CMAs throughout AD 3LNO over time. Finally, minimum sample size thresholds also became implemented into the protocol as harvesters expressed concerns that areas were being closed based on limited measurements. In its current form, the protocol requires minimum sample sizes of 43–45 legal-size crab per trip per cell to be measured in the small grids and 130–135 measurements in the large grids, with sample sizes depending on size of the fishing vessel.

The soft-shell protocol relies on at-sea observers to detect and report soft-shelled crab incidence in the fishery. In turn, the level of observer coverage directly depends on harvester funding, with the program operating on a ‘quasi-user-pay’ system. To fund the program, a fixed amount of money based on landings (currently 0.67 cents per pound) is required from each harvester. However, this obligatory contribution does not guarantee a harvester will receive observer coverage in any given year, with monies allocated to a common pool within each AD to distribute observers throughout the fishery.

Beginning in 2012, the scientific assessment began formally expressing concerns that the soft-shell protocol was ineffectual in controlling handling mortality (DFO, 2013). The major concerns were low levels of observer coverage, too many grid cells, and often unachievable minimum sample sizes to invoke closures.

To investigate the ability of the soft-shell protocol to provide protection to the resource, we undertook an analysis to quantify ‘detectability potential’ by quantifying the proportion of grid cells that could be closed in any given year based on present rules. For this analysis, we plotted and qualitatively interpreted the proportion of cells fished in any given area that both received observer coverage and met minimum sample size thresholds to potentially invoke closures.

2.5. Collaborative research

Collaborative research is often a key component of successful co-management arrangements as it promotes increased trust and can broaden the scope of available information (Kofinas, 2002; Kaplan and McCay, 2004; Berkes, 2009). Consistent with these ideologies, the FFAW has sought to expand their research and assessment and management capacities over the past 10–15 years, and worked alongside DFO to develop the Collaborative Post-Season Survey (CPS), a Province-wide trap survey snow crab that began in 2003. Reflecting the spirit of such collaborative research initiatives, the FFAW website states (http://ffaw.nf.ca/en/snow-crab-post-season-trap-survey#.XR4GKE2P4ic):

> *“Industry felt that a survey dedicated solely for snow crab using commercial and modified commercial snow crab traps would allow the fishing industry to more accurately assess and ultimately better manage the valuable snow crab resource”* and that by 2008 *“It is widely accepted that recent snow crab assessments have accurately reflected stock status.”*

The CPS survey is a large undertaking, typically occupying between 1000 and 1200 sites in any given year throughout all ADs. Notwithstanding a myriad of logistical tasks carried out by both DFO and FFAW, the survey essentially gets started by the FFAW identifying harvesters to conduct it, which occurs through a random-draw process. Harvesters conduct the fishing with their own gear. At-sea observers accompany the harvesters to take biological measurements from the catch. Data are subsequently submitted to DFO Science Branch to be quality checked, key-punched, archived, and analyzed for the stock assessment. Harvesters are paid for their efforts through a ‘quota-for-survey’ arrangement, whereby additional quota is allocated in the following year as compensation for assuming risks and efforts to conduct the survey. No survey catch is kept in the present year.

Collaborative research is most effective when there are clearly defined, agreed upon, and trusted sources of information (Linke and Jentoft, 2013). The CPS survey was originally designed as a fixed-station initiative focusing on commercial fishing grounds with a maximum spacing of 10’x10’ nautical miles between sites (Mullowney et al., 2019), although site locations were spaced as close as 5’x 5’ nautical miles in areas of high crab abundance (Stansbury et al., 2014). At each station, 6 (inshore) or 10 (offshore) commercial fishing traps (133 − 140 mm mesh) are set, with biological sampling for size and shell composition of individuals conducted by at-sea observers. Until recent years, a limited number of small-mesh (25 mm mesh) traps were haphazardly distributed to capture smaller crab for assessment of stock recruitment potential. Explicit objectives for the survey were poorly captured during its infancy, although anecdotal accounts suggest original positions were loosely based on harvester knowledge on distributions of commercial crab aggregations. Ultimately, the survey was not originally designed in a manner conforming to conventional statistical sampling designs.

Coupled with an unbalanced statistical design, the CPS survey underwent attrition of some sites in its early years and since 2010 a set of core stations were identified for stock assessment purposes. However, the number of core stations occupied in any given AD and year continued to fluctuate, although not excessively so, with an overall total of 800–1020 core stations occupied each year from 2004 to 2013 (Stansbury et al., 2014).

In recent years, the CPS survey has become criticized during DFO scientific peer review for its limited utility in stock assessment (Mullowney et al., 2019). Fundamental concerns revolve around the ability of the survey to measure all resource components including small males and females, which are often found shallower than large commercial-sized males (Mullowney et al., 2018a). This deficiency reflects omission of shallow areas from the survey footprint and an associated issue of too few small-mesh traps deployed in shallow areas. Further, upward catch rate biases in the data have been identified stemming from disproportionately high levels of survey coverage in areas of highest crab abundance and omission or outright abandonment of poorly performing areas. To address these concerns, since 2016 the survey has been transitioning to a hybrid fixed-random survey design with improved horizontal and vertical spatial coverage. Furthermore, a small-mesh trap is being added to every survey station, with newly randomized stations first receiving the additional influx of small-mesh traps. In 2018, 50 % of the survey locations were randomized and that plan remains in place for the foreseeable future with a goal of having a small-mesh trap at every station within the next few years.

To qualitatively examine the direction and degree to which omission of stations has potentially affected data integrity, we constructed boxplots of average station CPUE in relation to the number of years a station was occupied during the 2005–2015 period.

Beyond participating in a collaborative survey, harvester representatives also act as reviewers at annual stock assessments. A consistent concern raised by harvesters over the years (both at assessments and in other fora) is that the short survey long-lines of gear (termed 'fleets') used in various trap surveys are too short to properly capture the signal of relative abundance in any given time and space. By extension, survey catch rates may not constitute a valid comparison to the fishery, which uses fleets of gear that can range from 25 to 200 pots or more. These concerns have been raised in context of the CPS trap survey, the DFO inshore trap surveys (fleets of 6–10 baited traps), and most recently in offshore trap surveys conducted in AD 3LNO as part of a suite of potential impacts of seismic noise on snow crab (see papers throughout this journal theme section). Our understanding is that part of this perspective comes from the gear simply not being heavy enough to remain steadfast to the seafloor and part of it stems from a potential inability of short fleets to attract crab from a broad spatial area.

This criticism of potentially low catch rates in trap surveys is important to address to better understand potential differences between surveys versus logbook information, particularly in light of the necessity to make comparative inferences from data sources within the co-management system. To address the concerns, we isolated and examined instances where commercial fishing and assessment surveys occurred directly alongside one another in time and space. For this analysis, we used the DFO inshore trap survey series (see Mullowney et al., 2019 for more details), whereby in some bays (loosely conforming to inshore CMAs) annual surveys are in-season. From the two respective datasets, we identified set locations that occurred within 8 nautical miles (about one hour steam apart) of one another and had < 24 h difference in gear soak times upon hauling. We also limited the analysis to depths beyond 75 m to ensure the comparison was made on what would normally be deemed commercial crab grounds. We plotted and compared CPUE (kg/trap) of legal-sized crab between the two data types (logbook or survey) at the CMA and year level and tested for differences in catch rates across the two data types using a linear model defined in [2];

$$\ln(\mathrm{CPUE})_{ijk} \sim \mathrm{type}_i + \mathrm{yearj} + \mathrm{CMA}_k + (\mathrm{type}_i{*}\mathrm{yearj}) + (\mathrm{type}_i{*}\mathrm{CMA}_k) \quad (2)$$

Where, *ln(CPUE)* denotes natural-log transformed CPUE (kg/trap), and type denotes data type. Year and CMA were also incorporated as explanatory factors, testing for main effects of all factors as well as the interaction of data type with both year and CMA. It should be noted that the survey gear was baited with 2–3 pounds of squid (*Illex spp.*) and traps were spaced about 45 m apart. Specific baiting and spacing practices are unknown in the comparative fishery data but are undoubtedly not standardized across vessels. However, with the exception of fleet length, the survey gear and methods are designed to mimic general practices in the fishery. Furthermore, in the survey gear, small-mesh traps were placed intermittently between large-mesh traps, and those small-mesh traps were omitted from the analysis. Although this could potentially introduce bias in the form of unknown differences in catchability or intra-fleet trap competition, unpublished observations suggest there is no difference in CPUE in small-mesh versus large-mesh traps for crab larger than about 115 − 120 mm CW, with a gradual decreasing divergence occurring as crab get smaller thought to reflect size-specific escapement ability from commercial fishing gear after capture.

2.6. Perception of stock size

Fleet Committee recommendations in the fishery decision-making process for establishing annual quotas and associated issues are intuitively based on perceptions that harvesters have about the size and health of the snow crab resource in their given CMA(s). In fisheries in general, CPUE is usually of central importance to harvesters in assessing stock status (Branch et al., 2006). CPUE reflects harvester experiences and knowledge in prosecuting the fishery, and most likely reflects learned practices to maximize catch and minimize effort.

