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Harvesting strategies during a forecasted decline in the Newfoundland and Labrador snow crab fishery

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ABSTRACT

A predicted and communicated decline in the Newfoundland and Labrador snow crab (*Chionoecetes opilio*) resource, the basis of the world's largest snow crab fishery for two decades, has come to fruition. Given considerable lead time, this scenario creates an interesting dynamic to investigate how crab harvesters may have formed anticipatory behavioural responses to mitigate against the decline. In this analysis, economic, stock status, and vessel activity indicators are examined along with spatiotemporal fishing patterns before, during, and after the decline to assess harvester behaviour and fleet dynamics. We hypothesize that behaviours indicative of increased competition and a race to fish would emerge in response to the forecasted decline. Contrary to our expectations, we find no evidence of earlier or more rapid fishing, nor broader or more intense fishing patterns. Increased gear soak times were the most common adaptive response employed by harvesters, which were marginally successful in mitigating against declining catch rates and reducing discards. The majority of harvesters appeared to prosecute the fishery in a similar fashion as they historically had, and simply accepted reducing catch rates on known fishing grounds. Some historically dominant fishing grounds even became abandoned with little to no apparent adaptive responses by harvesters. Specific reasons for the general lack of behavioural adaptations to the forecasted fishery decline are unknown but are associated with an Individual Quota system, favourable product prices that have more than offset revenue losses from reduced catch, and small-scale management areas that may have rendered little or no capacity to develop adaptive strategies.

1. Introduction

1.1. Fleet dynamics and harvester behaviour

Fisheries science cannot just be about biology, ecology, and mathematics. Most fisheries problems are associated with a failure to understand harvesters, thus to be most effective, fisheries science needs to include the study of harvester and fleet dynamics (Hilborn, 1985).

Broadly defined, fleet dynamics encompasses the capacity and activities of groups of fishing vessels in time and space (van Putten et al., 2011).There is widespread agreement that harvester behaviour is a fundamental element of fisheries management (Ikiara and Odink, 2000; van Putten et al., 2011; Fulton et al., 2011). Despite this recognition, in Canada, as elsewhere, there has been a traditional belief that studies on the topic are more the domain of economists than ecologists (Hilborn, 1985). However, in circumstances where management strategies revolve around bioeconomics, such as in the Canadian Province of Newfoundland and Labrador (NL) Snow Crab (*Chionoecetes opilio*) fishery (DFO, 2019), the need for scientific understanding of economic and socio-political factors is high (note see Table 1 for list of acronyms used in analysis).

Harvester strategies are associated with their perceptions, preferences, abilities, level of resource access, and financial dependency (Pradhan and Leung, 2004; Salas and Gaertner, 2004; del Valle et al., 2008). A myriad of other psycho-social factors including family history, traditions, perceived legitimacy, and job attachment are also important determinants of harvester behaviour and overall fleet dynamics (Cove, 1973; van Putten et al., 2011; Daw et al., 2012).

The dynamic behaviour of fishing fleets can be broken into four components: investment, movement, catching power, and discarding (Hilborn, 1985). Within these components, harvesters develop adaptive strategies to respond to changes in resource abundance, environmental conditions, and market or regulatory constraints (Salas and Gaertner, 2004; Broderstad and Eythórsson, 2014). These adaptive responses affect decisions on where, when, and what to fish (Hilborn, 1985).

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Table 1
List of definitions for common acronyms used in the analysis.

Acronym	Full Text
AD	Assessment Division
CMA	Crab Management Area
CPUE	Catch Per Unit of Effort
DFO	Department of Fisheries and Oceans Canada
DPUE	Discards Per Unit of Effort
EBI	Exploitable Biomass Index
EI	Employment Insurance
ERI	Exploitation Rate Index
FAO	Food and Agriculture Organization of the United Nations
IQ	Individual Quota
NAFO	Northwest Atlantic Fisheries Organization
NL	Newfoundland and Labrador

1.2. Growth and decline of fisheries

FAO (2018) states that 7, 60, and 33 % of fisheries stocks fall into respective groupings of underfished, fully fished, and overfished. These stock states roughly align with the three respective fisheries catch stages ranging from developing to senescent (Graigner and Garcia, 1996). In development stages of a fishery, rapid investment and fleet growth typically occurs. It is common that initial fleet sizes become too large and stocks quickly begin to decline as overcapacity fosters overfishing (Clark and Munro, 2002). Subsequently, in mature stages of fisheries, management becomes more intrusive, limited entry is often introduced, and stock assessments become essential (Branch et al., 2006). Management interventions normally focus on vessel and gear types, fishing areas, seasonality, and restrictions on catch and effort. These processes generally cause or exacerbate a race for fish (Branch et al., 2006). Subsequently, when fisheries become senescent, management actions often focus on attempts at fleet rationalization and large reductions in quotas (Branch et al., 2006).

Allen and McGlade (1986) divided fishermen into stochasts, who lead the fishery in new directions and accept significant risk, and cartesians, who follow the leaders to exploit discovered resources. Within the context of fisheries stages, developing fisheries would commonly be associated with stochasts or 'generalists'(Branch et al., 2006), while well-established fisheries would commonly consist of cartesians or 'specialists' (Smith and McKelvey, 1986; Branch et al., 2006).

1.3. Development and status of the Newfoundland and Labrador snow crab fishery

Commercial landings from the snow crab fishery first occurred in the late 1960s, with crab taken as gillnet by-catch from groundfish fisheries along the northeast coast of Newfoundland (DFO, 2019). Directed fisheries further expanded along the northeast coast in the 1970s and subsequently off Labrador and around the remainder of the island of Newfoundland (Fig. 1) in the 1980s. Total landings remained below 5,000 t until the late 1970s, when an initial peak of 12,000 t occurred prior to a resource decline and quota adjustment to 7,000 t in the mid-1980s (Taylor and O'Keefe, 1999; Mullowney et al., 2019).

Harvesters who fished snow crab prior to fishery expansion in the 1980s (e.g. in Northwest Atlantic Fisheries Organization [NAFO] Divisions 3K, 3L, 3N, and 3O (Fig. 1)) were designated as "full-time" license holders. Although this group of harvesters initially fished inshore, in accommodation of fishery expansion, this fleet sector progressively became restricted to operating in furthest offshore Crab Management Areas (CMAs) within the NAFO Divisions where they resided. As groundfish stocks declined in the mid-late 1980's, a "supplementary" fleet was added to the crab fishery and given access to mid-distance CMAs. In Divisions 3LNO, the supplementary fleet was further divided into "small" and "large" groups based on vessel tonnage and granted access to mid-distance CMAs on the Grand Bank in Divisions 3LNO (Fig. 1). The small and large supplementary fleets of Divisions 3LNO both receive quotas in CMAs MS and 8B in the mid-portion of the Grand Bank. Additionally, there are spatial overlaps in quotas among fleet sectors in CMA S5440 in Division 2J, CMA 4 in Division 3K, CMA 3N200 in Division 3N, and CMA 11S in Division 3Ps.

The NL snow crab stock grew rapidly following an ecological regime shift and collapse of most finfish stocks throughout the region in the early 1990s (Dawe et al., 2012; DFO, 2014). With new discoveries of large abundances of snow crab, the pace of fishery expansion increased. Of particular note, a 'temporary' small boat (< 35') fleet sector developed in inshore bays and shoreline areas surrounding Newfoundland beginning in 1995. The 'temporary' designation was removed from this fleet sector in 2003.

The ultimate results of the complex fishery expansion system was that by 2007 a peak total of over 3,500 enterprises were operating under an Individual Quota (IQ) system based on small spatial scale management areas holding no biological relevance (DFO, 2019; Mullowney et al., this volume).

As is common in rapidly developing fisheries, the NL snow crab resource only grew for a few years before stock declines began in the mid-1990s. Landings peaked at 69,000 t in 1999 (Mullowney et al., 2019; Baker et al., in press). The exploitable biomass (≥95 mm carapace width [CW] males) declined by about 90 % over the 1996–2017 period (Mullowney et al., 2019; Baker et al., in press). The fishery has concomitantly declined, with approximately 2,200 enterprises landing about 34,000 t in 2017. The number of processing facilities has also shrunk from 42 in 2003 to 25 in 2017 (DFO, 2019). At present, the NL snow crab fishery most closely aligns with a senescent stage fishery.

The gradually diminishing number of enterprises reflects management rationalization measures progressively introduced over the past two decades. Two particular measures are pertinent to detail. First, with the establishment of the temporary inshore fleet in 1995, a 'buddy-up' policy was introduced to allow two IQ holders from the same CMA to fish from a single vessel if desired. Second, in 2008, an enterprise combining policy was introduced to allow IQ holders within a given CMA to purchase an additional IQ from a peer exiting the fishery. Both rationalization measures serve to reduce the number of vessels participating in the fishery on a temporary (buddy-up) or permanent (combining) basis, but maintain the overall number of IQs in the fishery. The combining policy was further expanded in 2012 to allow IQ holders in CMAs of Divisions 2J and 3K to acquire up to a maximum of three IQs, and this IQ maximum was subsequently applied to CMAs in Divisions 3LNO and 3Ps in 2013 and 2017 (DFO, 2019).

Despite the prolonged and recently exacerbated resource and industry decline, the snow crab fishery remains the most valuable fishery in NL and one of the most valuable fisheries in Canada, with landings valued at $325 million in 2017 (DFO, 2019). There is a high level of social, economic, and political pressure on the snow crab resource in NL, with this fishery comprising 25–90 % of annual revenue for fishing fleets throughout the Province (DFO, 2019).

Relative to many other regions of the world, the fisheries in NL are of short duration, particularly in the northern divisions (e.g. Divisions 2HJ and 3K) where sea ice restricts access to fishing grounds during winter and spring. Moreover, in southern divisions which normally remain ice-free, severe weather conditions make prosecuting fisheries from small vessels too dangerous during winter. Ultimately, notwithstanding varying degrees of diversification in quota portfolios that allow access to other fisheries, for most harvesters in the Province, it is imperative to maximize income from snow crab fishing each year. As a general rule, harvesters would typically avail of Canada's federal Employment Insurance (EI) system to supplement income during periods when they are not fishing.

Recent stock assessments have shown both the biomass and fishery catch per unit of effort (CPUE) to be at or near historically measured lows in all areas (Baker et al., in press). The latest, most substantial biomass decline (2013–2016) was both predicted and broadly

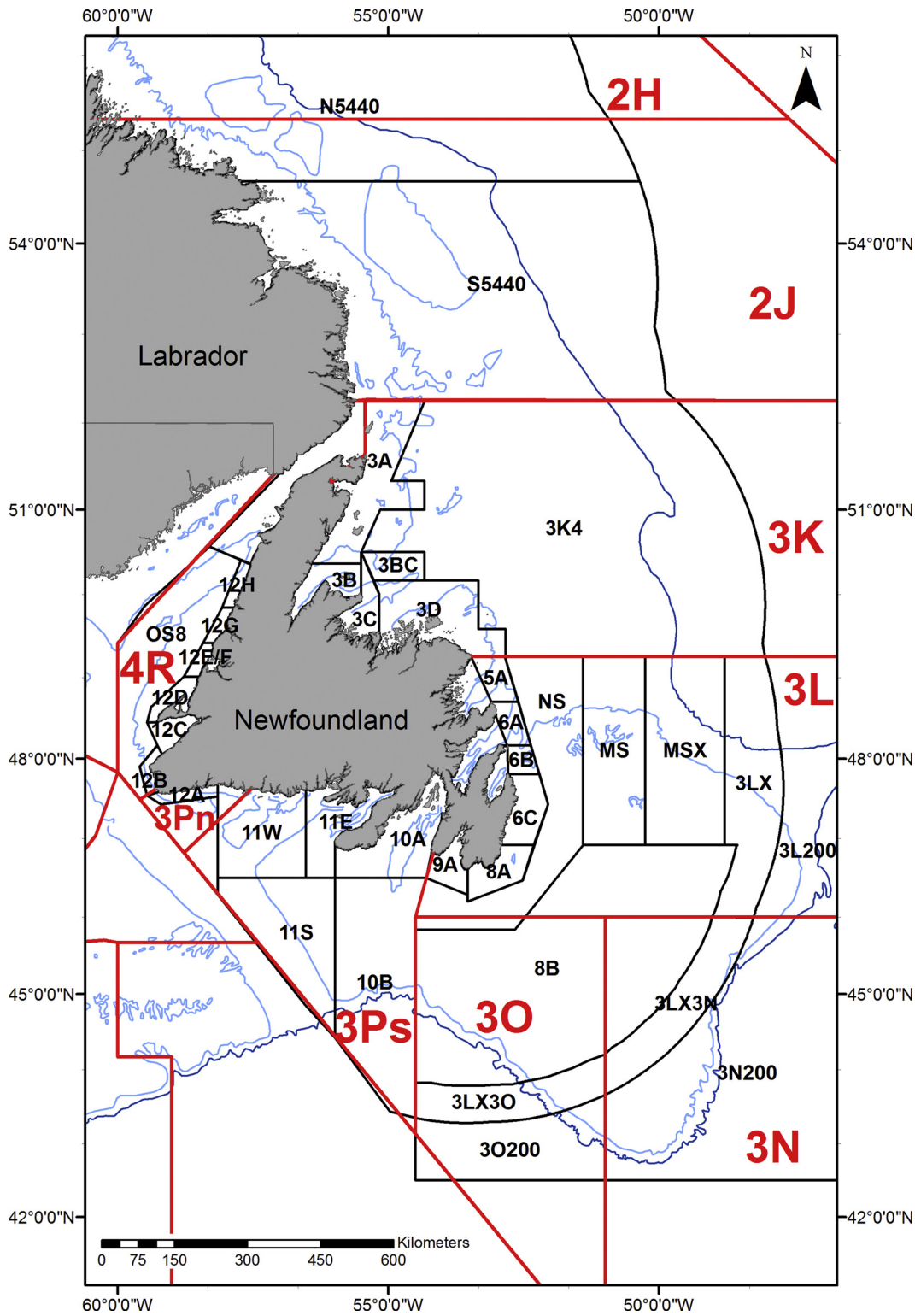

Fig. 1. Map of study area, identifying Northwest Atlantic Fisheries Organization Divisions (red) and Crab Management Areas (black). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

