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Development of biological reference points and precautionary approach framework for the Dungeness Crab (*Cancer magister*) fishery in Crab Management Areas I and J

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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.

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ABSTRACT

This paper identifies reference points for Dungeness Crab in Crab Management Areas I and J in British Columbia. We estimated an Upper Stock Reference (USR = 0.456 female standardized CPUE) and a Limit Reference Point (LRP = 0.228 female standardized CPUE), as described in A Fishery Decision-Making Framework Incorporating the Precautionary Approach (DFO 2009) also known as DFO's Precautionary Approach (PA) policy. These reference points will inform the assessment of stock status of Dungeness Crab in Crab Management Areas (CMAs) I and J. Candidate reference points were estimated using three methodologies: a data-driven empirical method, a model-based method which estimates the stock-recruitment relationship, and a simulation model-based method. We recommend applying the empirically-based methodology for determining reference points for the Dungeness Crab in CMAs I and J as they are more interpretable than the simulation model-based reference points, and are more estimable than the stock-recruitment reference points. Subsequent research can use this framework to develop reference points for Dungeness Crab in other CMAs.

1. INTRODUCTION

Dungeness Crabs (*Cancer magister*) are found from Alaska to Mexico along the west coast of North America, inhabiting areas of sandy substrate (Jensen 1995). Across British Columbia (BC), Dungeness Crabs are harvested by trap in commercial, recreational, and First Nations' Food, Social, and Ceremonial (FSC) fisheries (DFO 2021a). Commercial fishing primarily uses traps deployed from fishing vessels, but a significant amount of recreational and some FSC fishing occurs from shore. Currently, the BC Dungeness Crab population is considered healthy based on previous assessments. A 2017 risk assessment of the recreational Dungeness Crab fishery found stock status to be "low concern" (DFO 2021a). A recent Fisheries and Oceans Canada (DFO) Sustainability Survey assessed the commercial fishery as "sustainable", based on the current management measures in place (DFO 2021b). Management for the commercial fishery does not set a Total Allowable Catch (TAC); instead, the fishery is managed with minimum size limits, non-retention of females, and seasonal closures (i.e., "Size, Sex, and Season"). The sustainability of the fishery is therefore dependent on the abundance of female and sublegal-sized male crabs remaining at a level high enough to support recruitment. Recreational fisheries are managed with licenses and daily limits. These management measures are considered to be sustainable despite estimates of commercial exploitation rates of harvestable male crabs over 90% in certain areas (Zhang et al. 2002). However, there are currently no reference points defined against which the stock status of BC Dungeness Crab can be quantitatively assessed.

Compliance with DFO's Precautionary Approach (PA) policy requires that a management strategy include reference points that define three zones of stock status ("Healthy", "Cautious", and "Critical") and the removal reference for each zone (DFO 2009). The Limit Reference Point (LRP) defines the boundary between "Cautious" and "Critical" stock status, and sets the limit below which productivity of the stock is sufficiently impaired to cause serious harm to the stock and impact the long-term sustainability of the fishery. The Upper Stock Reference Point (USR) defines the boundary between "Healthy" and "Cautious" and is the threshold below which the removal rate is progressively reduced to avoid reaching the LRP. If the LRP is breached, then a rebuilding plan must be developed to minimize further decline and allow the stock to rebuild.

One common approach for defining the three zones of stock status is to use reference points based on B_{MSY}, the biomass that is expected to produce the maximum sustainable yield over the long term assuming equilibrium conditions. For many marine invertebrates stocks, including Dungeness Crab, MSY-based reference points cannot be estimated directly due to the life history characteristics of the species and the methods by which they are fished (Smith et al. 2012). The PA outlines empirical proxies for B_{MSY}, such as the average biomass over a productive time period, or 50% of the maximum observed biomass (DFO 2009). Close to half (43%) of LRPs for all Canadian stocks are set at 40% of B_{MSY} or a suitable B_{MSY} proxy, and approximately 65% of USRs are set at 80% B_{MSY} or B_{MSY} proxy based on default guidance provided within the PA policy (Marentette et al. 2021). Another common approach for setting LRPs empirically is to use the lowest observed abundance (or abundance proxy such as a survey index) from which the stock has recovered (e.g., Wang et al. 2017).

Alternative approaches to B_{MSY} have been used to estimate reference points for crab stocks worldwide. These approaches include both model-derived methods, based on some measure of biomass and exploitation rate, and empirical reference points. For example, the model-derived LRP for Gulf of St. Lawrence Snow Crab (*Chionoecetes opilio*) is based on biomass estimates from a trawl survey (Hébert et al. 2010), while the LRP for Blue Crab (*Callinectes sapidus*) in Chesapeake Bay is based on the number of female crabs estimated from a dredge survey at the start of the season (Bromilow 2021). Mullowney et al. (2018) developed a multi-indicator approach to reference points for Newfoundland and Labrador Snow Crab, which includes fishery discard rates of non-target crabs and fishery catch-per-unit-effort (CPUE) standardized based on trawl survey data. Many crab stocks, including the BC Dungeness Crab stock, lack active fishery-independent sampling methods such as trawl or dredge surveys, limiting the usefulness of traditional biomass-based reference points. Oregon Dungeness Crab have an empirically-based LRP, using commercial landings over a period of four years. The LRP is breached when: (1) landings decline in three consecutive years; (2) the landings in the fourth year are projected to be declining and below 20% of the 20-year average; and (3) logbook-based commercial CPUE falls below the average of a historical period (Oregon Department of Fish and Wildlife 2014). Empirical LRPs for Alaskan Golden King Crab (Stratman et al. 2021) and Australian Giant Crab (Victoria Fisheries Authority 2020) are also based on commercial CPUE. In addition, some LRPs have been defined based on metrics associated with maintaining the reproductive potential of the crab stock (e.g., egg clutch fullness and discarding rates of non-target crabs for Newfoundland Snow Crab, Mullowney et al. 2018). It is especially important to consider the female population in male-only fisheries, where changes in female reproductive success can be used to indicate recruitment overfishing (Orensanz et al. 1998).

Simulation modeling has also been used to propose or evaluate reference points for crab stocks (e.g., Szuwalski and Punt 2012; Zhang and Dunham 2013). Zhang and Dunham (2013) developed an equilibrium-based simulation model to investigate the reduction in Dungeness Crab stock size when fixed fishing levels were applied to a small and declining population. Few other examples exist in the current scientific literature and in particular, examples that test for recruitment overfishing by assessing female stock size and the sex ratio in sex-selective fisheries that harvest only large male crabs. Size-based analyses are especially challenging for female Dungeness Crabs, as they can remain the same size for over two years by storing sperm and skipping moults (Hankin et al. 1989). Simulation-based estimates tend to rely on more assumptions about the biology, fishery, and environment and are less easily understood by broader audiences. For Dungeness Crab, additional challenges exist in modelling the stock-recruitment relationship, including the extensive larval transport (Park et al. 2007), metapopulation structure, and variability in ocean conditions (Shanks and Roegner 2007), which all increase the variability and complexity of the stock-recruitment relationship. Given these challenges, data-driven empirical methods may be more appropriate, as they inherently capture environmental variability over time.

To meet the requirements of the PA policy, reference points must be established for the BC Dungeness Crab stock and the current stock status must be determined based on such reference points. Stocks can be defined on a biological scale (e.g., coastwide range, single genetic population) or a management scale (e.g., a specific management area), but do require a detailed definition of the extent of the stock. In BC, the Dungeness Crab fishery is spatially divided into seven Crab Management Areas (CMAs). This paper focuses on CMAs I and J around the Fraser River Delta (Figure 1), as a case study to develop an analytical framework for the estimation of biological reference points that could be applied to other CMAs. CMAs I and J were chosen because they have been consistently sampled in the DFO fishery-independent survey. As there is no biological stock definition for Dungeness Crab, estimated reference points are considered provisional. In the absence of a biologically defined stock of Dungeness Crab, provisional reference points may be provided to guide interim management until a stock assessment for a defined stock can be completed. Further, once a stock definition is accepted, reference points can still be updated in subsequent stock assessments.

This case study has three main objectives. First, to develop a biological LRP and recommend a USR for Dungeness Crab in CMAs I and J. Second, to compare long-term trends in abundance indices for legal-sized males, females, and sublegal-sized males and, when appropriate, to compare these indices to the reference points to determine stock status. Third, to discuss sources of uncertainty, including the applicability of the methods developed here to estimate reference points for other CMAs and the need to evaluate alternative harvest strategies.

We use three methods to identify LRPs and USRs for Dungeness Crab in CMAs I and J: (1) an empirical-based approach as suggested in the PA framework (DFO 2009); (2) a stock-recruitment relationship approach, as outlined in Myers et al. (1994); and (3) a simulation-based approach similar to that in Zhang and Dunham (2013). Provisional reference points are estimated in terms of female CPUE, as it represents the reproductive potential of the stock and can act as an indicator of recruitment overfishing.

2. METHODS

2.1. OVERVIEW

This paper uses three different approaches to develop provisional biological reference points for Dungeness Crab in CMAs I and J. The reference points are based on female catch per unit effort (CPUE), as the stock is currently managed to preserve reproductive potential of Dungeness Crab (i.e., no retention of females and a minimum size limit for males allowing them to reproduce prior to capture in the fishery). We estimated reference points using: (1) empirical methods suggested in the PA framework (DFO 2009); (2) a Beverton-Holt stock-recruitment relationship, as outlined in Myers et al. (1994); and (3) a simulation framework similar to that in Zhang and Dunham (2013). We used a 3-year moving median of female CPUE to determine stock status, and a Bayesian probabilistic approach to incorporate aspects of uncertainty.

We first present the data available for estimating reference points for Dungeness Crab in CMAs I and J (Section 2.2) and then describe each of the methods used to estimate reference points. Justification for specific parameters, the standardization methodology, and the simulation framework are located in appendices.

2.2. DATA

2.2.1. Fishery-Independent Surveys

We used fishery-independent data to estimate the stock-recruitment relationship (Section 2.3.2), and to construct a time-series of abundance indices for legal-sized male, sublegal-sized male, and female Dungeness Crab. DFO has been conducting fishery-independent Dungeness Crab trap surveys in CMAs I and J for over 30 years. These surveys include both a spring (1991-2019, except 2002), and a fall (1988-2019, except 2005) survey each year. We included fishery-independent data from both Crab Management Areas (CMAs) I and J (Figure 1) in this analysis. We standardized the fishery-independent data using generalized linear models to account for changes in survey methodology, environmental conditions, and crab behaviour (Appendix E).

At each survey location in CMA I, a group of 10 traps was set. In the Fraser River delta, traps were set at six different target depths (5, 20, 40, 60, 80, and 100 m). In English Bay, Vancouver Harbour, and Indian Arm, traps were set across the available bathymetry, at depths ranging from ~10 m to ~85 m. Traps were typically baited with two herring, but other fish have been used occasionally. Strings set at less than 10 m, including all sets in CMA J, were single-floated, with a trap spacing of 100 m. Strings set deeper than 5 m used groundlines with a trap spacing of 40 m. The traps are constructed of circular stainless steel with two tunnels and two escape rings that are wired shut. The target soak time was 24 hours. Average soak time was 24.0 ± 11.9 h (mean ± SD), as soak times occasionally vary due to weather or other logistical difficulties (e.g., transit times, vessel traffic, etc.). The number, sex, carapace width, injuries, and shell condition of the crabs caught were recorded. For detailed descriptions of the survey methods and the data collected, see Dunham et al. (2011) and Zhang and Dunham (2013).

2.2.2. Commercial Catch Sampling

Commercial catch sampling data (fishery-dependent) from CMA I and J (Figure 1) were used to estimate proportions of females, legal-sized males, and sublegal-sized males in the catch (Appendix A.1). The current commercial catch sampling program began in 2009. A contracted service provider visits each commercial vessel once per season to collect data. These vessel visits are spaced over the entire season to ensure even sampling of the fishery. During a vessel visit, the service provider collects biological data from a minimum of 50 crabs. Traps are sampled in the order they are retrieved and in their entirety. A minimum of 200 crabs per month must be sampled from all vessel visits combined. For a detailed description of the service provider biological sampling program, see the Pacific Region Integrated Fisheries Management Plan for Dungeness Crab by Trap (DFO 2021a).