CPUE is often less favoured by fisheries scientists as it is prone to biases created by fleet dynamics, adaptive harvester behaviours, or other factors such as gear catchability (Beverton and Holt, 1957; Gillis, 1993, Harley, 2001). Two concerns of using CPUE as a measure of stock size have recently been identified in this fishery; first that it exhibits hyper-stability (remains 'stable' while stock size changes) associated with trap saturation and second that it lags behind measuring changes in stock size relative to signals from spatially-stratified surveys (Mullowney et al., 2018b). We investigate both processes first by plotting annual CPUE estimates taken from the most recent stock assessment (Baker et al., in press) in relation to trawl survey-based exploitable biomass indices, by AD, also taken from the most recent stock assessment. Data for each series were standardized at the AD level (mean of 0 and s.d. of 1) for the comparision. We further calculated Pearson Correlations for CPUE in relation to survey biomass lagged (shifted forward) by 0, 1, and 2 years to investigate the temporal relationships of CPUE responses to survey-detected changes in stock size. To examine hyper-stability dynamics of fishery CPUE, we fit log-log regression models to the relationships of annual CPUE versus one-year lagged survey biomass indices for each AD.

It should be noted that CPUE was based on a linear mixed regression model incorporating fixed effects of time, space, and soak times (Mullowney et al., 2019; Baker et al., in press).

3. Results

3.1. Spatial scales of management

The CMA map of NL snow crab is highly complex (Fig. 1). There are many nuances reflecting local differences in strategies of how crab should be managed and fished. For example, in AD 2H J the strategy is to utilize large management areas while in AD 3LNO smaller-scale management areas are preferred. As a second example of regional differences, within ADs 3K, 3LNO, and 3Ps there are strategies in place in some select CMAs to shift vessels between CMAs depending on local expectations of fishery performance each year. A more exhaustive list of regional-scale management strategies is available in DFO (2019).

The offshore tagging study in AD 3LNO showed that large terminally molted males can both remain in relatively fixed locations for extended periods of time and travel large distances in short periods of time. Based on seasonal movement patterns of animals tagged during fall and recovered in the following spring-summer, long distance movements do regularly cross CMA boundary lines (Fig. 2). The 56 recaptured crab in the study were caught in four different CMAs and moved an average distance of 41.1 ± 45.5 km (1 s.d.) while at liberty (Fig. 2) at a displacement rate of 0.19 ± 0.46 km/day (Fig. 2). Movement distances ranged from 0.13 to 181 km while displacement rates ranged from 0.0 to 3.4 km/day.

Trends in the exploitable biomass were strongly positively correlated with one another across all ADs over the time series. All AD combinations had correlation coefficients ranging from 0.50 to 0.80 (Fig. 3). All relationships among AD biomass trends were significant ($p < 0.01$) (Fig. 2).

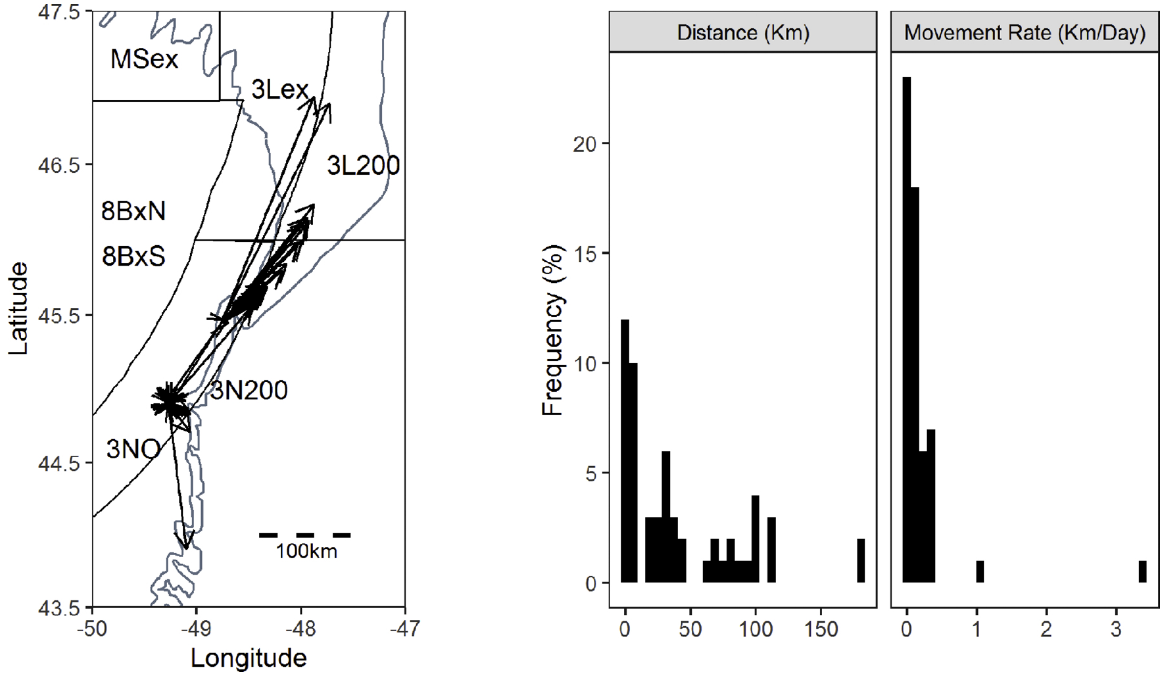

Fig. 2. Mark and recapture locations of snow crab in the 2015-2018 3 LNO tagging experiment and CMA boundary lines (left panel). Histograms of distance moved (km) and movement rates (km/day) by recaptured snow crab in 3 LNO tagging experiment (right panel).

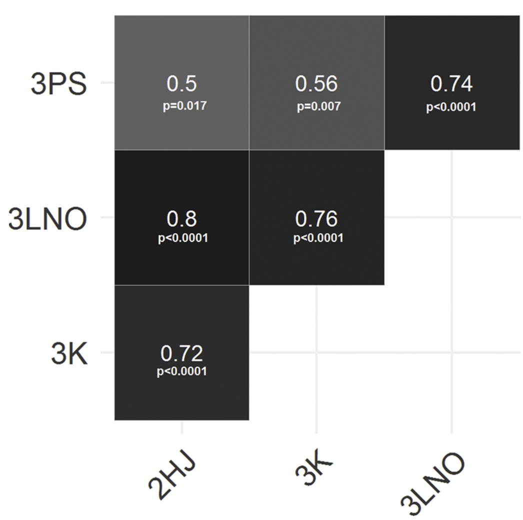

Fig. 3. Pearson correlation coefficients and significance of relationships for exploitable biomass indices from 1996-2018, by Assessment Division pairings.

3.2. Fishery timing

Over the 1995–2018 period, the fishery transitioned from summer-fall to spring-summer seasonality in all ADs, although the timing of the fishery is not the same everywhere (Fig. 4). There were two dominant shifts toward earlier fishing. The first shift occurred in 1998 when more effort occurred in June and less effort occurred in August in all ADs. With the exception of AD 2HJ, there was little fishing extending into the fall months (Sept.-Dec.) in any AD after the 2000 fishery. In 2005, another pronounced shift toward earlier fishing occurred in all ADs, with virtually all fall fishing stopping everywhere after that point. Effectively, the fishery systematically moved about a month earlier everywhere, with an April-May concentration in earliest ADs 4R3Pn and 3Ps and a later June-July concentration in lastest AD 2HJ.

The linear regression models showed that soft-shelled crab incidence in the catch increased as a function of time throughout the summer in all ADs (Fig. 5). Overall, soft-shelled levels were consistently highest and regression slopes greatest in ADs 2HJ and 3K. In these northernmost ADs, soft-shelled incidence in the fishery routinely ranged from 5 to 20 % at all points in the season and reached levels as high as 40 % during years with August fishing medians in AD 2HJ. In ADs 3LNO and 3Ps, soft-shelled incidence in the catch was overall usually low, at about 0–5 % in all years. A spatial difference in the timing of soft-shell incidence in the fishery occurred across ADs, with peak timing in AD 2HJ occurring in August, whereas it occurred in July in the other three ADs examined.

The meat yield study showed a sharp decline in shell fullness in soft and new-shelled crab from May to July (Fig. 6). The overwhelming majority of examined crab yielded observations of having shells 75–100 % full in June, versus 25–75 % fullness dominating the the July examinations. The regression model predicted that the legs of most crab were only about 40–50 % full of meat in July, and did not reach complete fullness until December (Fig. 6).

Survey sampling of population demographics showed that AD 2HJ has historically been problematic with respect to a lack of residual biomass, with few legal-size crab advancing beyond an intermediate-shelled condition throughout the time series, and a relatively low proportion of intermediate-shelled crab in the legal-size population relative to other ADs in most years (Fig. 7). AD 3K showed an increased proportion of intermediate and older-shelled crab in the population than AD 2HJ in most years, but low levels relative to ADs 3LNO and 3Ps, where it was common for intermediate and older-shelled crab to comprise 50 % or more of the legal-size component of the population in any given year.