communicated to the fishing industry since 2011 stock status updates (DFO, 2013; Mullowney et al., 2013). The first quota cuts thereafter occurred in Divisions 2J (-10 %) and 3K (-22 %) in 2012 (https://www.dfo-mpo.gc.ca/decisions/fm-2012-gp/atl-014-eng.htm) and harvesters quickly began to anticipate further reductions and more forcefully question reasons for the decline (https://www.cbc.ca/thebroadcast/archives/ [reference episodes June 6, 2012; Mar. 7, 2013; Mar. 22, 2013; July 23, 2013; May 7, 2014 for examples]). Fisheries and Oceans Canada (DFO – the federal management body for fisheries in Canada) was conscious to formally communicate diminishing recruitment prospects for snow crab over the entire NL marine shelf region (DFO, 2014) and a scientific review on factors affecting the decline was undertaken (Mullowney et al., 2014). It is important to note that prior to the 2011 stock status update, Division 3K had already been experiencing

reductions in quotas during 2010 − 2011. Nonetheless, like all other divisions, this division was braced to prepare for further reductions. Given the lead time provided to prepare for broad-scale declines of this large and lucrative fishery, this paper focuses on how harvester behaviours and associated fleet dynamics may have changed to mitigate impacts.

An important element to highlight regarding quota decisions and fishery seasonality along with other aspects of fisheries management plans set by DFO is that they follow a co-management system, with harvester representatives putting forth recommendations each year, and DFO making final decisions in context of scientific information and harvester perspectives (DFO, 2019; Mullowney et al., this volume). At present, there are no explicit harvest control rules established in the management system of the fishery to scientifically guide quota decisions.

1.4. Analyses and hypotheses

Economic, stock status, and vessel activity indicators are examined along with spatiotemporal fishing patterns before, during, and after the most recent resource decline. Beyond literature on harvester exit strategies from poorly performing fisheries (Ikiara and Odik, 2000; Pradhan and Leung, 2004; Daw et al., 2012), and more aggressively pursuing fisheries on other species (Salas and Gaertner, 2004; Broderstad and Eythórsson, 2014), there are few known explicit examples of behavioural responses to declining fisheries. Accordingly, our hypotheses of likely adaptive behaviours were based on intuition under the assumption that harvesters would make decisions to maximize profits (Bucaram and Hearn, 2014).

Given the high level of socio-economic dependence of most fleet sectors on the snow crab fishery (DFO, 2019), we expected most harvesters to be cartesians and maintain a high level of interest in the fishery during the decline, particularly as the price of snow crab has increased substantially in recent years (DFO, 2019). We further anticipated that harvesters would focus adaptive responses on maintaining fishery CPUE at high levels (Gillis, 2003; Branch et al., 2006). Accordingly, we hypothesized that tactics toward more aggressive fishing and increased efficiency would occur in response to the forecasted resource decline (i.e. Kiyama and Yamazaki, 2018). Our suppositions were that earlier fishing, increased trap hauls, broader and more intense fishing patterns, altered soak times, and overall greater financial and physical risks would occur. With respect to soak times, we had no best guess on directional changes, as they could plausibly become shorter if increased searching behaviour emerged in the fishery or could conversely become longer if searching behaviour remained relatively constant.

A final element that could introduce unknown influences into the analysis are the small spatial-scale management areas that do not conform to biological or bathymetric attributes (Mullowney et al., this volume). Hypothetically, this feature could restrict harvester abilities to employ new tactics if there are few alternatives to find new fishing grounds, or intensify competition at localized scales. This bioeconomic analysis on harvester behaviour and fleet dynamics during a forecasted decline of a large fishery resource should be of interest to a broad spectrum of interests studying fisheries including harvesters, managers, economists, sociologists, behavioural ecologists, and biologists.

2. Methods

2.1. Study area

The analysis considered 42 Crab Management Areas (CMAs) within a geographical region covering nine Divisions of the Northwest Atlantic Fisheries Organization (NAFO) boundaries in waters surrounding Newfoundland and Labrador (Fig. 1).

The spatial units used in this analysis reflect those of the annual stock assessment and are defined as Assessment Divisions (ADs) 2HJ, 3K, 3LNO, 3Ps, and 4R3Pn. Assessment Divisions 3L Inshore and 3LNO Offshore have been combined herein into AD 3LNO. Fishery and resource trends in ADs 3L Inshore and 3LNO Offshore are generally synchronous and their partitioning for stock assessments is based on differences in data availability and not on any biological reasoning (Mullowney et al., 2019).

2.2. Economic indicators

Numerous factors that could either result from or plausibly affect harvester actions or associated management decisions were used in quantitative and qualitative analyses. Information on the number of active vessels in each AD and the annual price of snow crab was provided by the Policy and Economics Branch of DFO in St. John's, NL. The price index was adjusted for inflation by calculating adjustment factors based on the annual Canadian inflation rate index (https://www.statista.com/statistics/271247/inflation-rate-in-canada/).

Quotas and landings data were taken from fishery quota monitoring reports, with enumeration occurring through an obligatory dockside monitoring program that oversees all vessel offloads. These variables were collectively used to assess the relative revenue potential of individual vessels (understanding individual circumstances vary) through calculation of landings per vessel and landed value per vessel indices. An assumption was invoked that harvesters try to maximize landings and landed values per vessel each year. An avenue to at least partially influence these variables would be enabled through the co-management system via which annual quotas are set.

2.3. Stock status indicators

The key variable of stock size used was the exploitable biomass index (EBI), defined as the estimated biomass of male crab ≥95 mm CW. As snow crab are sexually dimorphic, females do not grow above this size; thus it is a male-only fishery. The EBI is the major indicator of stock status provided to management to assist with quota decisions each year. The biomass indices were taken from the most recent stock assessment (Baker et al., in press).

Biomass estimation is a complicated process, with imprecision predominately associated with unknown catchability (q) factors associated with trawl and trap survey gears. Annual trawl and trap survey catches are initially spatially expanded into biomass estimates using ogive mapping (Evans et al., 2000) to derive raw and knowingly underestimated (trawl) or potentially over-estimated (trap) values. A q is derived through a comparison of complementary biomass estimates calculated from fishery logbooks through Delury depletion analysis (Baker et al., in press) and used to adjust biomass into levels deemed close to reality. Based on comparison of the two annual biomass estimates (e.g. survey versus fishery-based), a time-series median q is used to re-scale annual survey estimates. Subsequently, the time series of adjusted biomass indices in each AD is smoothed with a two-period average to account for annual year effects in survey efficiencies. Biomass estimates presented herein are based on trawl surveys (since 1995 or 1996 depending on AD) in all but AD 4R3Pn, which is based on localized and short-term trap surveys (since 2004).

The exploitation rate index (ERI) is defined as annual landings divided by the previous two-period moving average survey biomass estimate and represents the level of fisheries-induced mortality imposed on the resource each year. Trends in these indices were reviewed to assess changes in biological risk tolerance inherent in the management strategy over the study period.

Fishery CPUE was used as an index of fishery performance. CPUE reflects biomass changes at a delay of 1–2 years in most ADs (Mullowney et al., 2018). We expected fishery CPUE to be a key variable affecting harvester behaviours as it directly reflects knowledge and experiences in prosecuting the fishery. CPUE was estimated from

commercial logbooks detailing time and space of activity as well as effort (traps) and catch (tonnes). In most years and ADs, > 80 % of logbooks were returned from the fleet (Mullowney et al., 2019). CPUE per trap haul was predicted from a linear mixed model defined in Eq. (1)

$$\ln CPUE = Day + \ln Soak + r(Day) + r(Year{:}AD{:}CMA) + \varepsilon \quad (1)$$

Where, lnCPUE is natural log transformed CPUE for each logbook entry, Day is calendar day, lnSoak is natural log transformed gear soak times (hours), *r* denotes a random effect intercept, Year:AD:CMA is a nested interaction of year, AD, and CMA, and error denotes normally distributed residual variation. Throughout this manuscript, we follow the convention from Zuur and Ieno (2016) on reporting specifications of regression analyses, where regression coefficients are included implicitly in front of regression terms, so, for example, the term Day represents an estimated linear relationship between calendar day and lnCPUE. We included both a linear term for Day and a random effect for day to estimate both a linear trend of lnCPUE over time and any non-linear patterns between CPUE and date. The model was run using the lmer function in the *lme4* package (Bates et al., 2015) in R Version 3.3.3. (R Core Team, 2019).

2.4. Vessel activity indicators

Hauling days, trap hauls, and fishery duration per vessel were used to assess the relative level of effort expended each year, with each metric expected to partially reflect operating costs. The index of hauling days was based on the number of days a given vessel reported landings in the logbooks in a given year. The index of trap hauls was estimated based on the association of CPUE (kg/trap) to total landings (tonnes) for each logbook entry. The index of fishery duration was based on the difference (# of days) between the first and last hauling day reported for a given vessel in a given year. All three vessel activity metrics were calculated at the AD and year level as means ± 1.96 standard deviations. The expectations were that extended fisheries and more trap hauls would occur to compensate for decreasing CPUE in recent years.

The seasonality of the fishery was deemed a factor that could plausibly affect harvester planning and spatiotemporal activity patterns. The timing of the fishery has knowingly changed over time, shifting from summer-fall to spring-summer fishery seasonality in all ADs (Mullowney et al., this volume). We plotted median annual fishing days in each AD based on logbook recorded trap hauls and subsequently developed a suite of in-season vessel activity indicators described below, speculating that increased uncertainties in abilities to take quotas would be associated with a push towards a 'race to fish', with harvesters attempting to catch as much as possible early in the year before CPUE declined. This speculation was based on an *a priori* knowledge of increased incidence of quota short-falls in CMAs within all ADs in recent years (Baker et al., in press).

The pace of the fishery was first examined by relating annual percentages of cumulative landings to cumulative effort expenditure using Lorenz curves. Gillis (2003) described a 1:1 ratio line between these two indices as reflecting an Ideal Free Distribution in effort, whereby competition forces fleet-level effort to spatially spread itself out in any point in time such that catch rate versus economic return trade-offs become balanced among harvesters. Gillis (2003) further described the shape of such curves in terms of operating costs, with the maximum point of deviance of the catch from a 1:1 ratio line representing the point in the season when a harvester is likely willing to incur maximum costs to capitalize on high CPUE. In extension, we deemed that a harvester could also be willing to take maximum physical risks during this point in the season to gain a competitive advantage.

We calculated a maximum risk point index for each AD and year based on maximum deviance of the Lorenz curves from a 1:1 ratio line and related it to season stage, measured as the cumulative percentage of landings, to interpret if any shifts occurred in harvester risk taking behaviour. This risk index inherently incorporates both financial and physical risks. We expected to see a shift toward earlier maximum risk points within the fishing season in response to deteriorating stock status. In extension of the risk point logic, we developed an index of maximum operating capacity for individual vessels and broader fleet groups each year. This index was simply defined as the calendar day in the season at which the highest proportion of total season effort was occurring, based on logbook reporting. The vessel index was represented as a mean among vessels within each fleet at the AD level. The expectation was that a pattern toward earlier maximum operating capacity indices would emerge in recent years.

To further examine in-season concentrations of catch and effort, we estimated the annual gini index (Gini, 1909) for each fishery measure at the AD level. The gini index, typically used alongside Lorenz curve analysis, measures statistical dispersion of concentrations within a data series. We applied it to cumulative percentages of both catch and effort by cumulative day in the fishery each year using the *Ineq* package (Zeleis and Kleiber, 2014) in R (R Core Team, 2019). We expected to see increases in the index (toward one) in recent years with increasing concentrations of catch and effort near the beginning of the fishery.