2.2.3. Logbook Data

Vessel masters have been required to maintain logbooks documenting their fishing activity as part of their license conditions since 1990. We used this logbook data to estimate exploitation rates for CMA I and J combined (Appendix A.2). The data recorded have varied slightly over time, but in most cases include: the type of trap used, bait type, set position, the number of traps set, soak time, and the number or weight of crabs retained for each set. Using these records, total removals by the fishery and CPUE (crabs per trap) were estimated. However, reliability of the logbook data depends on the accuracy of reporting by each vessel master. Historically, logbook compliance was reported to be low and accuracy questionable prior to 2000 (DFO 2006). Consequently, only logbook records submitted after 2000 were used in the current analyses.

2.2.4. Data Standardization

Fishery-independent data were collected following a survey program that aims to use consistent gear, index locations, bait, and depth (Section 2.2.1). We used generalized linear models to further standardize the fishery-independent data for variation in environmental conditions, changes in survey methodology and animal behaviour (Appendix E). This standardization procedure was carried out for female, sublegal male, and legal male crabs. We used these standardized data to estimate empirical reference points, stock-recruitment relationships, and in the parameterization of the simulation model.

2.2.5. Stock-Status Indicator

We used the female crab standardized CPUE from the fishery-independent survey as the stock-status indicator. This indicator aligns with the management of the fishery, as it represents the reproductive potential of the stock.

We compare the three year running median of the indicator to the reference points to determine the stock status. This is similar to the approach taken in the Oregon Dungeness Crab fishery

(Oregon Department of Fish and Wildlife 2014), and is used to mitigate the high interannual variability in the indicators. The three year running median is used in the assessment of American Lobster to dampen the effect of anomalous years (Cook et al. 2020). A moving average approach is also used to account for variability in survey indexes for Atlantic herring (Clark et al. 2012). We estimated the uncertainty around the reference points and the running median of the indicators in the Bayesian standardization model (Appendix E). We used this approach to quantify the probability of the stock falling below the LRP and USR (i.e., the stock status is “Critical” or “Cautious”).

2.3. ESTIMATION OF REFERENCE POINTS

We estimated reference points using three different methods. First, we estimated empirical reference points using the time-series of standardized CPUE from the DFO fishery-independent spring and fall survey, using the methods outlined in the PA framework in the absence of a model-derived estimate of B_{MSY} (DFO 2009). Second, we estimated a LRP using the stock-recruitment relationship and the method outlined in Myers et al. (1994). Third, we estimated reference points using a modified version of the simulation model in Zhang and Dunham (2013). We describe each below. All reference points are expressed in terms of standardized female CPUE, as estimated in Appendix E.

2.3.1. Empirical Reference Points

We estimated empirical reference points using the standardized survey CPUE based on the guidelines set forth in the DFO PA framework (DFO 2009). This framework outlines two proxies for biomass at maximum sustainable yield (B_{MSY}) that can be used to estimate reference points. First, we used the mean standardized CPUE in the survey over the full time series of data (i.e. B_{Mean}) as a proxy for B_{MSY}:

$$B_{Mean} = \frac{\sum CPUE}{N_{years}} \tag{1}$$

where $CPUE$ is the standardized CPUE index in each year, and N_{years} is the number of years for which data was available.

Second, we estimated B_{MSY} as 50% of the maximum observed standardized index of CPUE (i.e. B_{Max}):

$$B_{Max} = 0.5 \times Max(CPUE) \tag{2}$$

The PA policy recommends an LRP of 40% B_{MSY} and an USR of 80% B_{MSY}. We estimated the LRP and USR for each B_{MSY} proxy: B_{Mean} (LRP_{Mean} and USR_{Mean}); and B_{Max} (LRP_{Max} and USR_{Max}).

We estimated reference points using fishery-independent survey data as it is preferable to commercial data given that it removes many of the biases and uncertainties associated with commercial catch which can result in it being a poor indicator of true underlying abundance (Hilborn and Walters 1992). For example, improvements to commercial gear over time increase gear efficiency resulting in CPUE in recent years that may be biased higher relative to earlier years. In contrast, the DFO crab surveys have used comparatively consistent methods over the entire time series. We used further statistical standardization to ensure as accurate an index as possible. Commercial catch data are also an imperfect measure of total removals, as there are considerable removals from recreational, FSC, and illegal fisheries that are not included in commercial catch reporting.

2.3.2. Stock-Recruitment Reference Points

We used the Beverton-Holt stock-recruitment model (Beverton and Holt 1957) to describe the relationship between female standardized CPUE and sublegal-sized male standardized CPUE:

$$R = \frac{(\alpha \times S)}{(\beta + S)} \times \mathrm{e}^{\epsilon} \tag{3}$$

where S represents female standardized CPUE and R denotes sublegal-sized male standardized CPUE four years later. α and β are the model parameters, where α is the asymptotic recruitment (sublegal-sized male CPUE) and β is the female CPUE needed to produce sublegal-sized male recruitment equal to $\frac{\alpha}{2}$. ϵ is a random variate from a normal distribution with a mean of 0 and variance of σ_{ϵ}. We estimated α and β using non-linear least squares regression after log-transforming both sides of Equation 3, because we assume model errors to be lognormally distributed. This assumption was verified through residual quantiles.

We used a lag of four years between female CPUE and sublegal-sized male CPUE for the stock-recruitment relationship because male Dungeness Crab take approximately four years to reach the legal size limit (165 mm "point-to-point") from the time of hatching (Butler 1961). Since the fall survey occurs prior to eggs hatching the following spring, a four year lag was assumed to best describe the recruitment dynamics of sublegal-sized males in relation to the females that acted as spawners.

We estimated the LRP based on the stock-recruitment relationship (LRP_{S-R}) by determining the spawners (female CPUE) that result in recruitment (sublegal-sized male CPUE) of half the asymptotic recruitment (i.e. $\frac{\alpha}{2}$; (Myers et al. 1994; Duplisea and Fréchet 2009)) which in the parameterization of the Beverton-Holt used in this paper is equal to β. Myers et al. (1994) do not define a method for estimating the USR this way, but following the logic of the PA policy (DFO 2009), we recommend the USR to be set at $2 \times \beta$.

2.3.3. Simulation Reference Points

Following methods similar to those originally described by Zhang and Dunham (2013), we used simulations to test how the Dungeness Crab stock in CMAs I and J might respond to fixed fishing effort if productivity of the stock changes. We evaluated the impact of sustaining the current fishing effort in scenarios where Dungeness Crab abundance is low (defined as initial female CPUE between 0.1 - 4 female crabs per trap) and calculated the resulting equilibrium female CPUE. The reference points developed from these simulations originally relied on the assumed shape of the underlying stock-recruitment relationship, in this case a Beverton-Holt model. This assumption was not appropriate because the Beverton-Holt model assumes recruitment rate increases when spawning stock size decreases, when the population may actually stabilize at a low equilibrium (Peterman 1977). We therefore made the more conservative assumption that when female abundance is low, the Dungeness Crab population would have lower compensatory recruitment than expected from the Beverton-Holt model. This assumption is intended to reflect scenarios where productivity may be reduced due to changing physical (e.g., ocean temperature, salinity, acidity, etc.) and biological (e.g., predation, mate limitation, etc.) variables.

The basic framework for each simulation is as follows. We estimated the number of female crabs at the start of the season in reverse, from the selected initial value of female CPUE at the end of the season, assuming no fishing (equilibrium without fishing) and using estimates of natural mortality and moulting rates. This equilibrium number of females at the start of the season was used to estimate the number of legal-sized males at the start of the season, which in turn was used to initialize the next step of the simulation where fishing effort was included. The starting value of female CPUE in the simulation acts to scale the productivity of the stock. In the fishing step of the simulation, the population in each year grew based on the assumed stock-recruitment relationships, size-ratios, and moulting rates, and decreased through natural, fishing, and handling mortality. The stock was simulated on an annual time step until a new equilibrium female CPUE was reached (equilibrium with fishing). This simulation framework is presented in detail in Appendix B and in a schematic in Figure 2.

Simulation-based reference points (LRP_{Sim}, USR_{Sim}) were derived from the fished equilibrium female CPUE and combined with the empirical reference points (Section 2.3.1) to account for a potential decrease in productivity at low levels of female abundance. Specifically, the empirical reference points were matched to the nearest fished equilibrium female CPUE, and the corresponding initial unfished equilibrium female CPUE was taken as the simulation-based reference point. We specifically used the empirical reference points derived from B_{Mean}, the mean value of the female CPUE in the DFO survey, although any of the reference points derived from the other methods could have been used.

2.4. ABUNDANCE TRENDS

We estimated standardized CPUE (crabs per trap) for legal-sized male crabs, sublegal-sized male crabs, and female crabs and assessed qualitative trends (i.e., periods of increase or decrease). We compared female crab CPUE to estimated reference points. Since crab populations naturally fluctuate with environmental variables (Shanks and Roegner 2007), we used a three year moving median of CPUE to determine when the LRP and USR had been reached. The assessment of Dungeness Crab in Oregon applies a four-year approach to determine when the LRP is breached (Oregon Department of Fish and Wildlife 2014), and American Lobster uses a three-year approach (Cook et al. 2020). The three-year time frame here was chosen based on these considerations.

2.5. UNCERTAINTY

Fishery-independent standardized CPUE was estimated in a Bayesian framework (Appendix E), which resulted in 4000 posterior samples for each model parameter. For each posterior sample, we generated a time-series of standardized female CPUE using the methods outlined in Appendix E. We estimated stock-status indicators (three-year running medians) and empirical reference points for each of these time-series, thereby estimating a posterior distribution of the indicator and reference points. The same approach was used to estimate a posterior distribution for the stock-recruitment reference points, by randomly selecting a posterior draw each for female and sublegal-sized male CPUE, and using the equations in Section 2.3.2. We can then estimate the uncertainty in the stock status, by estimating the proportion of posterior samples in which the stock status indicator (three year moving median in CPUE) falls below the chosen limit reference point. Full information on the Bayesian standardization model is available in Appendix E. The simulation reference points estimated in Section 2.3.3, are entirely deterministic, and do not support estimation of uncertainty.

3. RESULTS

3.1. ESTIMATED REFERENCE POINTS

3.1.1. Empirical Reference Points

The female B_{Mean} (mean standardized female CPUE index in the DFO fishery-independent survey) is 0.57 female crabs per trap and B_{Max} (50% of the maximum observed female CPUE) is 0.775 female crabs per trap. Setting the LRP at 40% of B_{Mean} and B_{Max}, as per the PA (DFO 2009), results in LRPs (with 95% Bayesian credibility interval in brackets) of 0.228 (0.089, 0.542) and 0.310 (0.117, 0.776) female crabs per trap, respectively. The corresponding USRs, set at 80% of B_{Mean} and B_{Max}, are 0.456 (0.179, 1.083) and 0.620 (0.233, 1.552) female crabs per trap. We assumed the entire time series represented a productive time period, as previous risk assessments have consistently considered the stock to be healthy.

3.1.2. Stock - Recruitment Reference Points

We estimated the best-fitting Beverton-Holt stock-recruitment parameters α and β as 1.283 (0.927, 1.969) and 0.439 (0.105, 2.611), respectively (Figure 3). The corresponding stock-recruitment LRP (LRP_{S-R}) was 0.439 female crabs per trap in the DFO fall survey. Doubling the value results in a recommended USR (USR_{S-R}) of 0.878 female crabs per trap.

3.1.3. Simulation Reference Points

The simulation-based LRP and USR correspond to the empirical reference points estimated from B_{Mean} (40% and 80% respectively of the mean female CPUE in the DFO fall survey), but are expressed in terms of which initial equilibrium female CPUE in the simulation resulted in a final fished equilibrium female CPUE equal to the LRP_{Mean} and USR_{Mean} (Table 1). The simulation-based LRP_{Sim} and USR_{Sim} are 0.3 and 0.5 female crabs per trap, respectively.

3.2. ABUNDANCE TRENDS

3.2.1. Legal-sized Male Crabs

The survey standardized CPUE time series for legal-sized male crabs shows considerable variation. There are cycles between periods of high and low abundance (standardized CPUE) throughout the time series (Figure 4). Legal-sized male standardized CPUE ranged from 0.358 to 1.856 crabs per trap.

3.2.2. Sublegal-sized Male Crabs

The survey CPUE time series for sublegal-sized male crabs also shows considerable variation. The same cycles between periods of high and low abundance (CPUE) that appear in the legal-sized male time series appear for sublegal males. The survey CPUE index reached a minimum in 2009 (Figure 5). Sublegal-sized male standardized CPUE ranged from 0.939 to 4.339 crabs per trap.