It must be noted that shell condition-based analyses are qualitative and can be affected by numerous factors including subjectivity in shell condition classification, changes in pattern or intensity of fishing effort, or spatiotemporal variability in pre-recruitment strength or molt timing. Nonetheless, the overall patterns are consistent with the findings of recent stock assessments highlighting consistently high fishery exploitation rates in ADs 2HJ and 3K (e.g. often above 50 % of the exploitable biomass), low exploitation rates in AD 3LNO (e.g normally below 30 % of the exploitable biomass), and an associated low residual biomass in the heavily exploited northern ADs contrasting a high

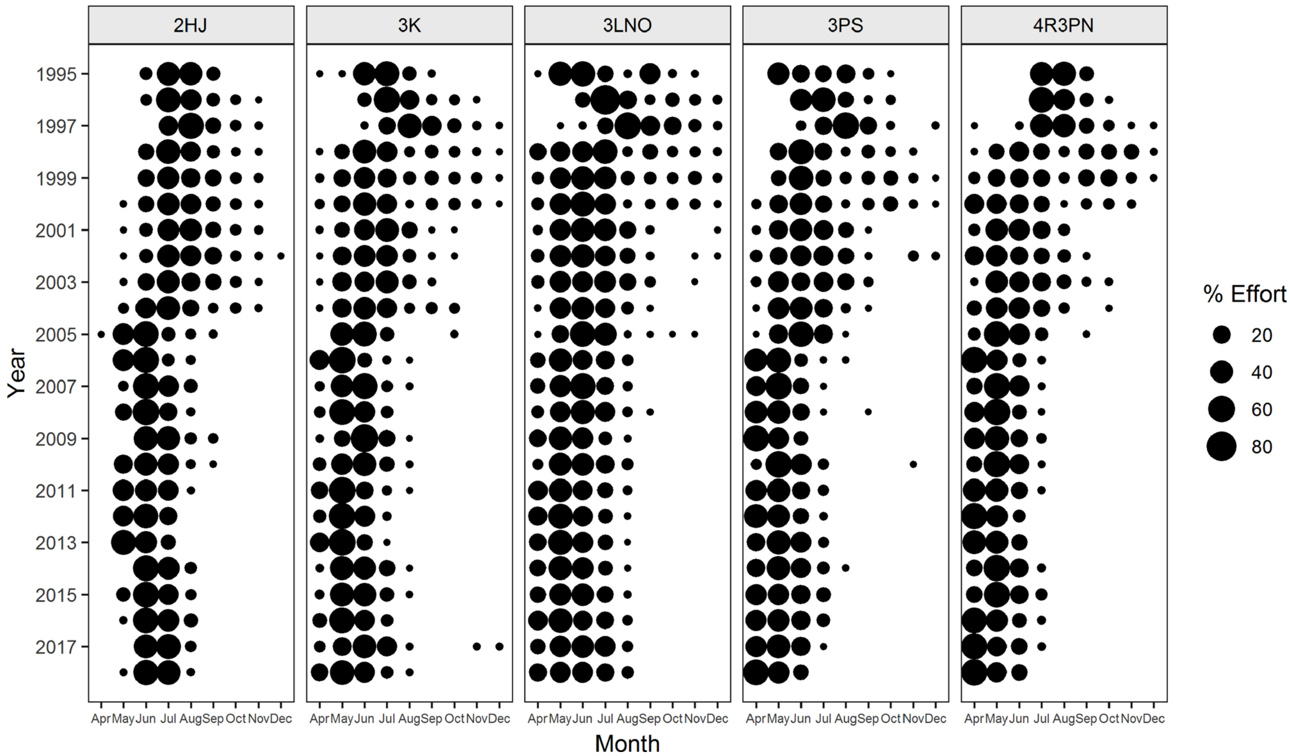

Fig. 4. Bubble plots of the percentage of seasonal fishing effort (trap hauls) per month by Assessment Division and year.

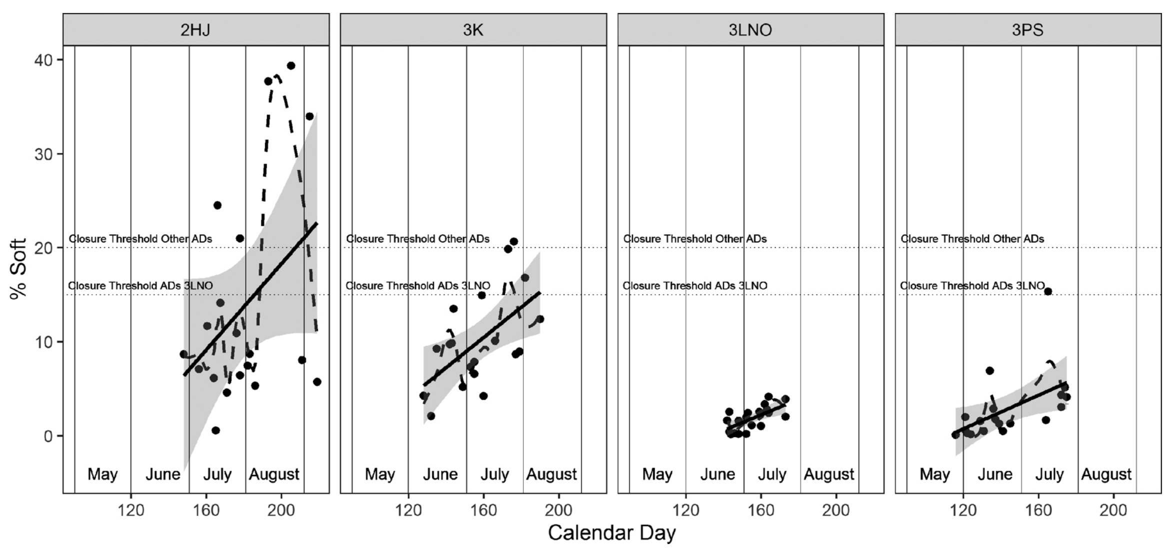

Fig. 5. Linear regression models of the percentage of soft-shelled crab observed in the catch versus median fishing day in the fishery. Horizontal dashed lines denote closure thresholds for the soft-shell protocol and vertical solid lines show monthly time bins. Underlying dashed lines are loess regression curves showing temporal trend in each AD. Data from 2000-2018.

residual biomass in the more lightly exploited southern ADs throughout most of the 1995–2018 time series (Baker et al., in press).

3.3. Fishery closures

The primary spatial footprint of the fishery is readily discernable (Fig. 8). In the north, two relatively discrete patches of effort occur off Labrador with the southern mass of effort extending southward into the offshore portion of AD 3K. A horseshoe pattern occurs in AD 3LNO along the Grand Bank, with the southwest corner larger void of effort. All inshore bays east of about -56°00.00’W are intensively targeted, and a continuum of effort extends from inshore to offshore in the eastern half of the south coast of the island in AD 3Ps. The observer distribution pattern generally reflects that of the fishery, although few cells are occupied every year, and offshore portions of ADs 3K and 3LNO receive the most frequent coverage.

The analysis of detectability potential for the soft-shell protocol showed relatively few cells to have a chance of being closed in most years in any given AD (Fig. 9). Only offshore portions of ADs 3 K and 3 LNO have ever had an opportunity to potentially close about 50 % of cells in a given year, with a very low ability to close cells in most other areas and years (0–25% in most years).

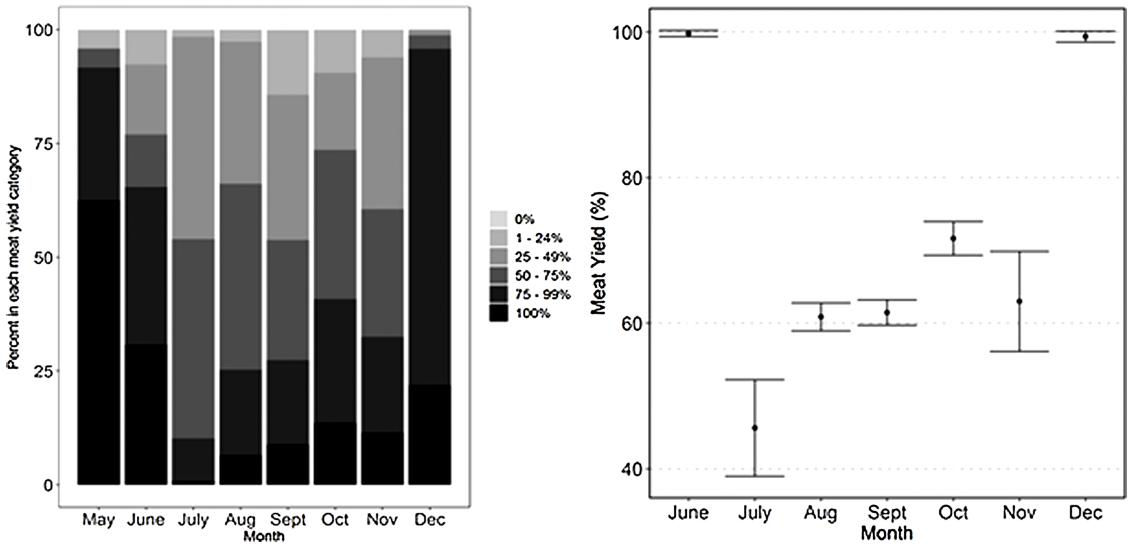

Fig. 6. Percent of male, recently molted snow crab sampled within each meat yield category by month (left panel) and model-predicted meat yield of recently molted snow crab by month (right panel).