Finally, trap soak times were thought to be a potential behavioural adaptation that harvesters might employ in response to declining biomass or CPUE. Annual mean soak times for set hauls reported in the logbooks were examined along with stage-specific mean soak times (± 1.96 s.d.) within the fishing season. The stage-specific analysis was conducted because of *a priori* knowledge that CPUE normally declines throughout the season (Mullowney et al., 2019), thus it was likely that soak time fishing strategies could most substantially change as the season progressed. For this analysis, data were binned to seasonal stages based on one-third, two-thirds, and the entirety of cumulative seasonal trap hauls in any given AD and year.

2.5. Spatial fishery indicators

The fishing grounds were partitioned into 10'×10' nautical mile cells to examine the areal extent and relative intensity of fishing. It was thought that more intense fishing within cells could emerge either in localized areas or broadly throughout any given AD as biomass and CPUE declined. The annual number of sets within each cell was plotted to qualitatively assess time-series changes in spatial fishing intensity patterns. The number of intensively fished cells, defined as > 25 sets in any given year, was subsequently related to fishery CPUE using simple linear regression models, hypothesizing that a negative relationship between the two variables would occur. The CPUE index used in this analysis came from Eq. (1). Both the cell-specific annual fishing intensity (# sets) and CPUE were mapped for the entirety of the region to visually assess changes in fishery and catch rate patterns over time.

The extent to which fishery abandonment has occurred over time was examined through annual quota shortages within specific CMAs. The logic of this analysis is that quota shortages reflect abandonment of the fishery, invoking an assumption that as long as there was quota available a harvester would continue fishing until catch rates were low enough that there was no longer sufficient economic returns from doing so. We expected to observe a broad-scale pattern of increased fishery abandonment in recent years. Deviations within ± 2% of the quota were plotted as 0% difference, understanding it is normal to have slight overages and shortages associated with matching landings to quotas each year. Deviations exceeding ± 20 % were plotted as 20 % for visual interpretation.

2.6. Outcomes of behavioural responses

A dedicated analysis to investigate the effects that altered soak times could have on fishery CPUE and discard rates, defined as discards per unit effort (DPUE), was conducted. The data for CPUE were taken from

commercial logbooks while discard information came from at-sea observer monitoring data, which are deemed the most reliable source of discard information in the fishery (Mullowney et al., 2018).

At-sea observers are deployed throughout the fishery each year to collect biological measurements of the catch. In a typical year, 2–5 % of the fishing trips in any given AD are covered (Mullowney et al., 2018). The observers began measuring crab in 2000, thus the time series of data was shorter than the logbook series, which began in 1995. There is potential for spatiotemporal bias in observer data to arise from low percentages of trips observed, a historical practice of targetting observer coverage to areas of known or suspected poor fishery performance, and potential unwillingness of a vessel to carry an observer on any given trip.

A discarded crab was defined as a measured crab that was either soft-shell or below legal-size. Observers did not weigh the crab, thus we applied a width-weight relationship to each animal defined as Eq. (2), which was based on a log-log regression analysis of all weighed and measured crab contained in our databases from various trap and trawl surveys in all ADs since 1995. Information on various surveys can be found in Mullowney et al. (2019). The expectations were that longer soak times would be associated with increased CPUE and reduced DPUE as the traps continued retaining large crab while small-crab escaped.

$$\text{weight (grams)} = e^{((\ln CW*3.11)-8.27)} \quad (2)$$

Where, lnCW is natural-log transformed carapace width (mm).

CPUE and DPUE, both defined as kg/trap, were modeled as a function of soak time using linear mixed models defined in Eq. (3).

$$\ln CPUE \mid \ln DPUE = \ln Soak + r(Year{:}AD) + \varepsilon \quad (3)$$

Where, lnCPUE is natural log transformed CPUE for individual logbook set entries, lnDPUE is natural log transformed DPUE for individual observer set entries, lnSoak is natural log transformed gear soak times (hours), r denotes a random effect intercept, and Year:AD is a nested interaction effect of year and AD.

Independent models were run for each fishery stage, again binned to seasonal increments based on one-third, two-thirds, and the entirety of cumulative trap hauls in any given AD and year, and again meant to investigate if altered soak time strategies were effective. Predicted CPUE and DPUE values were plotted in relation to soak times by AD, and year and overall model slopes for CPUE and DPUE were interpreted to assess the effectiveness of adaptive soak time strategies on catch magnitude and composition.

Finally, to assess the financial implications of fishery abandoment or quota over-runs, we additively applied annual quota deviances from the CMAs to the AD level. Based on absolute differences (tonnes) in AD level quota deviations in relation to the annual inflation-adjusted price of crab we determined the monetary value of the excess or unharvested catch. This analysis again assumed that most harvesters would not forego potential revenue unless the resource was in sufficiently poor shape.

3. Results

3.1. Economic indicators

The majority of results are interpreted in context of how indices have changed since 2011, with the 2012 fishery being the first to operate after initial warnings of imminent biomass declines were given. Further emphasis is placed on 2015 as a point after which biomass declines were fully realized in most ADs.

The fishing fleet is largest in AD 3LNO, which has comprised 36–42 % of the overall contingent of active vessels in any given year (Fig. 2). In 1998, there were 2,964 active vessels while in 2018 only 1,652 vessels participated in the fishery. Fishing vessel exit rates have ranged from 37 % in AD 4R3Pn to 51 % in AD 3Ps over the 1998-present time series. Although the number of active vessels is presently at or near historic lows in all ADs, only AD 3Ps has shown an increase in the pace of fishery exit rates in recent years, with a pronounced decrease in 2015 and an overall decrease from 446 to 323 active vessels from 2014 to 2017.

The inflation-adjusted price of snow crab (back to 1998 equivalent) varied between 0.40–1.28 $/kg from 1998 to 2013, but has since escalated substantially to 3.02 $/kg in 2018 (Fig. 2).

Quotas in AD 2HJ decreased from 2,197 t in 2011 to 1,765 t thereafter while AD 3K quotas were reduced from 12,053 t in 2011 to 5,794 t in 2017 (Fig. 2). In contrast, AD 3LNO quotas increased from 33,222 t in 2011 to a record high of 38,173 t in 2015, before reductions to 18,840 t in 2018. AD 3Ps quotas dropped substantially from 7,027 t in 2011 to 1,792 t in 2018. Finally, AD 4R3Pn quotas remained virtually unchanged at 1,029 − 1,048 t from 2011 to 2017 before decreasing to 551 t in 2018.

Landings trends reflected quotas in most ADs. Landings were at an overall decadal low in 2018 (Fig. 2). The 1.8 kt and 6.0 kt landed in ADs 2HJ and 3K in 2018 respectively represent decreases of 68 % and 72 % from the 1999 peak. AD 3LNO landings ranged from 27 kt to 35 kt each year from 1999 to 2016, but a 49 % decrease has occurred since 2015 to a low of 18 kt in 2018. In AD 3Ps, the 2018 take was 1.9 kt, a 72 % decrease from 2011. Finally, in AD 4R3Pn, the 0.25 kt landed in 2018 is a decline of 85 % from the 1.7 kt peak in 2002.

Landings per vessel differed both within and across ADs, but have generally been highest in ADs 2HJ and 3LNO (Fig. 3). In response to biomass decline warnings, landings per vessel increased from 29 to 34 t during 2011–2018 in AD 2HJ, while they were scaled back from 22 to 15 t in AD 3K during that period. Per-vessel landings increased from 40 t to 47 t in AD 3LNO from 2011 to 2015, before being reduced to 26 t in 2018. In AD 3Ps, large reductions in landings per vessel from 14 t to 5 t occurred from 2011 to 2018, while in AD 4R3Pn they initially increased from 3 to 4 t from 2011 to 2013 before successively declining to 1.5 t in 2018.

The response in landed values per vessel to forecasted biomass declines differed markedly across ADs (Fig. 3). In ADs 2HJ and 3LNO, landed values per vessel systematically and substantially increased from 2011 to record high levels in 2017 − 2018. Conversely, in ADs 3K and 3Ps, they remained flat (3K) or decreased (3Ps) during the 2011–2015 period before positive responses to high product prices occurred in the past three years. Finally, in the small-scale AD 4R3Pn fishery, landed values per vessel increased gradually during 2011–2017 before a modest reduction occurred in association with a quota cut in 2018.

3.2. Stock status indicators

AD 3LNO dominates the overall exploitable biomass (Fig. 2). In that AD, the EBI gradually declined following the 2011 assessment warnings from 117 to 112 kt during 2011–2013 before abruptly declining to 31 − 40 kt during the past three years. In AD 2HJ, the biomass fluctuated without trend from 2,800 to 5,500 t from 2011 to 2018. In AD 3K, the EBI declined steadily from 22,000 kt in 2011 to 13,000 t in 2018, while in AD 3Ps the post-2011 outcome was immediate and strong, with a reduction from 28 kt to 4.3 kt in the EBI over the 2011–2017 period. Meanwhile, in AD 4R3Pn, the EBI fluctuated from 800 to 1,000 t from 2011 to 2013 before declining to 400 − 500 t in 2017 − 2018.

Like biomass, overall stock exploitation rates are driven by AD 3LNO (Fig. 2). In that AD, the ERI was allowed to increase steadily from 26 % in 2011 to a historic high of 67 % in 2017. In AD 2HJ, with the exception of an unusually low level of 23 % in 2015 (associated with a spike in the EBI in 2014), the ERI remained very high following 2011, fluctuating from 42 to 81 % each year. The AD 3K ERI also remained high following warnings of imminent biomass decline, fluctuating at 33–63 % per year since 2011. In AD 3Ps, the ERI increased substantially from 31 % in 2011 to 97 % in 2017, before plummeting down to just 10

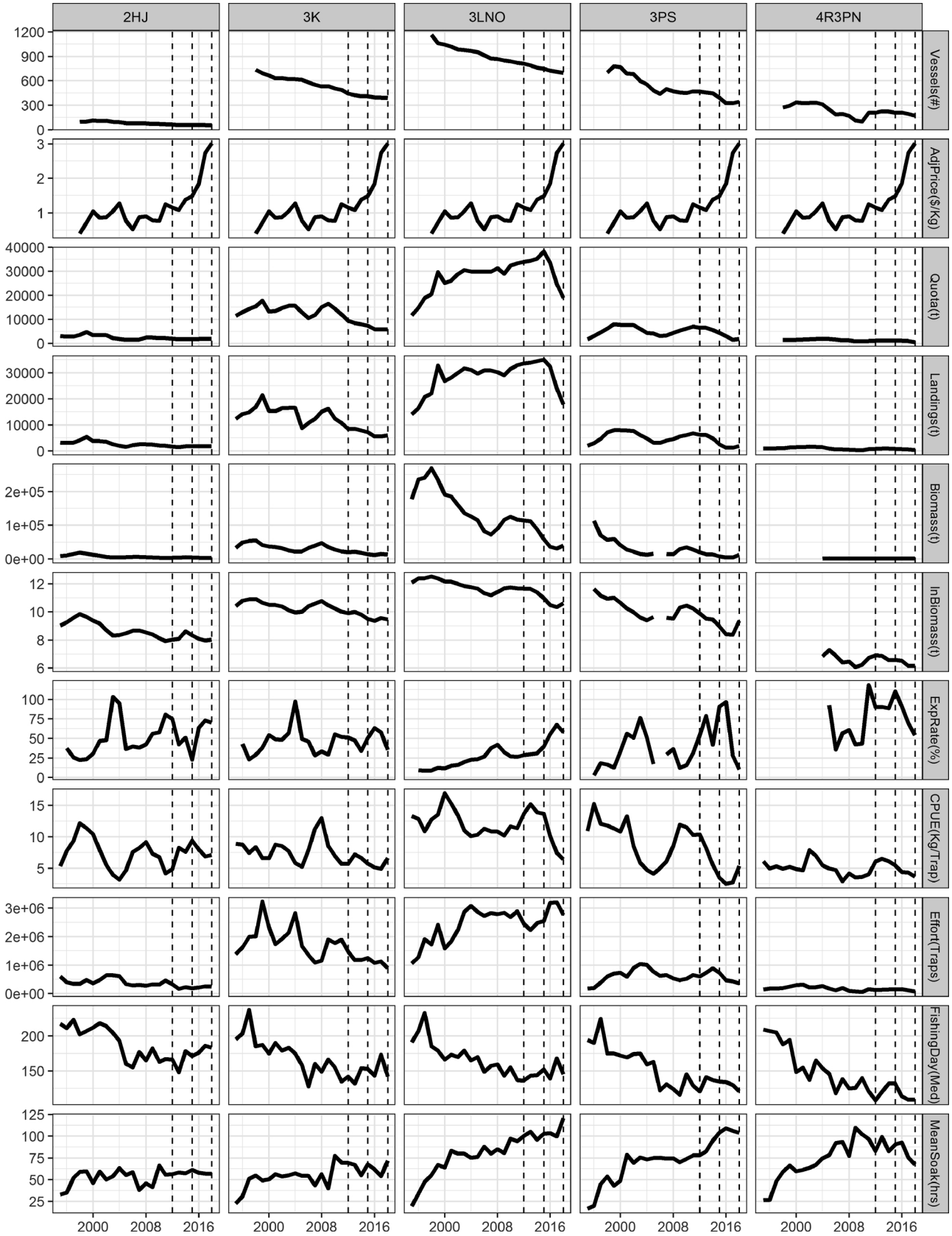

Fig. 2. Trends in Newfoundland and Labrador Snow Crab Fishery variables of interest in each Assessment Divison. Vertical dashed lines denote 2012, 2015, and 2018, and identify short and mid-term response periods to forecasted biomass declines.