3.2.3. Female Crabs

The cycles between periods of high and low abundance (standardized CPUE) that appear for male crabs are less apparent in the female CPUE time series. The time series of female abundance (standardized CPUE) has declined since the start of the survey in 1988, but has been stable for the past ~15 years. The female survey standardized CPUE reached the minimum value in 2009 (Figure 6, Figure 7). Female standardized CPUE ranged from 0.174 to 1.438 crabs per trap.

3.3. UNCERTAINTY IN STOCK STATUS AND REFERENCE POINTS

The uncertainty around the stock status indicators in each year was estimated using a Bayesian approach (Appendix E). The uncertainty around the reference points was estimated in the same framework. We estimated the probability LRP_{Mean} was breached by both the female indicator in each year (Table 2). In 2019, there was a probability of < 0.001 that the indicator was below the LRP_{Mean} . The indicator had the highest probability of breaching the LRP in 2010 (0.411). We only included the uncertainty estimates for the Limit Reference Point we consider to be most appropriate (LRP_{Mean}).

4. DISCUSSION

In this paper, we used CPUE-based abundance indices to assess long-term trends in Dungeness Crab abundance for CMAs I and J and to develop reference points based on empirical, stock-recruitment, and simulation-based approaches. Females and sublegal-sized males have both shown some decline in standardized fishery-independent CPUE over the time series (1988-2019), although both have been stabilized or increasing in the recent years. Empirical and simulation-based reference points were relatively similar, with LRPs ranging from 0.228 (LRP_{Mean}) to 0.3 (LRP_{Sim}) and USRs ranging from 0.456 (USR_{Mean}) to 0.5 (USR_{Sim}) female crabs per trap. These reference points suggest the CMA I and J indicator is currently in the Cautious Zone. The stock-recruitment-based LRP (LRP_{S-R}) was higher at 0.439, with a USR (USR_{S-R}) of 0.878 crabs per trap.

4.1. EMPIRICAL REFERENCE POINTS

Despite being derived independently of each other, there is very little difference between the two empirical LRPs based on either mean (B_{Mean}) or max (B_{Max}) CPUE, at 0.228 and 0.310 female crabs per trap. The Precautionary Approach framework favors the B_{Mean} method over the B_{Max} method. This is especially relevant in this case, as the fishery predates the fishery-independent survey. We therefore cannot reasonably assume the B_{Max} is representative of the unfished biomass.

Based on our chosen empirical reference points (B_{Mean}), the Dungeness Crab stock in CMAs I and J is assessed as being in the Cautious Zone using the female indicator (i.e., below the USR, but above the LRP). The stock has never breached the empirical LRP. The Bayesian estimate of the probability that the stock breached the LRP in 2019 is < 0.001. There has generally been very low (<5%, per the PA policy (DFO 2009)) probability of the stock being in the Critical Zone (Table 2).

Although these empirically-based B_{MSY} proxy methods are computationally simple, they are among the most commonly used methods to estimate biological reference points in Canada, especially for crustaceans (Marentette et al. 2021).

4.2. STOCK-RECRUITMENT REFERENCE POINTS

There is only a scientific basis for estimating a LRP from the stock-recruitment relationship; however, following the logic of the PA policy (DFO 2009) the USR can be estimated as double the LRP. We do not recommend this method moving forward, as the results are biologically implausible due to the inability to characterize the stock-recruitment relationship. There is very little evidence of asymptotic recruitment in Dungeness Crab based on the shape of the stock-recruitment relationship (Figure 3). The lack of support for the stock-recruitment relationship is further evidenced by the high degree of uncertainty in the stock-recruitment parameters. A number of factors contribute to the uncertainty in the stock-recruitment relationship. The recruitment data does not appear to approach an asymptote, making it impossible to estimate the parameter for asymptotic recruitment (α), as well as the correlated β parameter. Environmental variation has a significant effect on crab recruitment, making the stock-recruitment relationship complex and statistically noisy (Shanks and Roegner 2007).

Based on the stock-recruitment relationship, the estimated stock status has not been above the LRP_{S-R} since 2004 (Figure 6, Figure 7). In spite of this, commercial landings remained consistent through the 1990s and increased up to 2009 (Figure 8) and the survey female CPUE index has showed periods of increase and stability. The reference point based on the stock-recruitment relationship appears to be inestimable because of the lack of asymptotic recruitment in the time series and large interannual variability. We therefore do not consider this reference point to be credible for CMAs I and J.

4.3. SIMULATION REFERENCE POINTS

Based on the simulation reference points (LRP of 0.2 and an USR of 0.5 female crabs per trap) the stock is in the Cautious Zone, having reached the USR in 2008. The stock reached the LRP in 2008, based on these reference points, and recovered above the reference point in 2012. The simulation-based reference points are slightly higher than the empirical reference points (e.g., LRP_{Mean} is 0.228, while LRP_{Sim} is 0.3 female crabs per trap).

The simulation framework we adapted from Zhang and Dunham (2013) required making some key assumptions about the relationship between female abundance and sub-legal male recruitment four years later (i.e., the stock-recruitment relationship). This includes a lack of compensation at low abundance (CPUE) and that the productivity of the stock depends on the initial female CPUE at the beginning of the simulation. At low levels of abundance (i.e., where an LRP would typically be set) traditional stock-recruitment models such as the Beverton-Holt (Beverton and Holt 1957) may not be appropriate for modelling population growth. At low levels of spawning stock, stock-recruitment models predict high levels of recruitment, known as compensatory growth. In reality, we may see lower levels of recruitment at these low abundances, due to factors such as the Allee effect (Courchamp et al. 2008). The assumptions of the model may result in some unrealistic stock dynamics in the simulated scenarios. For example, the simulated crab stock will not recover even if fishing stops. These depensatory dynamics hypothesized in Zhang and Dunham (2013) may not be at play in the Dungeness Crab stock in CMAs I and J. Due to the complex nature of the simulation framework, the simulation-based reference points can be more challenging to interpret and apply relative to the other candidate reference points that rely on simpler analyses of field data that require fewer assumptions about underlying population processes. However, they provide a complementary approach against which to compare LRPs estimated using other methods.

4.4. UNCERTAINTIES

4.4.1. Impacts of Climate Change

Changes in ocean conditions due to climate change are a major concern for many marine species, including Dungeness Crab. The productivity of Dungeness Crab in the future is uncertain due to possible changes in ocean temperature, acidity, and oxygen concentration (Berger et al. 2021). Increasingly hypoxic ocean conditions will be particularly harmful for the adult life stage. Hypoxia may be unlikely in the Fraser delta, due to the constant supply of oxygenated fresh water, but could be a concern in other regions. Larval life stages are expected to be adversely affected by decreasing ocean pH, due to the impact on calcified structures. These changes in ocean conditions may manifest in increased natural mortality or decreased productivity. The coastwide population of Dungeness Crab in BC may also be affected by changes in larval transport, due to changes in ocean circulation (Mcconnaughey and Armstrong 1995). In the Dungeness Crab fisheries in Oregon and California, most of the fluctuations in abundance were due to oceanographic conditions affecting juvenile life stages, not due to fishing pressure (Shanks and Roegner 2007).

4.4.2. Population Structure

It is assumed that sub-populations of Dungeness Crab are connected via larval transport; however, the degree of connectivity remains uncertain. The Strait of Georgia may be oceanographically isolated from the coastwide population. Based on morphological differences between Dungeness Crab megalopae, the Strait of Georgia Dungeness population may be semi-isolated from the offshore population (DeBrosse et al. 1990). There is evidence of genetic isolation in other species; for example, Yelloweye Rockfish (COSEWIC 2008) and Pacific Cod (Cunningham et al . 2009) populations in the Georgia Basin have been shown to be genetically distinct from coastwide populations. Genetic analysis of Dungeness Crab in British Columbia and Oregon identified some connectivity between Oregon and Boundary Bay, but minimal connectivity between Boundary Bay and Allison Sound (within BC) (O'Malley et al. 2017). It is therefore uncertain that there is one single coastwide stock Spatial mismatch between operational units (e.g., assumed coastwide stock) and biological units (e.g., possible multi-stock structure) represents a serious conservation concern (Reiss et al. 2009). A coastwide assessment of Dungeness Crab connectivity would allow for better estimation of the most appropriate spatial scale at which to derive reference points.

4.5. APPLICATION TO OTHER CMAS AND FUTURE CONSIDERATIONS

The approach used in this paper can be applied to other CMAs to estimate reference points, but some adaptations will need to be made based on the available data. CMAs I and J are considered the most data-rich areas for Dungeness Crab in BC, as other areas do not have the same degree of fishery-independent data. It is quantitatively possible to apply this approach to the commercial catch sampling data; however, there are some considerations. Given that female crabs cannot be retained in commercial fisheries, commercial harvesters tend to avoid areas that are suspected to contain more female crabs. Female and male crabs have been shown to occupy different habitats and exhibit different behaviours (Stone and O'Clair 2002). The Precautionary Approach empirical reference points (DFO 2009) can be applied using commercial landing data, as has been done in other crustacean fisheries (e.g., Tremblay et al. 2012). Future programs could be developed to collect more appropriate fishery independent data, similar to the surveys in CMAs I and J. Alternatively, new forms of data such as larval abundance could be collected, as it has been shown to be predictive of commercial catch (Shanks et al. 2010). The flexibility of the empirical reference points to a wide range of data sources make them an attractive option for estimating reference points in the future.

The abundance index of female crabs in CMAs I and J has decreased since the inception of the survey, despite management effort to protect female crabs. Illegal retention and excessive handling of female crabs are likely sources of mortality causing this decline. Also, illegal retention of sublegal-sized male crabs combined with the high exploitation of legal male crabs, may have reduced the number of males in the population, which can have a detrimental effect on the reproductive dynamics. However, as observed from survey data, the magnitude of the decline in female survey index is greater than the decline in legal-sized and sublegal-sized males. A focus on protecting female crabs, specifically with respect to illegal fishing, may improve the stock status.

5. RECOMMENDATIONS

1. We recommend using empirically based methods for setting reference points for Dungeness Crabs in CMAs I and J. Specifically, reference points should be based on the mean value of the fishery-independent time series (LRP_{Mean} and USR_{Mean}). These empirical reference points are simple to compute and understand unlike the stock-recruitment and simulation reference points. The methodology outlined is consistent with other Canadian crustacean fisheries and involves fewer assumptions about underlying population processes.
2. Use the three-year running median in female standardized CPUE in order to account for natural variability in crab populations.
3. Set a LRP at 0.228 female standardized CPUE in the fishery-independent survey.
4. Set a USR at 0.456 female standardized CPUE in the fishery-independent survey.
5. Explore the utility of applying the empirical methods to estimate reference points for Dungeness Crabs in other CMAs in British Columbia. This approach may require modification of existing sampling programs or the implementation of new sampling programs, where none exist, to develop an index of female abundance.

6. ACKNOWLEDGEMENTS

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8. TABLES

Table 1. Estimated reduction in female and sublegal-sized CPUE for an initial female CPUE.

Initial Female CPUE	Final Female CPUE	Female Percent Reduction	Initial Sublegal CPUE	Final Sublegal CPUE	Sublegal Percent Reduction
0.1	0.087	12.581	0.988	0.900	8.855
0.2	0.183	8.666	1.491	1.422	4.611
0.3	0.278	7.203	1.796	1.741	3.078
0.4	0.373	6.677	2.001	1.953	2.387
0.5	0.468	6.322	2.148	2.106	1.943
0.6	0.564	6.068	2.258	2.221	1.634
0.7	0.659	5.877	2.344	2.311	1.409
0.8	0.756	5.529	2.413	2.384	1.192
0.9	0.851	5.445	2.470	2.443	1.068
1.0	0.946	5.375	2.517	2.493	0.968
1.1	1.042	5.316	2.557	2.534	0.884
1.2	1.137	5.264	2.591	2.570	0.813
1.3	1.232	5.220	2.621	2.601	0.753
1.4	1.327	5.181	2.647	2.629	0.701
1.5	1.423	5.147	2.670	2.653	0.656
1.6	1.518	5.116	2.691	2.674	0.616
1.7	1.613	5.089	2.709	2.693	0.581
1.8	1.709	5.064	2.725	2.710	0.549
1.9	1.804	5.042	2.740	2.726	0.521
2.0	1.900	5.022	2.754	2.740	0.495
2.1	1.995	5.003	2.766	2.753	0.472
2.2	2.090	4.986	2.778	2.765	0.451
2.3	2.186	4.971	2.788	2.776	0.431
2.4	2.281	4.956	2.798	2.786	0.414
2.5	2.376	4.943	2.807	2.796	0.397
2.6	2.472	4.930	2.815	2.804	0.382
2.7	2.567	4.919	2.823	2.812	0.368
2.8	2.663	4.908	2.830	2.820	0.355
2.9	2.758	4.898	2.837	2.827	0.343
3.0	2.853	4.888	2.843	2.834	0.332
3.1	2.949	4.879	2.849	2.840	0.321
3.2	3.044	4.871	2.855	2.846	0.311
3.3	3.140	4.863	2.860	2.851	0.302
3.4	3.235	4.855	2.865	2.856	0.293
3.5	3.330	4.848	2.870	2.861	0.285
3.6	3.426	4.842	2.874	2.866	0.277
3.7	3.521	4.835	2.878	2.871	0.269
3.8	3.616	4.829	2.882	2.875	0.262
3.9	3.712	4.823	2.886	2.879	0.256
4.0	3.807	4.818	2.890	2.883	0.249

Table 2. Bayesian estimate of the probability that the three-year moving median of female CPUE from the fishing-independent survey is less than the LRP_{Mean} and USR_{Mean} in a given year.

