Fisheries and Oceans Canada
Pêches et Océans Canada

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Canadian Science Advisory Secretariat (CSAS)

Research Document 2018/054

Newfoundland and Labrador Region

Basis for A Precautionary Approach and Decision Making Framework for the Newfoundland and Labrador Snow Crab (*Chionoecetes opilio*) Fishery

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October 2018

Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

Published by:

Fisheries and Oceans Canada
Canadian Science Advisory Secretariat
200 Kent Street
Ottawa ON K1A 0E6

http://www.dfo-mpo.gc.ca/csas-sccs/
csas-sccs@dfo-mpo.gc.ca

ISSN 1919-5044

Correct citation for this publication:

Mullowney, D., Baker, K., Pedersen, E., and Osborne, D. 2018. Basis for A Precautionary Approach and Decision Making Framework for the Newfoundland and Labrador Snow Crab (*Chionoecetes opilio*) Fishery. DFO Can. Sci. Advis. Sec. Res. Doc. 2018/054. iv + 66 p.

Aussi disponible en français :

Mullowney, D., Baker, K., Pedersen, E. et Osborne, D. 2018. Base d'une approche de précaution et d'un cadre décisionnel pour la pêche du crabe des neiges (Chionoecetes opilio) à Terre-Neuve-et-Labrador. Secr. can. de consult. sci. du MPO. Doc. de rech. 2018/054. iv + 69 p.

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ABSTRACT

This document was devloped from a peer-review process in June 2018 on the development of a Precautionary Approach (PA) and Decision Making (DM) management framework for the Newfoundland and Labrador Snow Crab resource and fishery. The document highlights some of the history surrounding the establishment of a PA/DM framework for this fishery and presents a suite of models to test the efficacy of key resource status indicators as the basis for stock status reference points and harvest control rules. As per the role of DFO Science Branch in establishing PA/DM frameworks for Canadian fisheries resources, limit reference points (LRPs) and associated removal references for fishery exploitation are provided. A multi-indicator approach is applied in the assessment of the resource and development of a framework. Three resource and fishery metrics (egg clutch fullness, fishery catch per unit effort [CPUE], and fishery discards) are examined, with an underlying focus on two key principles of biological protection and efficient resource extraction guiding the philosophy of the approach.

INTRODUCTION

Fisheries and Oceans Canada (DFO) produced guidance for development and implementation of Precautionary Approach (PA) and Decision Making (DM) frameworks into the management of fisheries resources in Canada in 2006 (DFO 2006, 2009). However, DFO has yet to adopt a formal PA/DM framework for the management of Newfoundland and Labrador (NL) Snow Crab (*Chionoecetes opilio*) resource and fishery. PA/DM frameworks have been implemented into the management of other Atlantic Canadian Snow Crab fisheries for several years (i.e. DFO 2010, 2015). A key underlying objective of implementing a PA/DM framework is to prevent serious harm to aquatic resources through fishing. When scientific uncertainty about stock status parameters is high, management decisions are advised to err on the side of caution.

Ultimately, nearly all iterations of PA/DM frameworks strive to develop transparent, target-based management of fisheries resources. Under such frameworks, stock status is assessed relative to pre-described indicators ('reference points') and management decisions are made consistent with prescribed harvest control rules that reflect risk tolerance relative to stock status. A typical PA framework entails a measure of stock size, often spawning stock biomass (SSB), in relation to a measure of a fishing effect, such as harvest rate. A PA/DM framework is both mandated by DFO and necessitated for this stock due to its Marine Stewardship Council (MSC) eco-certification. The NL fishery for Snow Crab received eco-certification as a sustainably managed resource by this certifying body in 2012, under the stipulation that a PA/DM framework would be implemented in the forthcoming years.

A PA Working Group (WG) consisting of members from DFO Science, DFO Resource Management, and fishing industry representatives was established to address the implementation of a PA/DM framework into the management of NL Snow Crab in 2012. To date, the WG has not established a proposal satisfactory enough to proceed with implementation of a formal framework. The WG has advocated that the confluence of unique biological attributes of Snow Crab, a high level of climate regulation of the resource (Mullowney et al. 2014), and a stringent set of management regulations already constitutes a sufficient PA/DM framework for this fishery (Dawe and Mullowney 2016). A major point the WG has advanced is that the exploitable biomass of male Snow Crab (≥95 mm carapace width [CW]), the portion of the resource targeted by the fishery, is not an appropriate analog for SSB (or a similar measure of stock status) in a framework. The rationale for this is that current management measures and gear selectivity sufficiently protect virtually all females from capture and to-date have consistently ensured only a portion of males are retained (Fig. 1). Accordingly, the theory is that there is continuous safeguarding of stock reproductive capacity under current management practices. The WG has advised that alternate approaches from conventional biomass-based frameworks be pursued for the NL Snow Crab resource, such as one that strives to promote fishing efficiency in resource extraction.

This document presents quantitative and qualitative analyses supporting a PA/DM framework for NL Snow Crab that addresses safeguarding of stock reproductive capacity as well as minimizing wastage in resource extraction. In alignment with the perspectives of the WG, a multiple-indicator approach is presented. This approach focuses on three key resource metrics of stock status:

1. Female egg clutches,
2. Fishery catch per unit of effort (CPUE); and
3. Fishery discards.

All three metrics are intended to directly and indirectly address two key ideologies of biological protection and efficiency in resource extraction.

In this analysis, as per policy guidance from DFO (DFO 2006, 2009), we provide bases for limit reference points (LRPs) for the focal metrics and guidance for upper stock references points (USR). Associated removal references are identified and advice on harvest control rules (HCRs) for sustainable exploitation of the resource is provided.

METHODS AND RESULTS

SPATIAL UNITS OF ASSESSMENT

Five Assessment Divisions (ADs) based on the Northwest Atlantic Fisheries Organization (NAFO) divisional boundaries and conforming to those used in the annual assessments of NL Snow Crab are presented in the analyses (Fig. 2). The ADs extend from central Labrador in the north (2HJ) through coastal waters off the northeast coast of the island of Newfoundland (3K), to the largest AD represented by the Grand Bank (3LNO) in offshore areas off the southeast coast of Newfoundland. AD 3Ps occurs off the south coast of Newfoundland. AD 3L Inshore is assessed seperately from the broader scale offshore (i.e., AD 3LNO) due to differences in data availability, with multi-species trawl surveys not routinely extending into inshore bays where high biomass of Snow Crab occurs (Mullowney et al. 2017).

Areas off the west coast of Newfoundland in the Gulf of St. Lawrence (AD 4R3Pn) are not considered in this analysis due to data deficiencies necessary to establish indices for all focal metrics; specifically, there is no trawl survey conducted by the NL Region of DFO, logbook return rates have been historically low, and there has been a virtual absence of at-sea observer coverage throughout the time series (Mullowney et al. 2017). This framework does not take into consideration stock variations between the smaller scale Crab Management Areas (CMAs) used to manage the fishery because data are not sufficient to conduct this analysis at such small spatial scales. Moreover, the CMAs are generally too small to constitue biologically meaningful units. The genetic stock spans all of Atlantic Canada (Puebla et al. 2008), suggesting larval drift dynamics are much broader in scale than the CMAs, and ontogenetic and seasonal movements of crab extend across CMA boundaries (Mullowney et al. 2018).

ASSESSMENT METRICS

Egg Clutches

Data on egg clutch fullness in mature females captured in offshore multi-species trawl surveys and inshore trap surveys for Snow Crab conducted by DFO have been recorded wherever surveys have occurred for the past two decades. Multi-species trawl surveys have consistently occurred in NAFO Divisions 2J3KLNO during fall (September to December) since 1995 and in Subdivision 3Ps during spring (March to May) since 1996. Inshore trap surveys have occurred in AD 3K (White and Notre Dame Bays) since 1994 during late-August to mid-September. In AD 3L Inshore, long-term surveys have occurred in Bonavista (late July) and Conception (late-September/early-October) Bays since 1979, while Trinity (early-August) and St. Mary’s (mid-June) Bays have been surveyed only in the most recent 4-5 years. In AD 3Ps, a trap survey has been conducted in Fortune Bay during early June since 2007. Further details on all trawl and trap surveys are available in Mullowney et al. 2017.

From all surveys, data captured on clutch fullness of mature females are coarse grain, identifying subjects as either having full or partial clutches, with no finer quantification of the relative fullness of partial clutches. Accordingly, the clutch fullness index was treated as binomial, with individuals either being ‘full’ or ‘not full’ of viable eggs. However, additional codes in the datasets identifying recently liberated egg clutches (i.e., trace evidence of viable eggs remaining) were grouped with the full clutch classification, operating under the assumption that the animal had recently released a viable clutch of eggs.

Growth and reproductive aspects of Snow Crab biology are complicated. Growth is a stepwise process associated with molting, which ceases after a terminal molt (Conan and Comeau 1986). Terminal molt occurs over a broad size range of about 40–160 mm CW for males and 30-95 mm CW for females (Sainte-Marie and Hazel 1992; Sainte-Marie et al. 1996). For males, sexual maturity is achieved before the terminal molt. Males become ‘morphometrically mature’ by growing enlarged claws upon terminally molting. A sexually but not morphometrically mature male is termed an adolescent. For females, the sexual and terminal/morphometric maturity molt occur at the same time. It takes an estimated minimum of 8–10 years for male crab to reach exploitable size (95 mm CW) in NL (Mullowney et al. 2017), with maximum longevity following terminal molt about 7–8 years (Fonseca et al. 2008), although such longevity to maximum post-terminal molt age is likely not common.

Reproductive dynamics suggest full clutches of viable eggs should be common in mature females. Mating is promiscious such that breeding females may be inseminated by several male partners each year (Sainte-Marie and Hazel 1992; Sainte-Marie et al. 1999, 2008). Further, females can store sperm to fertilize subsequent clutches of eggs (Sainte-Marie and Carriere 1995). Under-size (<95 mm CW) adult males can successfully mate females, although largest adults are likely the most successful breeders in the presence of mating competition (Sainte-Marie et al. 1999). Moreover, adolescent males may also participate in mating (Kolts et al. 2015), although the extent to which this occurs is unknown. Finally, egg incubation time can be prolonged, specifically in cold conditions where females may carry eggs for up to two years before release (Kanno 1987, Sainte-Marie 1993), as opposed to the more common one-year period in warmer areas.

Different life-history strategies between the sexes creates the potential for egg clutch levels to be naturally ‘dampened’; such variation depends on the state of the development ‘cycle’ of a given cohort (Sainte-Marie et al. 1996). For an initial example, if the population features a relatively high proportion of senesent females the presence of full egg clutches in mature females would be expected to be relatively low. As a second example, as females from any given cohort would be expected to reach the age of sexual maturity before males, there is potential for relatively low levels of successful fertilization in the paucity period before most males mature. However, in a healthy stock comprised of multiple mixed cohorts at any given size, such occurrences of low clutch fullness should be relatively infrequent. This is supported by perpetually high levels of egg clutch fullness across a broad spatial scale (Fig. 3).

High proportions of females carrying less than full clutches of viable eggs is viewed as a potential biological concern on stock reproductive capacity through fishing. Sainte-Marie et al. 2008 describe some of the potential implications of excessive fishing of large males as promoting mating of less fecund males, reducing opportunity for female mate choice, and increasing the likelihood of sperm limitation. They state that these changes have mixed but still incompletely appreciated effects on female reproductive fitness and that long-term potential for genetic selection against large size-at-maturity remains uncertain. Moreover, large mature males are important for the post-molt protection of vulnerable soft-shelled females (Rondeau and Sainte-Marie 2001).

The offshore multi-species trawl surveys are known to have a low catchability for female-sized Snow Crab (Dawe et al. 2010). Trawl catchability is highest for largest crab on softest substrate. There was concern that small sample sizes of females from the trawl surveys could detract from the reliability of egg clutch fullness as a metric of concern in a PA/DM framework. To account for this, two-year cumulative sums of each group of females (full vs. not full) were calculated before deriving percentages of clutch fullness. Although sample sizes were higher in inshore trap surveys, the same cumulative sum procedure was applied to inshore trap-captured samples for consistency. The greatest concern over small sample sizes of mature females is in the offshore trawl surveys from AD 2HJ, where the two year cumulative sum ranges from about 100-250 animals in any given year (Fig. 4).

There was strong consistency in levels of clutch fullness between offshore trawl-captured samples and inshore trap-captured samples across a broad spatial spectrum. With little exception, the proportion of females carrying full clutches of viable eggs has remained above 0.6 wherever measured, with proportions above 0.8 the norm (Figs. 3, and 5). One notable exception to this is Fortune Bay (AD 3Ps), with the egg clutch fullness index dropping to 0.5 in 2014 (Fig. 5). This is an area where the biomass of exploitable males and fishery CPUE have been low for an extended period (Mullowney et al. 2017).

In AD 3L Inshore, the only available data on egg clutches came from localized trap surveys in Bonavista, Conception, Trinity, and St. Mary's Bays, as well as off the Avalon Peninsula (Fig. 5). However, there were broken and disjoint time series' across bays. To account for spatial differences in sampling, for final inclusion of this AD in a PA/DM framework, a stratum-area weighted mean was used to calculate a composite divisional estimate of egg clutch fullness each year.

Fishery CPUE

CPUE is known to reflect the relative strength of the exploitable biomass in all ADs, with the annual catch rate index lagged a year (i.e., trap) or two (i.e., trawl) in reflecting annual survey biomass estimates. Further, CPUE has also knowingly been negatively related to annual fishery discard levels in all ADs throughout the time series (Mullowney et al. 2017), thought to reflect an increased catchabilty of under-size and/or soft-shell crab in the absence of large males.

The CPUE metric used in this framework is a predicted annual average catch per trap haul (total catch divided by total traps per set) based off a prediction model defined below, and not an instantaneous measure of CPUE at any specific point in time. Other CPUE metrics were considered during the peer review process, such as start of fishing season CPUE, which would best correlate with biomass at the start of the year, and end of year CPUE, which would integrate both beginning-of-year biomass and fishing effort. However, it was demonstrated at the peer review process that annual average CPUE was tightly correlated with both early and late-season point esimates for each AD.

Although lagged annual CPUE estimates are generally consistent in reflecting annual survey biomass point estimates in this resource/fishery, CPUE has several potential issues when interpreting it as a metric of relative stock size. Along with changes in stock size, CPUE is also sensitive to changes in both fishing technology and spatial distributions of fishing effort (Hilborn and Walters 1992). Accordingly, using CPUE as an indicator may mask changes in stock size. In many fisheries, CPUE will decline at a slower rate than the biomass/abundance of the fished stock (i.e., is hyperstable; Harley et al. 2001). In NL, this phenomenon played out during the collapse of northern cod (*Gadus morhua*) in the early-1990s as fishery CPUE remained artifically high in some areas, reflecting hyperstability introduced by fishing on extant dense aggregations of fish (Rose and Kulka 1999). Hyperstability of CPUE indices in relation to stock size can occur both within-season as well as over prolonged time scales. For example, the 1-2 year lag commonly observed between directional changes in annual survey biomass indices versus responses in annual CPUE reflects a gradual (i.e., not instantaneous) process. Annual measures of CPUE also have the potential to mask the relative magnitude of the two key processes it reflects, the magnitude of the initial biomass and the associated extent of exploitation. For example, a similar annual catch rate estimate could arise from an initially dense population that is heavily exploited versus an initally sparse population that is lightly exploited. However, this outcome largely reflects one of the underlying philosophies of most PA/DM frameworks, which is to lower the harvest fraction when relative biomass is low and allow an increased harvest fraction when relative biomass is high.

Given a suite of negative resource indicators from the most recent stock assessment (DFO 2018) including low exploitable biomass levels, high exploitation rate indices, declining landings, increasing and high total mortality of exploitable crab, expected low recruitment into the exploitable biomass, and low CPUE, the risk of negative outcomes stemming from over-interpretation of potentially hyper-stable CPUE could be high at-present. However, the relationship between CPUE and biomass is well understood in this fishery and demonstrated in this framework. CPUE also offers several advantages over biomass for this framework. First, CPUE has a longer time series than all survey series. In extension, it is also more spatially broad than any given survey series, with neither trawl nor trap surveys consistently covering all managed crab fisheries in NL. Accordingly, with no consistent source of long-term survey-based information from which to derive biomass for all ADs, different estimation sources are invoked for different ADs. Second, CPUE is directly related to population density per unit area rather than absolute abundance. Population density would more strongly affect local inter- and intraspecific interaction rates. As ADs vary substantially in overall area and the amount of each AD constituting crab habitat is unknown, it would be difficult to develop consistent abundance based reference points for each AD, whereas it is possible to develop a single reference point for CPUE in all ADs. Third, while CPUE does show hyperstability at high abundances in this fishery, the relationship between abundance and CPUE within each AD is approximately linear at the low abundances relevant for setting LRPs (see below). The numerous small spatial scale CMAs within which quotas are allocated are thought to partially safeguard against hyperstability at low biomass as they serve to force fishing effort to be spatially broad-based each year; marginal areas are consistently included in the CPUE index and the overall fishing pattern remains relatively constant each year.

The framework recommends setting management decisions based on predicted rather than current CPUE estimates. Examination of changes between observed and predicted CPUE could allow the ability to detect potential interferences arising from changing technolgies or fishing patterns that could potentially affect the efficacy of CPUE. We also highlight that CPUE predictions are partially based on fishery independent biomass indices, and that communicating changes in biomass through the metric of CPUE is expected to elevate the level of understanding, trust, and ownership of this PA/DM framework as CPUE has long been a measure of central focus for managers and harvesters in the co-management of this fishery. It should be noted that complementary and independent catch rate indices are available to help ensure catch rate reporting remains reliable (Mullowney and Dawe 2009).

This framework uses a series of modelling steps to address the issues identified with CPUE, and to develop a predictive metric of CPUE that can be used as an indicator:

- Use a mixed effect model of instantaneous CPUE as a function of day of year, year, and fishing location to account for small-scale fluctuations in CPUE across time. Predicted values from this model are used to estimate average CPUE per year.
- Use a depletion estimator based on instantaneous CPUE to estimate within-AD biomass for each year. Regress survey biomass estimates on this metric to determine AD-specific catchability (*q*) metrics.

- Regress average annual CPUE measures from step 1 on trawl biomass (scaled by *q*) from the prior year and lagged environmental and fishing effort measures.
- Use the model from step 3 to generate a prediction of what AD-specific average CPUE should be in a given year for a given trawl biomass, environmental conditions, and fishing effort.

The remainder of this section lays out these steps in detail.

Submission of logbooks detailing time and location of fishing activities as well as the level of catch (tonnes) and effort (trap hauls) are mandatory in this fishery. Logbook return rates in the fishery are generally above 70% of the given fishing trips occurring in any AD and year and have been generally above 80% in all examined ADs in recent years (Fig. 6). Previous studies have shown that logbook catch rate indices align closely with those from other sources such as an electronic vessel monitoring system (Mullowney and Dawe, 2009), and there is a continuous time series of data available throughout the fishery from which to base analyses.

Annual fishery CPUE estimates are standardized for time and space using a linear mixed model (LMM) (eq [1]). In this model, *y* indicates a given year, *t* indicates a given day, and *D* indicates a given division. α terms indicate intercepts, β terms indicate coefficients for specific covariates, the ϵ term indicate unmodelled error around predicted CPUE, and σ^2 terms indicate variances on random effects or the error term. The model regresses the response variable of square-root transformed CPUE (catch/trap haul) from individual observations (normally on a per set basis) against fixed effects of time, binned in 5-day intervals ($\overline{\beta_{Day}}$) and gear soak time, measured in days (β_{Soak}). Random effects were used to model root CPUE at the start of the season ($\alpha_{y,D}$) and slopes for time effects ($\beta_{Day,y,D}$) of year*CMA groupings are included in the model. The CMA parameter accounts for spatial variation across multiple management areas within any AD. The positively-skewed response variable was square-root transformed to normalize it, as stronger transformations such as logarithms were found to produced negatively-skewed distributions in some cases. Finally, the model is weighted by effort (traps). This model was used to predict average annual CPUE by averaging set-specific predicted values (as well as 95% lower and upper confidence estimates) for each AD and year.

$$\sqrt{CPUE_{y,t,D}} = \alpha_{y,D} + \beta_{Day,y,D} \cdot Day_{y,t,D} + \beta_{Soak} \cdot Soak_{y,t,D} + \epsilon_{y,t,D}$$

$$\alpha_{y,D} \sim N(\mu, {\sigma^2}_{intercept})$$

[1] $$\beta_{Day,y,D} \sim N(\overline{\beta_{Day}}, {\sigma^2}_{Day})$$

$$\epsilon_{y,t,D} \sim N(0, \frac{{\sigma^2}_{error}}{effort})$$

Fishery CPUE has varied in all ADs throughout the time series (Fig. 7). It is generally highest in Divs. 3LNO and is presently at or near a two-decade low in all but AD 2HJ.

Fishery CPUE is used to adjust survey biomass indices into comparable scales across and within ADs (i.e., account for differences in spatiotemporal survey catchability concerns). This is done through Delury depletion modelling (Delury 1947). A representative depiction of the method (from AD 2HJ) is shown in Fig. 8. Time-binned natural log (ln) transformed CPUE is regressed on cumulative fishing effort (measured as number of pots, binned into 5-day intervals) using a mixed effects model with a random effect for both the slope and intercept for each AD-year combination. Biomass is then estimated as the natural exponent (e^x) of the intercept divided by the negative of the slope of the regression for each year-AD combination, following the standard Delury population estimate (Delury 1947). These start of season biomasses were then compared to the prior fall trawl survey biomass indices to calculate annual catchability scaling factors (i.e., ‘q’s’) for the trawl survey biomass estimates. In AD 3Ps, where the survey is in-season, a third of the annual landings were subtracted from the estimated beginning of season biomass to compare with the trawl survey to derive q’s. In AD 3L Inshore, where no trawl survey occurs, fishery depletion-based estimates were compared with a trap-based biomass index developed from various DFO and collaborative trap surveys (Mullowney et al. 2017) to derive survey q’s.

The major point of developing the Delury (logbook) biomass estimates is to re-scale knowingly underestimated survey biomass estimates into near-absolute levels through adjustment q’s. A common q adjustment factor also brings trap and trawl survey biomass estimates into a common scale. Adjusted biomass is subsequently used as an input into predictive CPUE models and as the basis for calculating exploitation rate indices.

To account for changing q over time within each AD, an exponential weighted moving average (EWMA) was calculated using the *Proc Expand* function in SAS. This EWMA included a smoothing factor of 0.3 to allow historical observations to remain influential in affecting the terminal value of the time series. Essentially, the EWMA q smoother is lagged in responding to annual changes in survey q and when there is no pattern in q in the time series the EWMA differs little from an arithmetic mean. The q’s used in the analysis to re-scale biomass ranged from 0.08 in AD 3Ps, where a spring survey occurs, to 0.86 in AD 3L Inshore, where a trap survey using the same gear as the fishery occurs. Several factors including vessel, substrate, season, and latitude all likely affect trawl survey q’s (Mullowney et al. 2017 and references therein). The high *q* in AD 3L Inshore likely reflects survey gear, with that AD being surveyed with the same pots used in the fishery.

Trap survey biomass indices are less preferred than trawl survey indices as, on the broad-scale, they have shorter time series and are deemed to have a less representative sampling design, generally avoiding shallow areas. This is largely due to the inclusion of the Collaborative Post-Season (CPS) dataset in the analyses. This survey, conducted collaboratively with the Fish, Food, and Allied Workers (FFAW) Union, has been designed to target deep fishing grounds where the fishery concentrates (Mullowney et al. 2017). This is also the case for the DFO trap surveys in Bonavista and Conception Bays in AD 3L Inshore prior to 2012, with the survey designs becoming depth-stratified after that in those bays. Despite incomplete vertical coverage, a strength of the CPS survey relative to the DFO trap surveys is broad spatial coverage, with more CMAs surveyed each year by the CPS survey.

The AD 3L Inshore trap-based biomass index used in this analysis includes data from both the CPS and DFO surveys (Mullowney et al. 2017). The short time series reflects the fact that the CPS survey only began in most portions of AD 3L Inshore in 2004, therefore that point constitues the start of the biomass index time series. Nonetheless, the AD 3L Inshore trap survey index strongly correlates with the trawl survey biomass index from adjacent AD 3LNO (r^2=0.93) (Fig. 9), supporting the inclusion of the AD Div. 3L Inshore trap-based biomass index for analysis.

Although the depletion re-scaling method for exploitable biomass (herein termed ‘biomass’) estimation is generally deemed a dependable method, there are several factors that affect its reliability. Accordingly, final biomass estimates are not deemed absolute, rather they are deemed to be close to real values. First, the depletion estimation method relies on the fishery strongly depleting the resource. This has occurred in most ADs each year since 1999 (Mullowney et al. 2017). Second, there are concerns that the method may slightly overestimate biomass due to non-linearity created by traps saturating at a moderate CPUE at the start of the season, when biomasses are high, and an increased rate of depletion near the end of the season in some years. Further, CPUE may also increase near the end of the season as crab that were soft-shelled at the start of the season begin to more frequently trap (which would also lead to overestimating beginning-of-year biomass). The beginning and end 5% of the fishing effort in any given AD and season were removed prior to conducting the regression analysis to partially account for these issues, but it is recognized that biomass is still likely overestimated. This in-turn would underestimate exploitation rate indices derived and used in this study. It should be noted that non-linear methods of depletion-based biomass estimates are currently being developed to improve precision, and that exploitation rates developed and discussed as potential targets for harvest rates in the fishery are considered preliminary.

We explored the ability to predict CPUE first by examining the relationship between CPUE and survey biomass. Annual raw survey biomass estimates were initally re-scaled by AD-specific q's described above. Subsequenlty, the re-scaled annual biomass estimates were smoothed as two-period moving averages to account for concerns of 'year effects' created by inconsistent trawl efficiency. Such year effect concerns have been frequently raised at the stock assessments for NL Snow Crab (Mullowney et al. 2017). One example of their presence is that pre-recruit crab indices tend to be more strongly correlated with exploitable crab indices within year than at a lag. Moreover, it was suspected that the impact of biomass on CPUE would exhibit some degree of auto-correlated behaviour, with the biomass index from any given year resonating to affect the CPUE over a period of more than one subsequent year, particulary in cases where there was a strong residual component to the biomass.

The relationship between CPUE and biomass was found to be non-linear in all ADs, reflecting an asymptotic shaped process (Fig. 10). Among other possibilities, this process could reflect trap competition or saturation. In NL, in contrast to other crab fisheries in Atlantic Canada and the Eastern Bering Sea of Alaska (EBSA), crab pots are tied together in long-lines (termed 'fleets') and spaced close together, generally at a distance of about 45 m. To account for the relational shape between biomass and CPUE we fit a Type II non-linear response model of the form:

[2] $$\bar{C}_{y,D} = a_D \cdot \frac{(0.5 \cdot Biomass_{D,y-1} + 0.5 \cdot Biomass_{D,y-2})}{1 + a_D h_D (0.5 \cdot Biomass_{D,y-1} + 0.5 \cdot Biomass_{D,y-2})}$$

Where $\bar{C}_{y,D}$ represents expected CPUE in a given AD-year for a given biomass, a_D and h_D are division-specific shape parameters reflecting 'searching efficiency' and 'handling time' in the process and $Biomass_{D,y}$is the average survey biomass index in AD *D* in year *y* (Fig. 10). The parameters were estimated in *Proc NLIN* in SAS Enterprise Guide ver. 5.1.