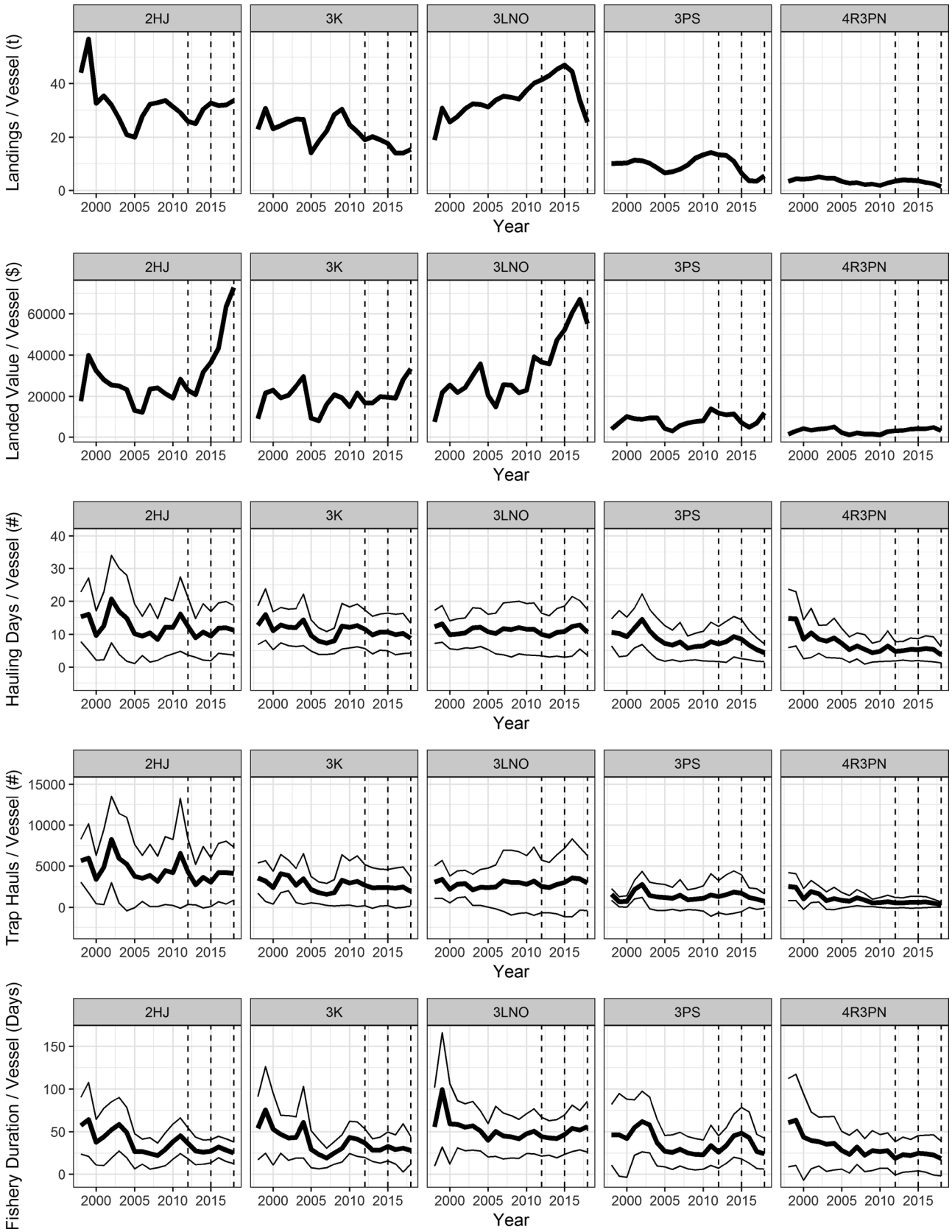

Fig. 3. Annual trends in landings, landed values, hauling days, trap hauls, and fishery duration per vessel in each Assessment Division. Thick lines are means and thin lines are 95 % confidence intervals. Vertical dashed lines denote 2012, 2015, and 2018, and identify short and mid-term response periods to forecasted biomass declines.

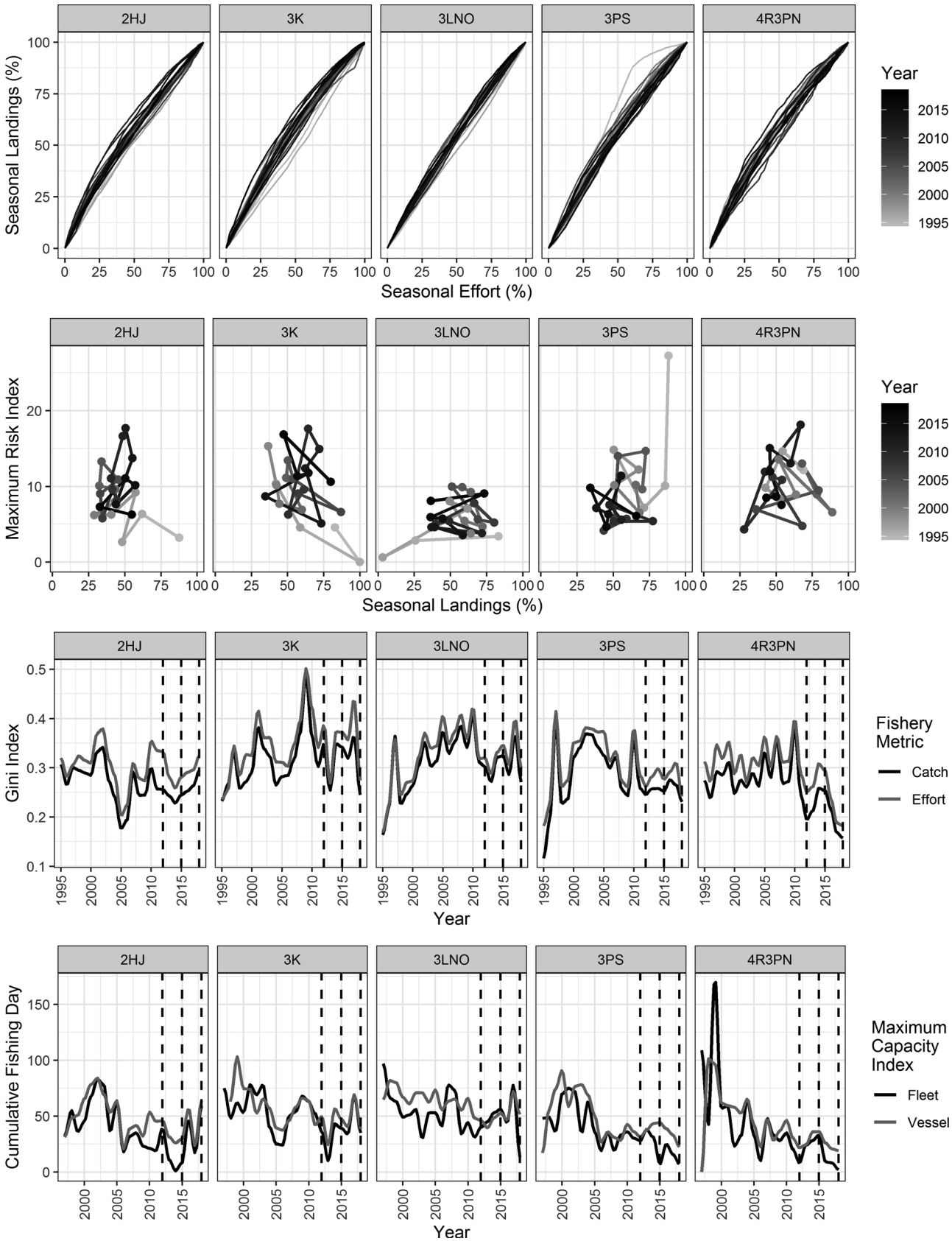

Fig. 4. Annual Lorenz curves of cumulative seasonal landings versus effort (first row), a maximum risk index defined as point of highest deviance from Lorenz curve and a 1:1 ratio Lorenz curve line (second row), annual gini coefficients of seasonal catch and effort (third row), and maximum fishing capacity index defined as point in the season where highest proportional trap hauls occurred (fourth row). Each index presented by Assessment Division. Vertical dashed lines in third and fourth rows denote 2012, 2015, and 2018, and identify short and mid-term response periods to forecasted biomass declines.

% in 2018 in the presence of a minimal fishery. There is a recognized high degree of imprecision in biomass estimation in AD 4R3Pn due to localized and sporadic trap survey coverage (Mullowney et al., 2019; Baker et al., in press). This affects the calculation of ERIs. Nonetheless, trends show that no reduction in ERI occurred from 2011 to 2016, with the index fluctuating from 90 to 119 % annually, but it has declined to 54 % in the past two years.

Fishery CPUE has been at or near historical lows in all ADs in recent years (Fig. 2); however, an exception to recent low CPUE is AD 2HJ where it has remained near a time-series average and fluctuating from 7 to 9 kg/trap since 2013 (Fig. 2). CPUE increased from 4 to 8 kg/trap from 2011 to 2013 after stock biomass declines were communicated. In AD 3K, CPUE remained unchanged at a low level following 2011, fluctuating from 5 to 8 kg/trap annually. In dominant AD 3LNO, CPUE initially increased from 11 to 15 kg/trap from 2011 to 2013, before precipitously declining to a historic low of 6 kg/trap in 2018. AD 3Ps experienced immediate declines in CPUE to the stock decline warning, dropping from 10 to just 3 kg/trap over the 2011–2017 period. Finally, CPUE increased from 4 to 6 kg/trap from 2011 to 2013 in AD 4R3Pn before declining back to 4 kg/trap during the past four years.

3.3. Vessel activity indicators

Like most variables, overall trends in total fishing effort are driven by AD 3LNO and recently increasing levels of effort in this large AD oppose other ADs (Fig. 2). Effort in AD 3LNO has varied from 2.2 to 3.2 million trap hauls per year since 2011, similar to time series norms. Effort became reduced in AD 2HJ since 2011, and in particular with a range of 167–247 thousand trap hauls per year, has remained near a time series low since 2013. Similarly, a substantial decrease in effort occurred in AD 3K following 2011, with a drop from 1.9 million trap hauls in 2011 to about 1.0–1.2 million trap hauls from 2013 until present. In AD 3Ps, effort increased from 624 to 728 thousand trap hauls per year from 2011 to 2015, but has since been reduced by half, to 355 thousand trap hauls in 2018. Finally, effort gradually declined from 149 to 110 thousand trap hauls during 2011–2017 and was reduced to just 69 thousand trap hauls in 2018.

The fishing season became progressively earlier throughout the time series in all ADs (Fig. 2). From 1995 to 1997, the median fishing day ranged from calendar days 191–237 in all ADs. Since 2011, the fishery has extended slightly in ADs 2HJ, 3K, and 3LNO in some years, while it has continued a trend toward earlier seasons in the ADs 3Ps and 4R3Pn. Nonetheless, overall, the fishery of recent years remains early relative to historic patterns in all ADs.

The mean number of hauling days per vessel has either declined gradually or remained relatively unchanged in each AD over the time series (Fig. 3). Since 2011, it has been relatively constant at approximately 9–12 days per year for vessels in ADs 2HJ and 3K, but it has shown a gradually increasing trend within the 9–12 day range in AD 3LNO. Vessels in ADs 3Ps and 4R3Pn normally spend less time on the water hauling gear than in the other ADs, and in both ADs historic lows of about 3–4 days hauling gear occurred in 2018.

Like hauling days per vessel, the mean number of trap hauls per vessel has declined gradually or remained relatively stable in each AD over the time series (Fig. 3). Since 2011, all ADs with the exception of 3LNO have remained near or below time series means, with 3LNO above long-term average levels in the most recent years. Since 2011, the mean number of traps hauls per vessel has ranged from 2,800 to 4,300 (2HJ), 2,000 to 2,500 (3K), 2,400 to3,600 (3LNO), 800 to -1,500 (3Ps), and 300 to 600 (4R3Pn).

Trends in fishery duration have closely reflected one another in ADs 2HJ and 3K throughout the time series (Fig. 3). Both ADs have remained near historic lows in terms of season length since 2011, ranging from 25 to 37 days per year. The longest season occurs in AD 3LNO, where the 42–55 day season since 2011 is long relative to the past decade. In AD 3Ps, the fishing duration increased from an average of 26–48 days from 2012 to 2015, but subsequently decreased back down to 24 days in 2018. Finally, in AD 4R3Pn, the quick 19–25 day seasons occurring since 2011 are the shortest in the time series.