Year	P(Stock<LRP)	P(Stock<USR)
1990	<0.001	0.000
1991	<0.001	0.216
1992	<0.001	0.000
1993	<0.001	0.009
1994	<0.001	0.000
1995	<0.001	0.000
1996	<0.001	0.000
1997	<0.001	0.000
1998	<0.001	0.000
1999	<0.001	0.002
2000	<0.001	0.002
2001	<0.001	0.000
2002	<0.001	0.036
2003	<0.001	0.067
2004	<0.001	0.150
2005	<0.001	0.822
2006	0.004	0.997
2007	0.004	0.990
2008	0.102	1.000
2009	0.326	1.000
2010	0.411	1.000
2011	0.129	1.000
2012	<0.001	0.791
2013	<0.001	0.787
2014	<0.001	0.984
2015	<0.001	0.989
2016	<0.001	0.889
2017	<0.001	0.893
2018	<0.001	0.970
2019	<0.001	0.980

9. FIGURES

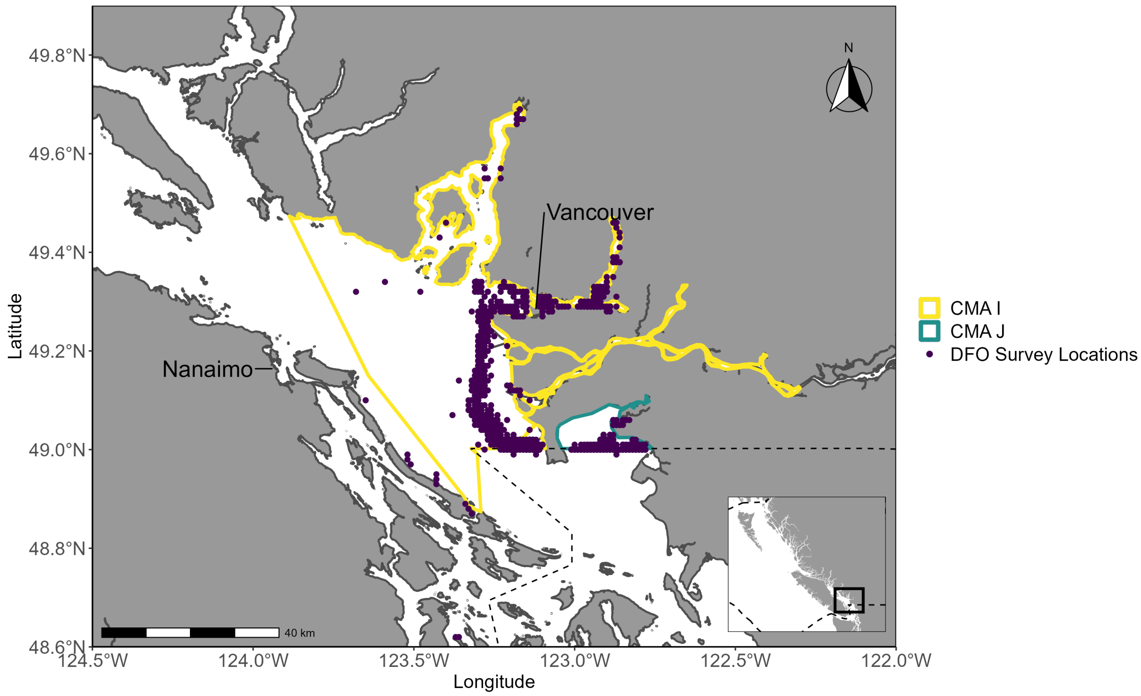

Figure 1. Commercial catch and fishery-independent data were collected in Crab Management Areas (CMAs) I and J. Points indicate locations of Fisheries and Oceans Canada (DFO) Dungeness Crab trap surveys.

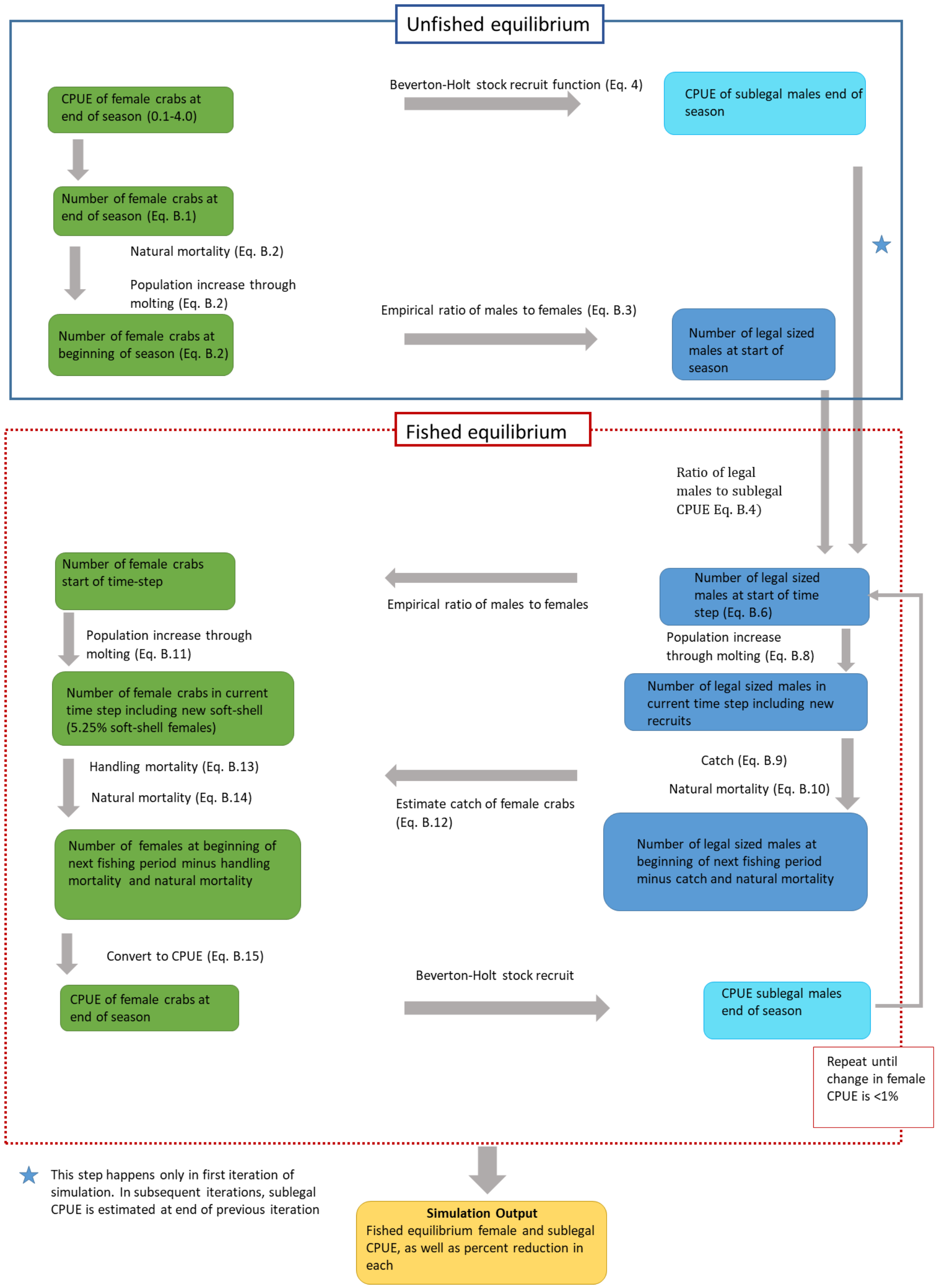

Figure 2. Schematic of simulation framework used to estimate provisional simulated-based reference points. For specific equations, see Appendix B.

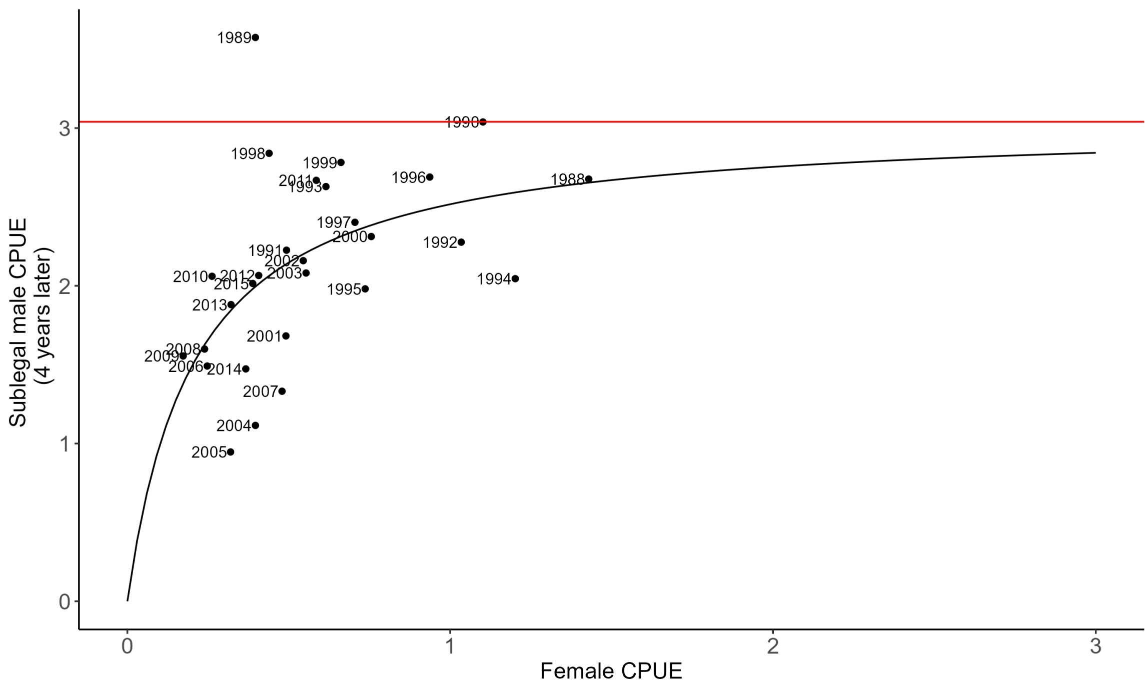

Figure 3. Beverton-Holt stock-recruitment relationship between sublegal-sized male catch per unit effort (CPUE, crabs per trap) (with a four-year lag) and female catch per unit effort (CPUE, crabs per trap) in the fall survey. The red line indicates the estimate of asymptotic recruitment.