The AD-specific predicted value from eq. [2], $\bar{C}_{y,D}$was used as an offset term in a LMM to estimate final predicted CPUE (eq. [3]). This offset term serves to provide both a linkage to biomass and a structural parameter to shape the response variable (CPUE) in the prediction model. An overall type II response model with ADs pooled produced a saturation point estimate of 14.5 kg/trap (Fig. 11), which was subsequently used with a varieity of other CPUE metrics to derive reference points. The fixed effects in the CPUE prediction model were the exploitation rate index (ERI), the ratio of exploitable to pre-recruit males from the most recent survey (Ratio), and a lagged index of the North Atlantic Osciallation (NAO, measured at some lag, *l*). All parameters were treated as random effects with AD as the grouping level. As predictors were not centered prior to inclusion in this model, the model also included a random intercept term (α_D) in addition to the offset term, to account for the fact that average CPUE would not be predicted to be equal to the offeset if all coeficients were set to zero. Predicted values from this equation are the indices to be used in the main framework.

[3]

$$\overline{CPUE}_{y,D} = \bar{C}_{y,D} + \alpha_D + \beta_{ERI,D} \cdot ERI_{y,D} + \beta_{Ratio,D} \cdot Ratio_{y,D} + \beta_{NAO,D} \cdot NAO_{y-l,D} + \epsilon_{y,D}$$
$$\alpha_D = N(\bar{\alpha}, \sigma_\alpha^2)$$
$$\beta_{ERI,D} = N(\bar{\beta}_{ERI}, \sigma_{ERI}^2)$$
$$\beta_{Ratio,D} = N(\bar{\beta}_{ERI}, \sigma_{Ratio}^2)$$
$$\beta_{NAO,D} = N(\bar{\beta}_{ERI}, \sigma_{NAO}^2)$$
$$\epsilon_{y,D} = N(0, \sigma_\epsilon^2)$$

The ratio of exploitable to pre-recruit males was included in the CPUE prediction model to account for the ‘buffering capacity’ of residual crab in the population to prevent less competitive pre-recruits from trapping. *A priori* analyses have shown that the presence of a relatively strong residual biomass is typically associated with increased CPUE, while a ratio skewed toward pre-recruits is often associated with low CPUE and high discard levels (Mullowney et al. 2017). As there was no trawl survey in AD 3L Inshore from which to formulate an exploitable:pre-recruit ratio, the ratio from the adjacent AD 3LNO was used.

The NAO is a dominant ocean climate forcing mechanism in NL (Colbourne et al. 2016) and at the most recent stock assessment this climate index was shown to be strongly correlated with future exploitable biomass in all ADs. Exploratory analyses showed strong lagged correlations of the NAO index with CPUE in all ADs. The NAO reflects the relative strength of atmospheric pressure at sea level between dominant centres in the western (Icelanic Low) and eastern (Azores High) north Atlantic. Under high NAO, Arctic northwesteriles prevail and the NL shelf experiences overall cold conditions (Petrie 2007, Colbourne et al. 2016). The NAO index data were obtained from the National Oceanographic and Atmospheric Association (NOAA) of the United States website. The NAO index used herein is a smoothed 3-period centred moving average of the annual NAO, which is calculated by averaging monthly values each year. Consistent strong cross-correlations between CPUE and NAO occurred at lags of 7-10 years in all ADs, with the best-fit lags used in the CPUE prediction models being 7 years in ADs 2HJ, 3K, 3PS, 8 years in AD 3K, and 9 years in AD 3LNO.

The CPUE prediction model reliably predicted fishery catch rates in most ADs and years (Fig. 12) with no strong systematic patterns in the residuals (Fig. 13). The presented predicted values for 2018 assumed status quo landings as the 2017 season in each AD. One notable period of exception of divergence between the CPUE prediction model and observed CPUE occurred in AD 3K in 2007-08. Reasons for this divergence are unknown. Interestingly, this exceptionally high level of observed CPUE and a corresponding abrupt 60% decline in the exploitable biomass index in that AD in 2009 have remained poorly explained by the stock assessment for NL Snow Crab. The biomass/CPUE increase was associated with a coincidental spike in pre-recruit crab abundance in the trawl survey but it was not strongly associated with any climate metric used to predict biomass and CPUE in the assessment in recent years (Mullowney et al. 2017). Reasons for other disparities in model-predicted versus observed catch rates such as in the mid-2000s in ADs 3LNO and 3Ps are unknown.

Fishery Discards

Theoretically, three key components of the Snow Crab population should comprise the majority of discards: females, under-size adult males, and soft-shell pre-recruit males. The inclusion of discards as a metric of concern in this analysis is intended to broadly safeguard all three biologically important components of the population from fisheries-induced mortality. Minimizing discards also serves to help maximize fishing efficiency through reduced handling mortality on crab not retained by the fishery.

The fishery imposes mortality to crab through discarding, although exact levels are unknown. This constitutes both biological and economic wastage. The out-of-water environment is very different from the cold, dark, deep, and relatively stable environment occupied by Snow Crab. Time out of water, air and water temperature, wind speed, sunlight, shell hardness, and crab size all influence the mortality level on discarded Snow Crab (Miller 1977, Dufour et al. 1997; Grant 2003). Soft-shell crab are likely subject to more damage and mortality than hard-shell crab. Prolonged exposure on deck and dropping or throwing crab induces limb loss and also leads to increased mortality levels associated with catching and discarding crab (Grant 2003). A recent study from the EBSA predicted only about 5% mortality on discarded Snow Crab (Urban, 2015), an estimate virtually identical to the estimate of Grant (2003) in NL Snow Crab. However, Grant (2003) cautioned that this low estimate was for crab subjected to best handing practices, specifically in the form of minimal dropping distances and little exposure time on deck, and showed mortality rates increased substantially under poor handling practices. Further, both studies featured predominately hard-shell crab and both authors cautioned that unobserved latent mortality is unaccounted for in their studies. It is quite likely that mortality rates are higher on soft-shell crab, particularly as it is common to see them floating near the surface for extended times following release (personal observations).

The management of the NL Snow Crab fishery already attempts to safeguard against mortality imposed to soft-shell pre-recruits through discarding. A protocol was initiated in 2004 that closes small grids to fishing when soft-shell crab is observed to constitute 15 or 20% of the catch, depending on AD (Mullowney et al. 2017). Extending discard protection to female and under-size adult males through this PA/DM framework increases the overall precaution inherent in the resource management.

The only reliable source of discard data available is from at-sea observer coverage. Discard estimates in logbooks are deemed poor, with frequent observations of nil discards and little precision in existing estimates when present. However, the at-sea observer data also have deficiencies that stem from low and non-representative coverage. Observer coverage levels can be variable, but in a typical year less than 5% of the fishing trips are observed and <0.4% of the catch is sampled (Fig. 14). Moreover, representative spatiotemporal distribution of the limited coverage is often compromised by the multiple demands placed on the observer program such as targeted deployments for enforcement concerns or non-random deployments for imposition of the soft-shell protocol.

In an attempt to account for spatiotemporal concerns in the observer data, discard percentages were modelled in a generalized linear mixed model (GLMM) for the most recent stock assessment (Eq. [4]). The binomial model with a logit link function regressed raw data from observations of discarded weights from individual fishing sets. The response variable was the ratio of discarded to total catch. Fixed effects were time (5-day bins) and soak times (days) and random intercepts for time in year*CMA groupings were included. As per the CPUE standardization model, the spatial CMA term accounts for the multiple management areas within each AD. Also like the CPUE model, the discard standardization model was weighted by effort (traps).

[4]

$$N_{discard,t,y,D} = Binom(N_{caught,t,y,D}, p_{t,y,D})$$
$$logit(p_{t,y,D}) = \alpha_{Discard,y,D} + \beta_{Day,y,D} \cdot Day_{t,y,D} + \beta_{Soak} \cdot Soak_{t,y,D}$$
$$\alpha_{Discard,y,D} = N(\bar{\alpha}_{Discard}, \sigma_{\alpha}^{2})$$
$$\mathrm{B}_{Day,y,D} = N(\bar{\beta}_{Day}, \sigma_{Day}^{2})$$

Observers estimate discards in two ways; first by visually observing fishing activities and second by physically measuring crab. To maximize precision, the physical measurements were modelled, classifying crab that were either female, under-size, or soft-shell as discarded and legal-size hard-shelled males as kept.

Discard percentages have been highly annually variable in most ADs (Fig. 15). In AD 2HJ, there have been two major episodes of high discarding since 1999, one during 2002-04 when the percentage of the catch discarded elevated to as high as 55%, and another during 2011-14 when discards reached ≥30% in some years. In AD 3K, discards have been steadily increasing in recent years, reaching a level of almost 40% of the catch in 2017. In AD 3L Inshore, discards have been at time-series lows, below 20%, in the past four years. A similar, relatively low, level of <20% has occurred throughout the time series in AD 3LNO, while in AD 3Ps such low levels have never been observed and discards are routinely >20% of the catch and have elevated to an exceptionally high level of about 50% of the catch in the past two years.

For the present analysis, we developed a predictive discard model (GLMM) toward enhancing the utility of advice provided from outputs of the PA/DM framework. This binomial model with a logit link regressed the ratio of discarded to total catch against fixed effects of CPUE, mean fishing week, and the exploitable biomass index from the most recent CPS trap survey. A random intercept was incorporated and all explanatory variables were treated as random effects against the subject of AD. For projections in 2018, the AD-specific projected CPUE values from the CPUE projection model were used and mean fishing weeks were assumed to be the same as 2017. For the presented discard projection (Fig. 16), status quo landings were used to predict the CPUE input variable. Variability about the projected means was generally high and model-estimated 95% confidence intervals were generally large. This could reflect many factors including the overall low level and sporadic nature of observer sampling. Residuals from the model showed no pattern in most ADs, but in recent years the model has systematically overestimated discards in AD 3L Inshore (Figs. 16 and 17). The performance of this model will need to be monitored closely in forthcoming years. Nonetheless, at present, the model is able to accurately predict directional trends in discards within its 95% confidence intervals in most ADs and years. Increased utility of observer data in the management of the Snow Crab fishery under this framework will likely necessitate improvements to the observer program including increased and more representative coverage.

The two predictive models developed for this PA framework collectively allow for the provision of scenario-based management advice regarding potential outcomes for CPUE and discards in the subsequent year. Landings and associated exploitation rates can be varied toward probability-based advice on potential outcomes of CPUE and discards at different levels of fishing.

REFERENCE POINTS

Egg Clutches

The first approach employed in developing a proposed LRP for egg clutch proportions was resource recovery. We define ‘$E_{recovery}$’ as the lowest observed level of egg clutches from which the population has recovered to remain productive. Productive is defined as the fishery CPUE achieving a level of ≥5 kg/trap 8-10 years later (the expected time for a crab to grow to legal-size). The term ‘productive’ is placed in context of the entire 1995-present period being a productive one for NL Snow Crab, with no exceptionally large biomasses knowingly present prior to then. Accordingly, although 5 kg/trap may appear low as a benchmark for some ADs, this is a level above which we do not suspect large-scale sustained fisheries could have been maintained historically during less productive times.

In examining both trawl and trap surveys, $E_{recovery}$ was determined to be 0.61, the lower of the two estimates from trawl versus trap-based surveys. This is the proportion of full egg clutches observed in AD 2HJ during 2006 (Fig. 18), with the subsequent 2014-2016 fishery achieving a CPUE of 7-10 kg/trap, a level close to the long-term mean (Fig. 7). A similar low level of egg clutches occurred in AD 3Ps in 2002, with the subsequent 2010-12 fishery CPUE exceeding 10 kg/trap. From the trap surveys, the lowest historical proportion of egg clutches of 0.73 in 2005 (Notre Dame Bay) was associated with CPUEs of 4.8-6.0 kg/trap from 2013-15 (not shown). However, concerns have been raised regarding over-reporting of effort and under-reporting of catch and a subsequent under-estimation of CPUE in logbooks in that CMA in recent years. This issue is being addressed separately. It is unknown how the recent declines in egg clutch fullness in the AD 3K and 3LNO trawl surveys (Fig. 18) and in the Fortune Bay and White Bay trap surveys (Fig. 19) will affect the future fishery but the outcomes should be monitored moving forward toward revision of $E_{recovery}$ if need be.

As a second approach for developing a potential LRP for egg clutches we examined the first and third standard deviations (sd) from the means for all observations of clutch fullness from the trawl and trap surveys respectively. We term this approach '$E_{history}$'. The underlying logic is based on the '68-95-99.7' rule for normal distributions, with 68% of observations falling withing 1 sd of the mean and 99.7% of observations falling within 3 sd of the mean. Accordingly, observations below 3 sd would not be likely to occur by chance alone. From the analysis, '$E_{history}$' was determined to be 0.59 for the trawl surveys (Fig. 20) and 0.64 for the trap surveys (Fig. 21). By extension, the 1 sd levels were used as suggested values for upper stock references for egg clutches. These values were 0.79 and 0.83 for the trawl and trap surveys respectively (Figs. 20 and 21).

Given the consistency across approaches and surveys, a LRP of 0.60 was proposed and accepted for the egg clutch fullness index and 0.80 was suggested as a benchmark for the USR.

Fishery CPUE

As a first approach for establishing a LRP for fishery CPUE we introduced the concept of '$C_{recovery}$'. The definition of recovery was as per that used for egg clutches, with recovery back to a level of CPUE ≥5 kg/trap 9-11 years later. The logic is that the offspring of crab participating in breeding in any given year would be expected to be in the fishery 9-11 years later. The extra year in relation to egg clutches reflects the year in which the male would have inseminated the female, with egg development occurring in the following year. $C_{recovery}$ was set at 3.3 kg/trap based on the CPUE in AD 2HJ in 2004 and CPUE ranging from 7.7-9.9 kg/trap from 2013 to 2015 (Fig. 22).

The second approach used to explore benchmarks for CPUE reference points was '$C_{history}$'. This was defined as the 40^{th} and 80^{th} percentiles of annual catch rates in the fishery since 1995. AD 3LNO was excluded from the analysis because CPUE there has been unusually high relative to other ADs throughout the time series. The 40^{th} and 80^{th} percentile approach was used as per recommendations from the guidance document for developing PA/DM frameworks (DFO 2009), with these measures being preferred targets in relation to a high level for a given metric in the absence of other biologically justifiable reasoning ('the 40/80 approach'). From the analysis, the $C_{history}$ LRP (40^{th} percentile) was 7.7 kg/trap and the 80^{th} percentile associated with a USR was 11.3 kg/trap (Fig. 23).

A third approach employed to explore reference points for CPUE was '$C_{highlow}$'. For a LRP, this was defined as an average level across ADs from which the resource subsequently recovered. AD 3LNO Offshore was excluded from this analysis due to unusually high CPUE values throughout the time series relative to other ADs. The $C_{highlow}$ LRP was 5.0 kg/trap (Fig. 24). For a USR the 80^{th} percentile of an average of the time series high value for each AD was calculated. This USR level was 11.1 kg/trap.

As a fourth approach for establishing a LRP, the 40^{th} and 80^{th} percentiles of the modelled saturation point of CPUE (=14.5 kg/trap) for the period 1995-2017 was used as an index of '$C_{saturate}$'. From the analysis, $C_{saturate}$ was determined to be 5.8 kg/trap for the LRP (40^{th} percentile) and 11.6 kg/trap for the suggested USR (80^{th} percentile) (Fig. 25).

The fifth approach used to explore a basis for establishing a LRP for CPUE was based on fishing efficiency. This index, '$C_{efficient}$', was based on CPUE in relation to an index of 'recruit per pre-recruit (RPP)'. RPP was deined as:

[5] $$RPP = P2ma[y-1] / R2ma[y]$$

Where, P*2ma* denotes the abundance of the two-period moving average of pre-recruit males (65-95 mm CW adolescents), *R2ma* denotes the two-period moving average of recruits (≥95mm CW new-shelled males), y denotes the current survey year and y-1 denotes the previous survey year.

The RPP index assumes a pre-recruit male will grow into a recruit in the following one to two years. In reality, several factors such as skip-molting (Dawe et al. 2012) could violate this assumption. Nonetheless, the broad signal that emerges from the index is deemed to reflect relative levels of wastage in the fishery. The RPP index was positively related to CPUE in all ADs (Fig. 26), suggesting fishing efficiency is higher when CPUE is high. A generalized linear model (GLM) with a normal distribution and log link was used to model the relationship between RPP and CPUE. For selection of potential CPUE targets for reference points, the 40^{th} and 80^{th} percentiles of the RPP index were calculated and plotted, with the intersection points of the regression curve forming the basis of the LRP (CPUE=3.8 kg/trap) and suggested USR (CPUE=16.0 kg/trap) (Fig. 27).

The average lower limit for CPUE across the four methods was 5.1 kg/trap. Based on consistency across techniques, the proposed and accepted LRP for CPUE was 5.0 kg/trap. The average of the USR across the three analyses was 12.5 kg/trap. We suggest a USR of 12.5 kg/trap to differentiate the cautious and healthy zones of the PA/DM framework.

Fishery Discards

Two analyses were conducted to explore bases for discard reference points, a '$D_{history}$' analysis, whereby the 40^{th} and 80^{th} percentiles of discard levels across all ADs and years were calculated, and a '$D_{efficient}$' approach whereby the RPP index was regressed against percent discards.

The 'D_{normal}' analysis produced a 40^{th} percentile of 18% discards and an 80^{th} percentile of 33% discards, which was associated with a LRP (Fig. 28).

A negative relationship between the RPP index and percent discards occurred in all ADs (Fig. 29). The intersection of the 40^{th} and 80^{th} RPP index percentiles along a regression curve produced through a GLM model (normal distribution, log link) was used to set potential reference points (Fig. 30). The LRP occurred at 28% discards and the USR occurred at 11% discards.

Based on consistency across the two analyses, a LRP for discards at 30% was accepted and 15% was suggested as a value for the USR.

HARVEST CONTROL RULES

Removal Reference

Harvest control rules (HCRs) normally focus on exploitation rates so several analyses were conducted to examine the relationships between exploitation rate indices (ERIs) and the focal metrics of CPUE and discards. However, prior to this we developed models to explore the efficacy of controlling ERIs in a DM framework.

The NL Snow Crab resource has been strongly regulated by climatic factors for over two decades (Mullowney et al. 2014, 2017). Impacts of fishing have not been as clearly demonstrated as have the relationships between stock biomass and fishery CPUE with lagged climate variables. The lagged NAO has a strong positive relationship with future CPUE in all ADs (Fig. 31). This relationship was examined in a simple GLM (normal distribution, identity link), regressing CPUE against lagged NAO with all ADs pooled. The model showed a strong ability of the NAO to predict future CPUE ($p<0.0001$, Table 1), with no patterns in the residuals (Fig. 32) and a scaled deviance statistic of 1.02 indicating a tight fit.

The residuals from the initial model were subsequently regressed against the ERIs, again with ADs and years pooled and once again in a simple GLM with a normal distribution and identity link. This analysis essentially investigated if ERI was an explanatory variable for differences between NAO-projected and realized CPUEs, with *a priori* knowledge that there was a negative relationship between the two variables in all ADs (Fig. 33). The model indicated a strong negative relation between ERI and departures of CPUE from NAO-projected values ($p<0.0001$, Table 2). Once again, there was no pattern in the modelled residuals and the scaled deviance estimate of 1.02 suggested a tight model fit.

A simple GLM (normal distribution, identity link) incorporating the main and interaction effects of lagged NAO (set at seven years in all ADs) and ERI as independent variables for the response variable of EBI showed a strong significant interaction ($p<0.001$) of the two explanatory variables in all but AD 3L Inshore (Table 3). In the case of AD 3L Inshore, the ERI was the only significant main effect in the model ($p<0.0001$). This simple model accurately predicted exploitable biomass indices within 95% confidence intervals in most years in all ADs (Fig. 34).

A simple GLM regressing CPUE on ERI showed that the relationship between CPUE and ERI was strongly negative (Fig. 35). GLM predicted values intersected levels suggested for CPUE reference points (5 and 12.5 kg/trap) at ERIs of 0.79 and 0.18, respectively. Based on historical data, it is observed that the resource has never been in the proposed CPUE healthy zone (>12.5 kg/trap).

Clearly, the ERI of the fishery exerts a strong influence over exploitable biomass and has a major impact on where the fishery lies with respect to stock status zones. This supports it as a focal metric for harvest control rules. The impacts of the other major factor knowingly regulating the exploitable biomass, climate, can not be controlled.

In exploring reference levels for ERI in harvest control rules, we initially examined the relationship between the residuals of NAO-predicted CPUE and ERI to determine if breaks occurred at any given level of exploitation that would produce positive [negative] CPUE residuals. The analysis showed breaks at ERI=0.21 and 0.63 for positive[negative] CPUE residuals (Fig. 36). We associated these two points with potential removal references at the LRP and USR.

The relationship between annual change in CPUE versus ERI was next examined toward identifying appropriate targets for ERI in HCRs. The relationship between the two variables was negative in all ADs (Fig. 37), indicating that high ERIs are commonly associated with subsequent reductions in CPUE. We modelled the relationship in a GLM (normal distribution, identity link) and looked for breaks to identify levels of ERIs that would promote no or negative changes in CPUE. The analysis showed that, on average, an ERI of 0.30 produced no change in CPUE while ERIs above 0.62 were associated with negative responses in CPUE (Fig. 38). We identified these as removal references to associate with the LRP and USR.

Finally, in exploration of targets for removal reference HCRs, we examined the relationship between changes in discard levels and ERI. This relationship was neutral or positive in all ADs (Fig. 39). A GLM (normal distribution, identity link) produced a positive relationship, albeit with a high degree of variability associated with the expected values (Fig. 40). In identifying break points associated with no or positive change in discard levels, we identified ERIs of 0.20 and 0.65, which we associated with potential removal references for the LRP and the USR.

Given the consistency in estimates associated with a removal reference based on ERI in relation to NAO-projected CPUE (ERI=0.63), changes in CPUE (ERI=0.62) , and changes in discards (ERI=0.65), a removal reference of 0.63 ERI at the USR was recommended. A removal reference point of 0.24 is suggested as the maximum ERI when the resource is in the critical zone (i.e. at or below the LRP) based on the average estimate from the three analyses. These ERI removal references are tentative. Biomass estimation continues to be refined and it is anticipated annual point estimates will change prior to the next assessment. As such, it is recognized that these tentative removal references will need to be reviewed upon revision of biomass and subsequent ERIs prior to formal adoption of them into a PA/DM framework.

The impacts of fishing resonate via many direct and indirect pathways in this fishery. High ERIs are associated with low CPUE and high discards. This reflects a deterioration of the residual biomass in heavily exploited areas (Mullowney et al. 2017). Perpetual high exploitation leaves the fishery heavily reliant on incoming recruitment each year. This is a risky approach given the possibility for unpredictable events to negatively affect productivity of the resource &/or recruitment into the exploitable biomass in any given year. Historically, areas where the fishery has performed best in terms of maintaining a high CPUE and low discard levels (i.e., ADs 3LNO and 3L Inshore) have been perpetually associated with a strong residual biomass and relatively low ERIs (Mullowney et al. 2017).

No Snow Crab fishery has ever knowingly induced prolonged serious impacts to reproductive capacity in wild populations. However, excessive exploitation of competive mating males can likely lead to sperm limitation. This has been demonstrated in populations residing in tanks, where the removal of too many males led to sperm limitation in females (Rondeau and Sainte-Marie 2001). Despite the inherent biological resilience created by the complex mating system of the species, ultimately, the probability that one male can fertilize a females lifetime production of eggs is small (Rondeau and Sainte-Marie 2001). Large, competitive, breeding males are an integral part of reproductive success of the population and sufficient protection of them in any PA/DM focused on biological precaution is obligatory.

Complementary Options

Although removal references have been proposed, various management actions that do not directly relate to ERI are available to reduce the risk of harm to the population. Although controlling ERI is a central measure likely to have direct and indirect effects on all three focal stock status metrics, complementary management measures relevant to the specific metrics used to classify the population within any given zone can be adopted. Although not considered an exhaustive list, potential management measures that could be adopted (or used in combination) for specific metrics are listed Table 4. These actions would likely help promote faster responses of desired outcomes than controlling exploitation rates alone. As a specific example, we elaborate on increasing mesh size as a potential strategy to rapidly decrease the consistently high level of discards in the AD 3Ps fishery.

AD 3Ps is a unique area in that it features an unusually high proportion of small terminally molted male crab in the population (Dawe et al. 2012, Mullowney et al. 2017). This is thought to reflect unusually small down-slope ontogenetic movements and a perpetual entrapment of crab in cold water, with the deep slope edges surrounding the AD too warm for inhabitation (Mullowney et al. 2018). This contrasts most other areas of the stock range in NL waters, where crab move large distances following settlement in shallow cold areas into deep warm water as adolescents, likely to promote increased size via molting in warm water (Mullowney et al. 2018). As a result of this unique situation and unusual population composition, the discards in AD 3Ps are commonly dominated by under-sized old-shelled males (Mullowney et al. 2017), which suggests they are small terminally molted adult crab. With relatively few large-size adult males in the population, these discarded crab are likely to be very important to mating success and reproductive capacity of the population in this AD. Accordingly, increased protection of these crab is advisable and encouraged in this PA/DM framework. The desired outcome could likely be quickly accomplished through an increase in regulated mesh size.

Suggested measures of shortened or shifted seasons are intended to promote a high level of CPUE and low level of discards. Over the past decade seasons extending beyond June have typically been associated with low CPUE and high discard rates in most ADs, particularly those featuring little residual component to the exploitable biomass (Mullowney et al. 2017). This likely reflects the increased catchability of less competitive crab, such as those recently molted, in the absence of competition from large hard-shelled males. A recent analysis showed that from July to November the meat content of these soft and new-shelled crab was low (unpublished data) and represented a concern for efficiency in resource extraction. It also represents biological wastage in that it needlessly imposes elevated and likely high mortality on pre-recruits that would contribute to breeding in subsequent years.

Suggested measures of depth restrictions on fishing could be beneficial in several ways. For example, mating is known to occur most typically over-winter and during spring in shallow areas (Mullowney et al. 2018). Prohibition of fishing in shallow water during spring could help protect spawning grounds and promote high fertilization rates. Another avenue whereby depth restrictions have been used in the past pertains to discards. In some inshore bays of ADs 3K and 3L inshore, in lieu of invoking the grid-based soft-shell protocol, deep areas have been closed to fishing as seasons have prolonged and soft-shell incidence been high. This practice is consistent with the movement dynamics of Snow Crab, whereby large adolescent males are known to commonly molt in deep water (Mullowney et al. 2018).