3.4. Collaborative research

The anlaysis on frequency of station occupancy in the CPS survey showed a positive relationship between time-series average CPUE and occupation frequency (Fig. 10). Stations with a time series average of less than about five crab per trap were rarely occupied more than four times while those with catch rates of about 15 crab per trap or more were occupied in all or most years. Given that stations remained allocated each year, omission of stations with poor catches reflects a systematic process.

The analysis on catchability of adjacent short versus long fleets of gear generally showed similar trends in catch rates between adjacent survey versus fishing sets wherever they occurred (Fig. 11). However, survey sets systematically yielded higher CPUE than fishery sets. The linear model showed a significant difference between gear types ($p = 0.002$, $t = 3.095$), with the positive coefficient confirming the visual assessment of typically higher CPUE in survey sets (Table 1).

3.5. Perception of stock size

Trends in survey biomass versus CPUE indices showed a dominant systematic pattern of changes first occurring in survey biomass and subsequently occurring in CPUE over a lag of a year or two (Fig. 12). A one year lag between the two indices was most apparent in ADs 2HJ, 3Ps, and 4R3Pn, where correlation coefficients ranged from 0.62 to 0.77 (Table 2). A two year lag best described the relationship between the two indices in AD 3LNO, with a correlation of 0.68. AD 3K was the only area to show the strongest correlation within year, with a correlation of 0.70. Given the chronology of the two indices, with the spring-summer fishery preceding the autumn survey in any given year, this indicates that contrary to other ADs changes in stock size may first be detected by the fishery in AD 3K.

An asymptotic-shaped curve occurred in the distributions of fishery CPUE in relation to biomass from the preceding survey in all ADs (Fig. 12). Generally, with exceptions within all ADs and in particular AD 4R3Pn where the survey times series is short, CPUEs during highest periods of biomass at the start of survey time series were approximately 2–3 times as high as most recent years, while biomasses have declined by factors of 4–5 or more.

4. Discussion

4.1. Spatial scales of management

The study indicates that CMAs used to manage the fishery are too small to constitute biologically meaningful units for resource assessment and provision of advice. This re-affirmation is bolstered by the newest available tagging information from the AD 3LNO slope edges. Current knowledge suggests that because the tagged crab were large terminally molted males concentrated in deep areas, minimal movements were likely as down-slope ontogenetic movements had most likely already occurred (Mullowney et al., 2018a). Although small-scale movements were common in crab from the southern tagging site, subjects from the northern site routinely travelled large distances and crossed CMA boundary lines during the overwinter period. This could suggest participation in up-slope breeding migrations (Mullowney et al., 2018a). Even the generally more sedentary subjects from the southern site crossed CMA lines.

To both assess and manage a natural resource at scales not conforming to biologically meaningful units is risky, as among other problems such as fracturing biological connectivity processes, it increases the likelihood of providing inaccurate advice and making decisions based on sub-optimal information. In the context of NL snow crab, the large number of irregular-shaped CMAs puts the science assessment program in a precarious situation. The probability of accurately and precisely forecasting stock health separately in all 42 CMAs in any given year is relatively low, particularly considering known transboundary movements. Even at the broader AD level, whereby six assessment units exist, we have encountered circumstances reflective of assessing at inappropriate spatial scales. For example, the stock assessment has been unable to explain an unforeseen decrease in biomass in AD 3LNO in 2007, which was coincidentally associated with a large and unexpected increase in AD 3K biomass in 2007–2008 (Mullowney et al., 2019). Similarly, in the most recent assessment, there were apprehensions on stock status advice for ADs 2HJ and 3K as the centre of distribution for a cluster of large surveys tows normally occurring south of the 2J/3K line atypically moved northward into Division 2J (Baker et al., in press).

The small spatial scales used to manage the NL snow crab fishery contrast large management areas in most other major global snow crab stocks including in the adjacent Eastern Scotian Shelf and Southern Gulf of St. Lawrence within Atlantic Canada, the Eastern Bering Sea of Alaska, and both the developing Norwegian and Russian management regimes for the Barents Sea stock. The synchrony in biomass trends

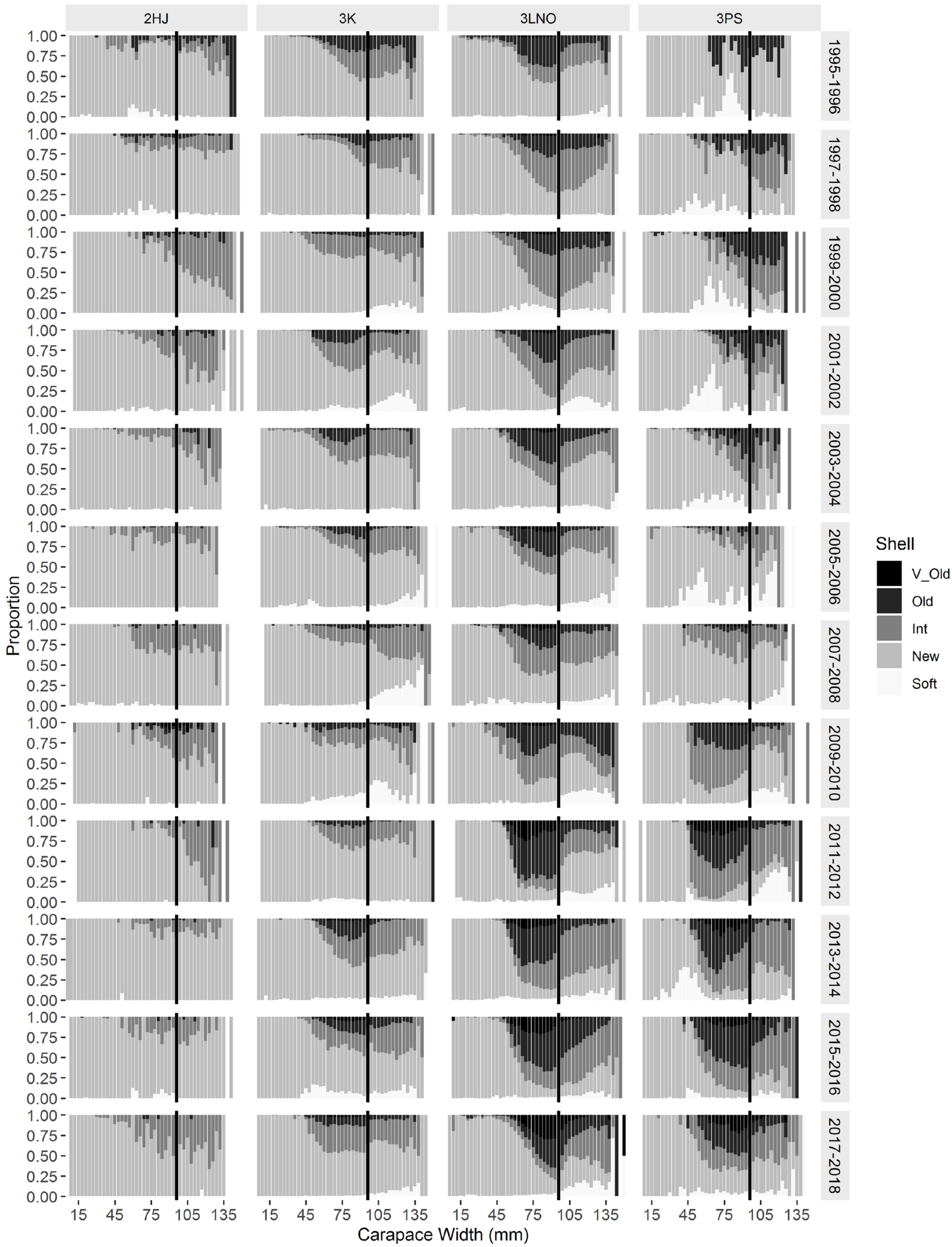

Fig. 7. Shell composition of 3 mm carapace width size bins of male crab captured in DFO trawl and trap surveys by Assessment Division. Data binned to 2-year time increments.

across a very large spatial area shown herein supports a common stock structure suitable for broad-scale resource assessment, particularly as within any given AD trends in CMA-specific CPUE are generally synchronous (Mullowney et al., 2019). Even though, with the accumulation of knowledge, the stock assessment now recognizes it is being conducted as inappropriate spatial scales, it is difficult for the science program to move toward a more appropriate approach to assess at the stock level because as it moves the assessment information and advice further away from the smaller spatial scale level sought by the two important client sectors of management and industry. This is an inconvenient situation for all parties.