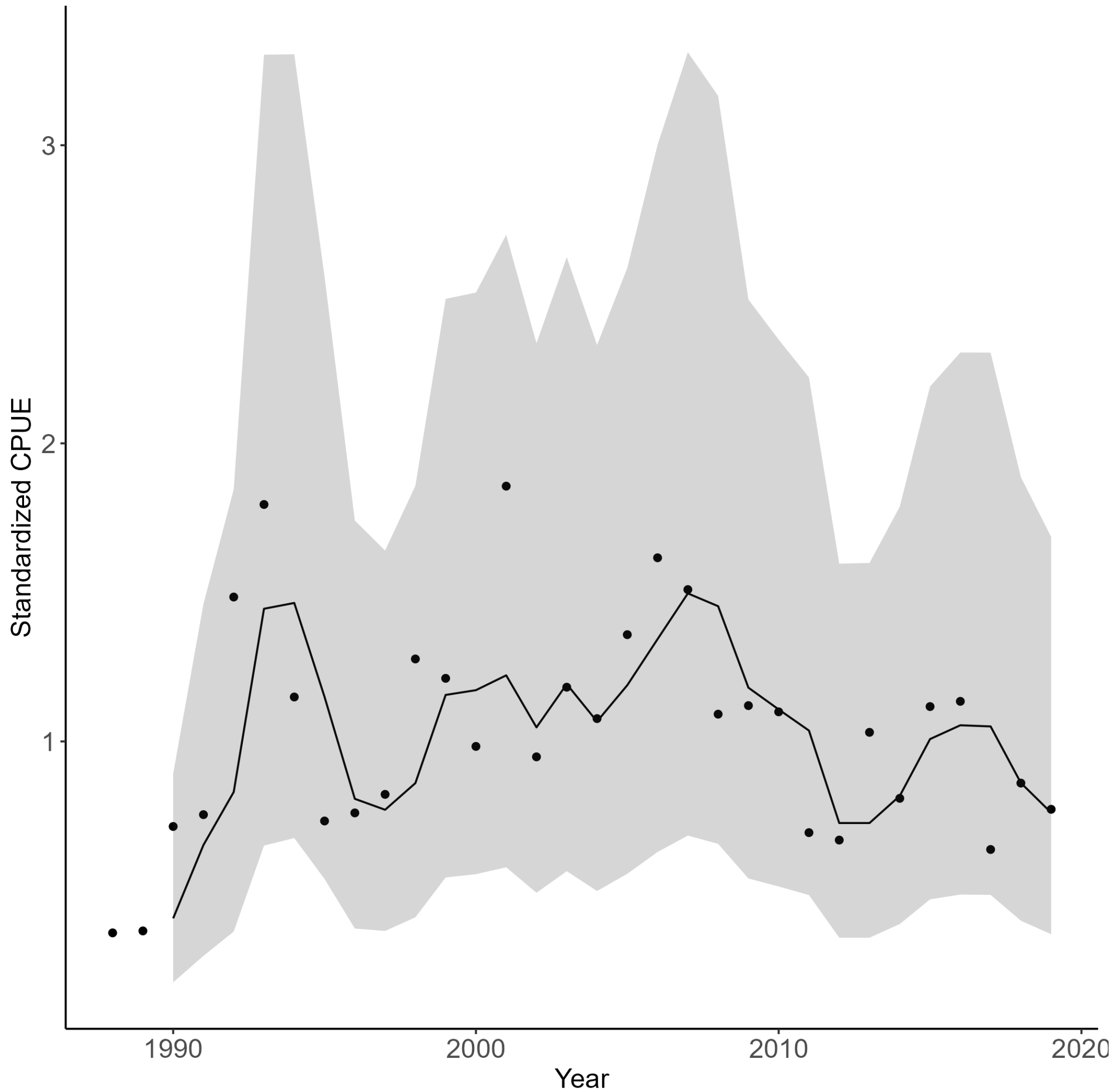

Figure 4. Legal male standardized catch-per-unit-effort (CPUE, crabs per trap) in the Fisheries and Oceans Canada fishery-independent survey. The black line represents a three-year moving median of legal male CPUE, with the 95% credibility interval represented by the shaded region.

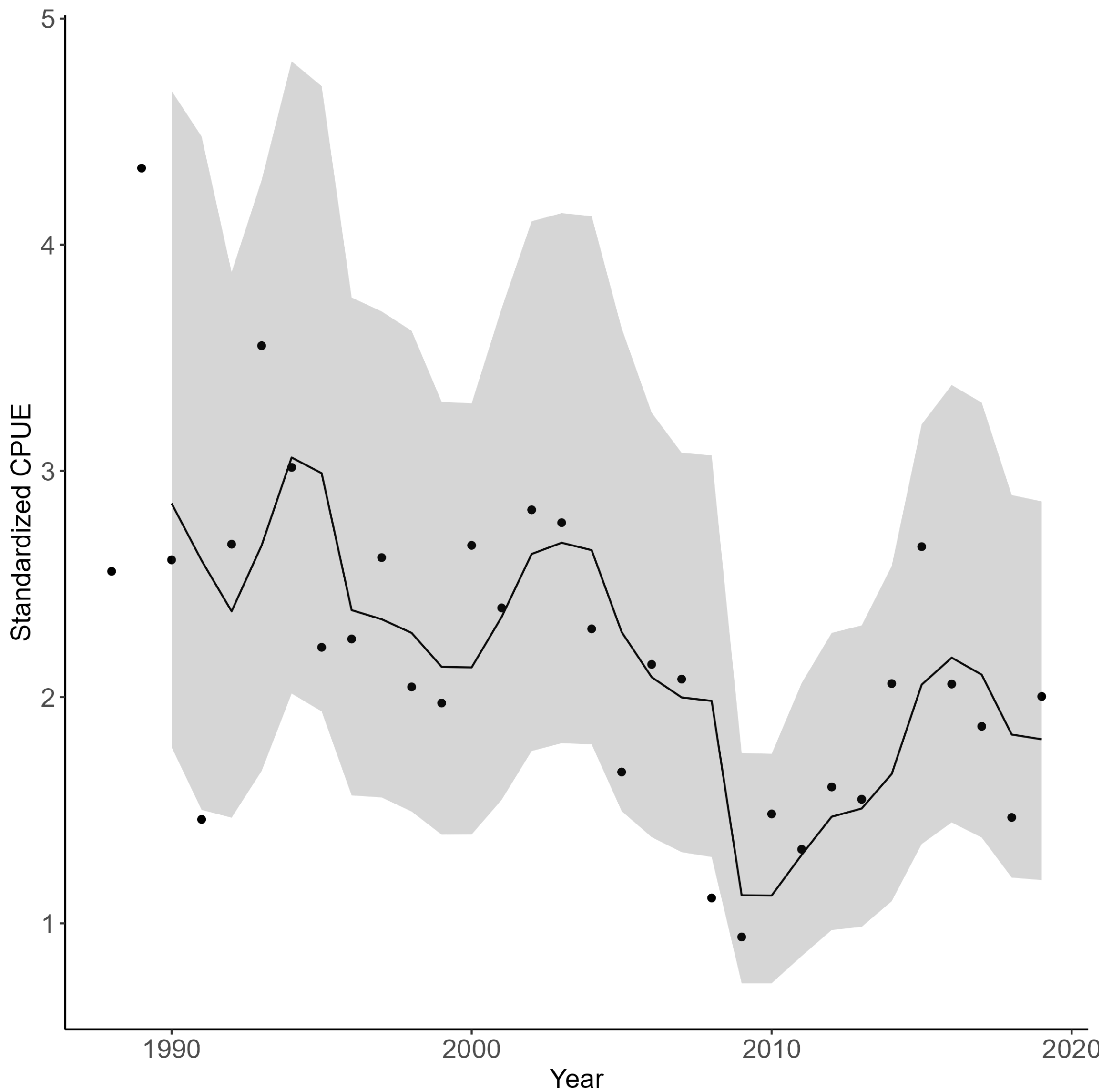

Figure 5. Sublegal male standardized catch-per-unit-effort (CPUE, crabs per trap) in the Fisheries and Oceans Canada fishery-independent survey. The black line represents a three-year moving median of sublegal male CPUE, with the 95% credibility interval represented by the shaded region.

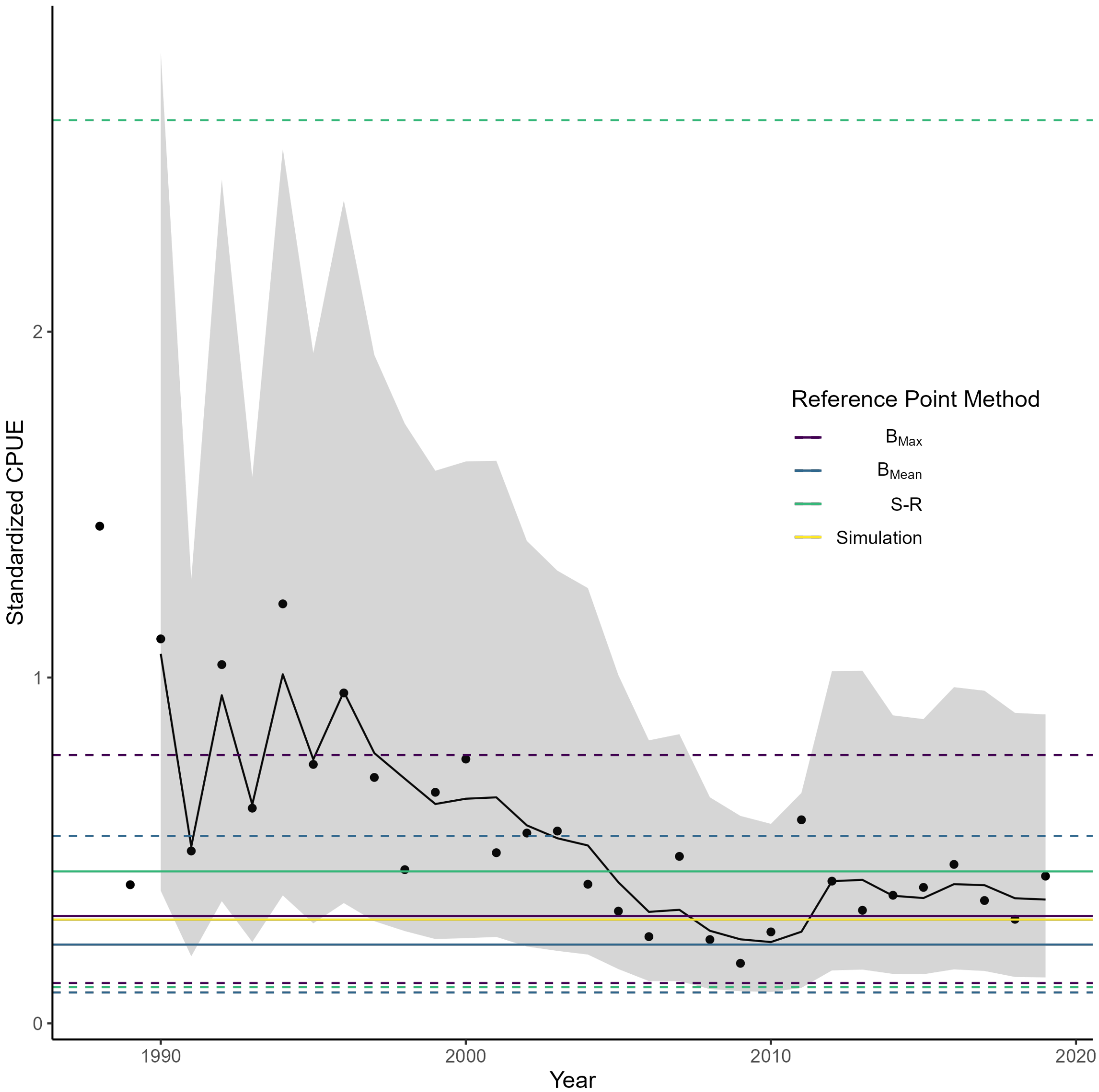

Figure 6. Female standardized catch-per-unit-effort (CPUE, crabs per trap) in the Fisheries and Oceans Canada fishery-independent survey. Horizontal solid lines represent limit reference points, and dashed lines represent Bayesian 95% credibility intervals. Each colour represents a different method of estimating reference points. The black line represents a three-year moving median of female CPUE, with the 95 % credibility interval represented by the shaded region.