STOCK STATUS

The resource is assessed to be above the LRP for egg clutches in all ADs (Fig. 41). The resource (fishery) is above the LRP for CPUE in all but AD 3Ps. The point estimates for CPUE in 2018 are projected to be in the cautious zone for all but AD 3Ps. For discards, the resource (fishery) is assessed to be in the critical zone in ADs 3K and 3Ps and in the healthy or cautious zones in all other ADs. For 2018, all but AD 3Ps are projected to be in the cautious zone, with AD 3Ps remaining in the critical zone.

DISCUSSION

SPATIAL UNITS OF APPLICATION AND DATA QUALITY ISSUES

This multiple-indicator PA/DM framework is applied at the spatial scale of Assessment Division. It cannot, and should not, be appiled at the smaller spatial scales of the CMAs due to data deficiencies and inconsistencies with the broad spatial scales over which movement dynamics (Mullowney et al. 2018) and synchronous resource indicators such as CPUE (Mullowney et al. 2017) operate. Management is advised to consider how to address the likely scenario of a given CMA not conforming to the stock status advice for a given AD in any given year.

The discard data originate from at-sea observer coverage during the fishery. Data quality concerns stemming from the observer program are not associated with the quality of work being done by observers sampling crab at sea. Rather, they reflect administration of the program. The percentage of catch observed is at or near time-series lows in every AD, with <0.4% of the catch sampled. Additional observer coverage is required to more precisely identify, model, and predict discards. Further, representative and random coverage should be invoked whenever possible to ensure results that are accurate and representative of the entire AD. Moving forward, an assessment metric based on discards will require that sufficient and representative observer coverage is in place within every AD.

Finally, it is highly advised to improve the data quality for all assessment metrics in AD 4R3Pn. Along with the aformentioned need for consistent at-sea observer coverage, improvements to the data quality in AD 4R3Pn would necessitate recording data on female egg clutch fullness during multi-species trawl surveys conducted by other DFO region(s) and/or the CPS trap survey. More stringent adherence to the licence requirement to return commercial fishing logbooks would also be necessary to adequately assess this AD.

HONOURING SOUND MANAGEMENT WHILE RECOGNIZING POTENTIAL FOR SERIOUS HARM

The history of the management regime for the NL Snow Crab fishery serves as testament to fundamentally sound management of the resource. Under historic and current management practices, prolonged serious or irreversable harm has never knowingly been inflicted upon the resource through fishing. Above all else, the large-mesh traps used in the fishery constitute a precautionary management measure (Dawe and Mullowney 2016). However, under the current regime there remains potential for serious biological harm through fishing to occur as there is no explicitly identified upper limit(s) on harvest rates. Further, under historic and current practices resource extraction has been highly inefficient for sustained periods of time as evident by very high episodic levels of discarding in several ADs.

Despite the current suite of management measures being fundamentally cautious in principle, a PA/DM framework is beneficial. Without reference points and an associated removal references, there remains potential for the fishery to be exploited at exceptionally high levels and in turn for detrimental impacts on the reproductive capacity of the resource to emerge. Indeed, recognizing that ERIs currently used in the assessment likely under-estimate true levels of exploitation, it is realized that the NL Snow Crab fishery generally exploits the resource much more aggressively than most other regions where Snow Crab fisheries occur. Conservative estimates of ERIs are routinely >50%, particularly when biomass is low. Such high exploitation rates are well above those allocated for the resource in the Southern Gulf of St. Lawrence, even when it is well inside the healthy zone (DFO 2010), and are purposely avoided no matter the state of the resource along the Eastern Scotian Shelf (ESS) (DFO 2015).

Warm (bottom temperature) areas such as ADs 2HJ and 3K are thought to be the least productive for Snow Crab (Mullowney et al., 2014). Along the ESS, another such warm area, the resource extraction strategy is to maintain a low exploitation rate (a target of 20% ERI) at all times toward promoting stability and resilience in the biomass. The situation in ADs 2HJ and 3K, where there has been a prolonged low level of residual bioimass in the population (Mullowney et al. 2017) is unique relative to most fished Snow Crab populations globally. Within Atlantic Canada, overall broad-scale ocean warming has occurred in the past decade (DFO 2017). This is to the detriment of Snow Crab productivity. Nothwithstanding spatiotemporal differences in rates of warming both within and across regions, the fisheries for Snow Crab have been least stable in NL waters, where the largest (both proportional and absolute) reductions in overall biomass have occurred. This is associated with a comparatively aggressive extraction level.

In recent years, exploitation rates in the biggest areas of supply (i.e. ADs 3LNO Offshore and Inshore) have elevated to exceptionally high levels relative to historic norms, reflecting more substantial reductions in the biomass than landings, and greatly increasing the potential for negative biological outcomes in those areas. An inability for fisheries to take quotas has been common in numerous CMAs in recent years. Thus, in several areas it is possible for fisheries to capture virtually all available exploitable males in a given year. Sperm limitation under excessive exploitation of large males is a real possibility. As previously mentioned, sperm limitation has been shown to occur in Snow Crab in tanks (Rondeau and Sainte-Marie 2001). Moreover, sperm limitation has been induced in wild populations of other heavily exploited male-only crab fisheries including Chilean mola rock crab (*Metacarcinus edwardsii)* (Pardo et al. 2015, 2017), Eastern United States blue crab (*Callinecetes sapidus*) (Hines et al. 2003), and Japanese coconut crab (*Birgus latro*) (Sato et al. 2010). Further, some data suggest sperm limitation may have occurred concomitant with the collapse of a Gulf of St. Lawrence Snow Crab population during the early-1990s (personal communication, Bernard Sainte-Marie). In some localized areas of the NL shelf where the exploitable biomass has been low in recent years, such as Fortune and White Bays, the proportion of mature females carrying full clutches of viable eggs has fallen to unusually low levels. A broad-scale monitoring program investigating for the presence of sperm limitation in NL Snow Crab populations is currently occurring.

Regarding controlling ERIs, a best advised approach on being cautious in a PA/DM framework is to ‘stick to what has worked’, and maintain ERIs at levels that have knowingly not been associated with detrimental impacts to stock reproductive capacity. This includes borrowing information from what has worked in other regions. To allow ERIs to elevate to new or sustained high levels, as could potentially occur in the absence of a PA/DM framework, invokes the possibility of biological harm to the resource via other potential routes such as depensation.

A second advisable approach to maintain or increase efficiency in resource extraction, and by extension biological protection, is to establish a strong residual biomass in the population in all ADs. For ADs 2HJ and 3K, in particular, this would likely necessitate reducing ERIs to levels below historic norms. Indeed, these ADs have been consistently fished near the upper removal reference level for ERI identified herein. A strong residual biomass also serves to reduce risks associated with unforeseen events that could negatively affect recruitment in any given year. For example, Taylor et al. 1993 described a scenario whereby a high incidence of skip-molting in the population resulted in recruitment failure and a localized fishery collapse off the Avalon Peninsula in the mid-1980s. They cautioned that the strategy of exploiting the biomass at 50-60% each year should be re-examined to avoid deleterious impacts to both the resource and fishery in the event such anomalous events occured.

PRECAUTIOUS AND ADAPTIVE FRAMEWORK

CPUE was used as a metric of relative biomass in this analysis in lieu of the exploitable biomass indices. Among other reasons, this was supported by the fact that CPUE is known to reflect survey biomass indices at a one to two year lag. Despite the historic agreement between the two indices, the inclusion of CPUE rather than exploitable biomass introduces flexibility into the PA/DM framework in the event the biomass continues to decline moving forward. Conventional biomass-based frameworks offer little possibility for management or harvesters to adapt to changing conditions when resources go into decline. In the present scenario for the NL Snow Crab resource, with the exploitable biomass at or near its lowest observed level since surveys began in all ADs, any biomass-based analysis would place the stock in or near the critical zone in all ADs. Invoking CPUE as a metric of relative biomass allows managers and stakeholders flexibility to introduce alternate measures to sustain CPUE at a relatively high level, even during periods of resource shortages. In this regard, this PA/DM framework enables a responsible fishery to adapt to changing productivity conditions associated with climate shifts, consistent with the adivice of the PA working group to recognize the underlying precautious nature of the male-only fishery in implementing a PA/DM framework. In extension of this flexibilty, the presence of objectives of maintaing egg clutches at a relatively high level and discards at a relatively low level extends the scope of precaution and efficacy of this framework beyond those currently used to manage Snow Crab fisheries in Canada.

FORTHCOMING CHANGES

Although the peer-review process and this document lay out the basis for a PA/DM framework, it is fully expected that some key quantitative variables will change prior to it being formally utilized in the management of the resource. The biomass indices for NL Snow Crab continue to be refined, and preliminary insights from advanced non-linear depletion techniques suggest current biomass indices may over-estimate absolute biomass. A consequence of this would be increased exploitation rate indices, thus the basis for removal reference point levels will need to be re-visited in the near future. The current upper removal reference level of 0.63 ERI should be considered preliminary. Further, in-part based on comments received following the peer review process, it is anticipated further work will be undertaken on both predictive models (CPUE and discards) prior to formal implementation of them as the basis of management advice at the next stock assessment meeting. This has no bearing on the currently established LRPs for CPUE and discards and will only affect the advice that is provided from the framework upon implementation versus the current demonstration phase.

REFERENCES

Colbourne, E., Holden, J., Senciall, D., Bailey, W., and S. Snook. 2016. Physical oceanographic environment on the Newfoundland and Labrador Shelf in NAFO subareas 2 and 3 during 2015. NAFO SCR Doc 16/07, 29 p.

Conan, G.Y., and M. Comeau. 1986. Functional maturity and terminal molt of male Snow Crabs, Chionoecetes opilio. Can. J. Fish. Aquat. Sci. 43: 1710-1719.

Dawe, E.G., and D.R.J. Mullowney. 2016. Baited traps used in the Newfoundland and Labrador fishery for Snow Crab (*Chionoecetes opilio*): A precautionary approach. J Ocean Tech 11: 13-23.

Dawe, E.G., Walsh, S.J., and E.M. Hynick. 2010. Capture efficiency of a multispecies survey trawl for Snow Crab (*Chionoecetes opilio*) in the Newfoundland region. Fish Res 101: 70-79.

Dawe, E.G., Mullowney, D.R., Moriyasu, M., and E. Wade. 2012. Effects of temperature on size-at-terminal molt and molting frequency in Snow Crab *Chionoecetes opilio* from two Canadian Atlantic ecosystems. Mar Ecol 469: 279-296.

Delury D. B. 1947. On the estimation of biological populations. Biometrics 3: 145-167.

DFO. 2006. A harvest strategy compliant with the precautionary approach. DFO Can Sci Advis Sec Sci Advis Rep 2006/023.

DFO. 2009. A fishery decision-making framework incorporating the precautionary approach.

DFO. 2010. Reference points consistent with the precautionary approach for Snow Crab in the southern Gulf of St. Lawrence. DFO Can Sci Advis Sec Sci Advis Rep 2010/014.

DFO. 2015. Assessment of Nova Scotia (4VWX) Snow Crab. DFO Can. Sci Advis Sec Sci Advis Rep 2015/034.

DFO. 2017. Oceanographic conditions in the Atlantic zone in 2016. DFO Can Sci Advis Sec Sci Advis Rep 2017/031.

DFO. 2018. Assessment of Newfoundland and Labrador (Divisions 2HJ3KLNOP4R) Snow Crab. DFO Can Sci Advis Sec Sci Advis Rep 2018/024.

Dufour, R., Bernier, D., and J.-C. Brêthes. 1997. Optimization of meat yield and mortality during snow crab (*Chionoecetes opilio* O. Fabricius) fishing operations in Eastern Canada. Can. Tech. Rep. Fish. Aquat. Sci. 2152 : viii + 30 p.

Fonseca, D.B., Sainte-Marie, B., and F. Hazel. 2008. Longevity and change in shell condition of adult male snow crab Chionoecetes opilio inferred from dactyl wear and mark-recapture data. Trans Am Fish Soc 137: 1029-1043.

Grant, S.M. 2003. Mortality of snow crab discarded in Newfoundland and Labrador's trap fishery: At-sea experiments on the effect of drop height and air exposure duration. Can. Tech. Rep. Fish. Aquat. Sci. 2481: vi + 28p.

Hines, A.H., Jivof,f P.R., Bushmann, P.J., van Montfrans, J., Reed, S.A., and D.L. Wolcott. 2003. Evidence for sperm limitation in the blue crab, *Callinectes sapidus*. Bull Mar Sci 72: 287-310.

Harley, S.J., Myers, R.A., and A. Dunn. 2001. Is catch-per-unit-effort proportional to abundance? Can J Fish Aquat Sci 58:1760–72.

Hilborn, R., and C.J. Walters. 1992. Quantitative fisheries stock assessment: choice, dynamics and uncertainty. Springer Science & Business Media.

Kanno, Y., 1987. Reproductive ecology of the tanner crab in the South Western Okhotsk Sea. Ip Sui Gak 53: 733-738.

Kolts, J.M., Lovvorn, J.R., North, C.A., and M.A. Janout. 2015. Oceanographic and demographic mechanisms affecting population structure of Snow Crabs in the northern Bering Sea. Mar Ecol Prog Ser 518: 193-208.

Miller, R.J. 1977. Resource Underutilization in a Spider Crab Industry. Fisheries. 2(3): 9-13.

Mullowney, D.R., and E.G. Dawe. 2009. Development of performance indices for the Newfoundland and Labrador Snow Crab (*Chionoecetes opilio*) fishery using data from a vessel monitoring system. Fish Res 100: 248-254.

Mullowney, D.R.J, Dawe, E.G., Colbourne, E.B., and G.A. Rose. 2014. A review of factors contributing to the decline of Newfoundland and Labrador Snow Crab (*Chionoecetes opilio*). Rev Fish Biol Fish 24: 639-657.

Mullowney, D., Coffey,W., Baker, K., Evans, G., Fiander, D., Colbourne, E., Maddock Parsons D., Koen-Alonso, M., and N. Wells. 2017. An assessment of Newfoundland and Labrador Snow Crab (*Chionoecetes opilio*) in 2016. DFO Can. Sci. Advis. Sec. Res. Doc. 2017/081. viii+172 p.

Mullowney, D., Morris, C., Dawe, E., Zagorsky, I., and S. Goryanina. 2018. Dynamics of Snow Crab (*Chionoecetes opilio*) movement and migration along the Newfoundland and Labrador and Eastern Barents Sea continental shelves. Rev Fish Biol Fish 28: 435-459.

Pardo, L.M., Riveros, M.P., Fuentes, J.P., Pinochet, R., Cardenas, C., and B. Sainte-Marie. 2017. High fishing intensity reduces females' sperm reserve and brood fecundity in a eubrachyuran crab subject to sex- and size-biased harvest. ICES J Mar Sci 74: 2459-2469.

Pardo, L.M., Rosas, Y., Fuentes, J.P., Riveros, M.P., and R. Chaparro. 2015. Fishery induces sperm depletion and reduction in male reproductive potential for crab species under male-only harvest strategy. PLOS ONE: DOI:10.1371/journal.pone.0115525.

Petrie B. 2007. Does the North Atlantic Oscillation affect hydrographic properties on the Canadian Atlantic continental shelf? Atmos Ocean 45: 141-151.

Puebla O., Sévigny, J., Sainte-Marie, B., Brêthes, J., Burmeister, A., Dawe, E., and M. Moriyasu. 2008. Population genetic structure of the Snow Crab (*Chionoecetes opilio*) at the Northwest Atlantic scale. Can J Fish Aquat Sci 65: 425-436.

Rondeau, A., and B. Sainte-Marie. 2001. Variable mate-guarding time and sperm allocation by male Snow Crab (Chionoecetes opilio) in response to sexual competition, and their impact on the mating success of females. Biol Bull 201: 204–217.

Rose, G.A., and D.W. Kulka. 1999. Hyperaggregation of fish and fisheries: how catch-per-unit-effort increased as the northern cod (*Gadus morhua*) declined. Can J Fish Aquat Sci (Suppl 1): 118-127.

Sainte-Marie B., and C. Carriere. 1995. Fertilization of the second clutch of eggs of Snow Crab, *Chionoecetes opilio,* from females mated once or twice after their molt to maturity. Fish Bull 93: 759-764.

Sainte-Marie B., and F. Hazel. 1992. Moulting and mating of Snow Crabs, *Chionoecetes opilio* (O Fabricius), in shallow waters of the northwestern Gulf of St Lawrence. Can J Fish Aquat Sci 49: 1282–1293.

Sainte-Maire B. 1993. Reproductive cycle and fecundity of primiparous and multiparous female Snow Crab, *Chionoecetes opilio*, in the Northwest Gulf of St. Lawrence. Can J Fish Aquat Sci 50: 2147-2156.

Sainte-Marie, B., Se´vigny, J., Smith, B.D., and G.A. Lovrich. 1996. Recruitment variability in Snow Crab (*Chionoecetes opilio*): pattern, possible causes, and implications for fishery management. In: High latitude crabs: biology, management,and economics. Alaska Sea Grant College Program AK-SG-96-02, Anchorage, Alaska, pp 451-478.

Sainte-Marie, B., Urbani, N., Hazel, F., Se´vigny, J.M., and U. Kuhnlein. 1999. Multiple choice criteria and the dynamics of assortative mating during the first breeding season of the female Snow Crab *Chionoecetes opilio* (Brachyura, Majidae). Mar Ecol Prog Ser 181: 141-153.

Sainte-Marie, B., Gosselin, T., Se´vigny, J.M., and N. Urbani. 2008. The Snow Crab mating system: opportunity for natural and unnatural selection in a changing environment. Bull Mar Sci 83: 131-161.

Sato, T., Yoseda, K., Okuzawa, K., and N. Suzuki. 2010. Sperm limitation: possible impacts of large male-selective harvesting on reproduction of the coconut crab Birgus latro. Aquat Biol 10: 23-32.

Taylor, D.M., O'Keefe, P.G., and C. Fitzpatrick. 1993. A Snow Crab, Chionoecetes opilio (Decapoda, Majidae), fishery collapse in Newfoundland. Fish Bull 92: 412-419.

Urban, J.D. 2015. Discard mortality rates in the Bering Sea Snow Crab, Chionoecetes opilio, fishery. ICES J Mar Sci 72: 1525-1529.

FIGURES

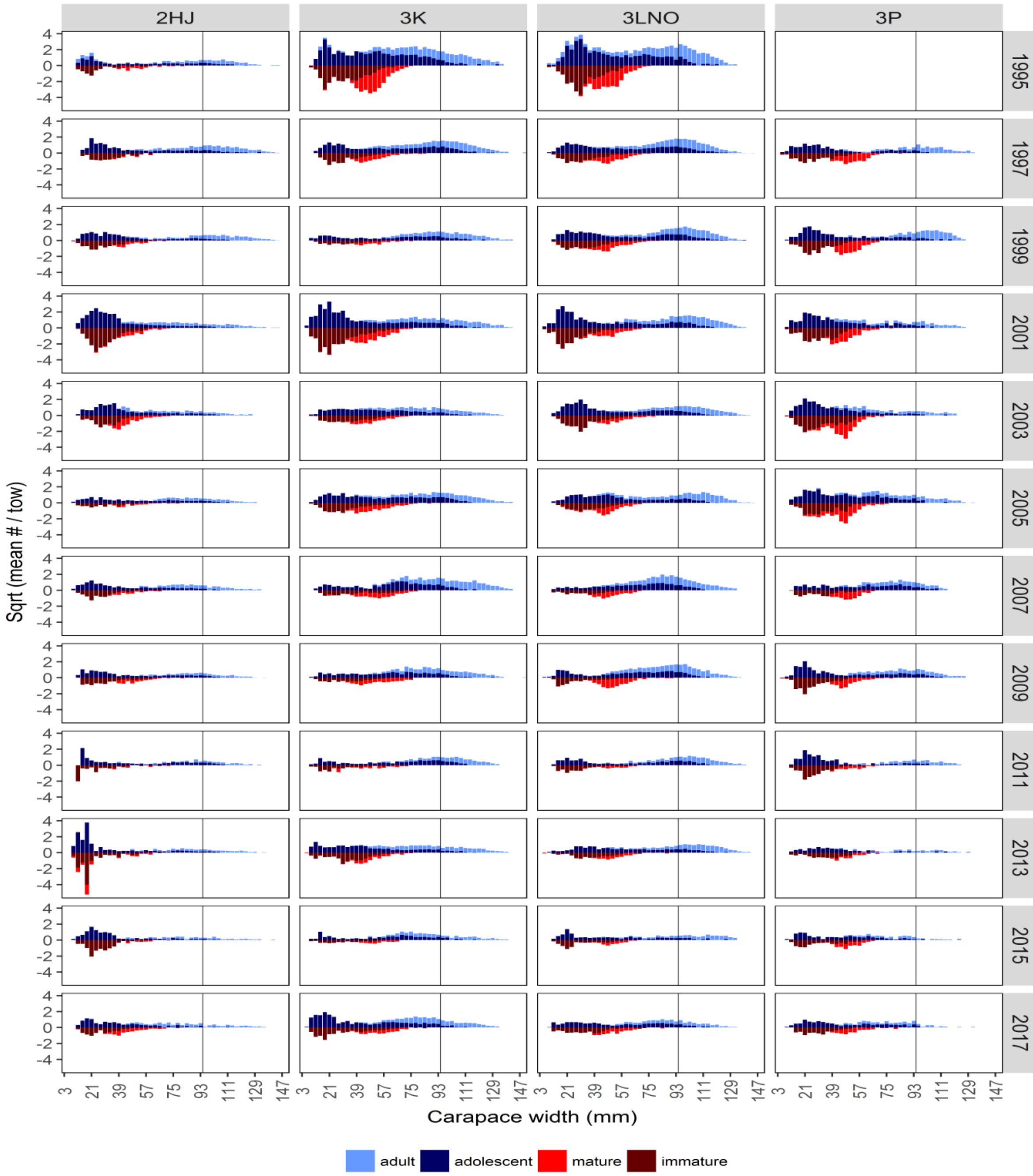

Fig. 1. Size frequecies of male (adult and adolescent) and female (mature and immature) Snow Crab from trawl surveys in Assessment Divisions 2HJ, 3K, 3LNO, and 3Ps (1995-2017). Vertical line indicates exploitable size (carapace width = 95 mm).

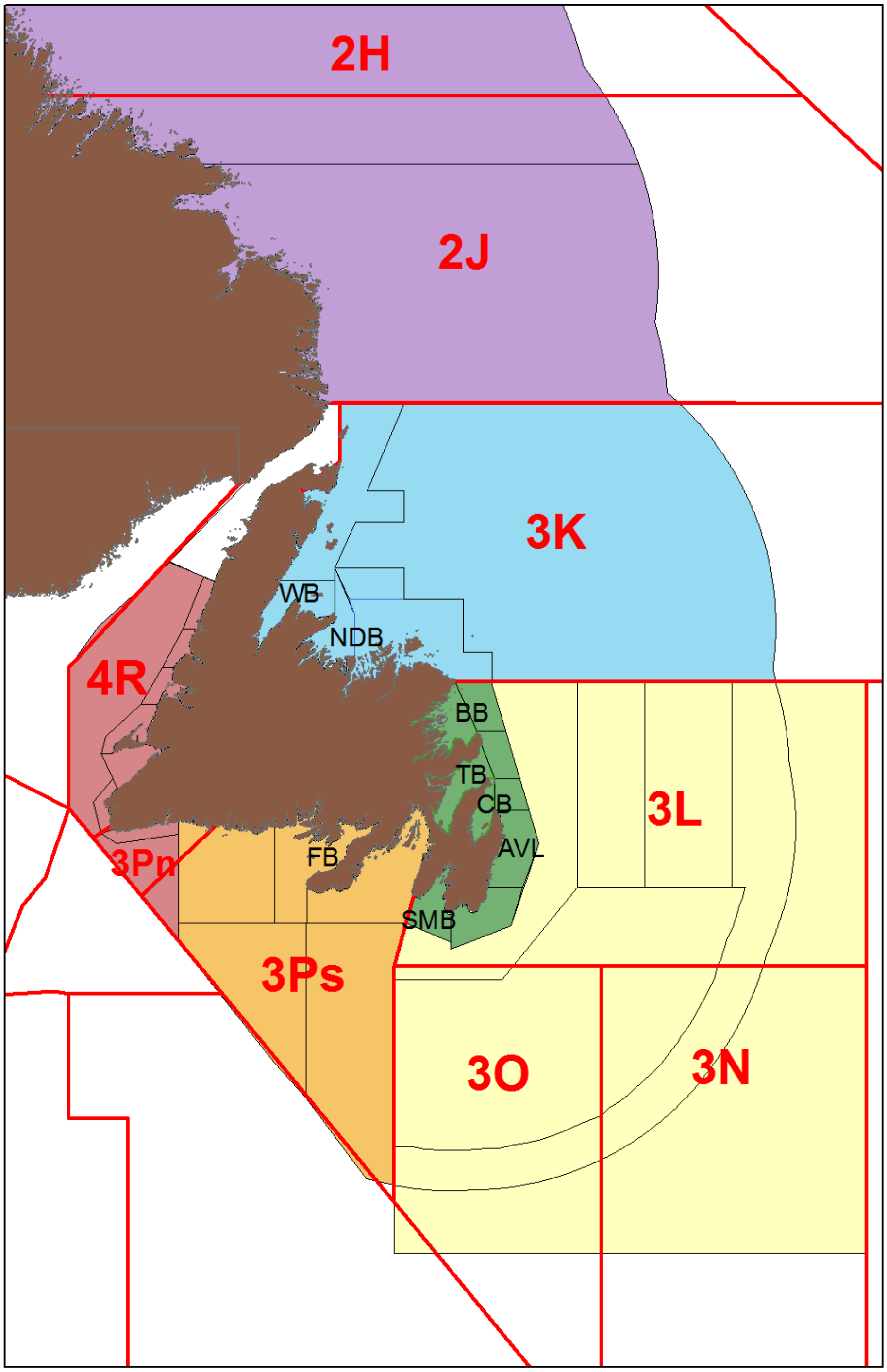

Fig. 2. Map depicting Assessment Divisions (shaded areas) used for the assessment of Newfoundland and Labrador Snow Crab. Bays where Fisheries and Oceans Canada inshore trap surveys occur are also identified.