To be most effective, co-management decision-making processes must be adaptive and open to change as improved information becomes available (Wilson, 2009; d'Armengol et al., 2018). Greatly improved scientific information has become available on movements (Mullowney et al., 2018a) and snow crab population dynamics (e.g. Mullowney

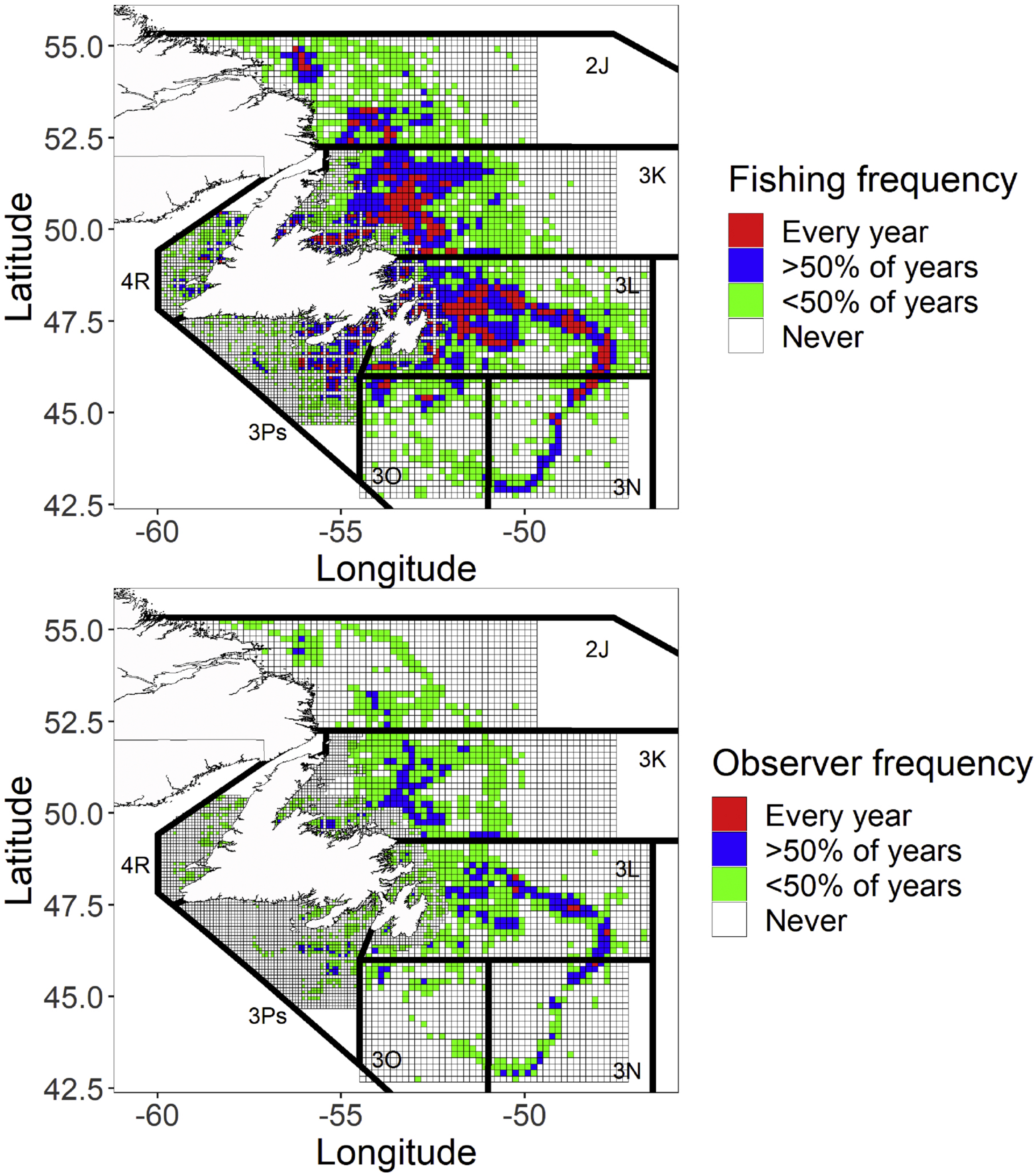

Fig. 8. Maps depicting the frequency at which harvesters fished (top panel) and observers sampled within (bottom panel) the soft-shell protocol monitoring cells from 2000 to 2017.

et al., 2014; 2018b) since the CMAs were developed and consistently suggests a disconnect between spatial aspects of species biology and management. This disconnect constitutes a clear example of how the processes of continual learning inherent in science necessitate willingness to be adaptive in resource co-management systems in order for science to be most effective and collectively beneficial.

In reviewing reasons for co-management failures in Asia, Pomeroy et al. (2001) found that management area boundaries should reflect ecosystem considerations and that effects of non-sustainable fishing practices were best reversed when partners had sufficient knowledge on basic biology and ecology of co-managed resources. Although knowledge on basic biology and ecology of NL snow crab has increased, a shortcoming of not adapting to it in the management system creates challenges and deficiencies for all co-management partners. For example, at-present, summary bullets from the stock assessment are developed at the AD level but management plan recommendations are taken from Fleet Committee members at the CMA level. This consequently forces both resource managers and Fleet Committee members to qualitatively disseminate how to apply stock status information to their respective circumstances and scientists to face questions they are not prepared to answer. In turn, it is easy to dismiss the science as being inapplicable to any given CMA and instead more heavily rely on direct observations from the previous fishing season (e.g. CPUE). A probable outcome of this would be management decisions that promote either under- or over-exploitation by fisheries in localized areas.

The CMAs were developed as a tool to broadly distribute effort toward avoiding local depletion (DFO, 2019). However, bioeconomic theory on optimal fishing intensity suggests this approach may plausibly prohibit broad effort distribution. Gillis (2003) reviewed fisheries distribution behaviour and described how in the absence of regulatory

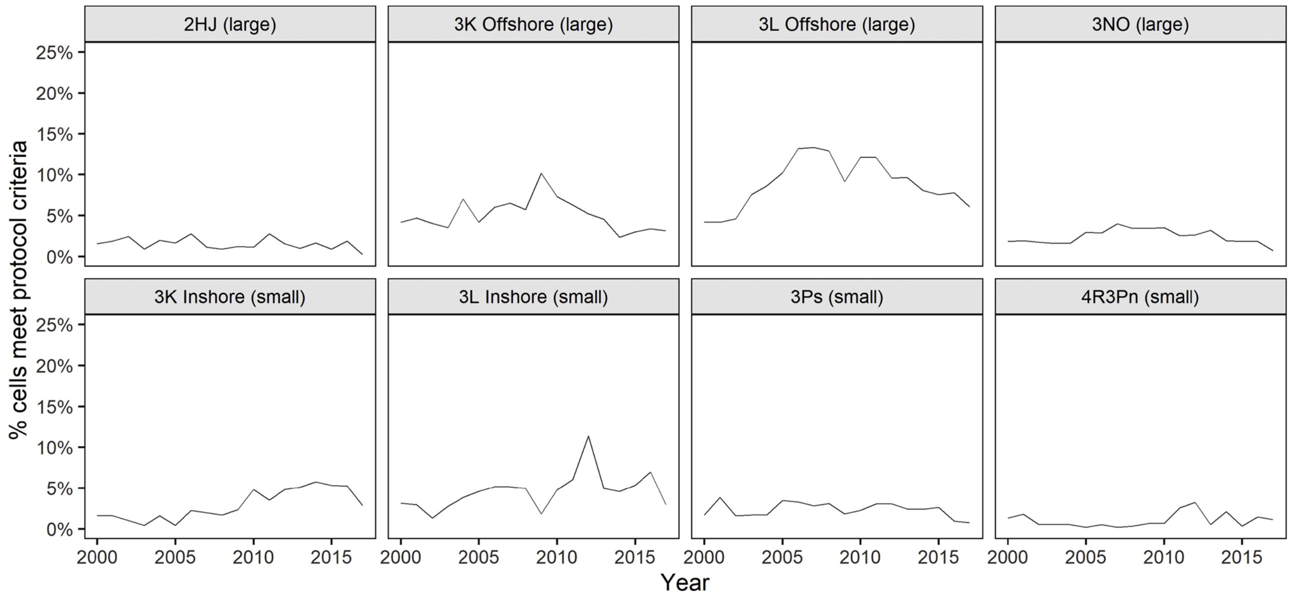

Fig. 9. Percentage of soft-shell protocol monitoring cells fished in any given year that both received observer coverage and met minimum sample size requirements to potentially invoke closures.

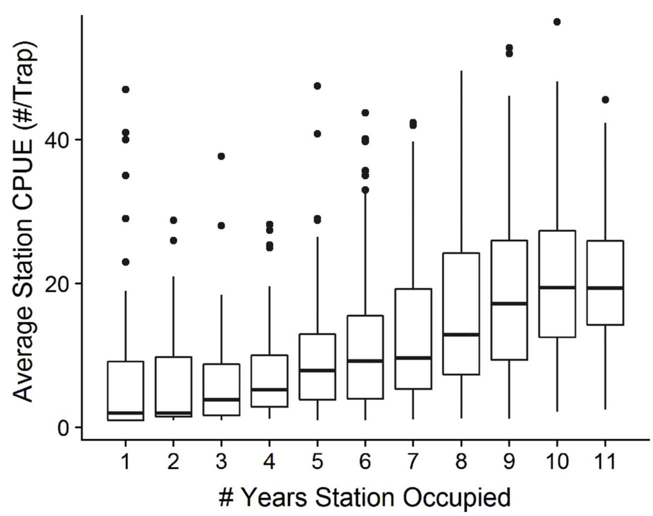

Fig. 10. Boxplots of average station CPUE versus the number of years a station was occupied by the CPS trap survey from 2005-2015.

interference, when sufficient competition exists, harvesters will spread themselves out toward development of 'Ideal Free Distributions', whereby overall economic returns become balanced across spatial domains. This reflects the optimal fishing intensity described by Gordon (1954), whereby individuals within a collective separate themselves into spatial densities that maximize differences in revenues versus operating costs throughout the fishing grounds (Hilborn and Kennedy, 1992).