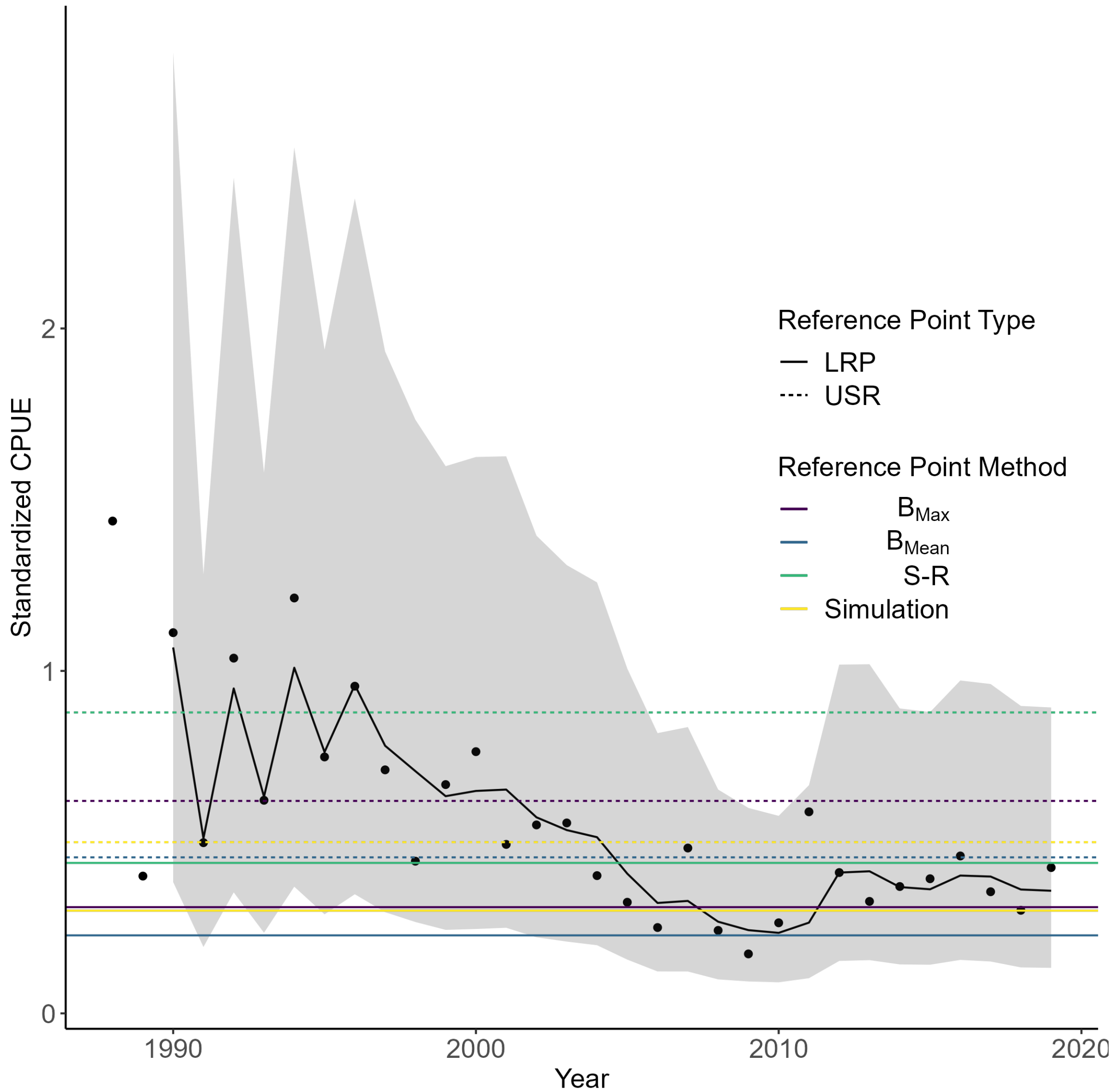

Figure 7. Female standardized catch-per-unit-effort (CPUE, crabs per trap) in the Fisheries and Oceans Canada fishery-independent survey. Horizontal lines represent provisional reference points. Each colour represents a different method of estimating reference points. Solid lines represent limit reference points (LRPs), and dashed lines represent upper stock reference points (USRs). The black line represents a three-year moving median of female CPUE, with the 95% credibility interval represented by the shaded region.

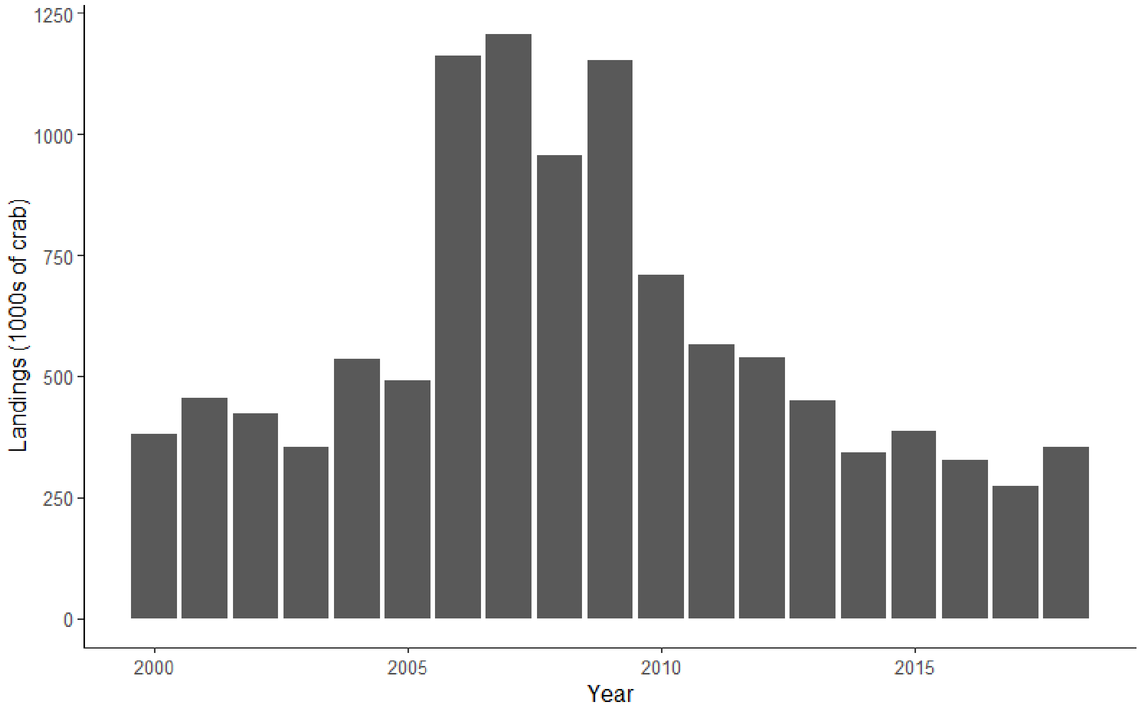

Figure 8. Commercial landings (1000s of crab) between 2000 and 2019 in the portion of Crab Management Areas I and J used in this analysis.

APPENDIX A. IDENTIFYING APPROPRIATE PARAMETER VALUES

A.1. ESTIMATING PROPORTION OF SOFT CRABS AND PROPORTION OF FEMALES IN CATCH

We used a Bayesian generalized linear model to estimate the proportion of sublegal-sized male, legal-sized male (PSL), and female crabs (PSF) that were soft following moulting in the commercial catch in each fishing period. We modeled time discretely because service provider sampling can be sporadic, and binning sampling events in time simplified the model. We also used this Bayesian approach to estimate the proportion of female crabs in the catch of female crabs and legal-sized male crabs (PF). For clarity, this section will focus solely on estimating the proportion of legal-sized males that were soft, though the same model was used to estimate the other proportions. The number of legal-sized male crabs that were soft-shelled ($N_{y,i}$) for a given year (y), and fishing period (i) was assumed to follow a binomial distribution as there are only two possible outcomes (i.e., a crab is hard or soft):

$$N_{y,i} \sim B(TN_{y,i}, p_{y,i}) \quad \text{(A.1)}$$

where $TN_{y,i}$ is the total number of hard and soft legal-sized male crabs in the catch, and $p_{y,i}$ denotes the probability that a legal-sized male crab will be soft in year y and period i. Effects of year (YE) and fishing period (PE) on p were estimated using the logit link function:

$$logit(p_{y,i}) = YE_y + PE_{y,i} + \phi_{y,i} \quad \text{(A.2)}$$

where ϕ is a random variate from a normal distribution with mean 0 and variance σ^2_ϕ. Year effects are assumed to be normally distributed with a hierarchical structure:

$$YE_y \sim N(\Upsilon, \sigma^2_\Upsilon) \quad \text{(A.3)}$$

with hyperpriors Υ and σ^2_Υ, where Υ is the overall mean of the year effect, and σ^2_Υ is the variance of the normal distribution. The hierarchical structure allows the proportion of hard and soft lega-sized males to vary between years, while still incorporating shared information between years. Fishing period effects are similarly assumed to be normally distributed with a hierarchical structure:

$$PE_{y,i} \sim N(\Psi_i, \sigma^2_\Psi) \quad \text{(A.4)}$$

with hyperpriors Ψ and σ^2_Ψ, where Ψ is the overall mean of the fishing period effect, and σ^2_Ψ is the variance of the normal distribution.

Expected proportion of soft legal-sized males in each period was calculated as:

$$PSL_i = \frac{e^{\Upsilon+\Psi_i}}{1 + e^{\Upsilon+\Psi_i}} \quad \text{(A.5)}$$

The Bayesian analyses were conducted to produce posterior probability distributions for the parameters using RStan (Stan Development Team 2020). Vague priors were imposed to allow parameters to be estimated from the data. Model priors are listed in Table A.1. Four chains were used, with 10000 iterations per chain. The first 5000 iterations on each chain were used as warm-up. Convergence was regarded to have been reached, as $\hat{R}$ values in the RStan output were close to 1 (Vehtari et al. 2021).

Table A.1. Priors used in Bayesian estimation of proportions

Parameter	Description
$\Upsilon \sim N(0, 10^2)$	Prior on Υ
$\Psi \sim N(0, 10^2)$	Prior on Ψ
$\sigma_\phi \sim Cauchy(0, 5)$	Prior on σ_ϕ
$\sigma_\Upsilon \sim Cauchy(0, 5)$	Prior on σ_Υ
$\sigma_\Psi \sim Cauchy(0, 5)$	Prior on σ_Ψ

A.1.1. Proportions of Soft Crabs Results

The estimated proportion of soft legal-sized males was relatively constant throughout the fishing season (Figure A.1). The proportion of soft sublegal-sized crabs decreased in the second half of the fishing season (Figure A.2). The proportion of female crabs that were soft peaked in the early season (Period 3) and was generally low otherwise (Figure A.3). The proportion of females in the catch of female and legal-sized male crabs peaked in the middle of the fishing season and was lowest at the end of the fishing season (Figure A.4).

Table A.2. Estimated proportion of soft female, legal-sized, and sublegal-sized crabs in commercial catch for each fishing period, as well as the proportion of female crabs in the catch of female and legal male crabs.

Period	Soft Females (PSF)	Soft Legals (PSL)	Soft Sublegals	Females in Catch (PF)
1	0.146	0.184	0.235	0.261
2	0.272	0.163	0.213	0.314
3	0.482	0.196	0.274	0.425
4	0.379	0.254	0.325	0.447
5	0.308	0.193	0.255	0.540
6	0.165	0.167	0.248	0.698
7	0.148	0.240	0.254	0.376
8	0.127	0.111	0.224	0.447
9	0.043	0.195	0.187	0.354
10	0.102	0.100	0.140	0.288
11	0.077	0.172	0.084	0.085

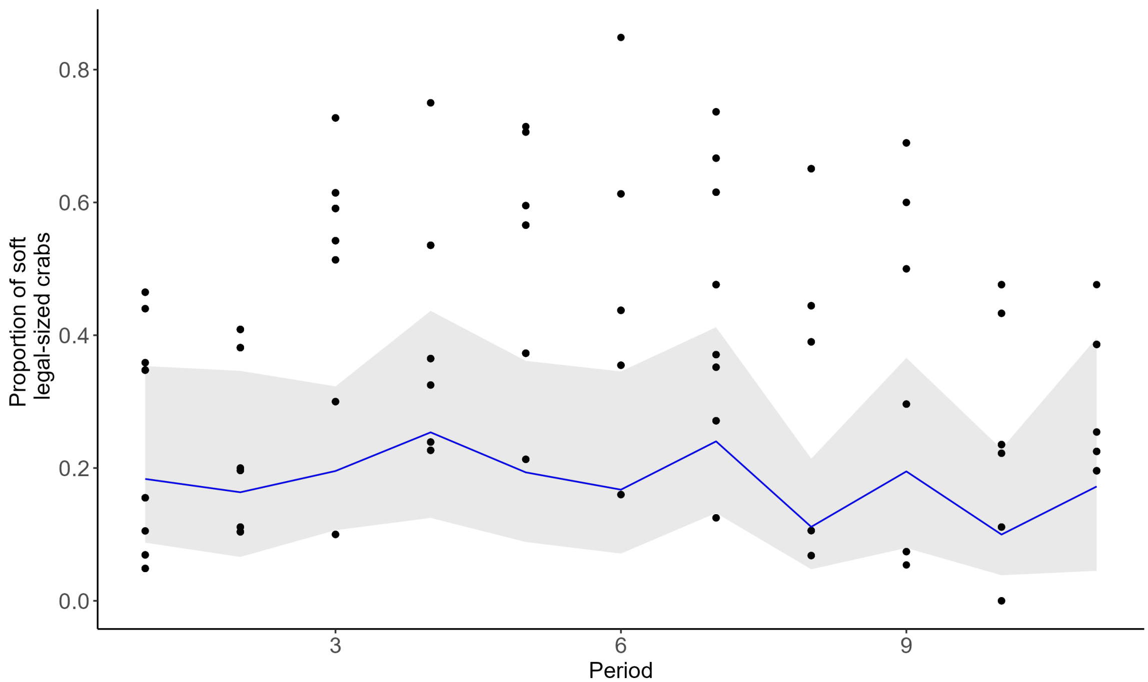

Figure A.1. Proportion of soft legal-sized male crabs in each fishing period (half month). The line represents the mean model estimate and the gray polygon represents 95% credible interval.