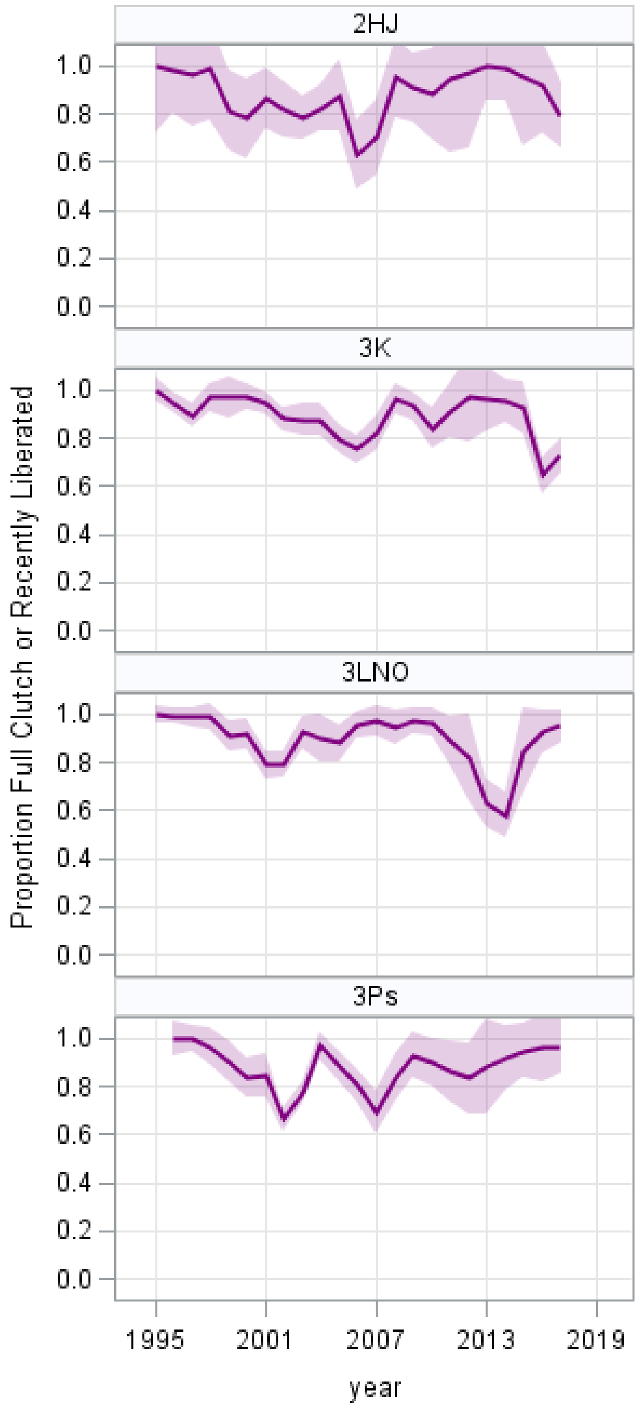

Fig. 3. The proportion of female Snow Crab with full clutches (or recently liberated) by Assessment Division (data from trawl surveys). Solid line is mean and shaded area is 95% confidence limits.

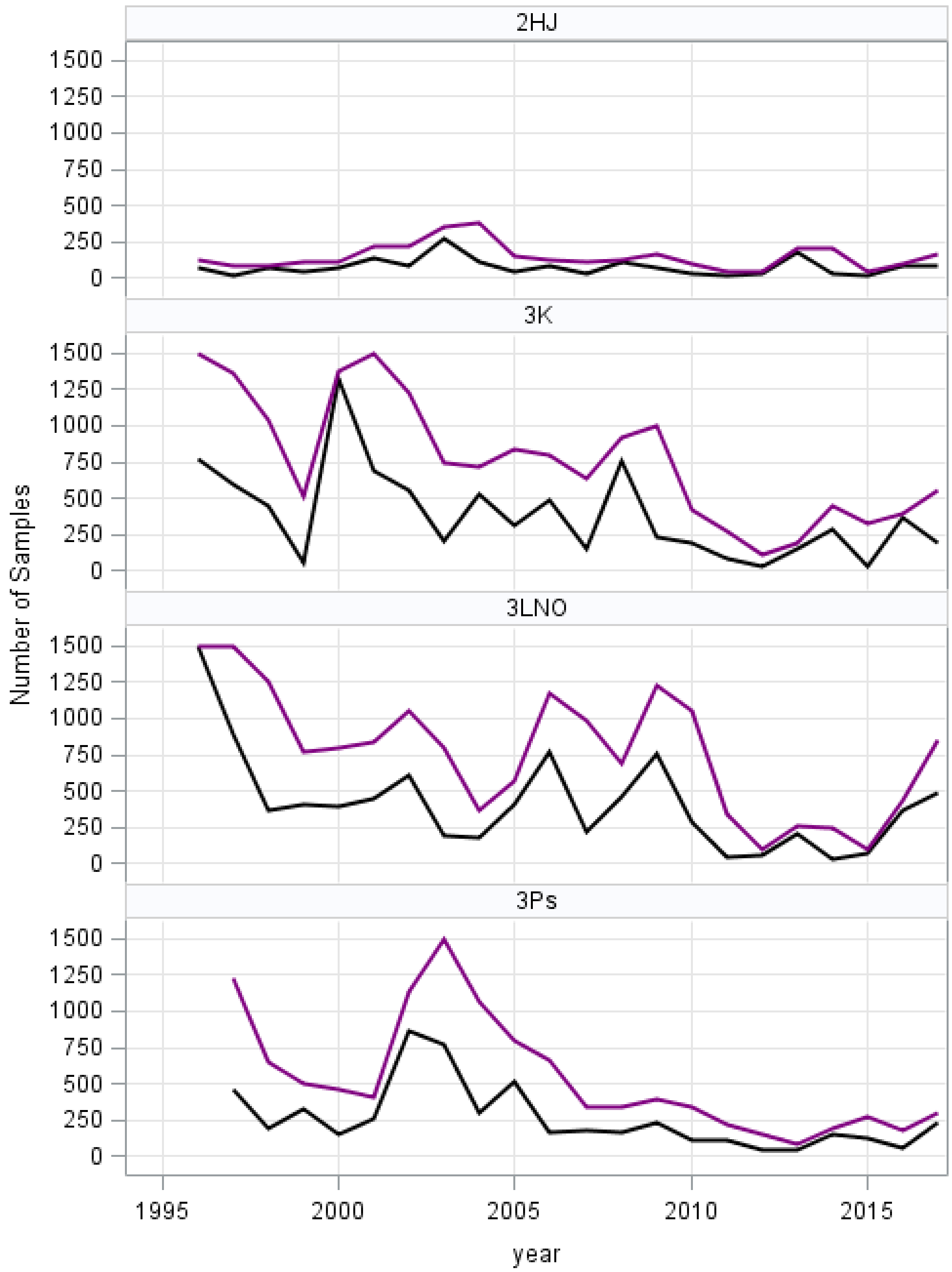

Fig. 4. Number (black) and 2-year cumulative sums (purple) of female Snow Crab sampled during offshore trawl surveys by Assessment Division.

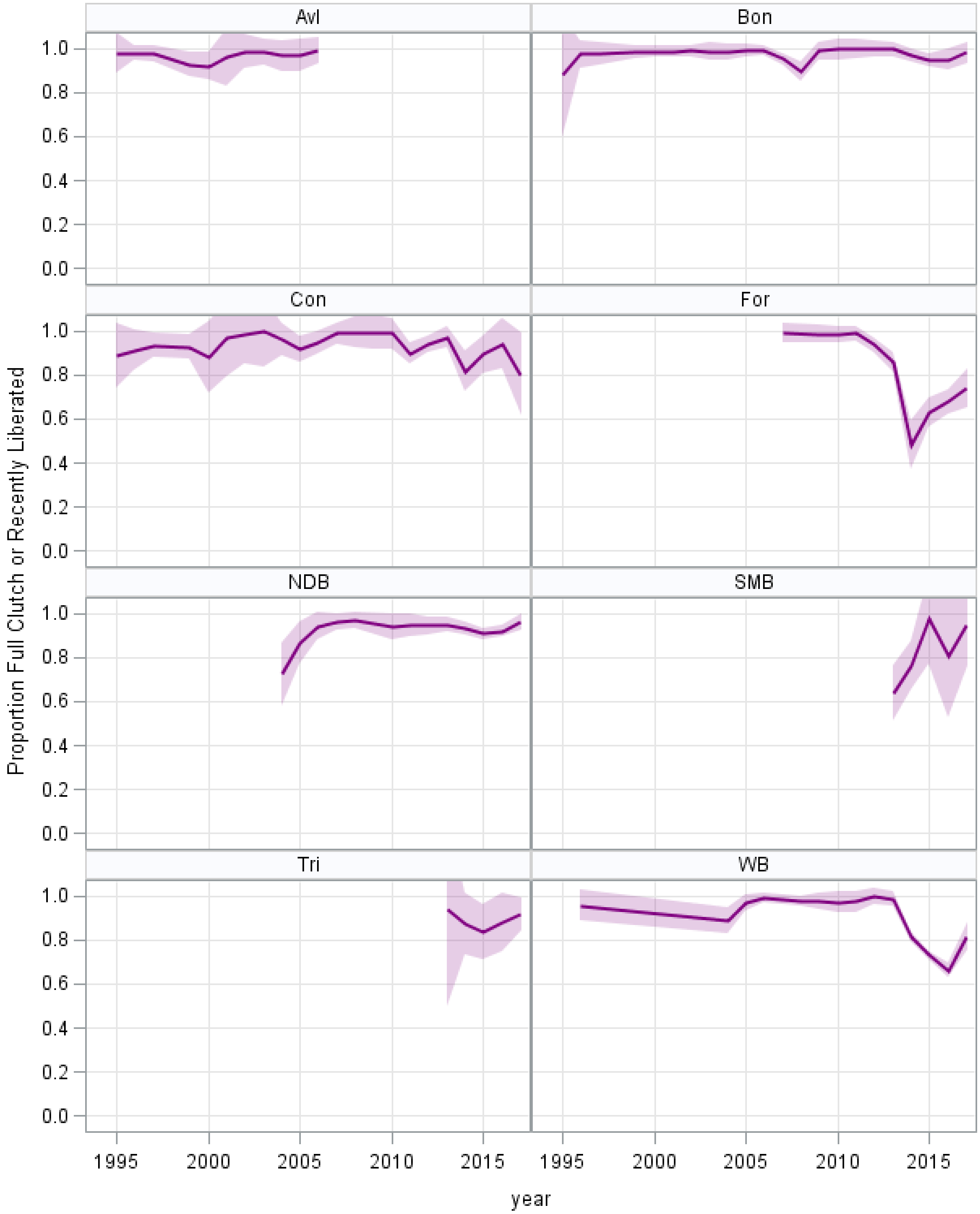

Fig. 5. The proportion of female Snow Crab with full clutches (or recently liberated) of viable eggs by bay (data from inshore trap surveys). Solid line is stratum-area weighted mean and shaded area is 95% confidence limits.

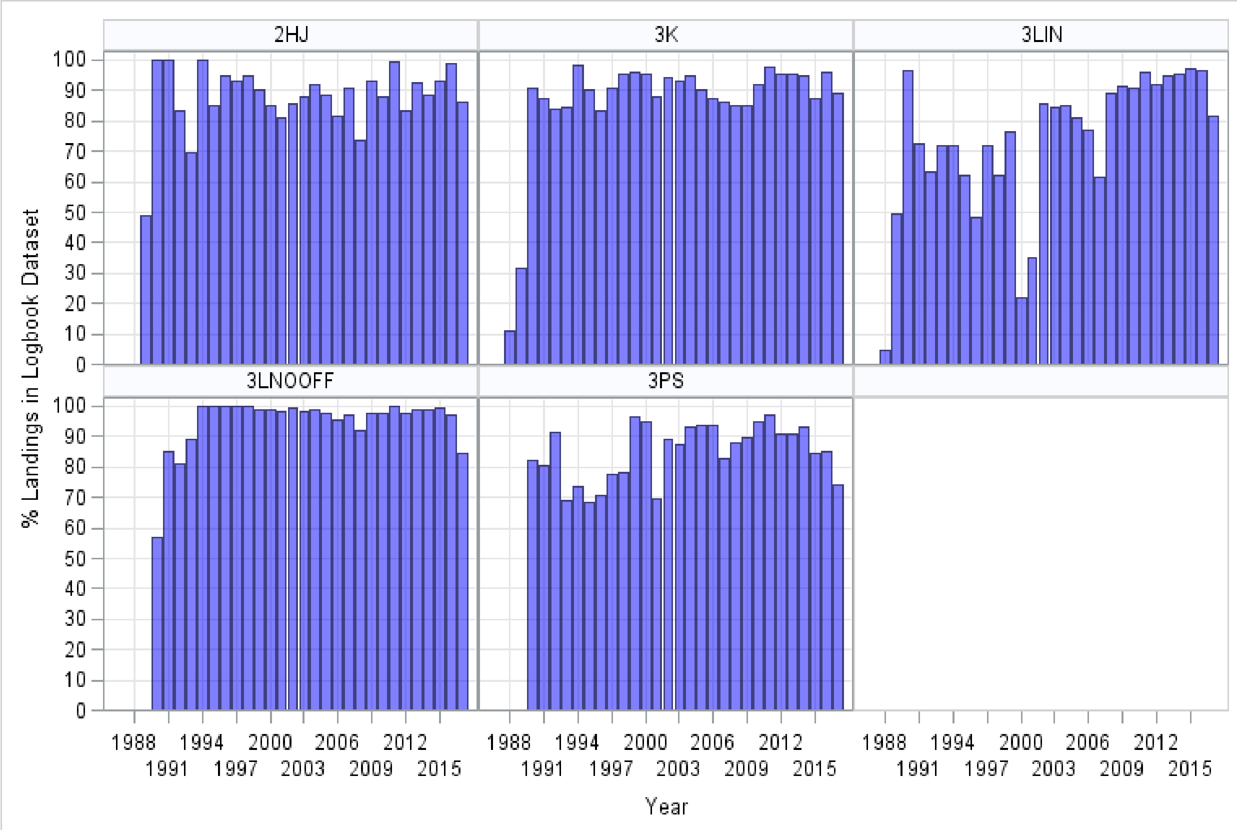

Fig. 6. Annual return rates of Snow Crab logbooks (percent landings in logbook dataset) in each Assessment Division.

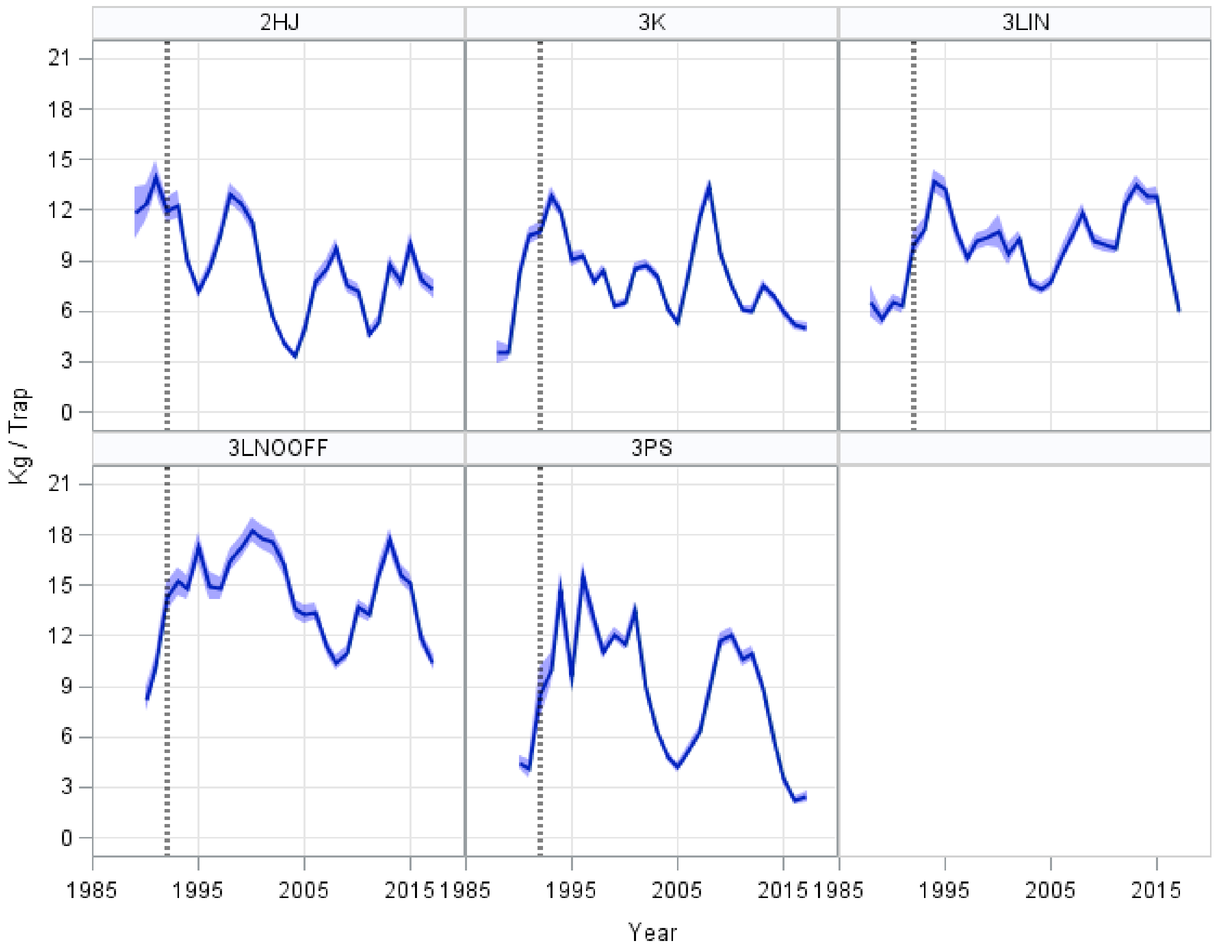

Fig. 7. Standardized fishery CPUE (kg/trap) based on linear mixed model (LMM). Shaded area represents the 95% confidence interval. Vertical dashed line in 1992 denotes the start of the cod moratorium.

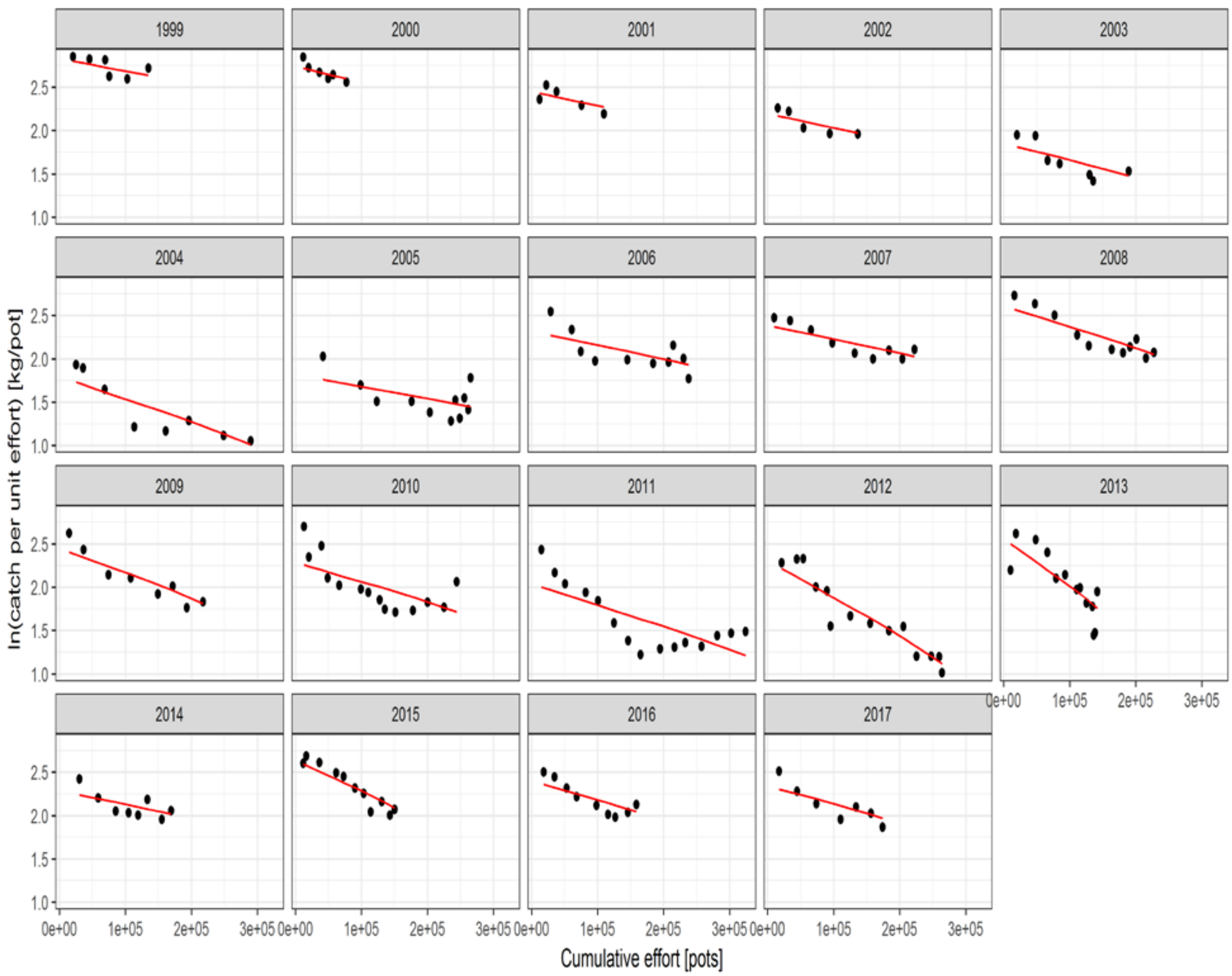

Fig. 8. A representative depiction of the Delury depletion analysis using Assessment Division 2HJ.

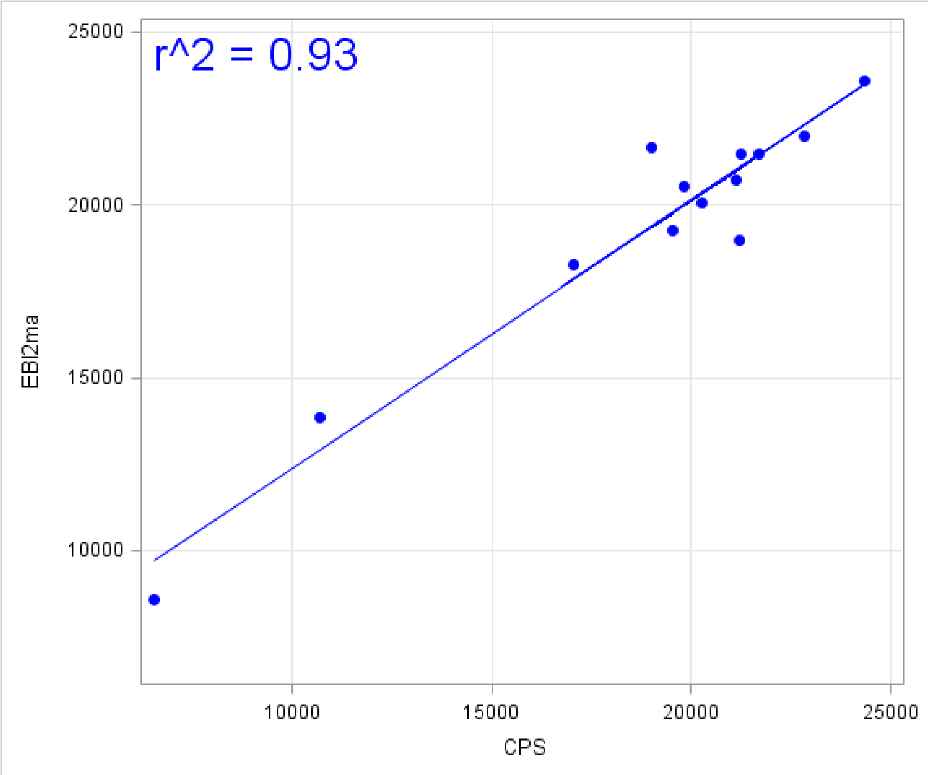

Fig. 9. Relationship between exploitable biomass index estimated from the trawl survey (2-year moving average) and exploitable biomass index estimated from the inshore trap-based surveys in Assessment Division 3L inshore.

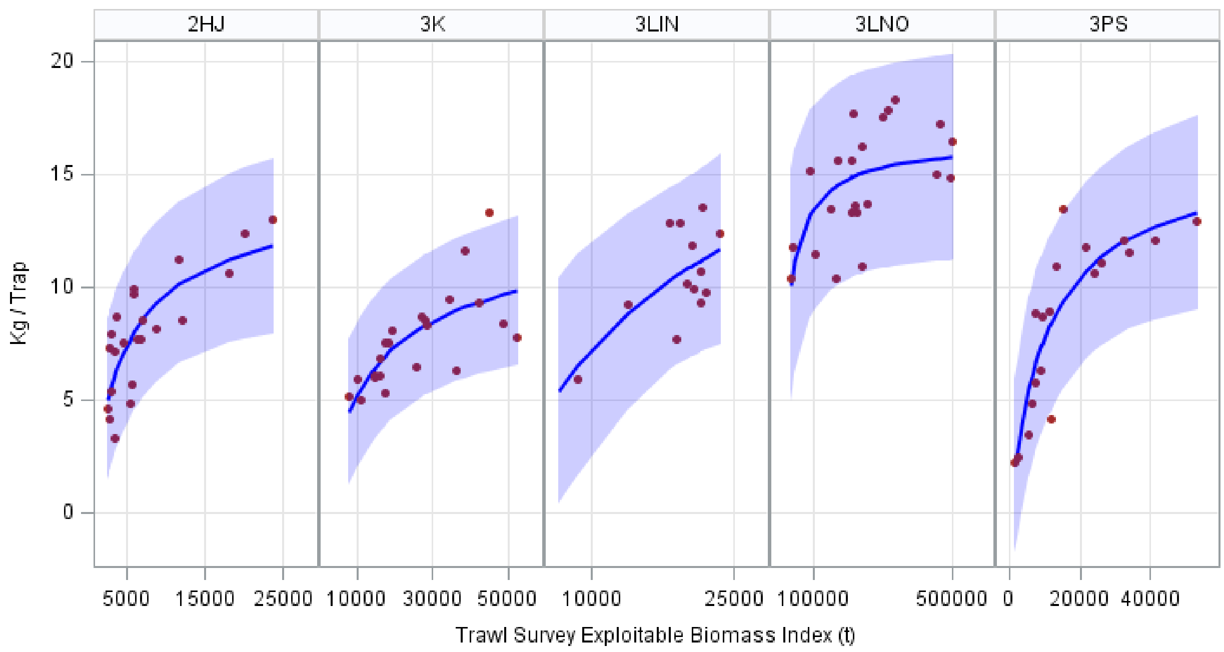

Fig. 10. The relationship between fishery CPUE (kg/trap) and exploitable biomass index (t) (a two-period moving average) from the trawl survey in each Assessment Division. The blue lines depict the predicted relationships and the shaded areas are the 95% prediction limits. Note AD 3L Inshore uses trap survey biomass data.