In all ADs and years, Lorenz curves showed a consistent pattern of landings accumulating proportionately fast relative to effort in the first half of the season (Fig. 4) with no systematic push toward more rapid accumulation of landings in recent years. In ADs 2HJ, 3K, and 4R3Pn it is common for about half the catch to occur while about one third of the effort is expended. The proportional difference between landings and effort is lowest in ADs 3LNO and 3Ps where the ratio only slightly deviates toward landings.

There were no strong indications of overall increased levels of risk being taken by individuals in the fishery as the stock has declined. The maximum risk point shifted toward earlier portions of the season in most ADs from 1995 to 1997, but there has been no systematic or directional shift in any AD over the past two decades (Fig. 4). Similarly, there has been no clear spatiotemporal patterns in the magnitude of the risk index.

The gini coefficient indices of both catch (landings) and effort fluctuated over the time series within each AD (Fig. 4). An anticipated directional upward shift toward unequal distribution of these fishery metrics within each season after 2011 was only sustained for a brief period in most ADs where it occurred (in all but AD 3K). In 2018, all ADs with the exception of 2HJ had proportional within-season distributions of catch and effort that were similar to or more evenly spaced throughout the season than historically occurred. Consistent with absence of any strong indications of a race to fish in other measures of catch and effort, the maximum fishing capacity index showed no sustained directional pull toward earlier fishing in any AD since 2011, except at the fleet-level in ADs 3Ps and 4R3Pn (Fig. 4). In fact, the index increased in largest ADs 3K and 3LNO toward late-season maximum operating capacity during 2012–2017.

Trap soak times have increased throughout the time series in most ADs (Fig. 2). From 1995 to 1997 soak time means ranged from 17 to 52 h in all ADs while during the past three years they ranged from 54 to 121 h. The level of soak time increases over the time series has been lowest in ADs 2HJ and 3K, with mean soak times ranging between 54 and 72 h during the past three years. The greatest level of soak time increases occurred in ADs 3LNO and 3Ps, where 100 − 120 hour mean soak times have occurred over the past three years. AD 4R3Pn has opposed the overall trend of continued progression of longer soak times. In that AD, soak times have been variable at 67 − 100 hours since 2003, and the most recent period has shown successive decreases from 93 to 67 h during the past three years.

Recently increased trap soak times have overall been most pronounced in the latter two-thirds of the season (Fig. 5). In AD 2HJ, a 2-day soak time strategy has been most commonly employed in the first third of the season throughout the time series and a 2–3 days soak time strategy has emerged in the mid-portion of the season since about 2010. Since the forecasted resource decline, a 3-day soak time strategy has been routinely employed in the latter third of the season from 2012 to 2018. In AD 3K, a 1–2 day soak time strategy has held in the first third of the season throughout the time series while a progressive push toward a 3-day soak time strategy has occurred in the mid-portion of the season over the past two decades. Since 2011, a 3–4 day soak time strategy has been most common in the late season. Soak times have increased in all parts of the season throughout the time series in ADs 3 LNO and 3Ps. Since 2011, a 3–4 day strategy has been routinely invoked at the beginning of the season in AD 3LNO, with a 3-day soak time strategy most readily apparent in AD 3Ps. In the latter part of the season, the gear is routinely soaked as long as 5–6 days in both ADs. Finally, in AD 4R3Pn, most harvesters have routinely hauled their gear after 2 days to start the fishery in all years, and like most other ADs, late-season fishing now has substantially increased soak times, with a 4–6 day soak time strategy consistently evident since about 2010.

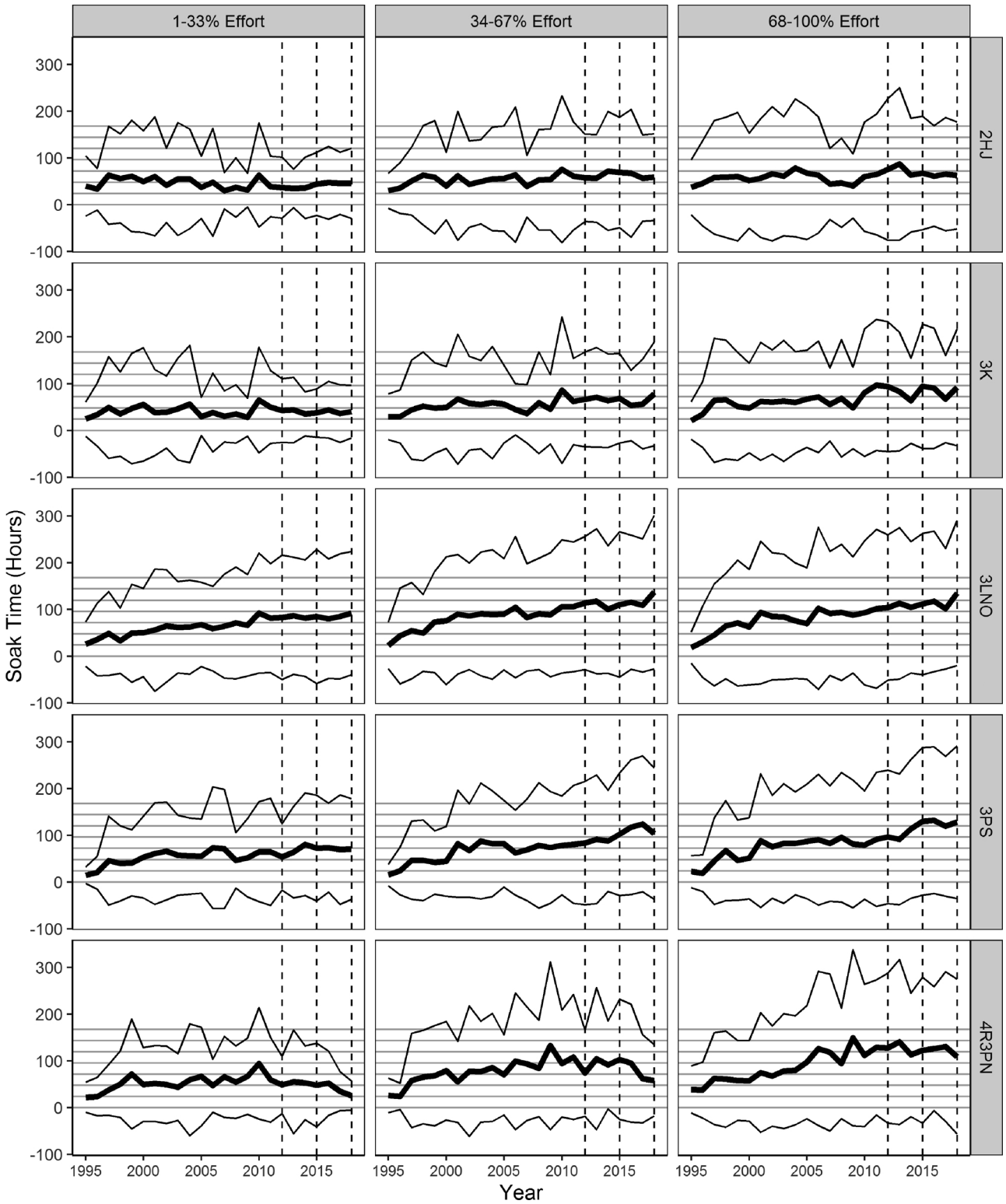

Fig. 5. Soak time (hours) at various stages of the season by year and Assessment Division. Thick lines are means and thin lines are 95 % confidence intervals. Horizontal grey lines denote daily intervals (e.g. 24, 48, 72 h, etc.).

3.4. Spatial fishery indicators

A negative relationship between CPUE and the number of intensively fished cells has held thoroughout the bulk of the time series, except in AD 4R3Pn (Fig. 6). However, this relationship has broken down in the last three years as the number of cells fished has decreased in most ADs, including intensively fished cells (26 sets or more per year) but CPUE has not shown a corresponding increase (Fig. 6).

In AD 2HJ, the total number of cells fished decreased sharply in 2005 and remained similar at about 50 cells per annum since 2004, with most cells consistently receiving 25 sets or less in any given year (Fig. 6). A negative relationship between CPUE and the number of intensively fished cells has held thoroughout the time series. The decrease in area fished after 2004 predominately reflects the abandonment of

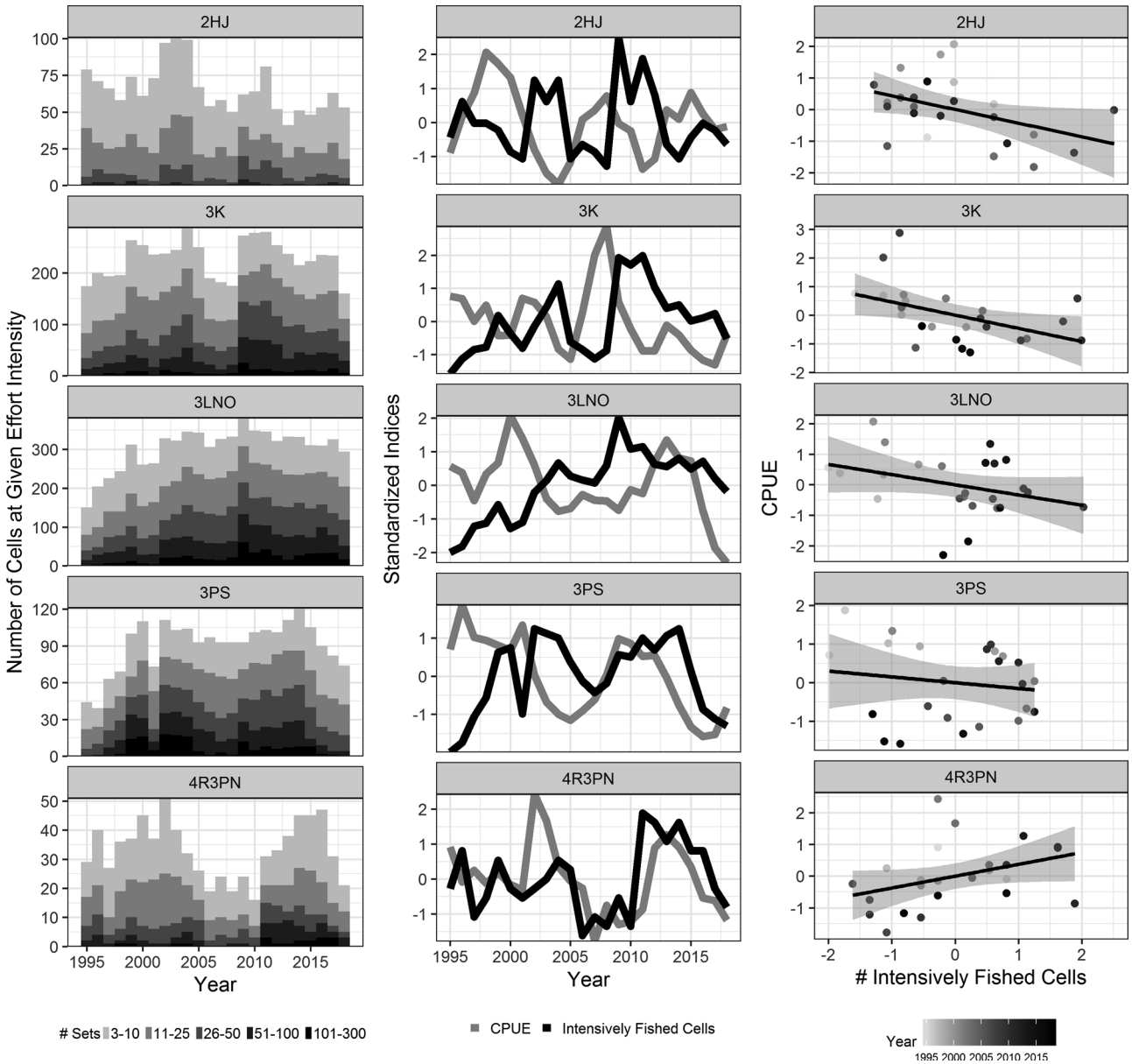

Fig. 6. Assessment Division-specific trends in total number of grid cells fished as well number of cells fished at different fishing intensities, defined as number of sets in each cell (left panels). Standardized indices of fishery CPUE versus intensively fished cells, defined as > 25 sets per year (middle panels). Linear regression models of standarized fishery CPUE versus intensively fished cells (right panels).

further offshore slope edge areas (Fig. 7). AD 2HJ fishing effort is now tightly concentrated in two dominant patches within discrete channels in the northwest (Cartwright Channel) and south-central (Hawke Channel) portions of the AD.

In AD 3K, there was an abrupt increase in total area fished in 2009 from about 175–275 occupied cells (Fig. 6). This shift was closely associated with heavily fished cells, with a tripling of the number of cells receiving 26 sets or more. A gradual decline in total area fished has occurred since 2011, with this trend predominately reflecting a dissipating amount of heavily fished cells. The 160 fished cells in 2018 is the lowest in the time series, and over half of these cells received 25 sets or less, reflecting an overall low intensity fishery. However, despite an increase in 2018, CPUE has not improved as effort has become contracted and less intense, remaining near historical lows since 2011. The sharp increase in both the total number of fished cells and an increase in the intensity of fishing in AD 3K during 2009 and subsequent years largely reflected increased activity throughout the offshore portions of the AD (Fig. 7). The effort pattern in AD 3K has since thinned, with effort in northwestern- and northeastern-most portions of the AD greatly dissipated.