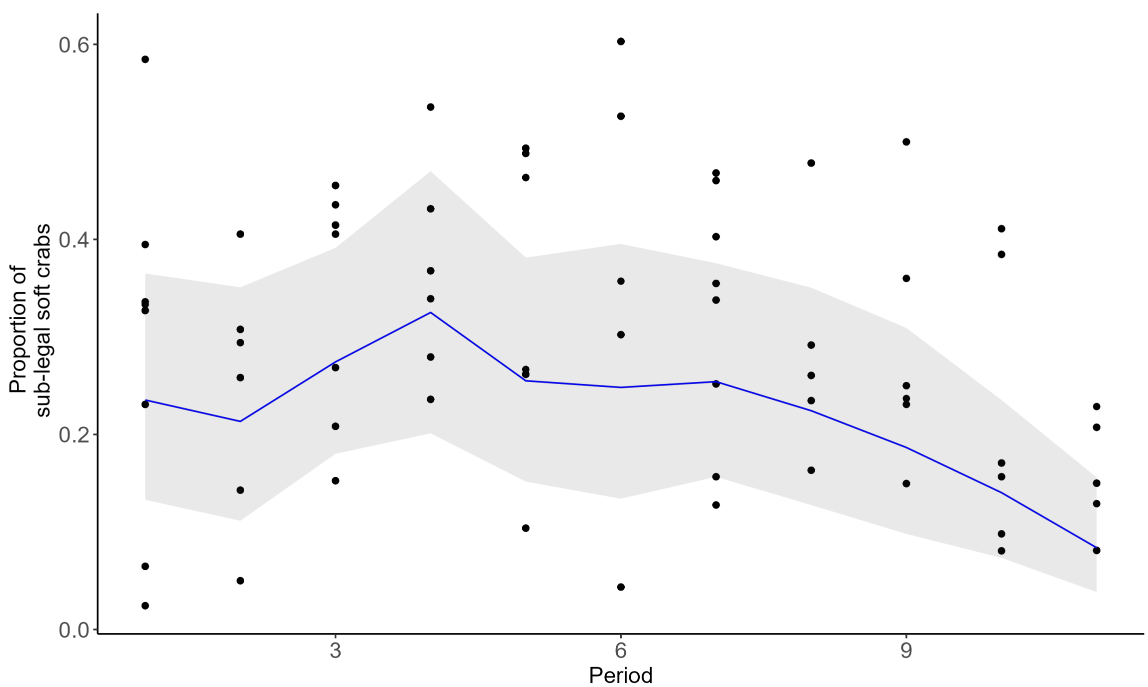

Figure A.2. Proportion of soft sublegal-sized male crabs in each fishing period (half month). The line represents the mean model estimate and the gray polygon represents 95% credible interval.

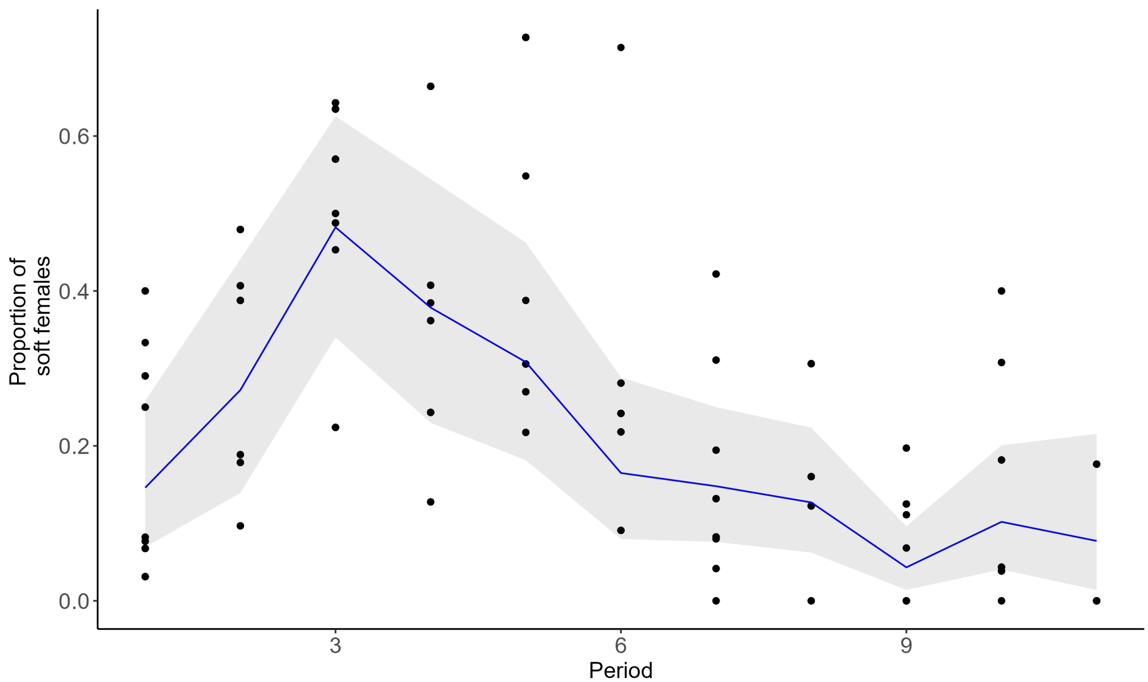

Figure A.3. Proportion of soft female crabs in each fishing period (half month). The line represents the mean model estimate and the gray polygon represents 95% credible interval.

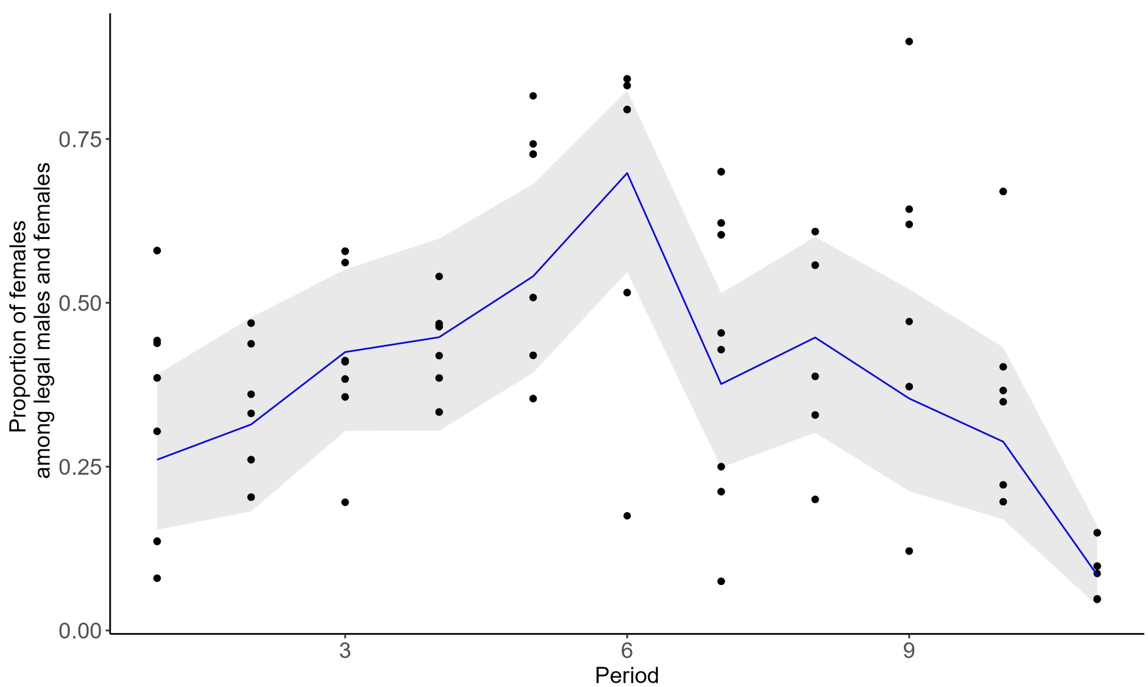

Figure A.4. Proportion of female crabs among catch of female and legal-sized male crabs in each fishing period (half month). The line represents the mean model estimate and the gray polygon represents 95% credible interval.

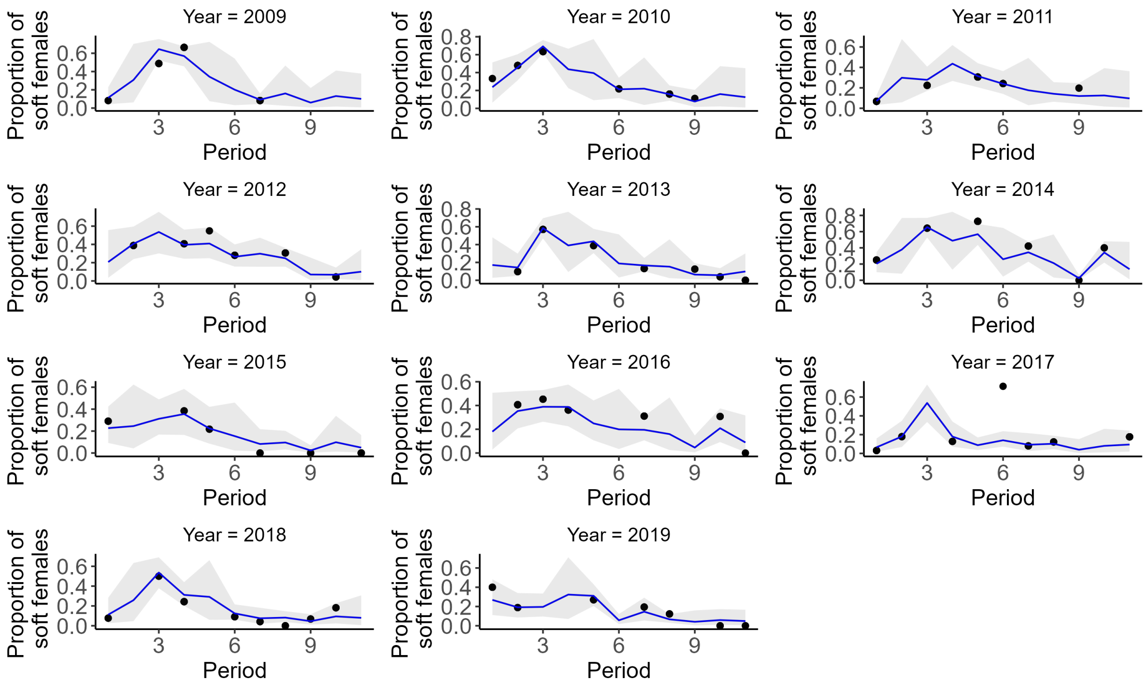

Figure A.5. Proportion of soft female crabs in each period in each year. The line represents the mean model estimate and the gray polygon represents 95% credible interval.