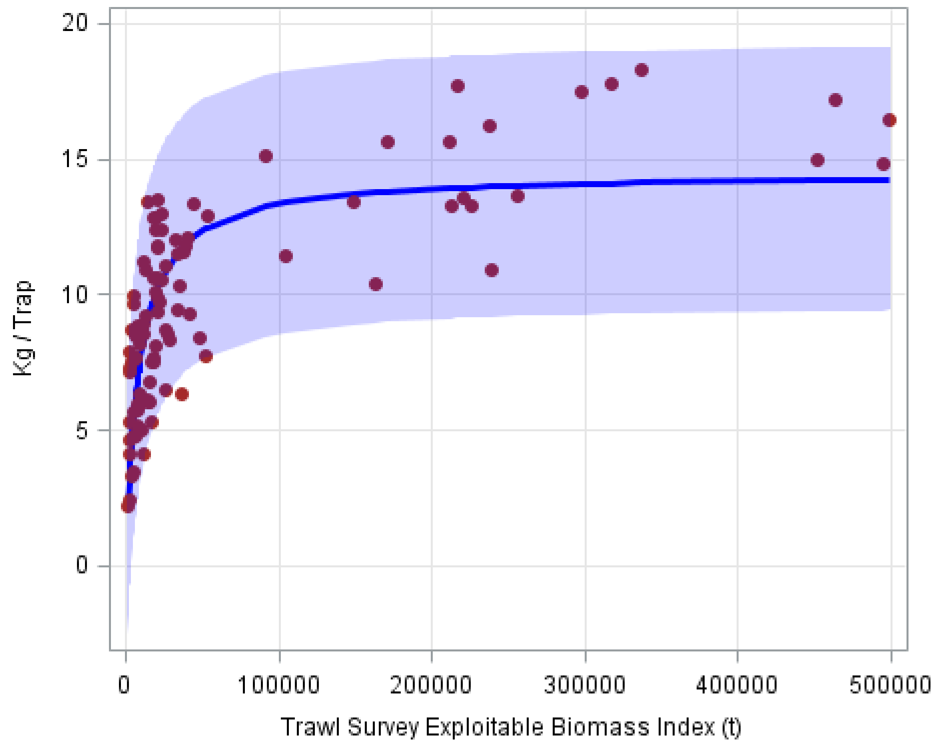

Fig. 11. The relationship between fishery CPUE (kg/trap) and exploitable biomass index (t) (a two-period moving average) from the trawl survey. The blue lines depict the predicted relationship and the shaded areas are the 95% prediction limits.

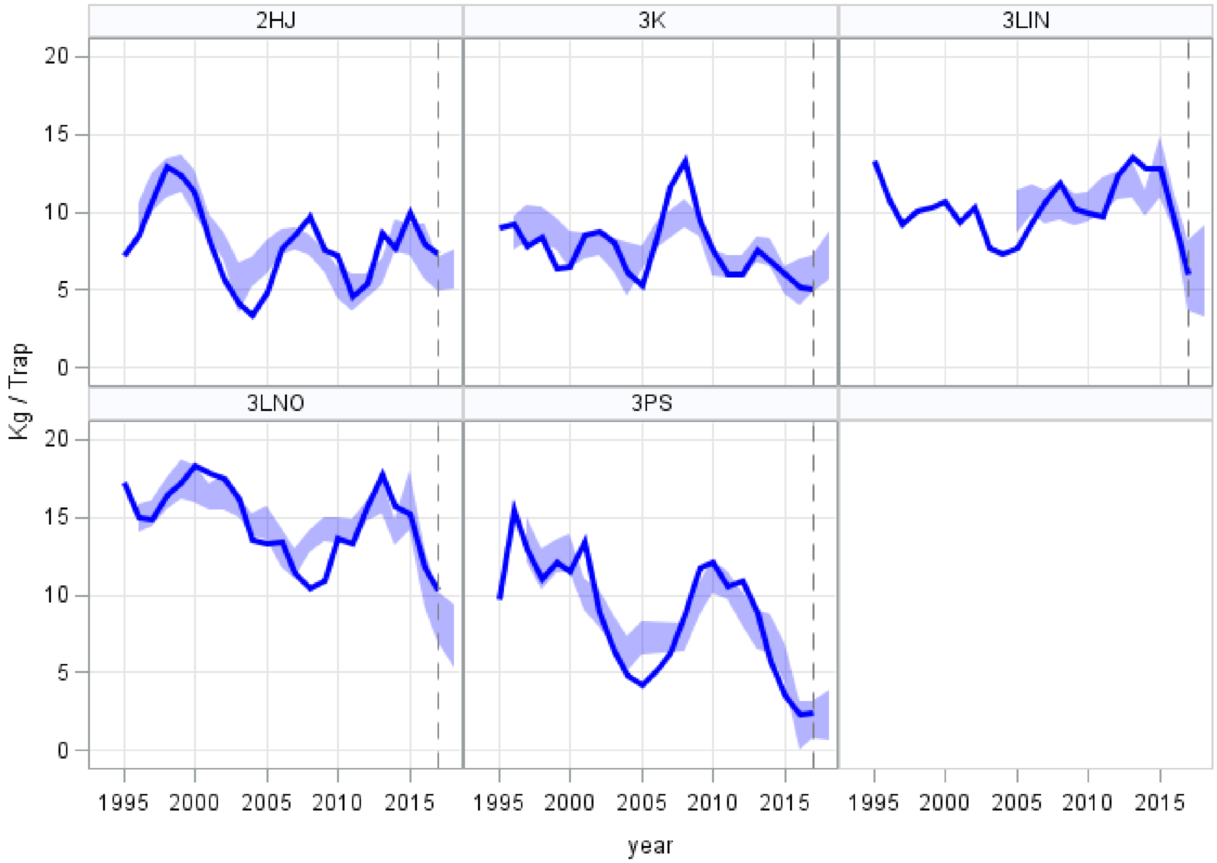

Fig. 12. Observed (thick line) versus predicted (band) CPUE by Assessment Division. Shaded areas depict 95% Confidence Intervals. 2018 projections assume status quo landings and fishery season dates.

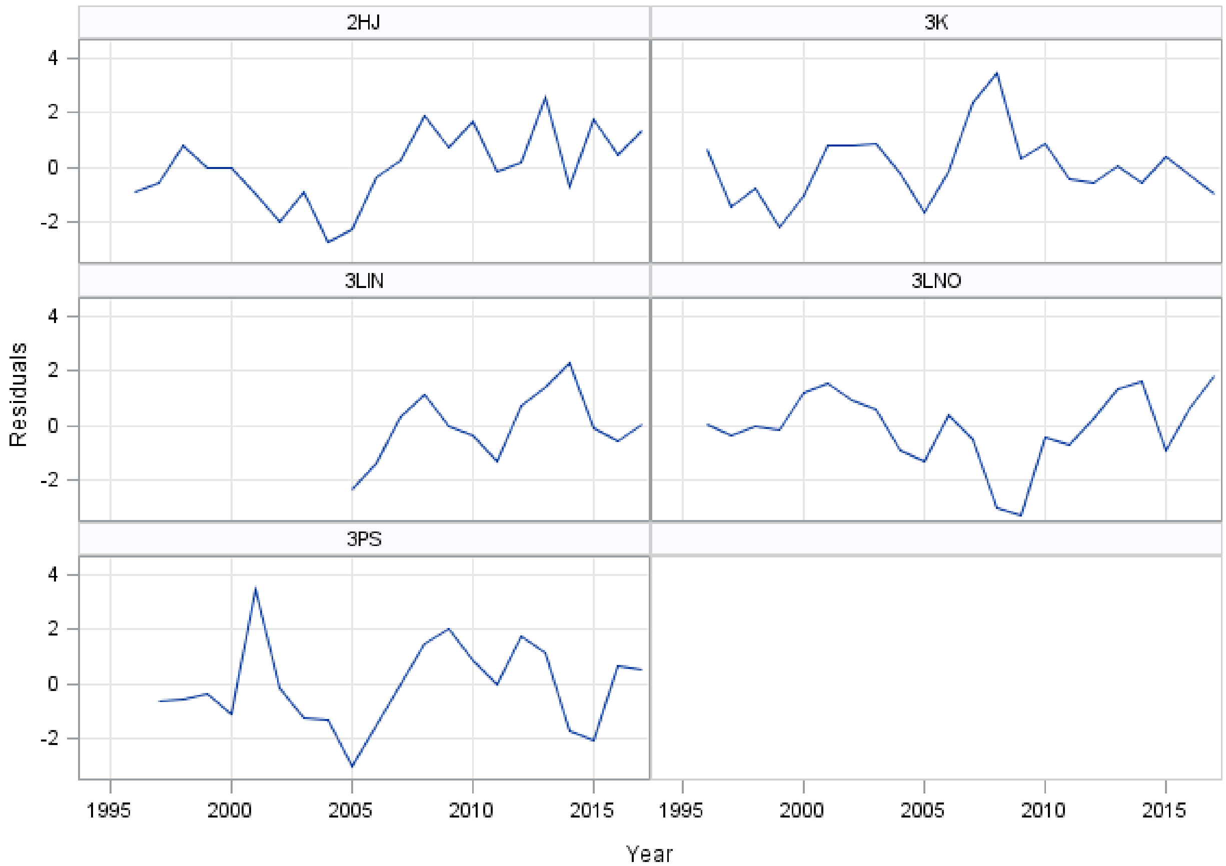

Fig. 13. Annual residuals from the predictive CPUE model.

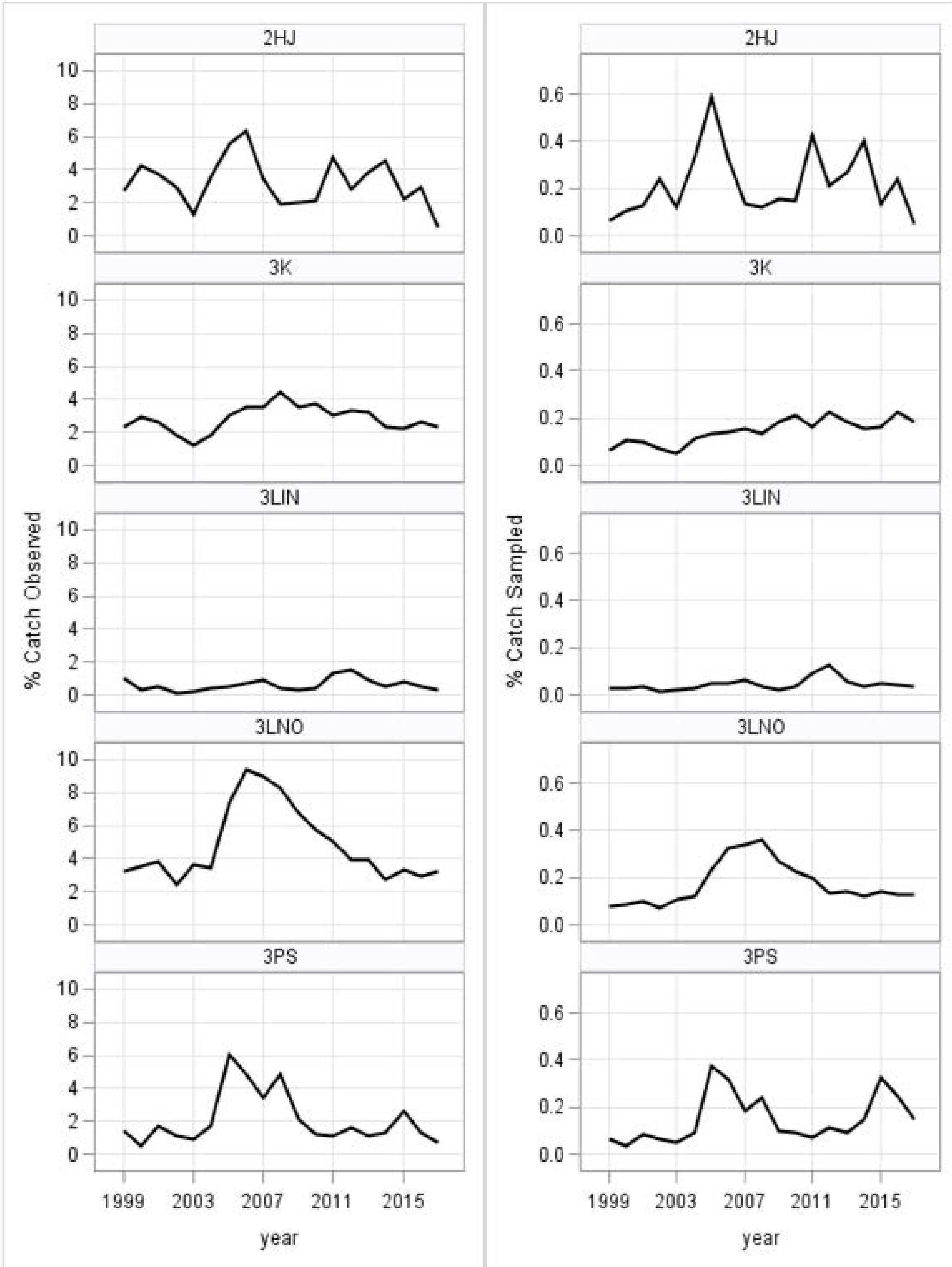

Fig. 14. The percentage of catch with observer coverage (left) and the percentage of catch sampled by observers (right) in each Assessment Division. Percentages made with dockside monitored landings totals representing the denominator.

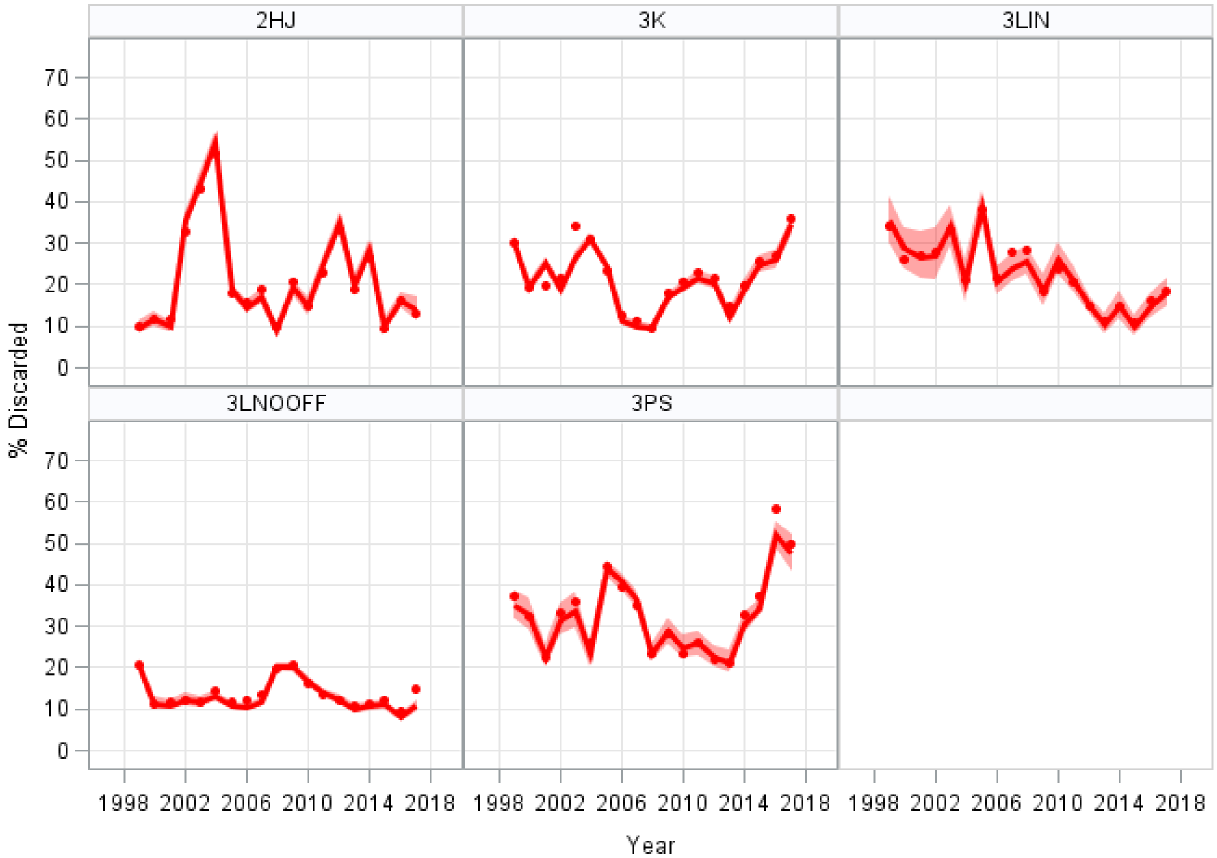

Fig. 15. Standardized fishery discards based on generalized linear mixed model. Shaded area represents the 95% confidence interval.

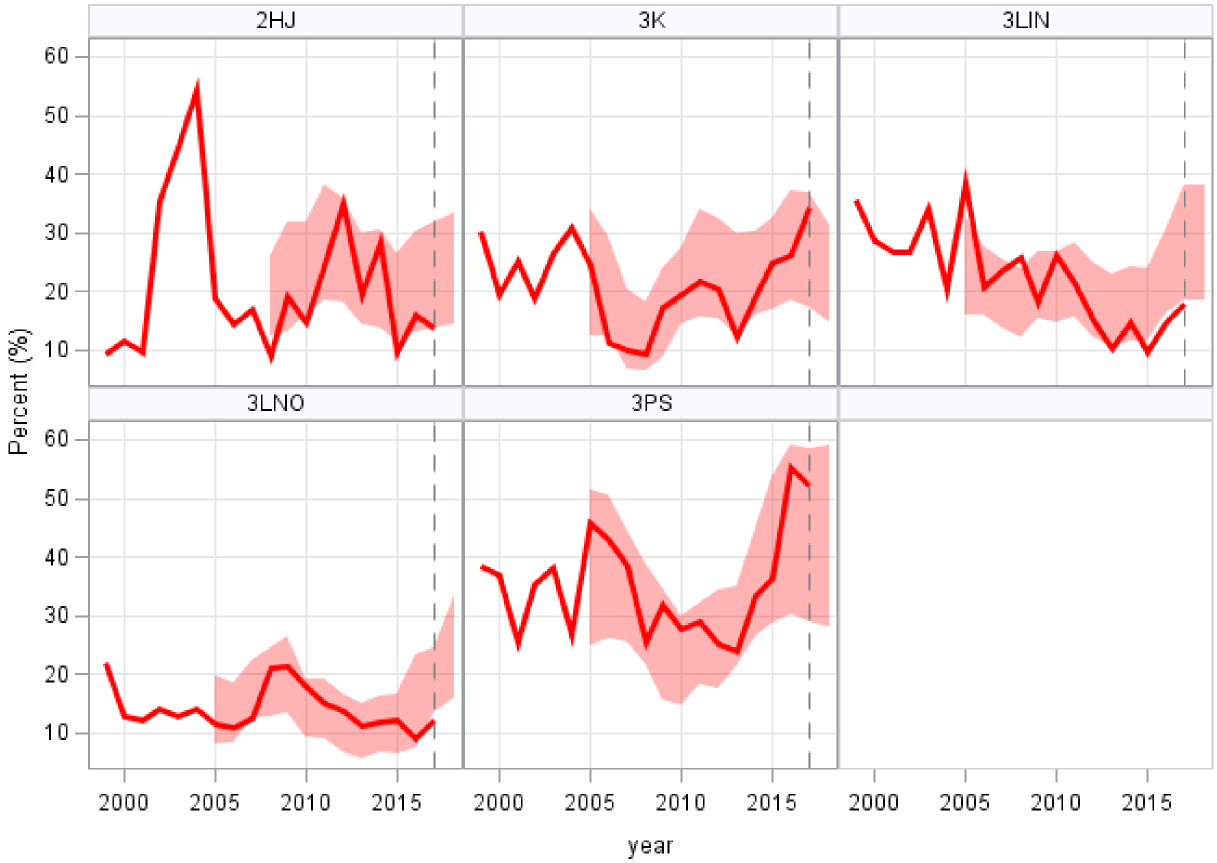

Fig. 16. Observed (thick line) versus predicted (band) discard percentages by Assessment Division. Shaded areas depict 95% confidence intervals. 2018 projections based on projected CPUE and assume status quo trap soak times.

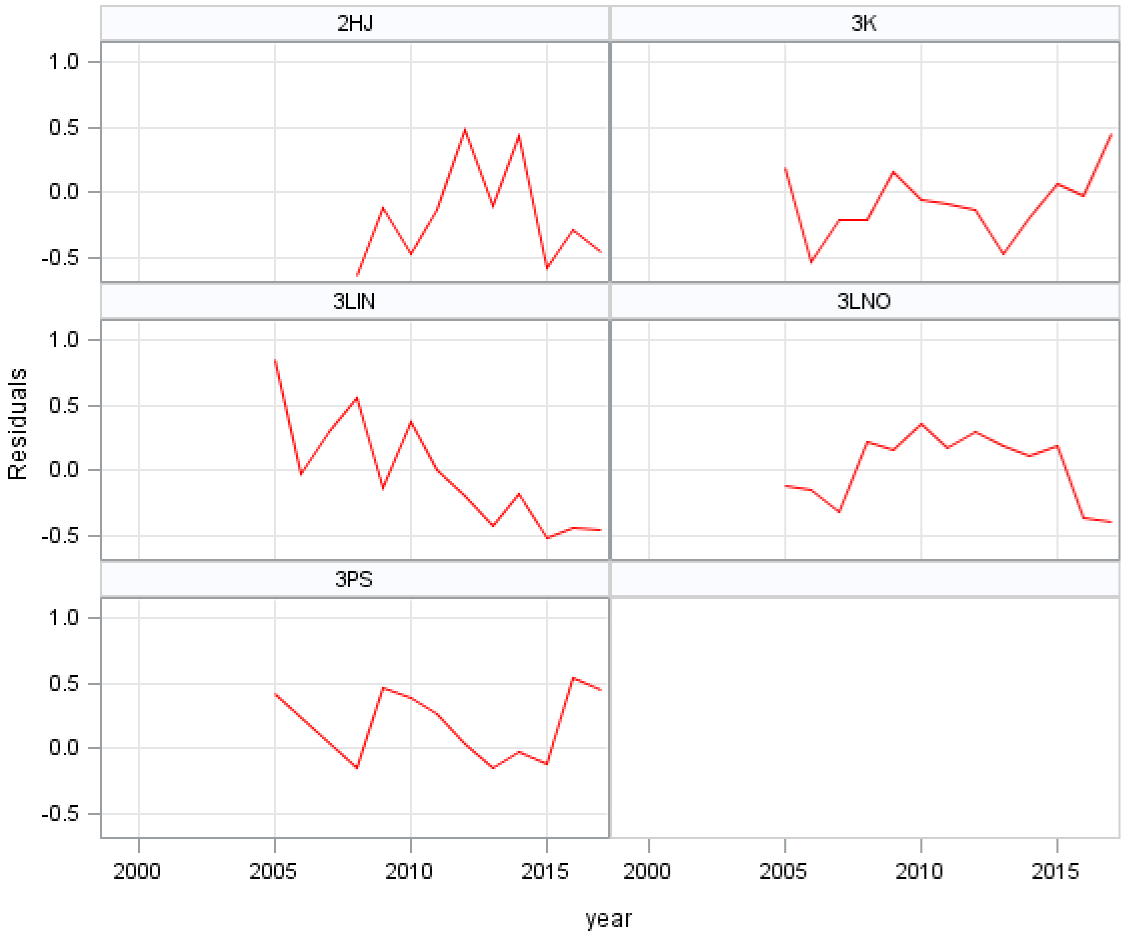

Fig. 17. Annual residuals from the predictive discards model.

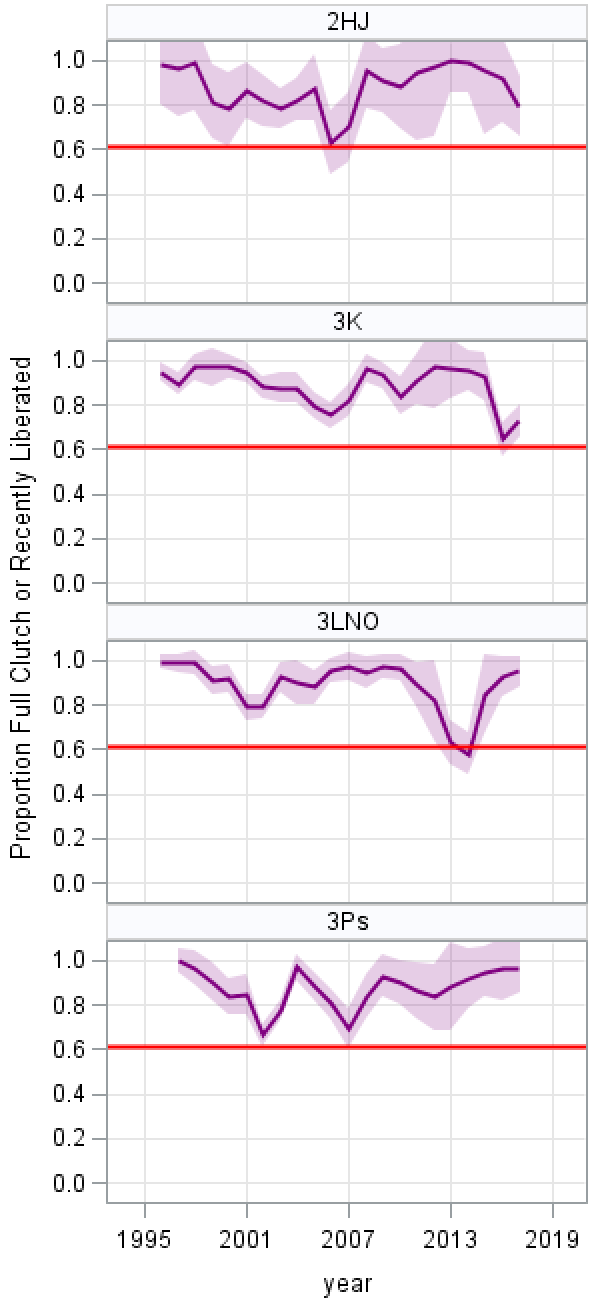

Fig. 18. Proportion of females carrying full or recently liberated clutches of viable eggs in relation to Erecovery LRP, by Assessment Division. Data from multi-species trawl surveys. Shaded areas are 95% confidence intervals.