The fishery in the large offshore CMA of AD 3K reflects the theory of optimal fishing intensity, whereby effort consistently spreads itself out each year in the absence of CMA barrier lines (Mullowney et al., 2019; Baker et al., in press). Similarly, we highlight the operational characteristics of AD 2HJ, which is characterized by both large-scale CMAs and persistent high exploitation rates (Mullowney et al., 2019; Baker et al., in press). Heavy exploitation can and does result in local depletion of the resource in AD 2HJ, evident by consistently high levels of soft-shelled crab in the fishery that can at times reach as high as 50 % or more of the total catch (Baker et al., in press). If one of the dominant fishing grounds fails, the fishery may shift and concentrate intensively into another area, with this exchange having worked in both directions in the past (Mullowney et al., 2012, 2019; Baker et al., in press). The free mobility theoretically enables potentially severe impacts of continuing to fish on depleted populations to be lessened, and partially offsets socio-economic impacts of a poor fishing year for the broader collective of harvesters in the area.

4.2. *Fishery timing*

From an economic perspective, the best time to fish snow crab is during winter, as wastage is minimized through low soft-shelled crab encounters. The meat yield study showed that even snow crab that molted in the most recent spring are normally full of meat by December. Biologically, the winter period does have potential to interfere with the mating period of primiparous (first-time spawning) females (Sainte-Marie et al., 1999), although as such mating is most common in shallow water (Mullowney et al., 2018a), such interferences may be partially nullified by fishing in deep waters. Moreover, interference on breeding from winter fishing is conceptually no different than that imposed by spring fishing during the mating period of multiparous (multiple time spawning) females, and less problematic than fishing intensively in deep waters during spring where molting of large adolescent males is common (Mullowney et al., 2018a).

In the absence of the ability to conduct a winter fishery, a best-advised strategy is to maintain a strong residual biomass in the population to safeguard against a high incidence of soft-shelled crab in the catch. The two contrasting extremes of shell composition demographics between populations in ADs 2HJ and 3LNO demonstrate the value of such a strategy. In AD 2HJ, the consistent lack of residual biomass in the population is associated with routine incidences of soft-shelled crab in the fishery. In contrast, in AD 3LNO where the residual biomass has been historically strong, there is rarely a high incidence of soft-shelled crab in the fishery. There must be soft-shelled crab in the AD 3LNO population, as the area has consistently produced the largest biomass of snow crab in NL for the past two decades (Mullowney et al., 2019). Soft-shelled crab simply do not readily trap when the residual biomass is strong due to trap competition exclusion. The inability to avoid soft-shelled crab in the AD 2HJ fishery is exacerbated by it being the last region to become ice-free in any given year; in many years, such as the past four, most vessels cannot access the fishing grounds until late May or even June (Baker et al., in press).

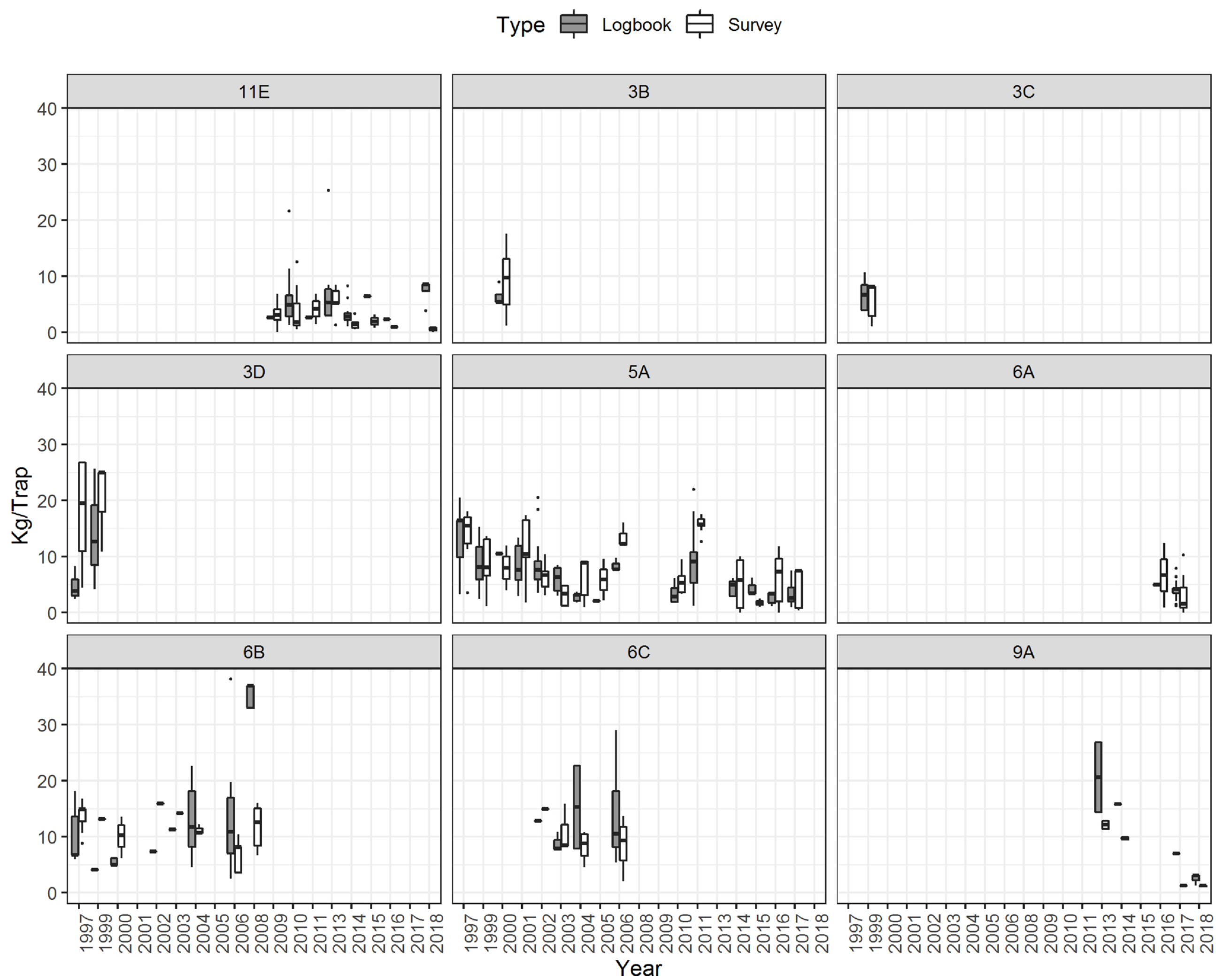

Fig. 11. A comparison of catch per unit effort (CPUE) from fisheries logbooks and nearby trap survey stations in each year during the period 1997–2015. Spatial units denote Crab Management Areas.

Table 1
Output of linear regression model comparing logbook versus trap survey CPUE.

	Estimate	Std. Error	t value	Pr(> |t|)
(Intercept)	100.60	30.42	3.31	0.000974
TypeSurvey	133.17	43.02	3.10	0.002015
year	−0.05	0.02	−3.26	0.001155
cma3B	−0.20	0.67	−0.29	0.768841
cma3C	−0.28	0.71	−0.39	0.700511
cma3D	−0.61	0.44	−1.38	0.1695
cma5A	−0.01	0.22	−0.06	0.9537
cma6A	0.11	0.39	0.29	0.770045
cma6B	0.53	0.27	1.94	0.053298
cma6C	0.63	0.40	1.57	0.116671
cma9A	0.90	0.59	1.54	0.124135
TypeSurvey:cma3B	0.36	0.95	0.38	0.705865
TypeSurvey:cma3C	−0.14	1.01	−0.14	0.886833
TypeSurvey:cma3D	1.28	0.62	2.05	0.04049
TypeSurvey:cma5A	0.32	0.31	1.03	0.301705
TypeSurvey:cma6A	0.16	0.55	0.29	0.772218
TypeSurvey:cma6B	0.21	0.39	0.54	0.590736
TypeSurvey:cma6C	0.16	0.57	0.28	0.778469
TypeSurvey:cma9A	0.57	0.83	0.69	0.491285
TypeSurvey:year	−0.07	0.02	−3.12	0.001867

Solutions to rectifying issues of seasonality in areas of little residual biomass are not easy to find. In a co-management context, it requires self-imposed tough decisions. The meat yield analysis on soft- and new-shell crab shows that fishing from July through November is a generally poor strategy with respect to extraction efficiency. This is problematic for areas like AD 2HJ where there is little choice due to ice coverage during the more optimal periods. To fish efficiently in the summer therefore necessitates low exploitation rates to continually promote a strong presence of residual crab in the population. The problem of soft-shelled encounters becomes circular and difficult to break once it becomes chronic. High exploitation leads to high incidence of soft-shelled crab, which in turn reduces fishery yield-per-recruit and further increases resource recovery time. To break the cycle necessitates one of two events; either the aforementioned reduction in exploitation rates or the emergence of a large recruitment pulse into the exploitable biomass. Such a pulse would need to be large enough to sustain high levels of soft-shelled mortality for a year or two while coincidentally establishing a remnant portion of itself as a residual biomass in the population.