The area of grounds fished in AD 3LNO steadily increased from 1995 to 2009, reflecting increasing numbers of all grid-specific effort intensitities (Fig. 6). Since 2009, the AD 3LNO fishery footprint has gradually declined from 348 to 295 cells occupied with proportional effort intensity remaining relatively fixed, featuring light-moderate intensity cells (25 sets or less) accounting for about half the fishery footprint in most years. Like AD 3K, the continued decline in the number of intensively fished cells has not been opposed by improved CPUE in recent years, with CPUE continuing to decline to new lows. Depite a gradually decreasing trend in areal fishing coverage in recent years, no single area appears to have been consistently abandoned, although cells in the furthest offshore regions along the eastern slope edges received little fishing effort in 2018 (Fig. 7).

The AD 3Ps fishing footprint expanded from 1995 to 2000 and ranged near 90–100 cells fished until about 2013 (Fig. 6). It peaked at 120 cells in 2014 and has since shrunk back to a smaller footprint of 75

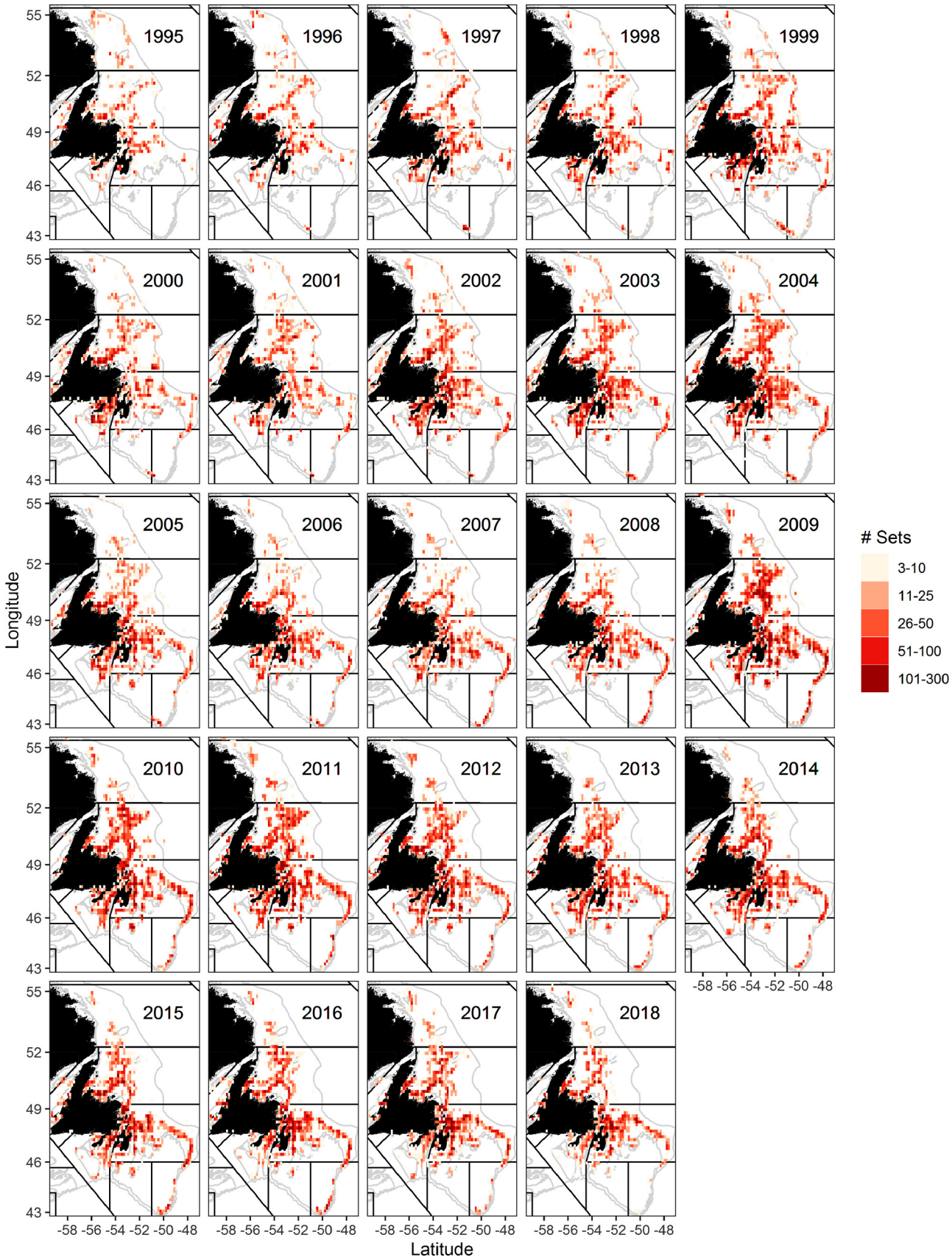

Fig. 7. Location and intensity (number of sets) of effort for the Newfoundland and Labrador snow crab fishery. Data mapped to 10' x 10' nautical mile cells.

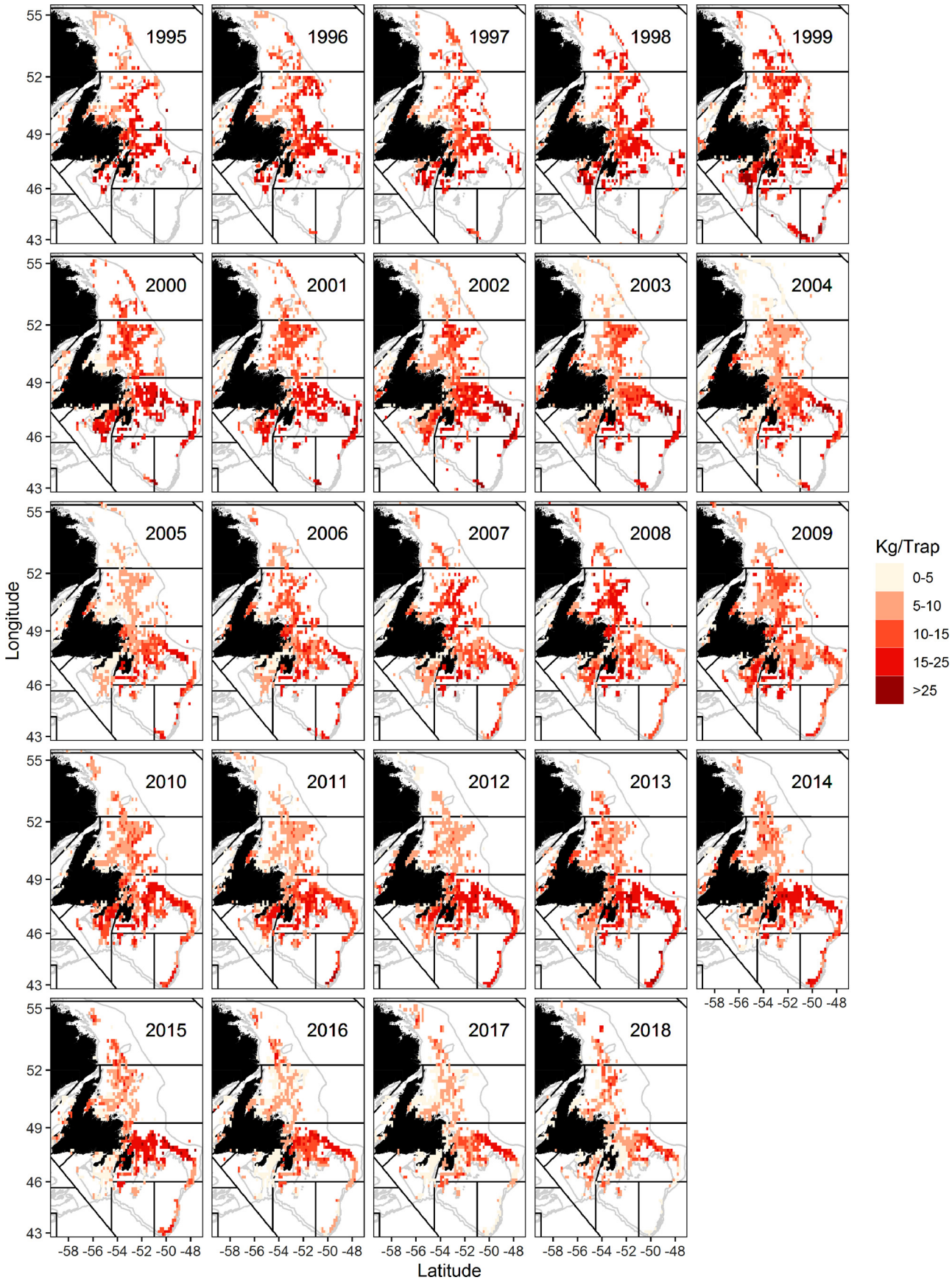

Fig. 8. Annual spatial patterns in CPUE (kg/trap) in the Newfoundland and Labrador snow crab fishery. Data mapped to 10' x 10' nautical mile cells.

cells. Like most ADs, fluctuations in the proportions of cells fished at varying intensities have been similar throughout the time series. The erosion of the fishing intensity versus CPUE relationship has been most apparent here in recent years, with the very low level of intensively fished cells associated with CPUE at or near times series lows in the past three years. The recent spatial contraction of the AD 3Ps fishery predominately reflects abandonment of furthest offshore areas (Fig. 7).

Finally, in AD 4R3Pn, two distinct phases of high fishery interest were evident during the early 2000s and mid-2010s (Fig. 6). Additional coverage in the high phases of the fishery were predominately attributable to light to moderately fished cells of 25 sets or less. The unusual postive relationship between fishing intensity and CPUE evident throughout the time series has held in recent years. For the most part, the oscillating phases of widespread versus localized fishing predominately reflect presence of absence of effort in the offshore (Fig. 7).

The spatial pattern of CPUE has changed throughout the time series but never has there been such a broad-scale phenomenon of low catch rates in all ADs as observed in 2018 (Fig. 8). Only a localized aggregation in offshore AD 3LNO produced CPUE in the 15 – 25 kg/trap range in 2018.

3.5. Outcomes of behavioural responses

With respect to share of the overall fishery quota (e.g. above about 5–10 % of the total), the CMAs of consistent major consequence are CMAs S5440 in AD 2HJ, CMA 3K4 in AD 3K, CMAs NS, MS, MSX, 3LX, 3L200, 3N200 and 8B in AD 3LNO, and CMAs 10A and 10B in AD 3Ps (Fig. 9). Overall, these dominant CMAs have systematically experienced quota shortfalls above expected enumeration inaccuracies (e.g. ± 2%) since the 2011 warnings on biomass decline were given. The CMAs in the central portion of the Grand Bank in AD 3LNO (CMAs NS, MS, MSX, 3LX) are the exception to this observation. Such incidence of increased quota shortfalls in recent years is not exclusive to the major CMAs and has occurred throughout numerous marginal CMAs within all ADs as well. Overall, the pattern suggests that the quota has not been a major prohibitive factor limiting fisheries catches in a high proportion of the CMAs in recent years.

In most ADs and years CPUE trends showed an asymptotic response to increasing soak times (Fig. 10). The magnitude of catch rates varied substantially both across ADs and years with the transition toward flat-topped catch rates typically occurring between about 5 and 20 kg/trap. The shape of the CPUE curves systematically differed in AD 4R3Pn and the late stages of the fishery in several ADs with flat or declining slopes across soak times. These curves where soak times was not positively associated with CPUE are both reflective of low biomass situations. Slopes of the CPUE regression models were positive in the early and mid-stages of the fishery, at about 0.05 to 0.7 kg per hour increase (not shown), while they were slightly negative in the late-stages of the season. There is little to no benefit of increasing CPUE in late-season fishing.

Discard rates were systematically either flat over the soak time range or highest in the first day or two of fishing (Fig. 10). Slopes of the DPUE regression models were negative at all stages of the fishery at -0.05 to -0.08 kg per hour decrease (not shown). Overall, longer soak times systematically help reduce discards in this fishery in most years.

From a fleet-level financial perspective, since 2011, AD 2HJ has been matching landings to quotas and fully subscribing potential economic rents available from quota allocations (Fig. 11). All other ADs have had one or more years whereby quotas could not be taken and potential economic rents enabled by quota allocations were unsubscribed. In the most extreme cases, AD-specific quota shortages in the range of 1,000–2,000 tonnes in ADs 3LNO and 3Ps in the past 1–3 years have equated to $3 million in potential revenue. Given the high price for the catch in recent years, such extreme economic shortfalls are undoubtedly indicative of the poor biological state of the resource.