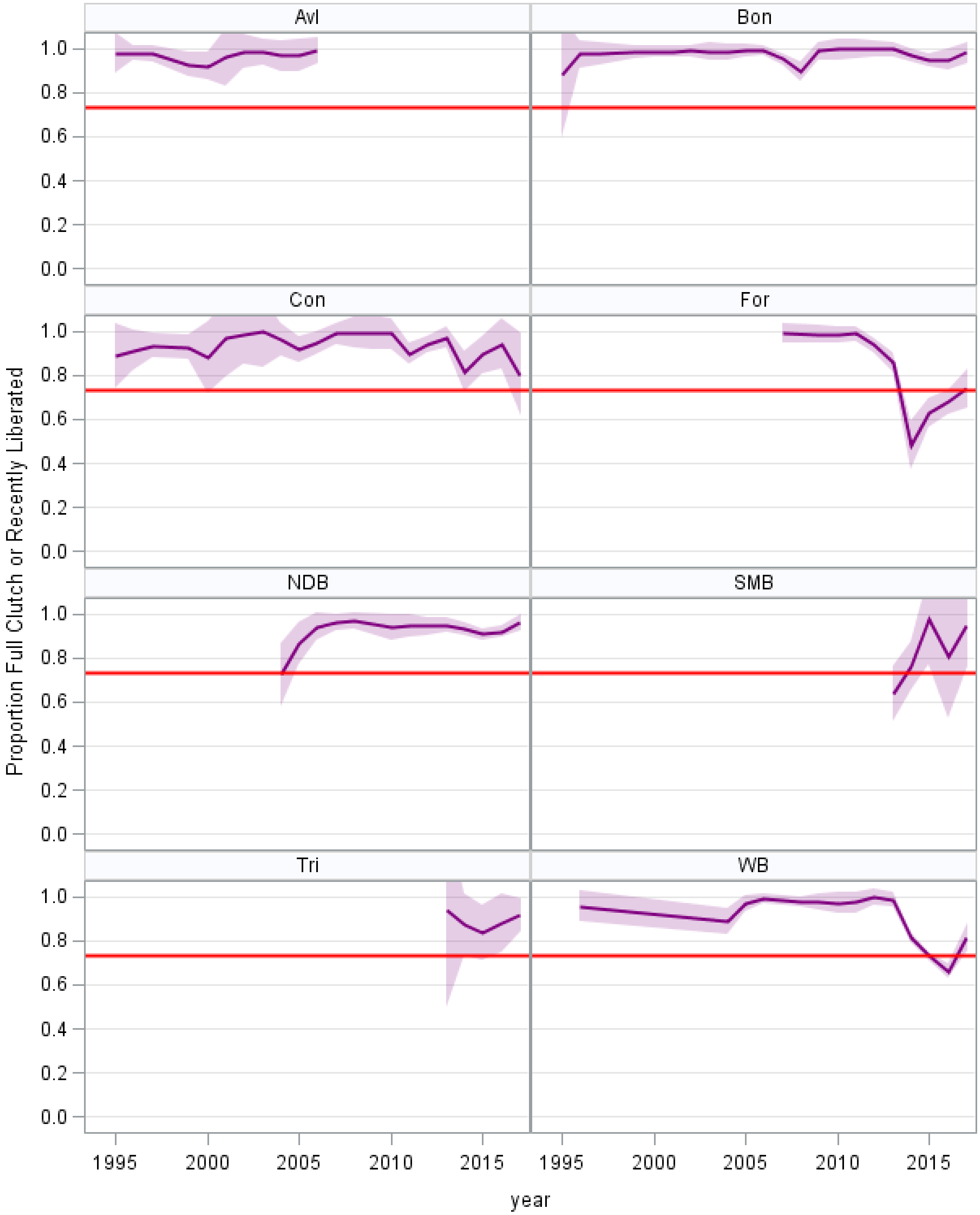

Fig. 19. Proportion of females carrying full or recently liberated clutches of viable eggs in relation to Erecovery LRP, by bay. Data from inshore trap surveys. Shaded areas are 95% confidence intervals.

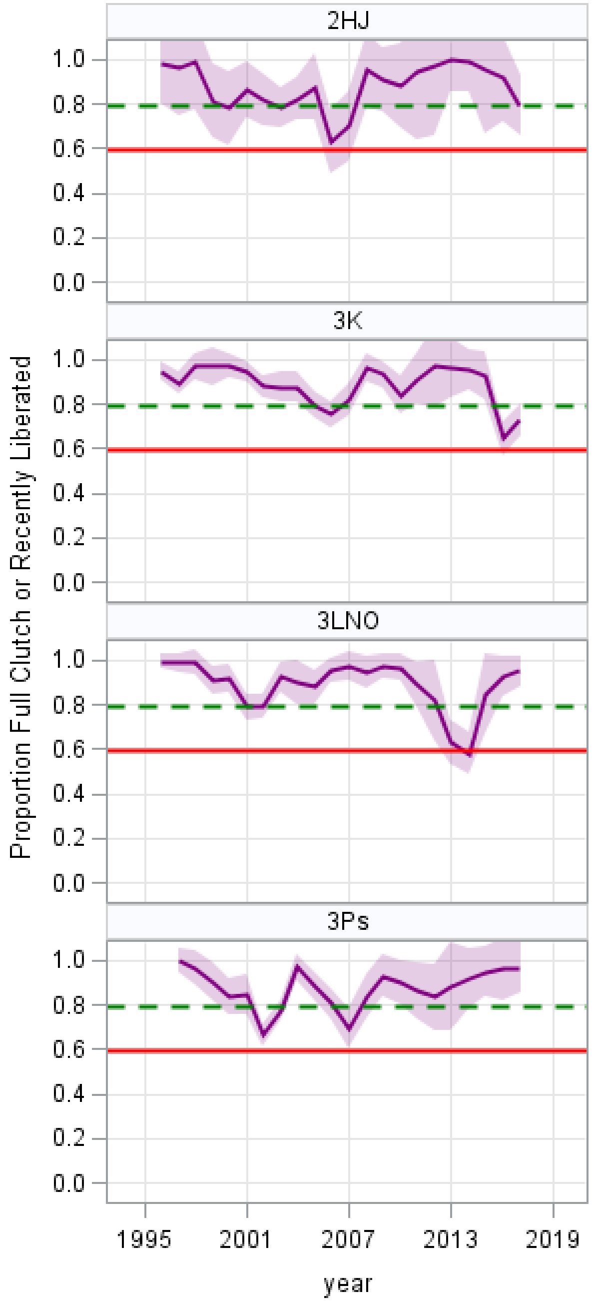

Fig. 20. Proportion of females carrying full or recently liberated clutches of viable eggs in relation to Ehistory limit reference and upper reference points, by Assessment Division. Data from multi-species trawl surveys. Shaded areas are 95% confidence intervals.

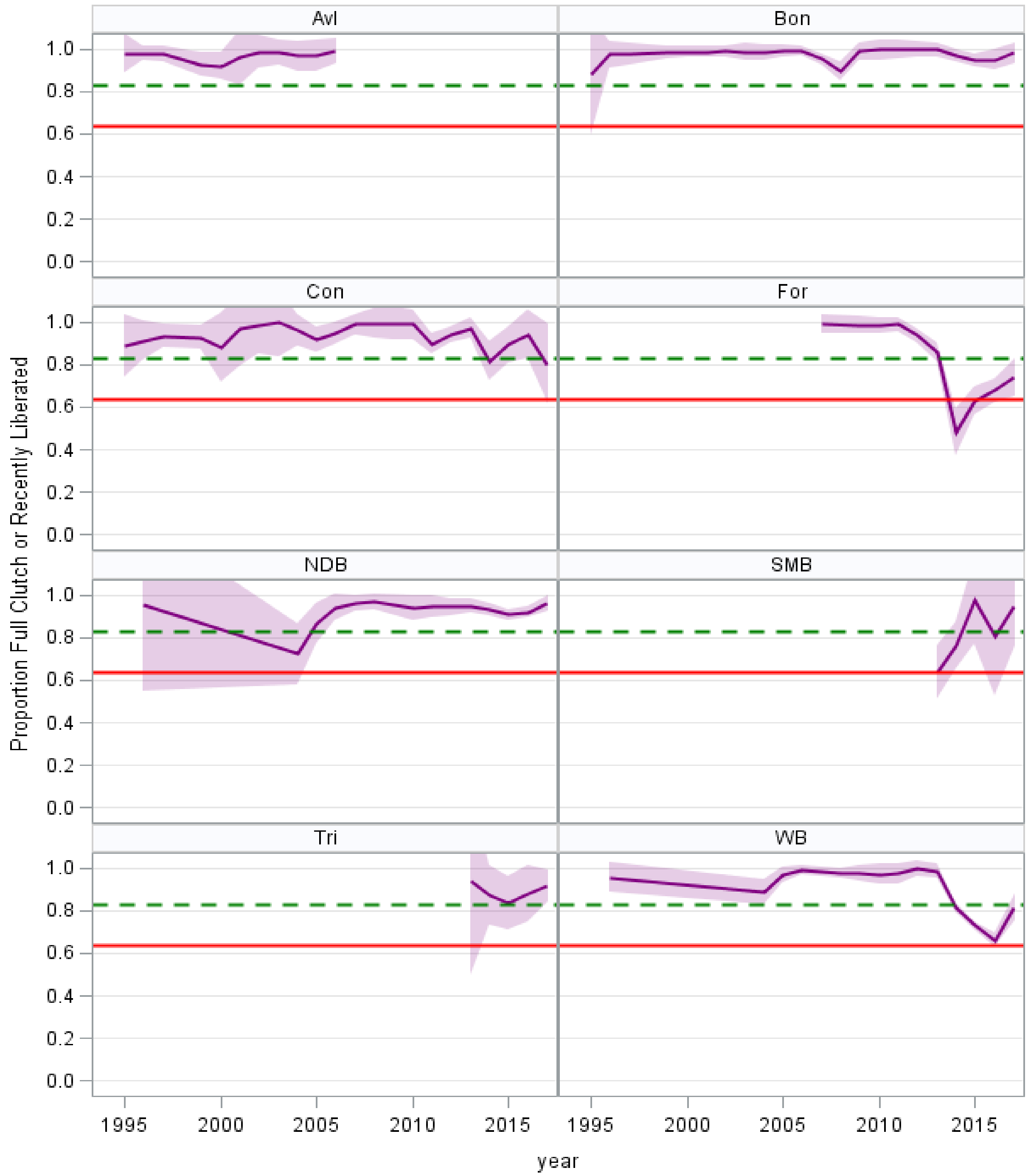

Fig. 21. Proportion of females carrying full or recently liberated clutches of viable eggs in relation to Ehistory limit and upper reference points, by bay. Data from inshore trap surveys. Shaded areas are 95% confidence intervals.

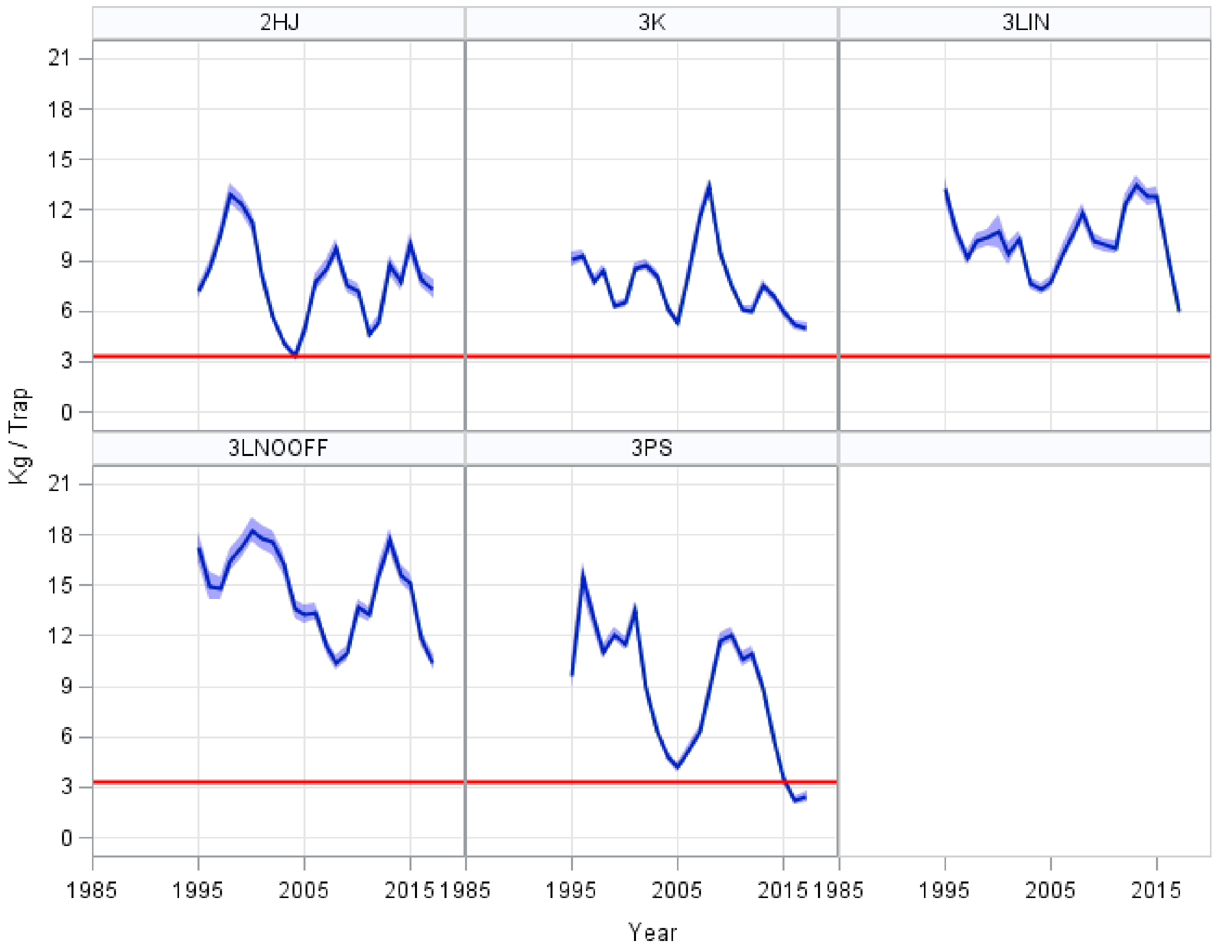

Fig. 22. Fishery CPUE in relation to Crecovery LRP, by Assessment Division.

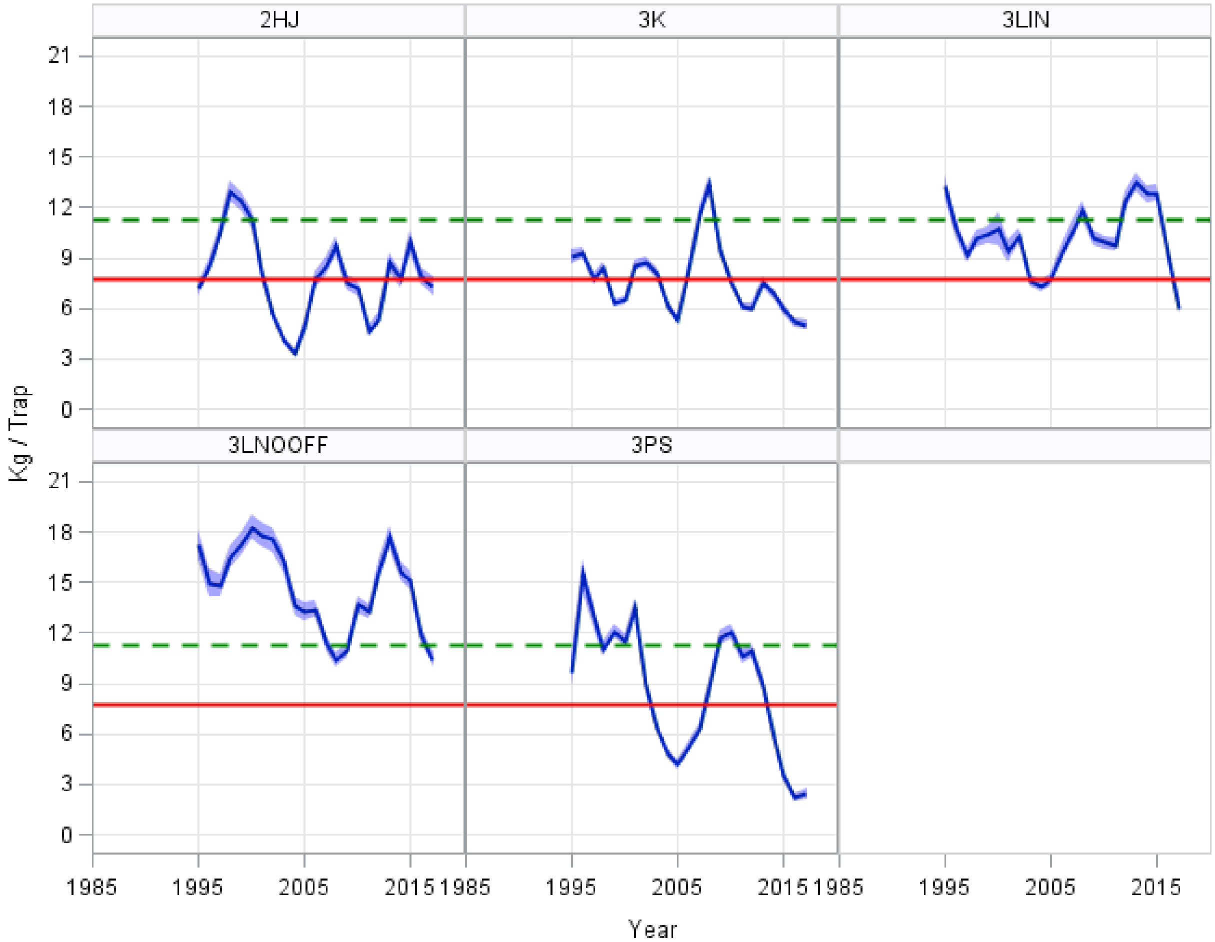

Fig. 23. Fishery CPUE in relation to Chistory limit and upper reference points, by Assessment Division.

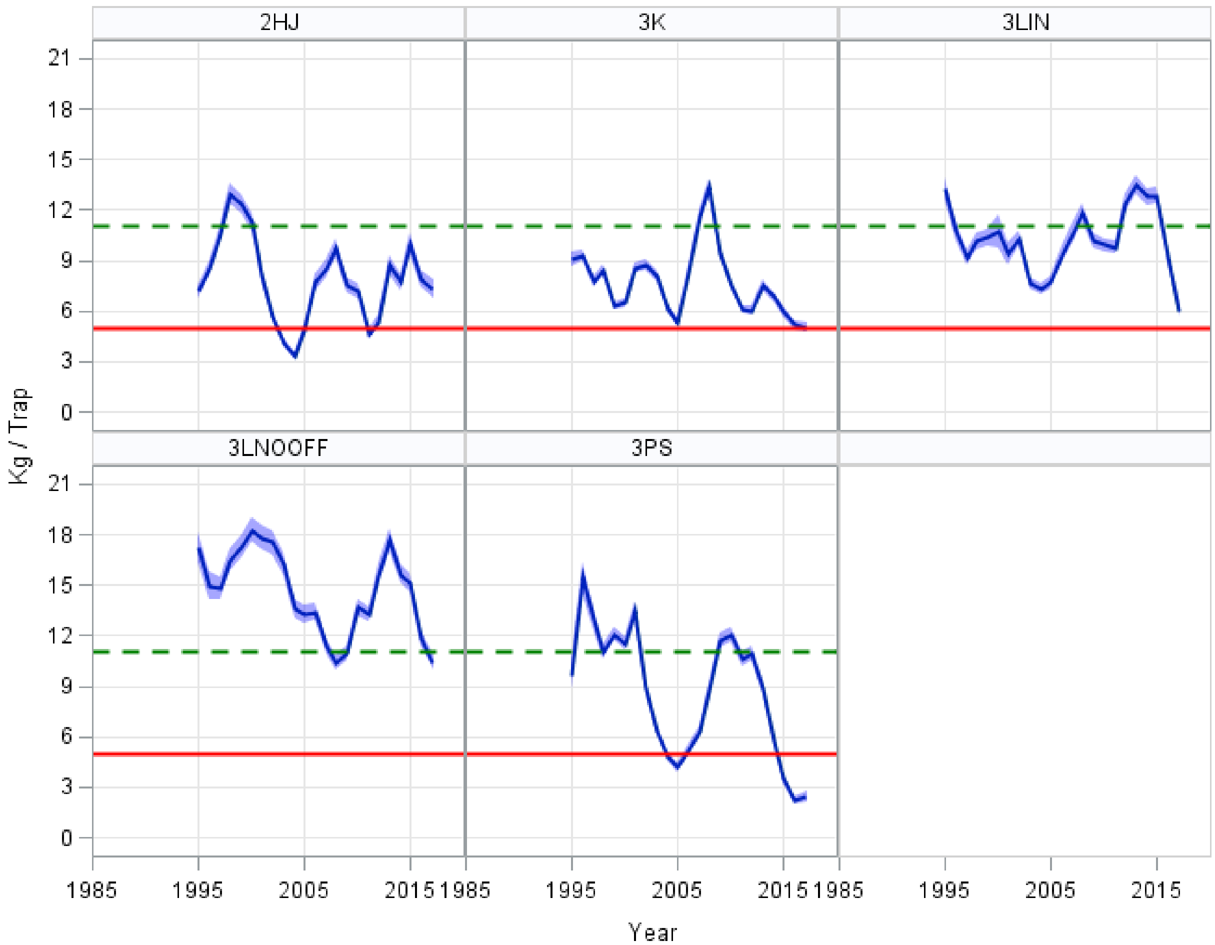

Fig. 24. Fishery CPUE in relation to Chighlow limit and upper reference points, by Assessment Division.

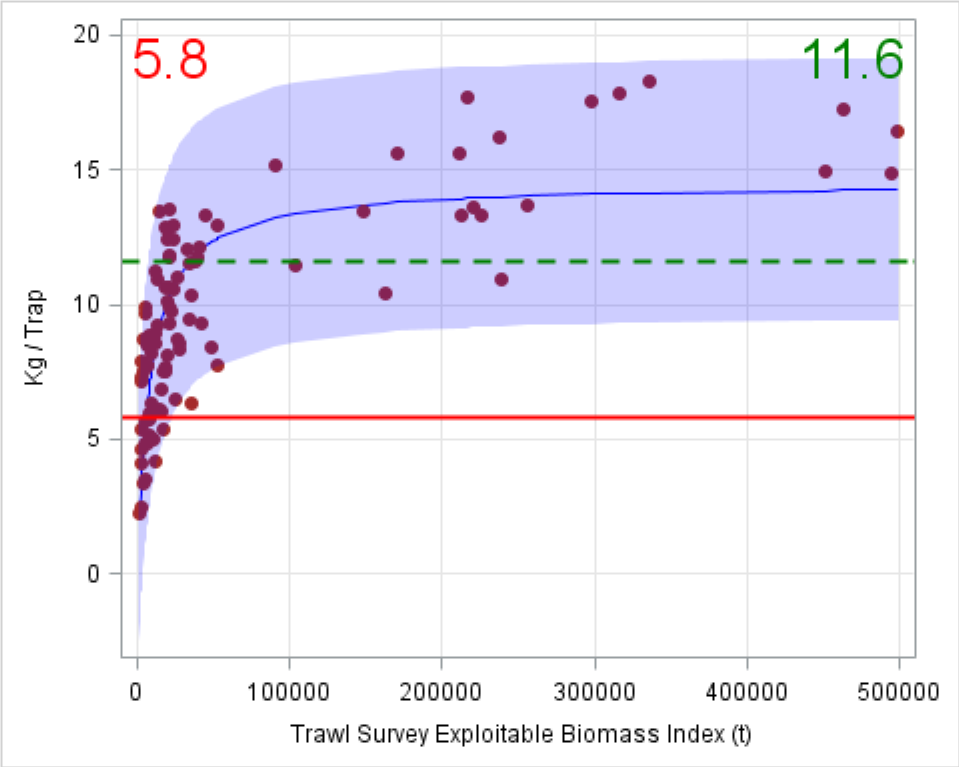

Fig. 25. Fishery CPUE in relation to Csaturate limit and upper reference points.

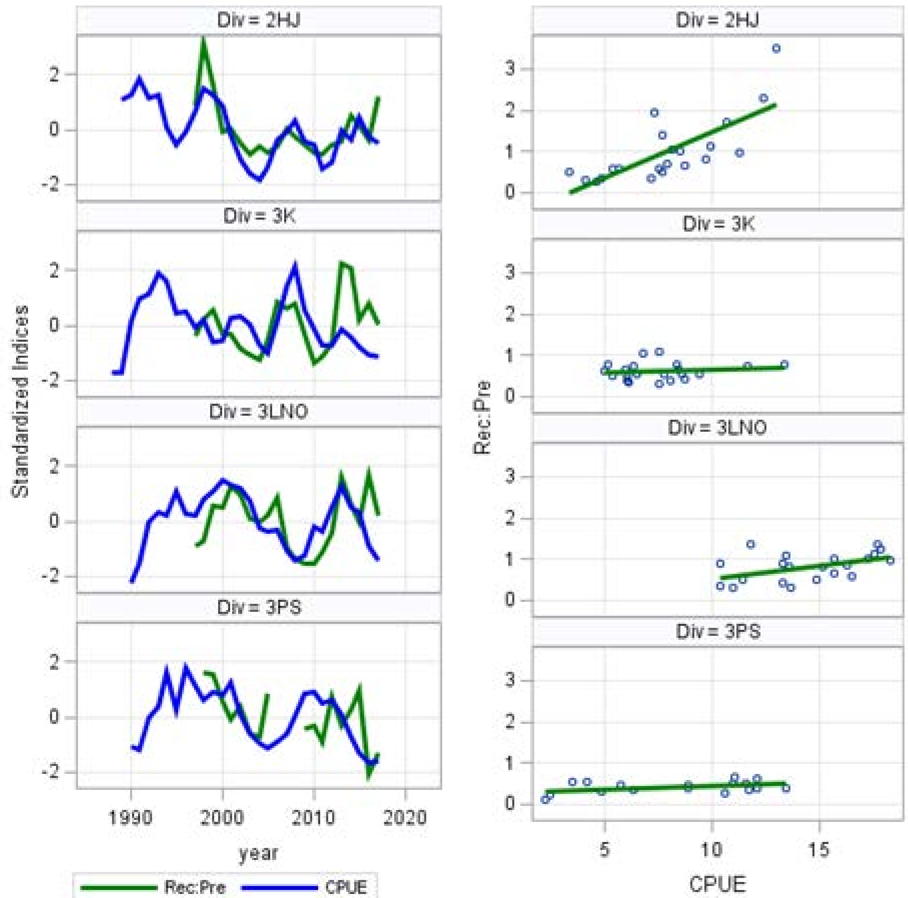

Fig. 26. Fishery CPUE in relation to recruit-per-pre-recruit index, by Assessment Division. Data standardized in line plots in left panels and unstandardized data used in scatter plots and linear regressions in right panels.