Consistent stringent quota control is needed to address chronic depletion of the residual biomass and the offsetting effects of recruitment overfishing. Issues of seasonality and wastage are inherently linked to exploitation rates and centrally epitomize how management decisions can affect the biological well-being of a stock. The issue becomes particularly complex in circumstances where outcomes of harvests in any given year may be cumulative. For example, reducing exploitation rates for a single year is not likely to promote establishment of a sufficiently strong residual biomass as irregular molting schedules mean that strong cohorts of crab recruit to fisheries over increments of multiple years.

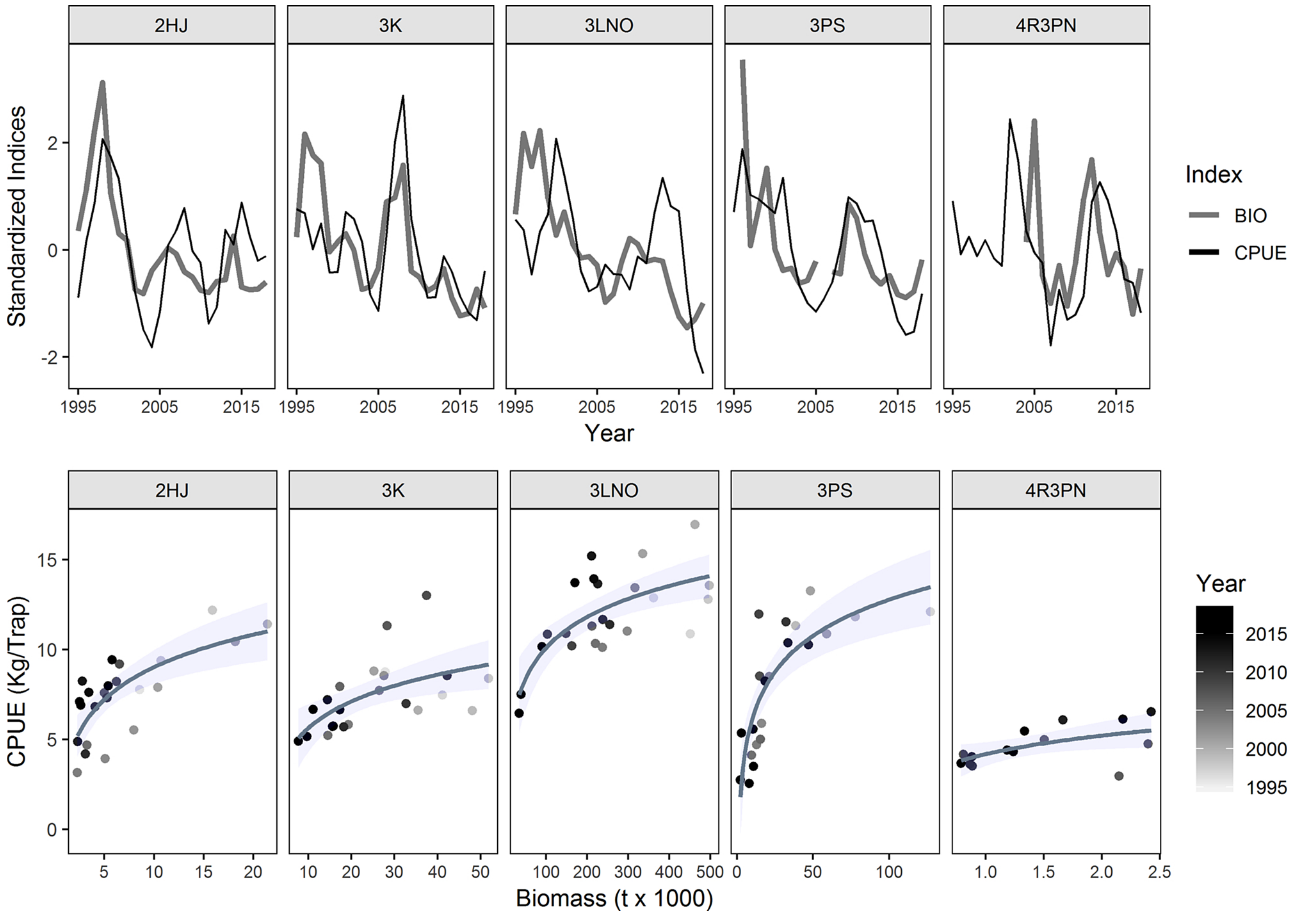

Fig. 12. Standardized indices of NL Snow Crab biomass and CPUE by Assessment Division (1995–2018) (top panels) and snow crab biomass indices versus fishery CPUE by Assessment Division (1995–2018) (bottom panels).

Table 2
Pearson correlation coefficients of CPUE versus exploitable biomass lagged by 0, 1, and 2 years, by Assessment Division.

		Biomass0	Biomass1	Biomass2
2 H J	CPUE	0.65	0.77	0.61
3 K	CPUE	0.70	0.59	0.34
3 LNO	CPUE	0.35	0.48	0.68
3 PS	CPUE	0.68	0.70	0.63
4R3 Pn	CPUE	0.51	0.62	0.22

4.3. Fishery closures

Issues prohibiting the soft-shell protocol from being an effective safeguard against soft-shelled crab incidence in the fishery are clear. There are too many cells, too little observer coverage, and minimum sample size thresholds that are too high to enable an effective monitoring program. In its current form, up to a maximum of 50 % of grid cells historically had the potential to be closed by the protocol during the fishery, with percentages in most years being between 0 and 25 %. This is a best case scenario, as the analysis was conducted at an annual level and did not consider that grids should be re-sampled to account for monthly, weekly, or even daily fishing impacts for the protocol to function best.

Experiences from other fisheries have shown that co-management initiatives may fail if there is a lack of problem recognition by resource users and a lack of common understanding of causes and solutions to problems (Pomeroy et al., 2001). This prevents successful adaptive management solutions from benefitting co-management decision-making. All groups are acutely aware of and concerned about problems associated with soft-shell crab mortality in this fishery; the protocol was intended as a means to address it. However, paradoxically, once the protocol became prohibitive in affecting fishing activities, the push to alter it began, specifically in the forms of reductions in grid cell sizes and introductions of minimum sample sizes to invoke closures. In this regard, due to adaptive measures implemented, the protocol can now serve to prolong fisheries when soft-shelled crab incidence is problematic.

Inabilities of the soft-shell protocol to protect vulnerable crab have become exacerbated in recent years as fishery catch rates and landings have declined, meaning both reduced levels of observer coverage and compromised ability to meet minimum sample sizes. Given that the major limiting factor of observer coverage levels directly depends on harvester funding, the soft-shell protocol could constitute a solid basis for harvesters to demonstrate abilities to self-impose responsible harvesting strategies to meet the 'reversed burden of proof' often necessary to allow decentralized resource management to become successful in the long-run (Linke and Jentoft, 2013). However, adaptive strategies to fix the soft-shell protocol to enable it to meet conservation objectives are necessary if this outcome is to occur.

Co-management of resources is inevitably a process of learning by trial and error (Berkes, 2009; Linke and Bruckmeier, 2014). With respect to the soft-shell protocol, good intentions likely remain from all partners vested in the management of NL snow crab. It is advisable to approach fixes to the protocol in the short term, as key resource signals such as size-at-maturity in males are suggesting that effects of heavy exploitation are negatively affecting recruitment potential in some ADs, and science continues to express concerns that this protocol can not control the impacts of recruitment overfishing (Baker et al., in press). A mutually beneficial knowledge partnership can not persist if effective application of progressive knowledge does not regularly occur.

4.4. Collaborative research

Major methodological differences between surveying and fishing affect the interpretation of their results. Surveys inherently aim to collect unbiased representative information through methods that can be easily repeated and data that can be examined with defensible statistical methods. By contrast, fisheries inherently attempt to maximize economic returns by catching as much of a given species as possible with the least possible amount of effort. Ultimately, from a scientific perspective, the CPS survey suffers from positive bias introduced by tendencies to gravitate toward fishing and away from surveying. Reliable surveys cannot be abandoned or omitted when resources are in decline, as has occurred in multiple areas and years in the CPS survey (Baker et al., in press), and abundances in fringe areas are as necessary to quantify as those on best grounds.

Clear objectives are required when collaborative surveys are developed and methods must be consistently followed for co-management measures to be effective (Pomeroy et al., 2001). The CPS survey does not appear to have had clearly or broadly defined objectives during its infancy, but anecdotal accounts and examination of the original survey design suggest a primary intent was to quantify commercial biomass on the best fishing grounds.

The ‘basin theory’ of fish population distributions was developed in 1990 (MacCall, 1990). It describes how populations exhibit patchy distributions linked to habitat, with large aggregations consistently maintained in best habitats under both high and low abundances, and marginal habitats more frequently occupied when abundances are high as density dependence factors force individuals into more marginal areas. In a fisheries context, this means that known prime grounds are likely to yield consistently high catch rates (e.g. be ‘hyper-stable’), even as the biomass in the larger area declines (Gillis and Peterman, 1998; Harley, 2001). From a survey context, it means that signals of change in stock size are likely to first become apparent in fringe and marginal areas. This design, coupled with tendencies to abandon or periodically omit marginal areas, have meant that the CPS survey was predictably the last source of data included in the stock assessment to detect the recent large decline in the NL snow crab resource (Mullowney et al., 2019). A survey that is not representative or is delayed in detecting changes in stock size is of little utility to anyone.