4. Discussion

4.1. Economic indicators

A key outcome of the economic indicators analysis was that warnings and realiazation of a reduction in the exploitable biomass did not

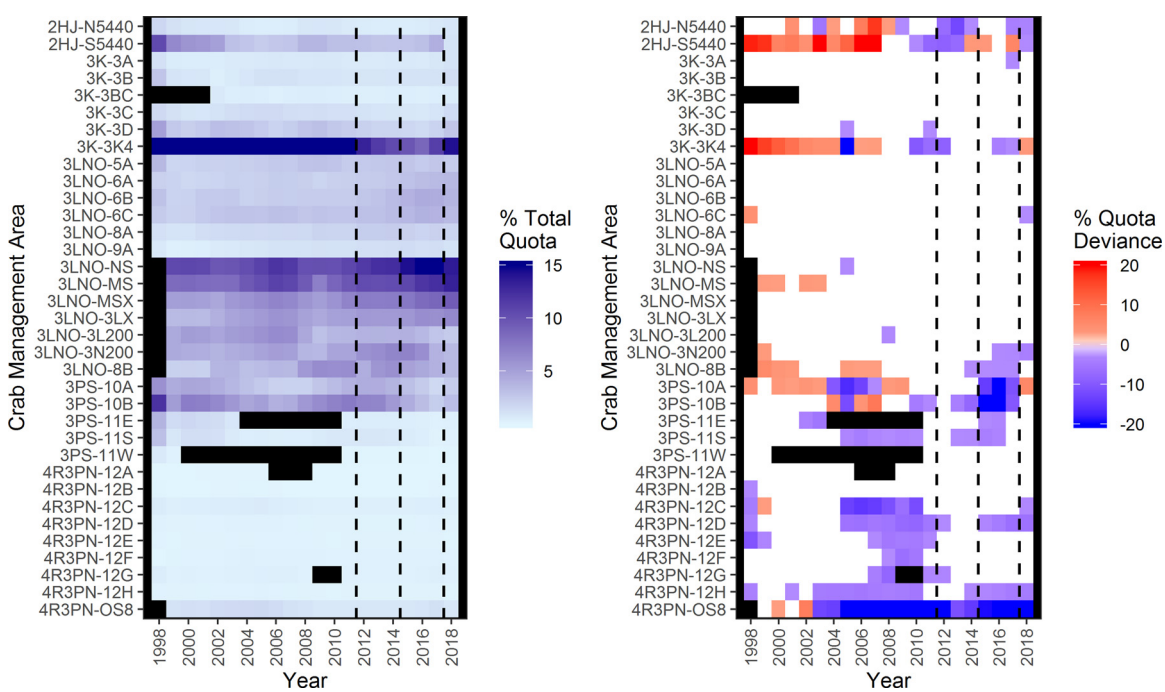

Fig. 9. Annual percent of overall fishery quota by Crab Management Area (left panel) and percent deviance of annual landings from the quota by Crab Management Area (right panel). Deviance of ± 2 % between landings and quota plotted as 0% and deviance exceeding ± 20 % plotted as ± 20 %. Black rectangles show years when no commercial quota was given within a CMA. Vertical dashed lines denote 2012, 2015, and 2018, and identify short and mid-term response periods to forecasted biomass declines.

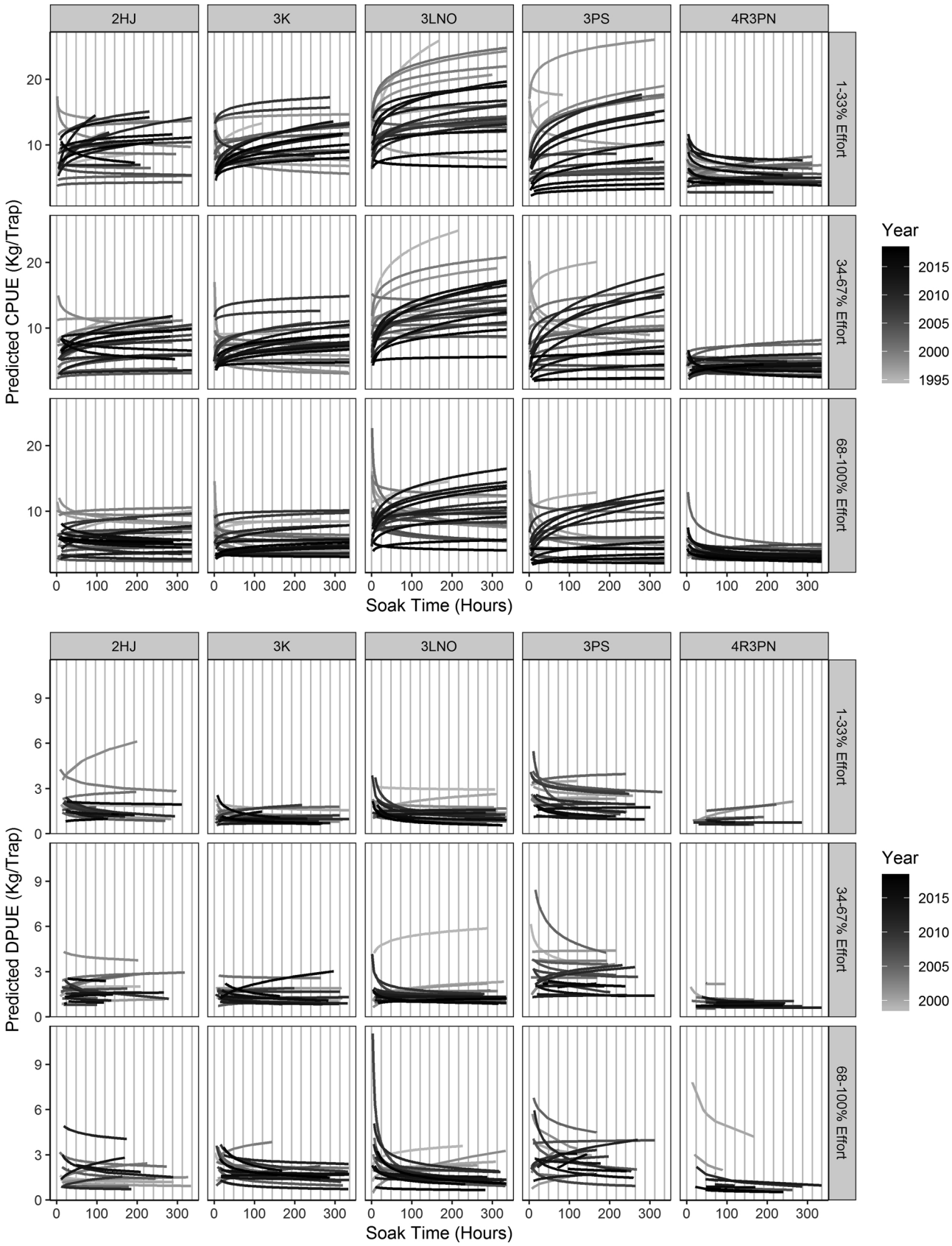

Fig. 10. Catch (CPUE) and discard (DPUE) rates modelled as a function of soak times in early, mid, and late stages of the fishery. Vertical grey bars are daily increments.

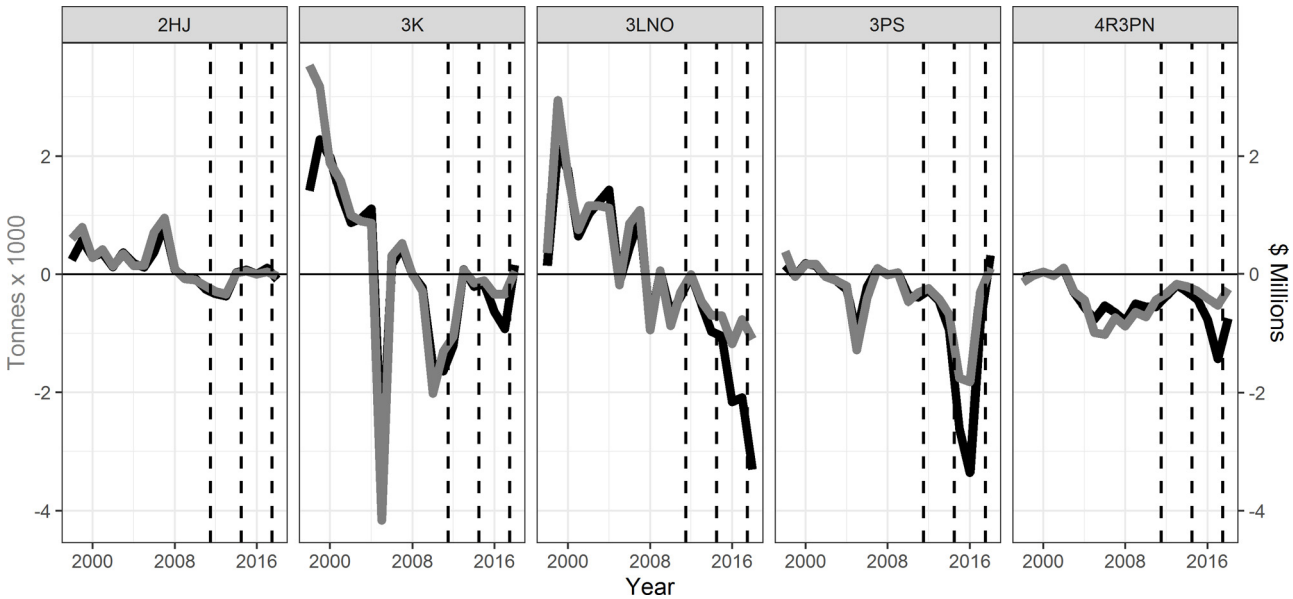

Fig. 11. Annual Assessment Division level deviance from quotas (grey lines) and associated monetary value of deviances (black lines). Vertical dashed lines denote 2012, 2015, and 2018, and identify short and mid-term response periods to forecasted biomass declines.

bolster broad-scale increases in the pace of fishery rationalization beyond what was already occurring prior to the 2012 season. Only AD 3Ps showed any evidence of increasing the pace at which vessels stopped participating in the fishery, which did not occur until 2015 when the resource decline was fully realized. Specific reasons for the overall lack of increases in either permanent (e.g. combining) or temporary (e.g. buddy-up) rationalization are unknown but could include a lack of trust in the science, a lack of alternate employment options, or economic circumstances sufficient enough to alleviate the need for adjustments within the fishery under reduced biomass.

The economic dependence on snow crab is not equal in all parts of the Province. The biomass, fleet size, and landings are greatest in AD 3LNO and smallest in AD 4R3Pn. In recent years, about 75–80 % of the biomass and landings occur in AD 3LNO (Mullowney et al., 2019). Within the most major ADs 2HJ, 3K, and 3LNO, 63-93 % of the landed value from fishing comes from snow crab (DFO, 2019). ADs 3Ps and 4R3Pn are less dependent on snow crab, with only 25–36 % of fishery landed values there coming from snow crab (DFO, 2019).

In general, the snow crab fishery is not likely an easy one to exit for most enterprise owners, particularly in AD 3LNO. The IQs are only partially liquid (maximum accumulation of 3 IQs by a given licence holder and a suite of residency and other policy constraints regulating buyer eligibility) and alternative employment opportunities in rural NL are generally lacking. The demographics of the industry are such that there are relatively few young people in the fishery, with the baby-boomer generation dominating and in the latter stages of their careers. The confluence of these factors are recognized by the Federal and Provincial governments as contributing to overcapacity in both the harvesting and processing sectors (FIR, 2006). The Federal Government, represented by DFO, only has managerial influence over the harvesting sector, and the recognition of overcapacity in the industry began a push toward more aggressive fleet rationalization through enterprise combining in the mid-to-late 2000s beyond levels already being enabled through the 'buddy-up' policy.

The escalating price of snow crab, beginning most substantially in about 2014, is a major factor to consider in how behavioural responses to the projected resource decline played out beyond the immediate reaction stage. Reasons for the price increase are not fully known and undoubtedly reflect changes in global demand, but it is noteworthy that the decline of the NL snow crab resource itself may have been a major contributor due to its status as the overall major global supplier in recent decades (Mullowney et al., 2014). Progressively bolstered by the recent realization of resource declines in AD 3LNO, overall and per-vessel fishery landings are now at their lowest level since fishery expansion in the 1990s. However, record high product prices have enabled the landed value per vessel (for most) and overall fishery value to coincidentally reach historic highs.

Given the participatory role harvesters play in determining quotas each year within a co-management context (Mullowney et al., this volume), the quota itself becomes at least partially reflective of behavioural responses to changes in the resource. Interestingly, different strategies were invoked on how to deal with forecasted resource declines, with the pivotal AD 3LNO in particular becoming increasingly aggressive in the resource extraction strategy. ADs 2HJ, 3K, and 3Ps experienced immediate quota reductions following 2011, while AD 3LNO continued to increase the quota and per-vessel landings to record high levels until 2015.