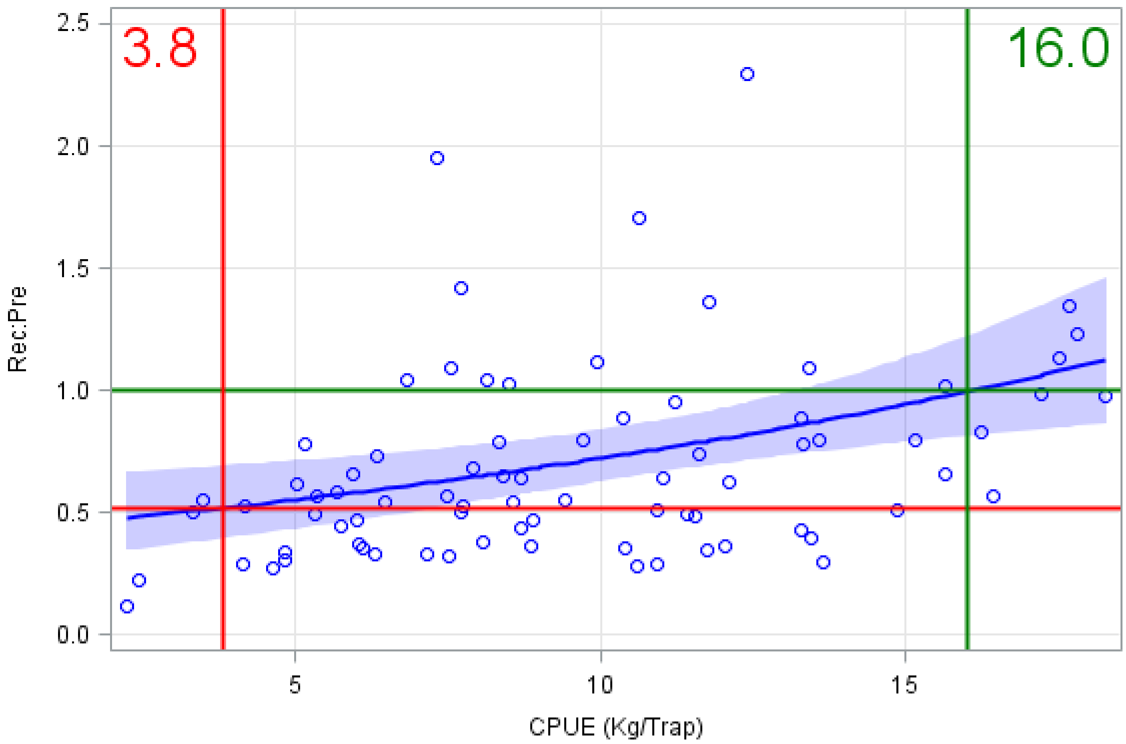

Fig. 27. Fishery CPUE limit and upper reference points based on Cefficient analysis. Shaded area depicts 95% confidence intervals from regression model.

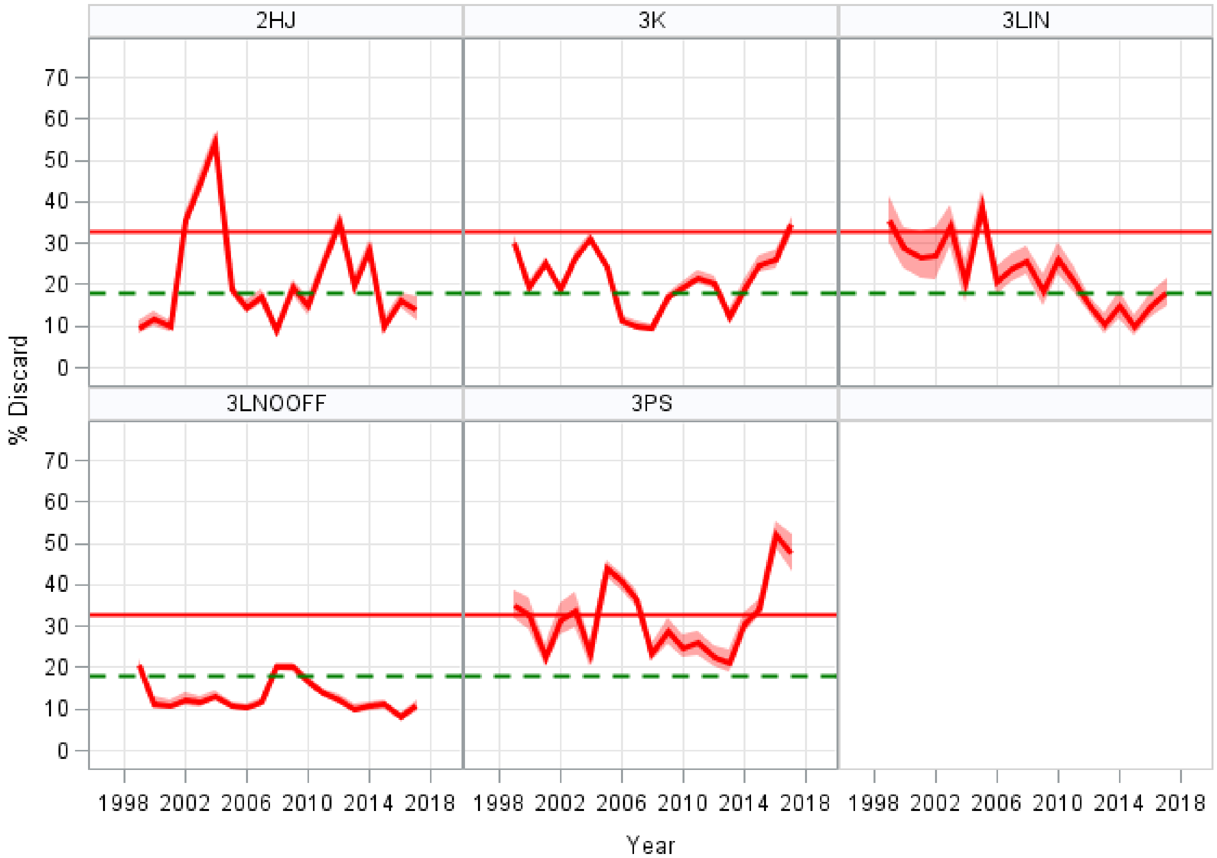

Fig. 28. Fishery discards in relation to Dhistory limit and upper reference points, by Assessment Division.

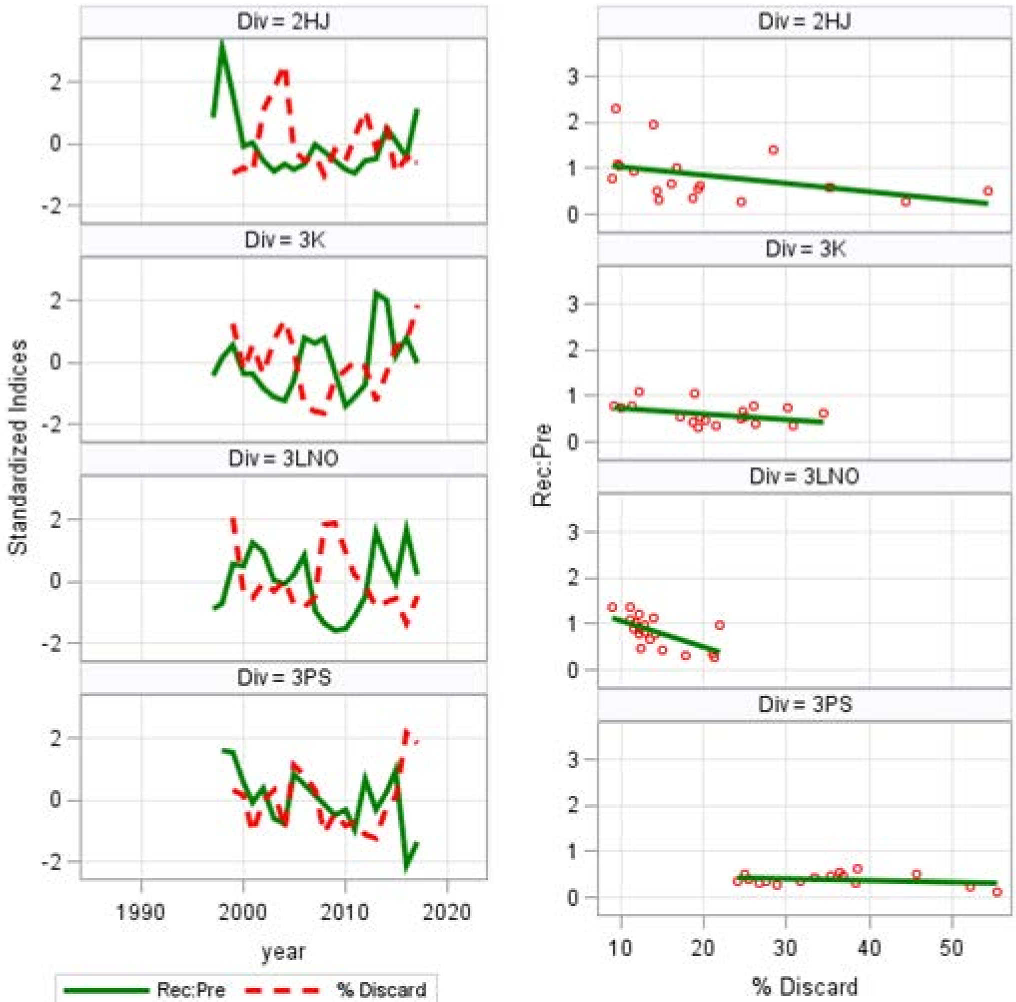

Fig. 29. Fishery discards in relation to recruit-per-pre-recruit index, by Assessment Division. Data standardized in line plots in left panels and unstandardized data used in scatter plots and linear regressions in right panels.

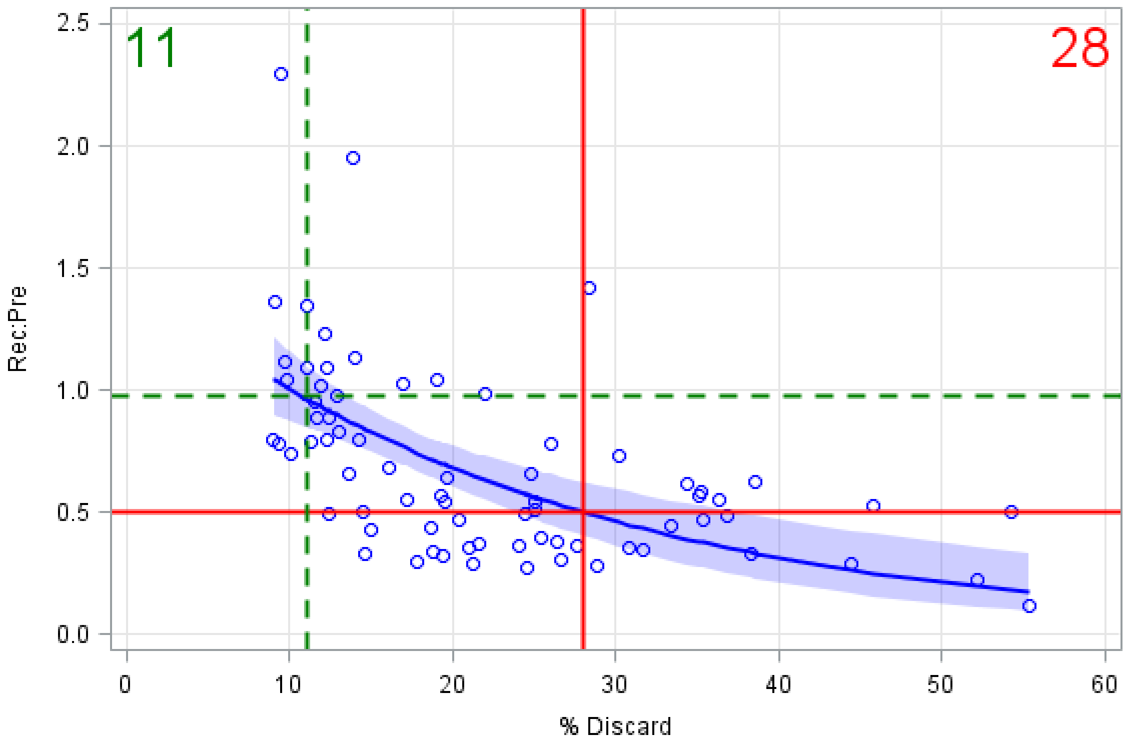

Fig. 30. Fishery discard limit and upper reference points based on Defficient analysis. Shaded area depicts 95% confidence intervals from regression model.

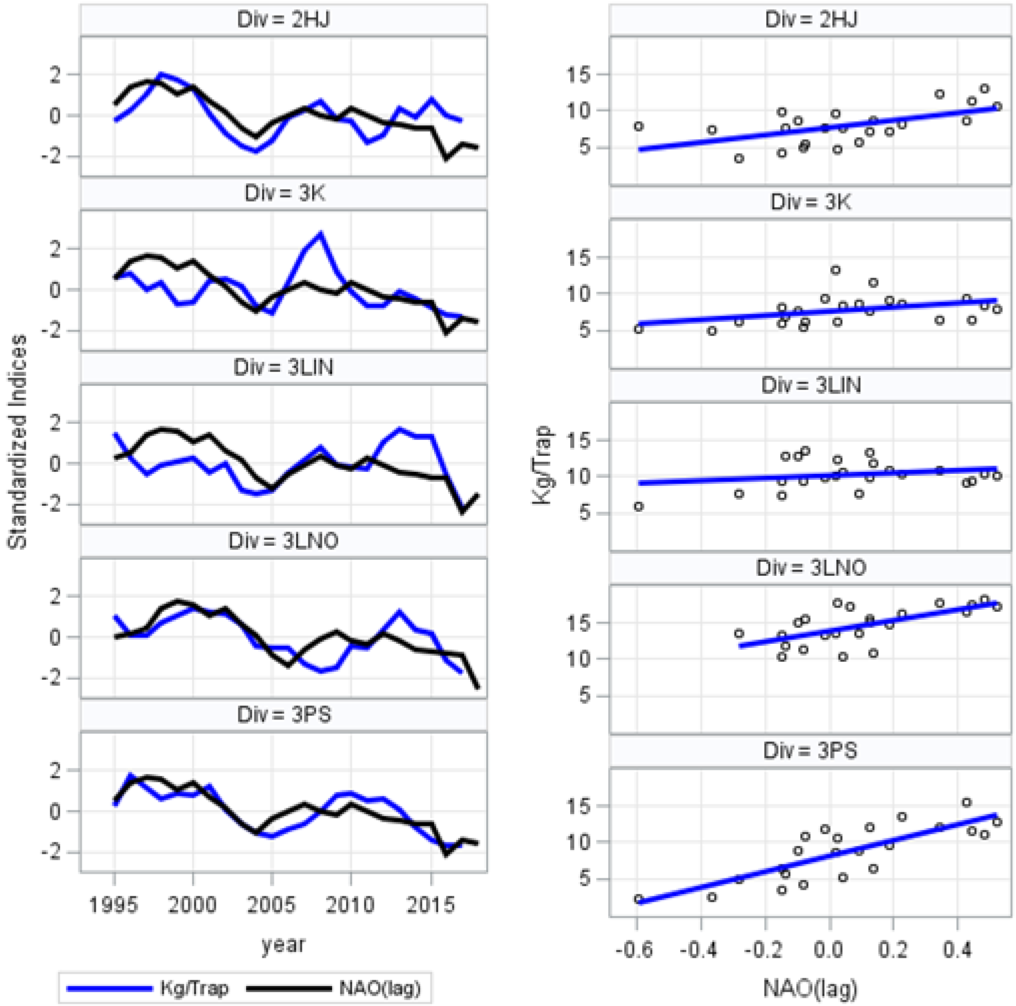

Fig. 31. Fishery CPUE in relation to lagged NAO index, by Assessment Division. Data standardized in line plots in left panels and unstandardized data used in scatter plots and linear regressions in right panels.

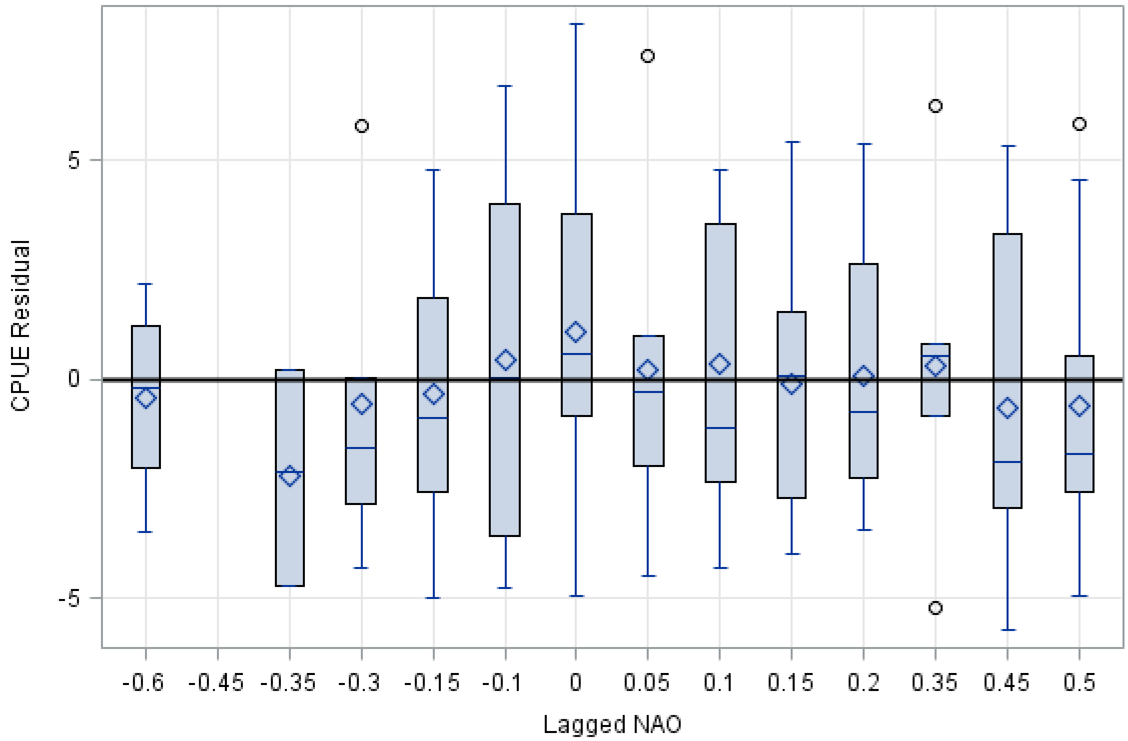

Fig. 32. Boxplot of residuals from CPUE versus lagged NAO regression model.

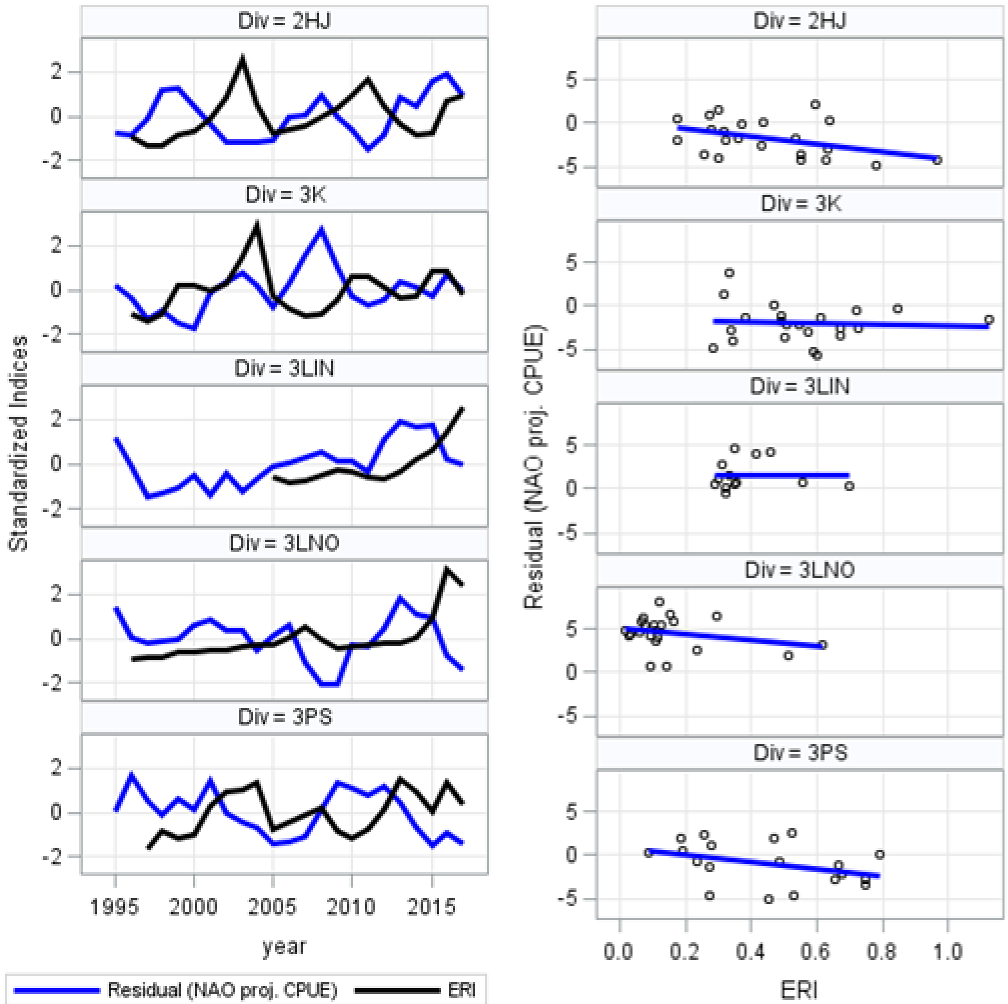

Fig. 33. Residuals from observed versus NAO-predicted CPUE in relation to exploitation rate indices, by Assessment Division. Data standardized in line plots in left panels and unstandardized data used in scatter plots and linear regressions in right panels.

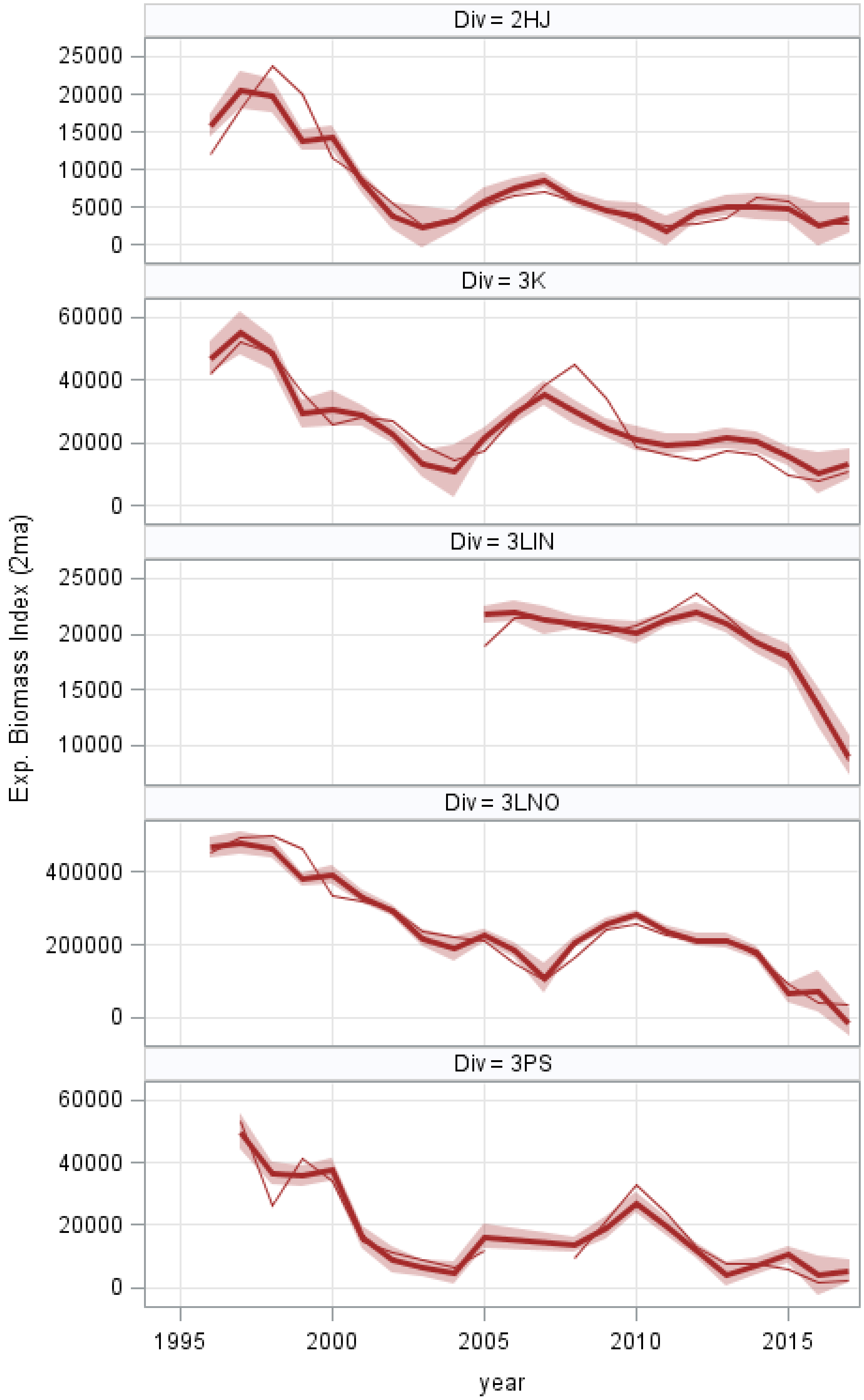

Fig. 34. Exploitable biomass indices for trawl-surveyed Assessment Divisions based on generalized linear model incorporating lagged NAO and annual exploitation rate indices. Thin brown lines are observed biomass, thick brown lines are model-predicted biomass and shaded areas are 95% confidence intervals from the model.

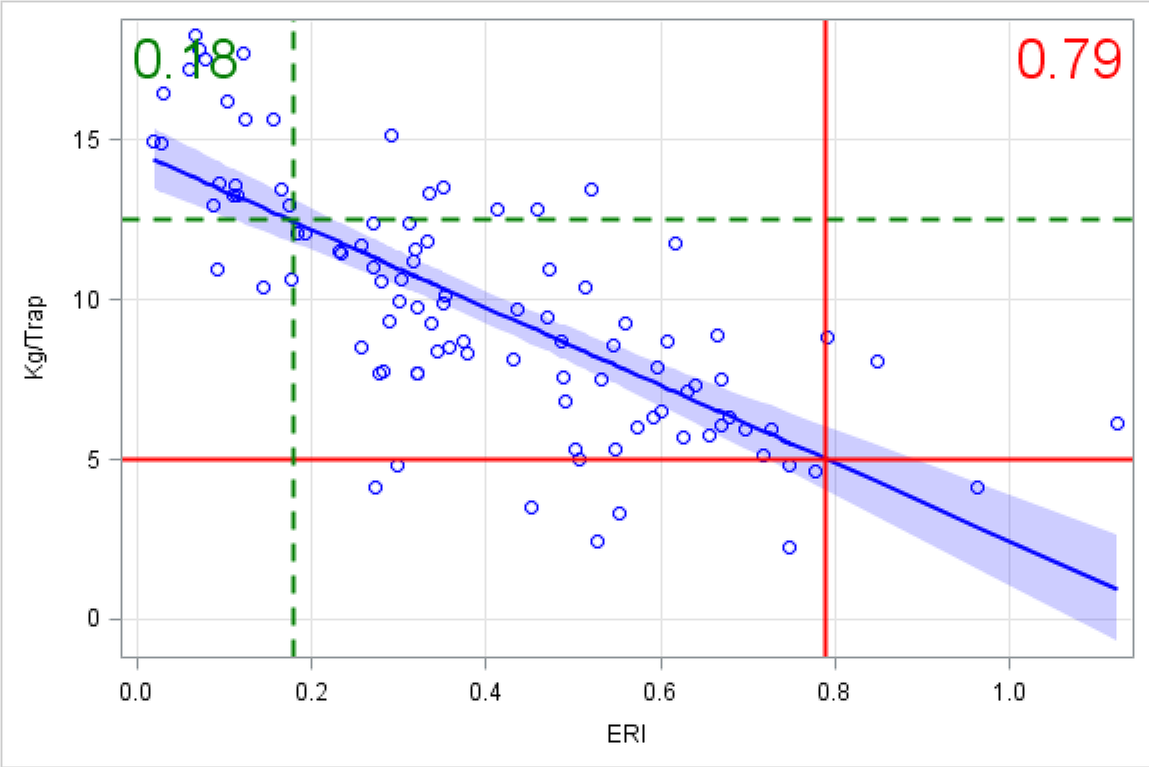

Fig. 35. Fishery CPUE in relation to exploitation rate indices. Regression line from generalized linear model. Shaded area is 95% confidence intervals. Vertical coloured lines depict exploitation rate levels where the regression curve intersects limit (red) and upper (green) reference point levels for CPUE.