With aforementioned changes to survey design, after a decade and a half, the CPS survey is on the cusp of becoming the valuable assessment tool it was intended to be. Underlying this improvement is a story of adaptive co-management to address a problem. Survey design changes were suggested by science, and accepted by co-management partners as part of implementing measures to make improvements following critical evaluation of data quality. The example of adaptation within the co-management system is of collective benefit to all parties involved. The DFO Science program simply does not have the capacity to undertake such a large initiative on its own and a data source trusted by all parties is the anticipated outcome.

It is important to note that the long-term abandonment or annual omission of poorly performing areas in the CPS survey does not reflect a direct attempt to omit such data from survey results. The situation reflects the compensation system for the industry survey, whereby harvesters are allotted additional quota in the following year for conducting the survey (catch is not kept in the present year and subsequent years allocation is proportional to number of stations a given harvester conducts in the survey). It is up to the harvester to decide if the financial risks to conduct the survey are acceptable. In circumstances where the resource state is poor and it is perceived that there will be little or insufficient monetary benefits associated with the additional quota in the following year, there is no incentive to conduct the survey (the perceived low likelihood of financial gains from doing the survey is most applicable to poorly performing areas). Nonetheless, it is ultimately the scientific assessment and by extension stock status advice that suffers as upward biases become inherent in the data. A clear example of the outcome of this problem occurred recently, whereby following the virtual abandonment of the entire AD 3Ps survey in 2015 and 2016, the status of a mode of pre-recruit crab approaching legal-size was lost to the assessment and stock status advice at a critical time preceding potential resource recovery (Mullowney et al., 2019).

With respect to the phenomenon of higher catch rates in short (survey) versus long (fishery) fleets of gear, we speculate that it reflects a lower element of cumulative intra-fleet trap competition within short strings. Under current configurations of trap spacing, the saturation points of the fishing gear are far below the maximum volume of a trap (Mullowney et al., 2018b). This suggests trap competition for localized groups of crab. This issue was important to investigate toward understanding potential biases in the various data sources, and by validating the efficacy of survey catch rates, highlights the value of informed questions stemming from differing perspectives and observations in resource co-management systems.

4.5. Perception of stock size

The issue of how harvesters perceive stock status is especially important in respect of timelines and procedures associated with the annual stock assessment and industry consultations. In most cases, Fleet Committee members are not privy to specific details from the assessment until the consultation meetings occur. Prior to these consultation meetings, it is common practice for harvester groups to hold discussions with peers from their respective CMAs to discuss strategies for the forthcoming fishery, and Fleet Committee members are charged with carrying forth the will of the membership.

Intuitively, harvester perceptions of stock status are primarily based on their experiences from the most recent fishery, and in particular CPUE (Branch et al., 2006). This can be problematic in the NL snow crab co-management system as seen by our demonstration of two classical deficiencies associated with using CPUE as a measure of stock size, a latent effect of responses to changes in stock biomass and a non-linear trap saturation process indicative of hyper-stability. When resources are in decline, both processes systematically promote over-estimation of stock size in any given time and space if it is judged by CPUE. Conversely, when stock size is increasing, CPUE may be slow to recognize it or under-estimate the scale of increase.

Despite its now recognized and communicated shortcomings, CPUE is routinely the focal point of harvester consultations and the primary basis of Fleet Committee recommendations for management measures. This largely reflects the historical co-management-type process that existed when there was little to no other data available upon which to base science advice. We argue that the learned behaviour of over-emphasis on CPUE in the current co-management system demonstrates a need for adaptive co-management interventions including broader education of resource user groups. As it currently stands, Fleet Committee representatives can be put in a precarious situation at consultation meetings. Even if after receiving the newest information on stock status, fleet representatives understand biases associated with CPUE and accept that the stock may not be in the state the represented group envisioned (either in positive or negative directions), it may be too late due to an inherent obligation to carry forth recommendations of the memebership. Accordingly, with the biomass presently at its lowest level since broad-scale measurement of it began, the risks associated with making CPUE-based quota decisions are higher than ever.

4.6. Lessons and application of findings

Despite having a surprisingly short history of wide-spread application (e.g. since the late 1970s), increasingly formalized resource co-management systems have rapidly become commonplace. In fisheries science and management, it is now typical to have harvesters involved in aspects of assessment and management of marine stocks ranging from conducting surveys, to self-assessment of stocks, to legally-binding decision-making authority. Given a rapid rise in co-management systems, as in all processes involving scientific input, critical evaluation of methods and outcomes is a best-advised strategy, particularly as scientific advice underpins the efficacy of many co-management systems.

In reality, although it is undoubtedly recognized that humans are an integral part of bio-ecological ecosystems, at-present, the benefits of comangement are predominately theoretical. There is minimal application-based evidence to suggest co-management can help improve the state of natural resources (Wilson, 2009; Bavington, 2010). In this regard, our elaboration on how science programs can be affected by operating within co-management systems is broadly beneficial to interests concerned with the biological management of natural resources and further accounts of how co-management can affect science programs is encouraged.

Science is inherently a process of continuous learning, which entails development and change in quantitative methods and shifting perspectives on best approaches for practical application of knowledge. This 'shifting working dynamic' may pose challenges for groups collaborating with scientific research programs. Such a dynamic may be particularly challenging in the context of co-management of natural resources, whereby decisions made at any given time can have long-standing implications. Our recognition of a disconnect between spatial scales of resource ecology versus co-management, and the impediments it poses for the application of best-possible science advice in the management of NL snow crab, epitomizes this challenge.

Beyond spatial management considerations, we elaborated on specific examples of how an inability or latency to apply updated knowledge can affect the health of a resource. For example, the long-standing recognition of a poorly designed protocol to safeguard against soft-shelled crab mortality in the fishery and a problematic long-standing practice of overly emphasising fishery CPUE to judge stock size undoubtedly pose considerable challenges to our co-management partners to adapt to best practices within this management system. Nonetheless, science has an inherent duty to advise on both strengths and weaknesses of resource management approaches as knowledge accumulates. It is recognized that to simply recommend change is much easier than actually implementing it, particularly in co-management systems where legal implications may arise from invoking changes. Further, we recognize that collaborative measures to manage resources need to be practical and well understood by all partners to be most effective. This can be particularly problematic when complex quantitative assessment methodologies are used to assess the efficacy of various approaches.

We feel the key to most effectively promote change to address (or avoid) challenges placed on science programs operating within co-management systems is consistent effective communication. The redesign of the CPS survey demonstrates this, whereby after continued dialogue and communication, an impressive stock assessment tool anticipated to be of collective benefit to an important industry is now emerging.

Among the major lessons learned from this case-specific evaluation of scientific complexities associated with resource co-management is the importance for science to be clear and persistent in its communication. This is particularly pertinent at the beginning of undertaking co-management initiatives, and it is advisable to anticipate where and how future deficiencies in a given co-management system may occur; this is arguably most relevant to the ability to consistently collect representative and statistically defensible data.

Finally, from a scientific communication perspective, it is advisable for scientists to be clear to partner groups that change is a constant and fundamental aspect of science, and that in order for science to best operate within co-management systems, avenues and capacities for all parties to be adaptive are required. We advise scientific institutes to be consistently active in detailing to client sectors the work they are undertaking and forthright in communicating that results could potentially necessitate change in current or on-going management practices. From a management perspective, it is advised to seek, to the extent possible, to acquire well-tested biological justification for long-term management measures instituted into co-management systems.

Although theoretically intuitive, in application, resource co-management remains far from affirmed as a best-practice to improve the biological state of natural resources. Increased challenges to the very ideologies of co-management are possible as more burgeoning co-management systems are examined, highlighting the consistent need for adaptive capacities, no matter the chosen structure for a resource management system.

5. Conclusions

The management system for the NL snow crab resource is regionalized and highly complex. It most rapidly developed during a period when there was little scientific information available to help inform the long-term basis of a management system, and while co-management regimes were being favoured. In the current system, spatial management units do not conform to population dynamics or to the scale of scientific assessment, decreasing the utility of science advice. An over-emphasis on recent CPUE introduces high risks of being overly-optimistic about stock size, and heavy exploitation consistently compounds issues of non-optimal seasonality in promoting high levels of resource wastage. Major collaborative initiatives to improve the management system such as the CPS survey and soft-shell protocol have had limited success, reflecting poor documentation of objectives and inconsistent application of sufficient measures to meet intended outcomes. The short-comings of the current system have not developed through actions of any one co-management party. We conclude that as per the CPS survey re-design initiative, that critical evaluation and adaptive response measures can have positive impacts on this and other co-management systems. If the co-management system for NL snow crab is going to result in long term sustainability of the fishery, further adaptive measures to promote stronger application ability for accumulating scientific knowledge and advice to feature within in the management system should be taken.

CRediT authorship contribution statement

Darrell R.J. Mullowney: Conceptualization, Formal analysis, Methodology, Investigation, Writing - original draft. **Krista D. Baker:** Conceptualization, Formal analysis, Methodology, Investigation, Writing - review & editing. **Sana Zabihi-Seissan:** Methodology, Investigation, Writing - review & editing. **Corey Morris:** Data curation, Writing - review & editing.

Declaration of Competing Interest

The authors report no declarations of interest

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