The more valuable a resource, the greater the likelihood of overexploitation (Clark and Munro, 2002). Steneck et al. (2011) described the scenario of a 'gilded trap' in the context of the Maine (USA) lobster (*Homarus americanus*) fishery whereby in non-diverse fisheries ecosystems attractive economic opportunities from the focal fishery can progressively encourage and re-inforce increased tolerence to social, ecological, or other risks. Clark (1973) similarly described how under a scenario of attractive economic opportunities, holders of property rights such as IQs may prefer non-sustainable harvest strategies over conservation on the basis of short-term profit maximization (Clark, 1973). This scenario becomes particularly plausible when stock recruitment prospects are deemed poor and expectations for extended economic rents are low. Indeed, recruitment prospects were deemed poor for the NL snow crab resource, particularly within AD 3LNO, with poor recruitment signals forming the very foundation of imminent biomass decline predictions (DFO, 2013, 2014; Mullowney et al., 2013, 2014).

Positive price movements typically encourage harvesters to stay and re-invest in fisheries, even when stock status is poor (Ikiara and Odjik, 2000). Accordingly, many major fisheries resource problems ultimately become associated with overinvestment (Hilborn, 1985). The 'bionomic equilibrium' (Gordon, 1954) for exploitation is reached when a stock has been reduced to the point that net income from fishing is no greater than would be expected from alternative employment. In the event that the value of the catch is high, the bionomic equilibrium becomes

associated with a depleted resource. Despite the current poor state of the exploitable biomass and low fishery CPUE, overall, the fishery is currently nowhere near reaching a bionomic equilibrium. With CPUE presently ranging from about 5 − 7 kg/trap throughout the major ADs, CPUE may not need to be far above zero before a bionomic equilibrium is reached under current high prices. A push toward an even lower CPUE at bionomic equilibrium could be encouraged by the Employment Insurance (EI) system, with income from it meaning zero profit or even losses during the fishing season could still translate into positive annual gross income.

Ultimately, it is clear that the suite of socio-political factors present in this fishery inherently exert strong downward biological pressures on the snow crab resource. As demonstrated herein, and consistent with previous similar demonstrations in other global fisheries, high product prices coupled with poor recruitment prospects may serve to increase top-down fishing pressures on valuable marine resources.

4.2. Stock status indicators

It is not uncommon for concerning stock status trends to be masked by high profits during periods of low abundance (Mackinson et al., 1997). Hilborn (1985) elaborated on how the iconic Peruvian anchovy fishery collapsed stemming from a failure to reduce harvesting pressure after a period of poor recruitment, despite prior biological warnings. All major stock status indicators are poor. Both the exploitable biomass and fishery CPUE are at or near historically measured lows in most ADs (Baker et al., in press), and for the first time, ERIs have recently coincidentally been at or near historic highs in all ADs. In response to the predicted resource decline, all ADs either maintained ERIs at high levels (ADs 2HJ, 3K, 4R3Pn), or enabled them to increase to new highs (ADs 3LNO, 3Ps). The top-down effects of fishing have never been so strongly been exerted across the entire stock range at the same time. Most divisions are currently exploiting the resource at levels above 50 % of the estimated available exploitable biomass each year, with ERIs above 75 % and approaching 100 % in multiple ADs in recent years.

Clark and Munro (2002) describe how in cases where fleet size is larger than required to capture quotas and fisheries are of short duration (typically associated with competitive fisheries), difficulties in controlling exploitation may become exacerbated by socio-political factors. Although decision making in the NL snow crab fishery ultimately remains with the federal government, the management system actively encourages harvester involvement in formulating annual management plans (DFO, 2019). Accordingly, at least theoretically, the management system is structured such that resistance to control exploitation may increase when the resource is in decline. Despite the fishery being non-competitive and based on IQs, as shown herein, the fleet size is larger than needed to take quotas and the fishery is of short duration, with a typical vessel hauling gear 5–10 days a year. It was also shown that quota shortfalls have become increasingly commonplace, even in the most important fishing areas. Interestingly, this scenario is such that there is an inherent and likely increasing level of competition within this IQ system.

Differences in the timing at which quotas became adjusted following resource decline warnings in recent years suggest a pattern of quota changes more closely following trends in CPUE than biomass. It is known that fishery CPUE lags behind biomass in showing changes in stock size in this resource, particularly in AD 3LNO where the best-fit lag between the two indices is two years (Mullowney et al., 2018, 2020 this volume). This delayed fishery response was demonstrated herein where fishery CPUE increased in AD 3LNO during 2012–2013 as the biomass began to decline.

CPUE is often a concerning metric used in fisheries science because 'hyper-stable' tendencies of it often mask true stock status signals (Harley, 2001). Consequently, if conscious of the phenomenon, a fundamental philosophical management dilemma can become deciding if it is more important to manage the fishery or manage the resource. Undoubtedly, decisions based on emphasizing one factor over another in a fisheries management system ultimately create feedback loops within and across socio-ecological processes. Interestingly, the most recent stock assessments have found that ADs 3K and 3Ps, where initial quota responses to the recent broad-scale decline were strongest, are the first to be entering into a phase of potential resource recovery (Baker et al., in press; Mullowney and Baker, this volume).

4.3. Vessel activity indicators

Like most indices, overall fishing effort trends are driven by AD 3LNO. In contrast to all other ADs, effort in AD 3LNO increased both in the short (e.g. from 2012 to 2014) and mid-term (e.g. from 2015 to 2017) in response to the projected biomass decline. This was manifest in all indicators including increases in total number of pot hauls within the AD, the number of hauling days per vessel, the number of trap hauls per vessel, and the fishery duration for a typical vessel in AD 3LNO. In all other ADs, relative measures of effort either remained unchanged or decreased either in the short (ADs 2HJ, 3K) or mid-term (ADs 3Ps, 4R3Pn) following 2011.

Contrary to our expectations, there were no obvious broad-scale signals indicative of an increased race to fish emerging in recent years, as interpreted by a suite of in-season fishing pattern indices examining temporal patterns of landings and effort, harvester risk tolerance, and periods of maximum operating capacity. It could be interpreted that the mere push toward an earlier season over time reflects a race to get on the water, but that process reflected a conscious management-regulated shift to help minimize wastage of soft-shelled crab in the fishery (DFO, 2019). Furthermore, in the major ADs the median fishing day did not advance any further toward earlier fishing following 2011.

The finding of a lack of increased fishery pace by most harvesters following the forecasted resource decline is intriguing, particularly in context of increased short (ADs 2HJ, 3Ps) or mid-term (ADs 3K, 3LNO) inabilities to capture quotas after 2011. It could be that the resource did not decline to a level sufficient enough for harvesters to perceive there would be problems in taking quotas, that most harvesters were already long-since operating at effectively maximum capacity early in the fishing seasons, or that other unknown factors are at play.

The most obvious change in fishing tactics in recent years has been increased soak times of the gear, particularly in the mid-late stages of the fishery. Overall soak time changes were least apparent in AD 2HJ and greatest in ADs 3LNO, 3Ps, and 4R3Pn. The adaptive behavioural response of increased soak times in AD 3LNO is consistent with the prolonged season duration in that area, while the negligibly changed behaviour in AD 2HJ is consistent with the majority of harvesters continuing a historic practice of rapidly turning over the gear during fishing operations in that area.

4.4. Spatial fishery indicators

The snow crab resource appears to be fully exploited, with effort distribution consistently maintained over a broad spatial area in most ADs for about two decades. Contrary to our expectation, there has been no further expansion in area fished as the biomass has declined in recent years; rather, the area fished has contracted to different degrees within each AD. The overall behaviour is indicative of reduced searching in the fishery and a concentration on known grounds.

The Marginal Value Theorem (Charnov, 1976) of predator foraging in patchily distributed resources suggests predators should only leave an area when capture rate drops to that expected in other patches within the accessible habitat range. This is similar to the optimal fishing intensity described by Gordon (1954), and the Ideal Free Distribution described by Gillis (2003), whereby in the presence of sufficient competition vessels spread themselves out among successful and marginal grounds to balance revenues in offsetting catch rate returns versus input costs associated with exploiting a given area. In this regard, given the

lack of spatial expansion in the fishery in recent years, it is likely that despite no apparent increases in the pace of the fishery, harvesters understood fishery prospects in fringe areas were poor and consciously chose to simply deplete the primary fishing grounds no matter the extent of catch rate decline.

From a biological perspective, the overall slowly shrinking fishery footprint in recent years likely reflects resource contraction into its core areas concomitant with decline, as per the principles of basin theory dynamics (MacCall, 1990).

Beyond biological reasoning, there may be psycho-social elements inherent in the overall conservative behavioural response to resource decline. Although there are always risk takers in the fleet, harvesters focused on social factors are generally risk adverse, feeling they need to maximize catch rates relative to the rest of the fleet to maintain social standing (Andersen, 1972; Palsson and Durrenberger, 1982; Vignaux, 1996). This attribute has been documented in historic NL fisheries, whereby low-risk NL trawler captains deliberately employed a strategy of fishing alongside one another in high seas fisheries for cod and other groundfish species (Cove, 1973). Whatever the reason, most snow crab harvesters have not been risky in exploring new areas in recent years and appear to have simply accepted the reality of diminishing catches on known grounds.

Spatial management restrictions have a more pronounced impact on harvesters only able to fish in a single area than those with autonomy to explore or fish multiple areas (Branch et al., 2006). In many small CMAs, particularly in AD 3LNO, the effort on the limited available fishing grounds is so dense that there is little possibility to explore and harvesters likely have little option but to simply deplete their limited available grounds until catch rates are poor enough to force them from the fishery. In context of the numerous small-scale CMA boundaries, it could be argued that forcing excessive effort into marginal areas may be more detrimental than allowing the extra catch to be taken from areas more able to withstand the fishing pressure in any given year. In this regard, small-scale management areas likely serve as a direct means to polarize winners versus losers during resource declines.

4.5. Outcomes of behavioural responses

The overall conservative (lack of) broad-scale spatiotemporal behavioural responses by harvesters to the forecasted decline of the NL snow crab resource in recent years is both intriguing and perplexing, particularly in light of potentially foregone economic revenues in the order of millions of dollars per year associated with unsubscribed quotas. It is rational to speculate that harvesters would take all possible actions to fully subscribe potential economic rents each year, thus it becomes reasonable to ask if they did in fact do so. From a tactical fishing perspective, the most obvious active response was increased soak times of the gear in latter stages of the fishery. From an economic perspective, there were outcomes indicative of attempting to maximize short-term rents from a declining resource. Soak time adaptations would reflect individual abilities of a given harvester while democratic management-type processes would reflect a more systematic response from collectives of harvesters.

The catch rate models suggest increased soak times have been marginally effective at mitigating CPUE decreases, with model regression slopes of about 0.05 kg/hour associated with soak times in the early and mid-stages of the fishery. The asymptotic shape and slow rate of CPUE increase in our models closely reflects the relationship between CPUE and soak time observed in the Bering Sea of Alaska, whereby catch rate increases of snow crab in the pots was negligible after about 72 h during a 1997–1999 study (van Tamelen, 2001). The increased soak time strategy has also been marginally beneficial toward reducing discards, with regression model slopes suggesting crab may escape at a rate of about 0.025 – 0.1 kg/hour as soak times accumulate. This gear selectivity feature is consistent with Pengilly and Tracy (1998), who described a reduced ratio of sub-legal to legal-size red king crab (*Paralithodes camtschaticus*) in the catch as trap soak times increased.

Ultimately, the confluence of a general lack of active behavioural responses by individual harvesters and systematic increased fisheries exploitation rates occurring after the forecasted resource decline have culminated in a situation where the stock has now become depleted throughout its entire range. Interestingly, there are now signals of improving stock status either presently or anticipated to occur throughout most of the stock range (Baker et al., in press). From both economic and biological perspectives, the critical question to examine moving forward now becomes to what extent enabling the stock to become depleted will affect long-term productivity and yield from of the resource. Answers to this fundamental question may serve as a future management guide for adaptation strategies in this and similar fisheries (most specifically male-only fisheries) moving forward when biological warnings over resource declines are given.

5. Summary remarks

Overall, the behavioural responses of harvesters to a predicted resource decline were more conservative than envisioned. Several of our intuition-based presumptions on how harvesters and fleets would likely respond to a forecasted resource decline were incorrect. There has been no strong indications of an increased race to fish, increased risk taking, or broader and more intense fishing patterns in recent years. Only AD 3LNO showed any indication of a prolonged season. Soak time changes were the most obvious behavioural adaptive response employed by harvesters to mitigate against the resource decline. Soak times became longer in most ADs, which marginally offset the impacts of reduced CPUE and coincidentally reduced discards. On the broad-scale, most harvesters and fleet sectors appear to have simply prosecuted the fishery in similar fashion as they historically had and accepted increased exploitation rates and associated reduced catch rates. In some historically dominant fishing areas, negligibly or unchanged fishing practices were associated with increased fishery abandonment. Two leading possibilities to explain the overall conservative adaptive responses to resource declines are favourable prices that from a revenue perspective more than offset reduced catch, and restrictive management lines that allowed little to no capacity to pursue alternate grounds or employ adaptive strategies.

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. **Eric J. Pedersen:** Methodology, Investigation, Writing - review & editing.

Declaration of Competing Interest

None.

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