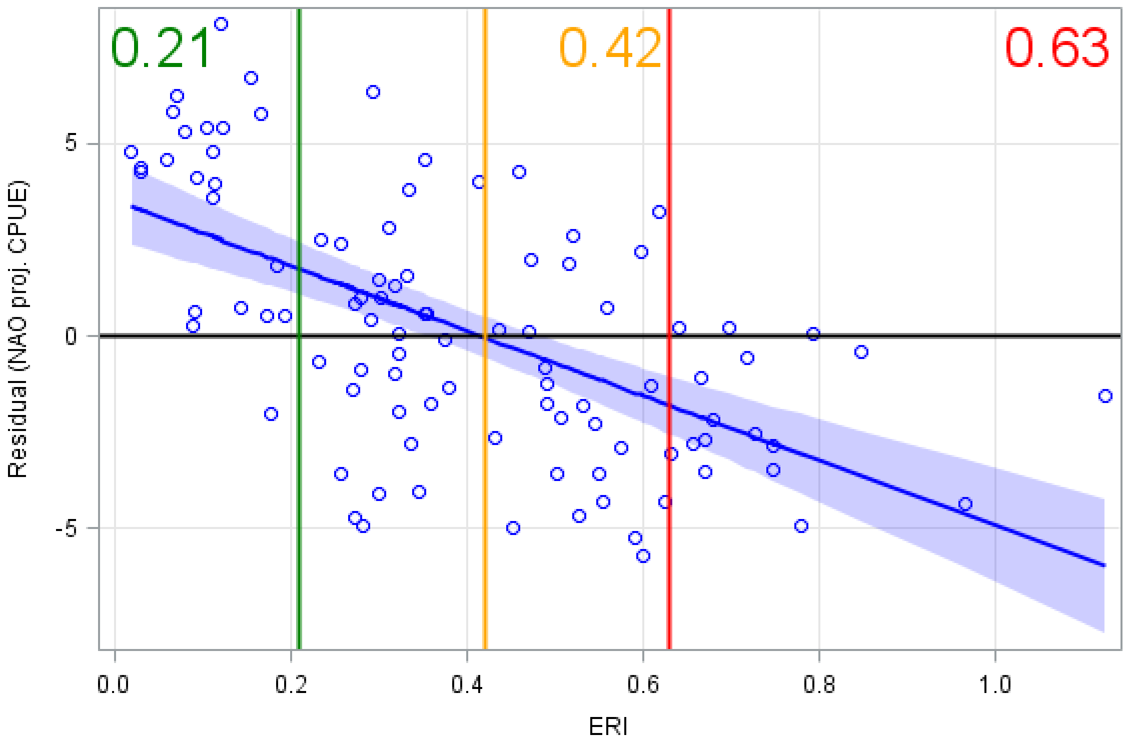

Fig. 36. Residuals of observed versus NAO-predicted CPUE in relation to exploitation rate indices. Regression line from generalized linear model. Shaded area is 95% confidence intervals. Horizontal black line shows zero value for residuals. Vertical coloured lines depict arbitrary exploitation rate levels where positive, neutral, and negative residuals would be likely to occur.

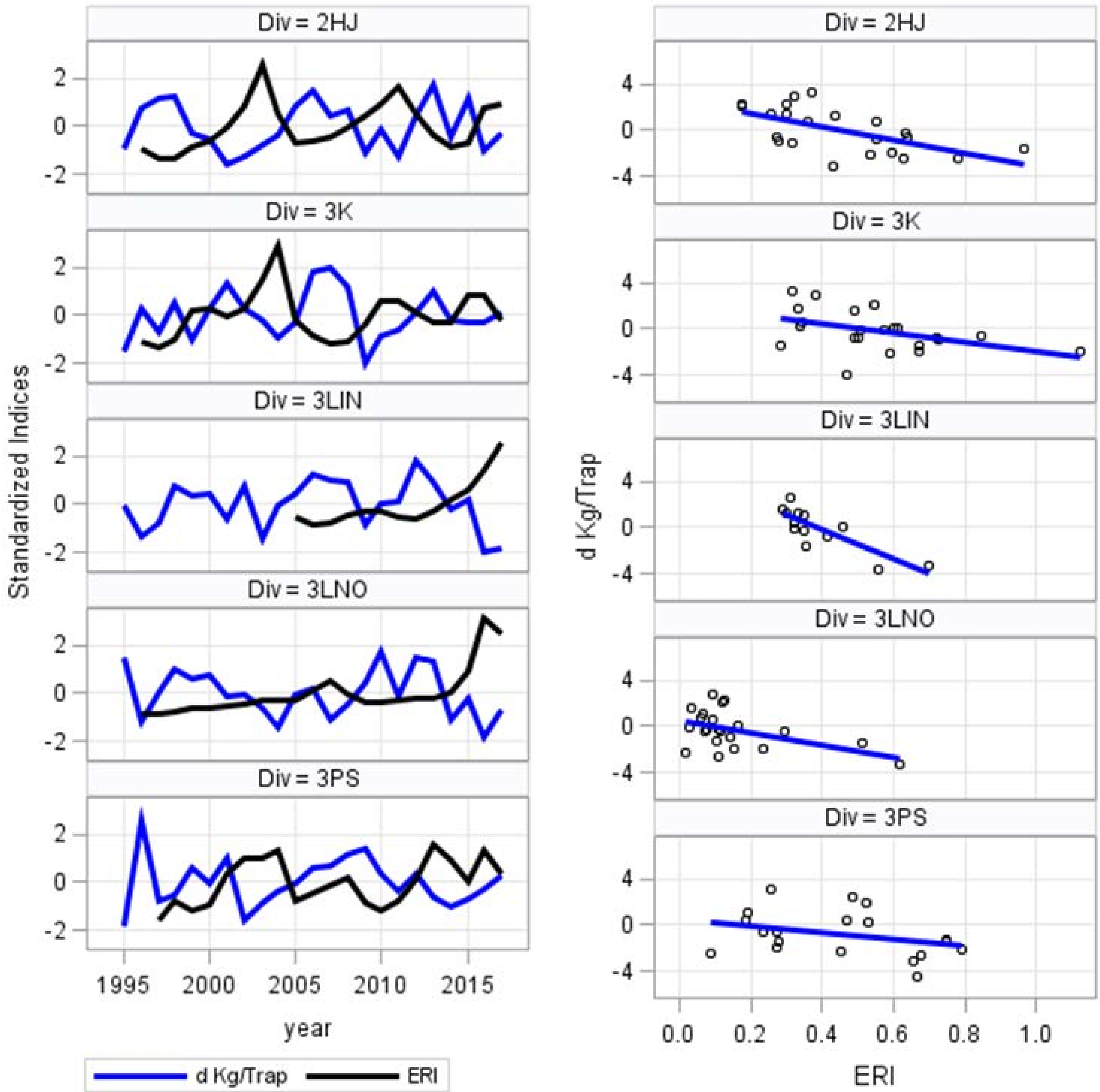

Fig. 37. Annual percentage change in fishery CPUE in relation to exploitation rate indices, by Assessment Division. Data standardized in line plots in left panels and unstandardized data used in scatter plots and linear regressions in right panels.

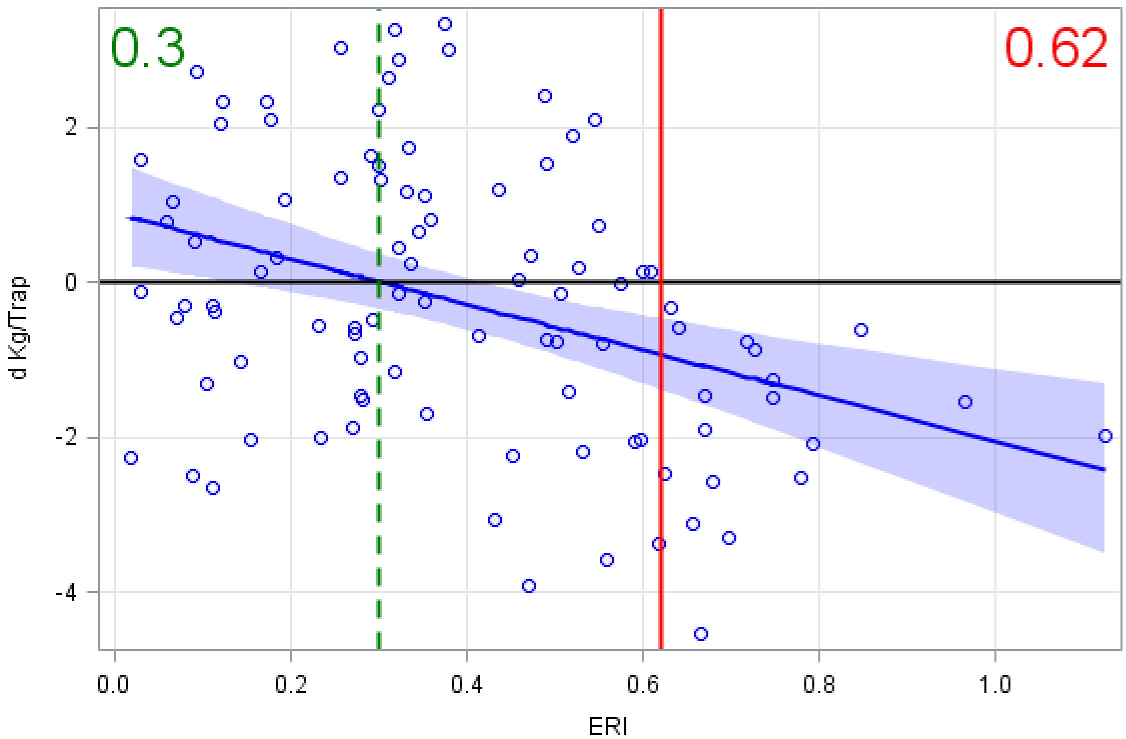

Fig. 38. Annual percentage change in fishery CPUE in relation to exploitation rate indices. Regression line from generalized linear model. Shaded area is 95% confidence intervals. Horizontal black line shows zero value for change in annual CPUE. Vertical coloured lines depict arbitrary or regression model intersection points for exploitation rate indices where negative (red) or no (green) change in CPUE would be expected to occur.

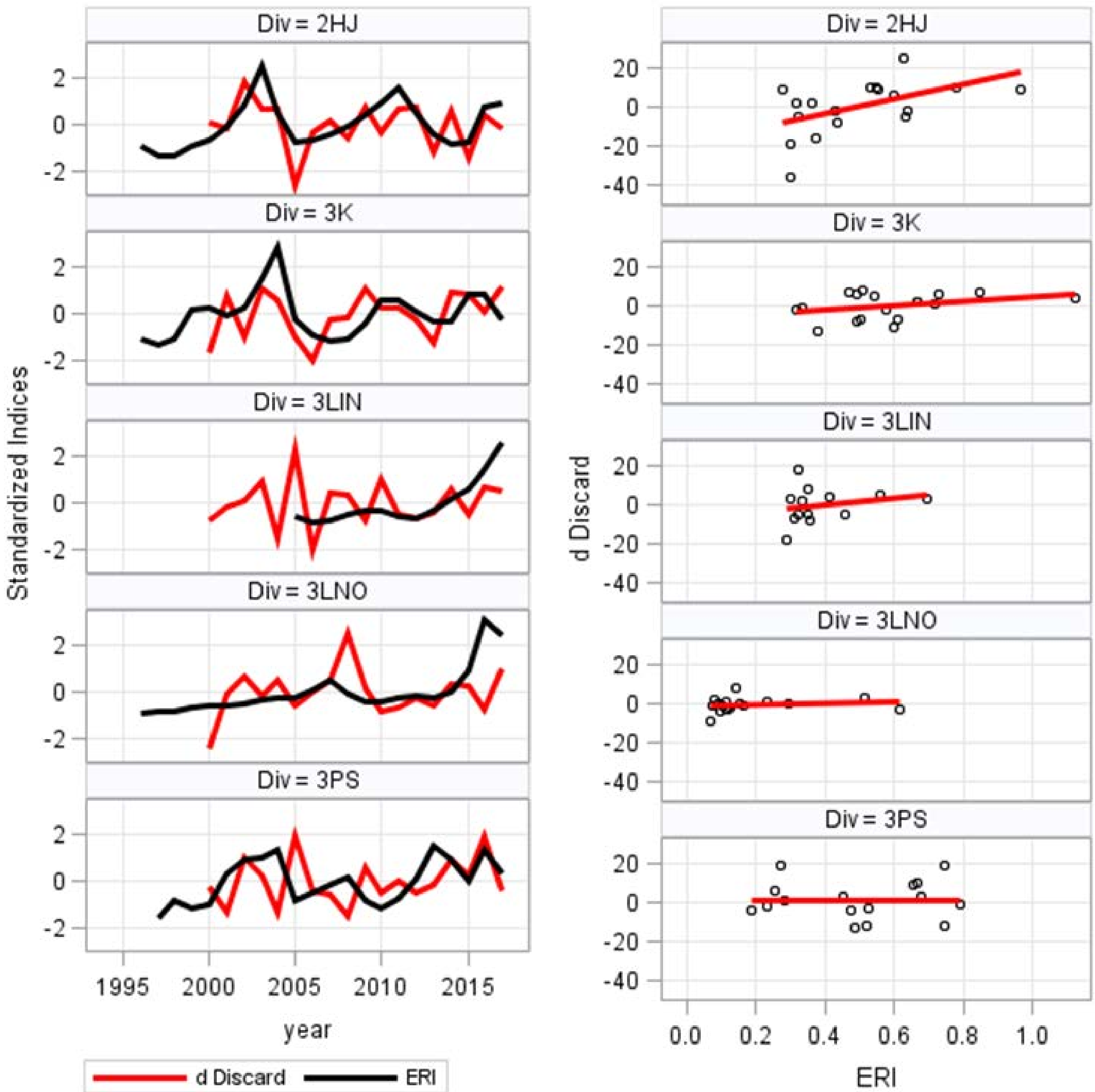

Fig. 39. Annual percentage change in fishery discards in relation to exploitation rate indices, by Assessment Division. Data standardized in line plots in left panels and unstandardized data used in scatter plots and linear regressions in right panels.

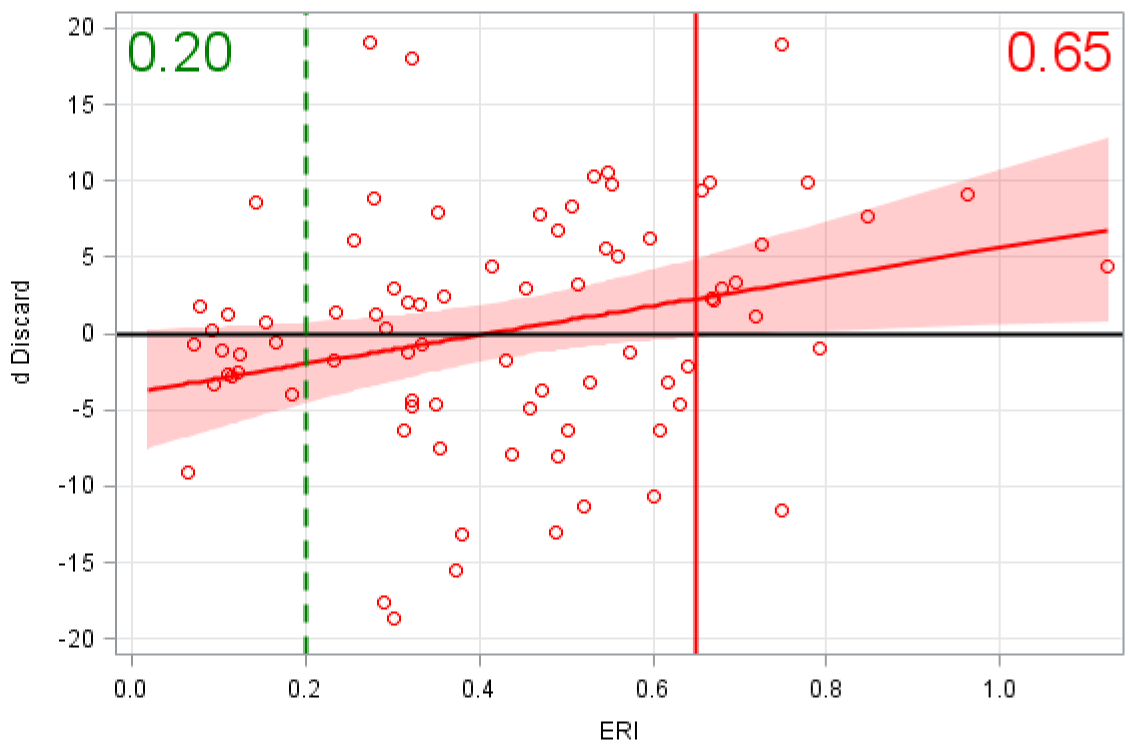

Fig. 40. Annual percentage change in fishery discards in relation to exploitation rate indices. Regression line from generalized linear model. Shaded area is 95% confidence intervals. Horizontal black line shows zero value for change in annual discard levels. Vertical coloured lines depict arbitrary or regression model intersection points for exploitation rate indices where positive (red) or no (green) change in discard levels would be expected to occur.

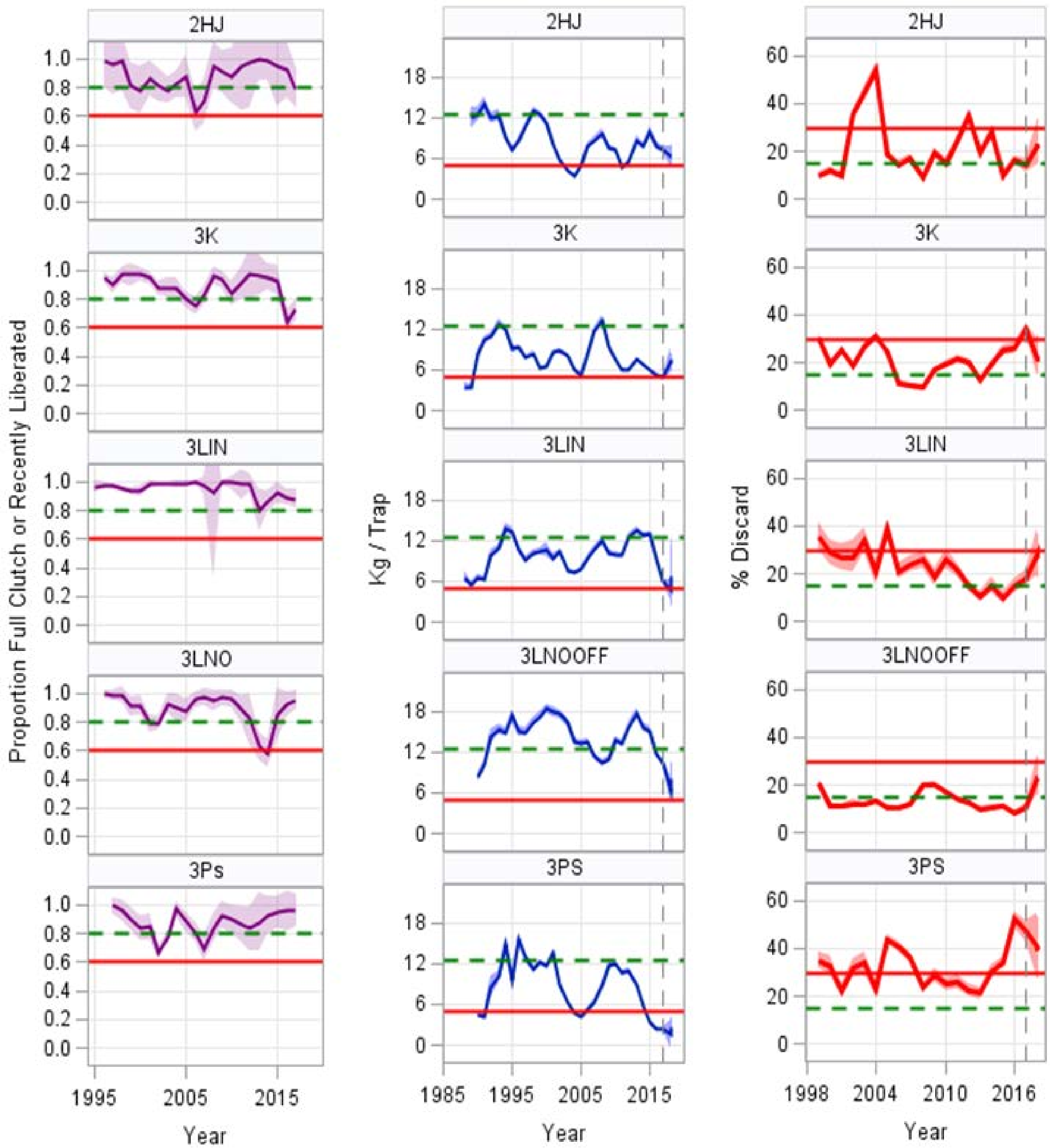

Fig. 41. Stock status in relation to proposed metrics and reference point levels for the PA/DM framework (egg clutches left panels, CPUE middle panels, discards right panels). Note projected 2018 CPUE assumes status quo landings and season dates while projected 2018 discards assume status quo soak times.

TABLES

Table 1. Generalized linear model output for CPUE versus lagged NAO - Analysis of Maximum Likelihood Parameter Estimates.

Parameter	DF	Estimate	Standard Error	Lower 95% CL	Upper 95% CL	Wald Chi-Square	PR> ChiSq
Intercept	1	9.4146	0.3136	8.7999	10.0292	901.19	<.0001
Nao	1	6.2388	1.164	3.9574	8.5201	28.73	<.0001
Scale	1	3.2703	0.2156	2.8739	3.7215	-	-

Table 2. Generalized linear model output for CPUE versus exploitation rate index - Analysis of Maximum likelihood Parameter Estimates.

Parameter	DF	Estimate	Standard Error	Lower 95% CL	Upper 95% CL	Wald Chi-Square	PR> ChiSq
Intercept	1	3.5264	0.5378	2.4722	4.5805	42.99	<.0001
Nao	1	-8.4724	1.1724	-10.7702	-6.1747	52.23	<.0001
Scale	1	2.6633	0.1902	2.3154	3.0635	-	-

Table 3. Generalized linear model output for Exploitable Biomass Index in relation to lagged NAO and annual exploitation rate indices, by Assessment Division - Analysis of Maximum Likelihood Parameter Estimates

2HJ

Parameter	DF	Estimate	Standard Error	Lower 95% CL	Upper 95% CL	Wald Chi-Square	Pr > Chi Sq
Intercept	1	10560.33	1351.547	7911.345	13209.31	61.05	<.0001
eri	1	-10939.8	2676.496	-16185.7	-5694.01	16.71	<.0001
nao	1	31345.74	4201.798	23110.37	39581.12	55.65	<.0001
eri*nao	1	-48626.4	9569.627	-67382.5	-29870.3	25.82	<.0001
Scale	1	2089.984	315.0769	1555.319	2808.448	-	-

3K

Parameter	DF	Estimate	Standard Error	Lower 95% CL	Upper 95% CL	Wald Chi-Square	Pr > ChiSq
Intercept	1	39103.01	4169.716	30930.52	47275.5	87.94	<.0001
eri	1	-29935.5	7227.548	-44101.2	-15769.8	17.16	<.0001
nao	1	68503.82	12595.79	43816.53	93191.11	29.58	<.0001
eri*nao	1	-77873.7	22494.86	-121963	-33784.6	11.98	0.0005
Scale	1	5446.754	821.1291	4053.352	7319.16	-	-

3LIN

Parameter	DF	Estimate	Standard Error	Lower 95% CL	Upper 95% CL	Wald Chi-Square	Pr > ChiSq
Intercept	1	29710.99	2151.416	25494.3	33927.69	190.72	<.0001
eri	1	-25910.3	6296.123	-38250.5	-13570.1	16.94	<.0001
nao	1	-14278.5	8283.92	-30514.7	1957.664	2.97	0.0848
eri*nao	1	30838.73	18427.15	-5277.83	66955.29	2.8	0.0942
Scale	1	991.6983	194.488	675.2199	1456.512	-	-

3LNO

Parameter	DF	Estimate	Standard Error	Lower 95% CL	Upper 95% CL	Wald Chi-Square	Pr > ChiSq
Intercept	1	352077.3	16872.91	319007	385147.6	435.41	<.0001
eri	1	-1029829	118512.4	-1262109	-797549	75.51	<.0001
nao	1	343989.8	37418.48	270651	417328.7	84.51	<.0001
eri*nao	1	-1532664	189213.6	-1903516	-1161812	65.61	<.0001
Scale	1	31917.36	4811.723	23752.18	42889.45	-	-

3PS

Parameter	DF	Estimate	Standard Error	Lower 95% CL	Upper 96% CL	Wald Chi-Square	Pr > ChiSq
Intercept	1	27134.77	3097.453	21063.88	33205.67	76.74	<.0001
eri	1	-29016.6	6195.504	-41159.6	-16873.7	21.94	<.0001
nao	1	54661.32	8315.223	38363.78	70958.86	43.21	<.0001
eri*nao	1	-69565.4	16018.33	-100961	-38170	18.86	<.0001
Scale	1	4129.883	669.9555	3005.07	5675.719	-	-

Table 4. Suggestions for management controls to incorporate into harvest control rules to address negative outcomes in each framework assessment metric.

Egg clutches	CPUE	Discards
- Reduce exploitation rate index - Fishing depth restrictions	- Reduce exploitation rate index - Shorten or shift fishing season	- Stricter soft-shell encounter protocol rules - Shorten or shift fishing season - Gear modifications to reduce catches of small individuals - Increase soak times - Fishing depth restrictions