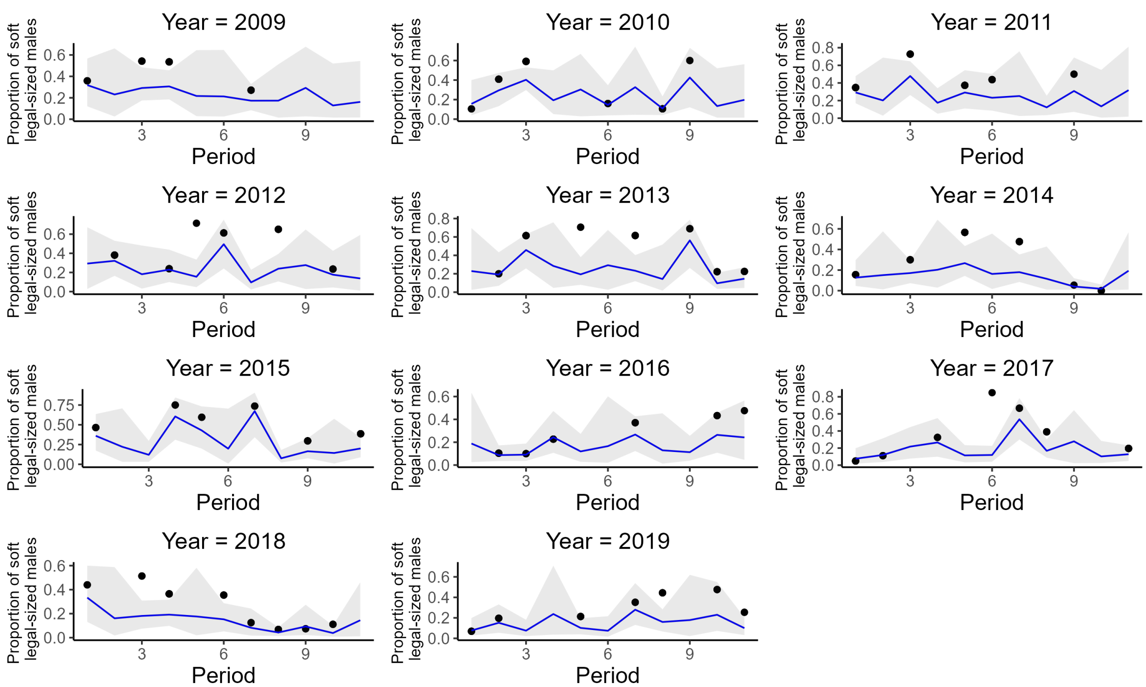

Figure A.6. Proportion of soft legal-sized male crabs in each period in each year. The line represents the mean model estimate and the gray polygon represents 95% credible interval.

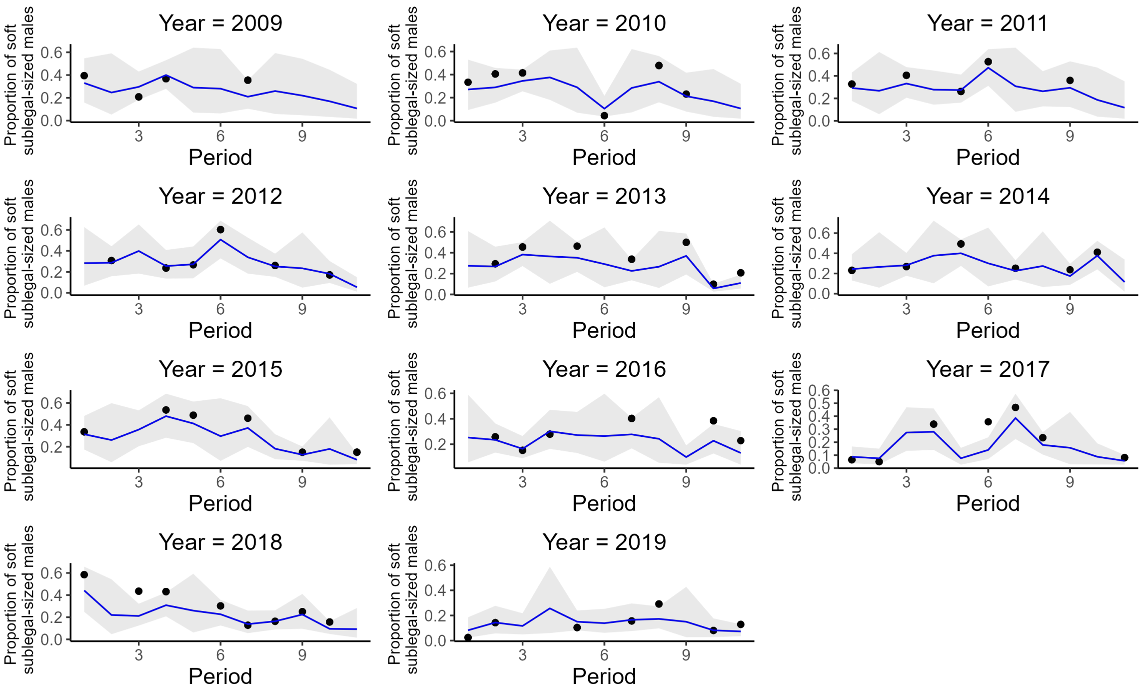

Figure A.7. Proportion of soft sublegal-sized male crabs in each period in each year. The line represents the mean model estimate and the gray polygon represents 95% credible interval.

A.2. ESTIMATING EXPLOITATION RATE FOR EACH FISHING PERIOD USING LESLIE METHOD

We estimated average exploitation rates in each fishing period using the Leslie method (Leslie and Davis 1939). We used the linear relationship between cumulative catch and CPUE (Figure A.8) to estimate the initial crab abundance $N0_{y,1}$:

$$N0_{y,1} = \frac{CPUE_{y,1}}{-q_y} \tag{A.6}$$

where $CPUE_{y,1}$ is the CPUE at the start of the fishing season in each year y and is the y-axis intercept in Figure A.8. q_y is the catchability at the start of the fishing season in each year y, and $-q_y$ is the slope of each line in Figure A.8. This catchability is assumed to be constant for the first four periods in each year, given the consistent slope ($-q_y$) through the first four points each year. We estimated the exploitation rate in the first period from the estimated initial abundance ($N0_{y,1}$), and the observed catch:

$$E_{y,1} = \frac{C_{y,1}}{N0_{y,1}} \tag{A.7}$$

where $C_{y,1}$ is the catch in the first fishing period of each year y.

We estimated the mean exploitation rate in the first fishing period ($\bar{E_1}$) across all years available in the dataset (2009-2019):

$$\bar{E_1} = \frac{\sum_y E_{y,1}}{NY} \tag{A.8}$$

where NY is the number of years.

We estimated the mean exploitation rates in the subsequent periods based on the level of effort (number of traps) in that period, relative to the effort in the first period needed to achieve mean exploitation rate $\bar{E_1}$:

$$\bar{E_i} = \bar{E_1} \times H_i \times c_i \tag{A.9}$$

where H_i is the relative effort in period i and c_i is a scaling factor to represent decreasing catchability. We assumed that catchability was constant for the first four fishing periods, decreased by 50% in period five, and decreased an additional 5% each subsequent period. This change in catchability is based on observations made by commercial harvesters. The high estimated exploitation rates in the first four fishing periods mean that uncertainty around changing catchability has a minimal effect on annual exploitation rates (i.e., most legal crabs are caught in the first two months of the commercial season).

Estimated mean exploitation rates are shown in Table A.3. Mean estimates of exploitation rate for each fishing period were used in the simulation testing (Section 2.3.3).

The five necessary assumptions of the Leslie method hold for the BC Dungeness Crab fishery. We assume the assumptions about closed population, trap competition, and catchability are met are based on the linear relationship between CPUE and cumulative catch, which is the guideline set forth in Delury (1947). The final two assumptions are that the entire population is available to be caught, and that fishing is significant enough to reduce CPUE. Both of these are reasonable in the BC Dungeness crab fishery. We only estimate exploitation rates for legal male crabs, and exploitation rates are high enough to catch the majority of legal male crabs in a fishing season.

A.2.1. Exploitation Rates Results

Estimated mean exploitation rates (proportion of crabs removed through fishing) were highest (over 0.4) in the first four fishing periods (June - August) (Table A.3). Estimated mean exploitation rate decreased throughout the fishing season as the assumed scaling parameter of the catchability coefficient (c_i) decreased due to declining abundance of legal-sized males. Estimated mean exploitation rates in the final three periods were below 0.1, when catchability was at its lowest. Total exploitation rate for legal-sized males during the fishing season was over 0.95.

There was very little variability in estimated exploitation rate. The standard deviation of the exploitation rate in the first fishing period was 0.046 with a coefficient of variation of 10%.

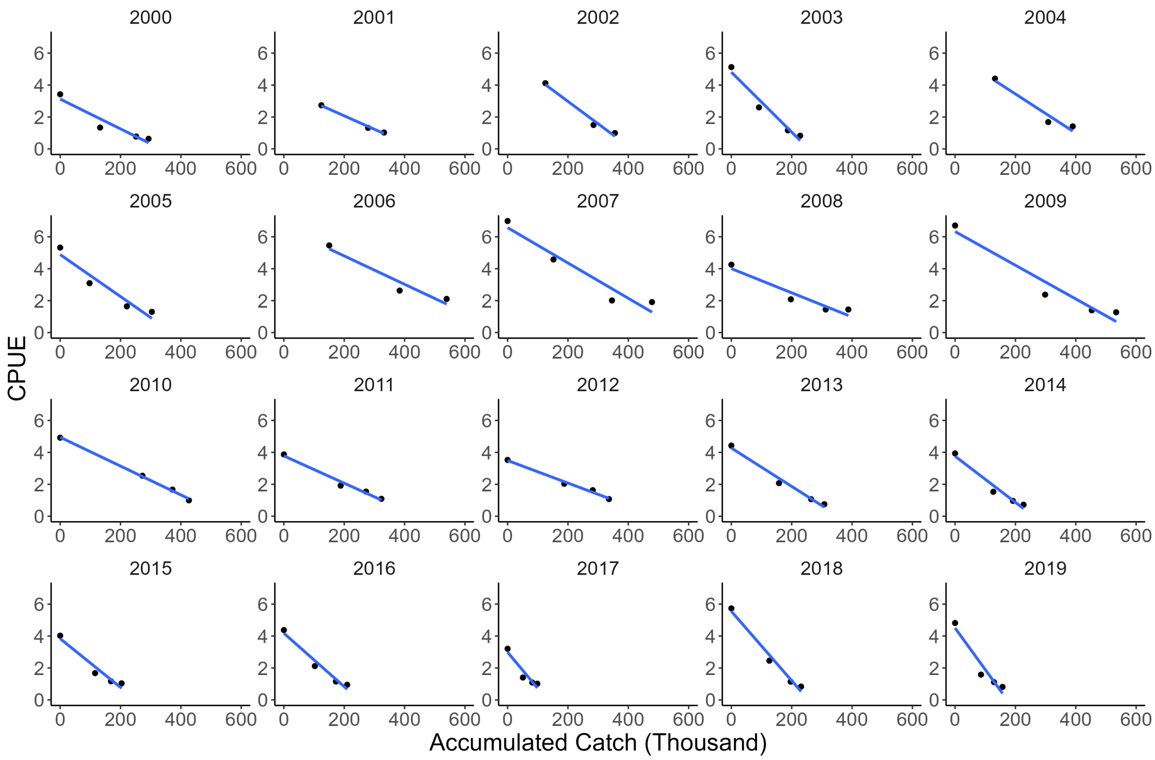

Figure A.8. Commercial CPUE of legal-sized males and total accumulated catch in the first four fishing periods in each year. The linear relationship between CPUE and accumulated catch was used to estimate initial CPUE and catchability for each year.

Table A.3. Mean exploitation rate during each semi-monthly period during the commercial fishing season.

Fishing Period (i)	$\bar{E}_i$
1	0.3907
2	0.5765
3	0.5411
4	0.4834
5	0.2218
6	0.2009
7	0.1635
8	0.1177
9	0.0838
10	0.0551
11	0.0260

A.3. ESTIMATING THE PROPORTION OF NEW SOFT LEGAL-SIZED CRABS IN THE CATCH FOR EACH FISHING PERIOD

Sublegal-sized crabs moult to become legal-sized crabs during the fishing season. This moulting represents recruitment that needs to be accounted for in the simulation process. We assumed that a newly moulted ("new-soft") crab would remain soft for a length of time NPH, during which it would be denoted "old-soft", before becoming a hard crab. NPH was assumed to be four fishing periods, based on the DFO criteria for a soft crab (e.g., Dunham et al. 2011). The following steps were taken to calculate the proportion of new-soft legal-sized (male) crabs for each fishing period:

1. To initialize the process, we assumed that the proportion of soft legal-sized crabs that were in each stage of hardness d (d ranges from 1-4) in period i , PSS_i was $\frac{1}{NPH}$ in the first fishing period, where NPH is the number of periods it takes for a newly soft crab to fully harden. The value for PSS_1 was used to estimate the number of soft legal-sized crabs in each stage of hardness ($NS_{d,i}$) in the first fishing period:

$$NS_{d,1} = NL_1 \times PSL_1 \times PSS_1 \tag{A.10}$$

   where NL_1 is the number of legal-sized crabs at the beginning of the fishing season (NL_1 = 30000; as this approach is CPUE-based, the value of NL_1 cancels out, and the results will be unchanged if a different value is used).

2. We then initialized the proportion of new-soft legal-sized crabs in the first period:

$$PNS_i = \frac{NS_{1,1}}{NL_1} \tag{A.11}$$

3. We estimated total catch of legal-sized crabs (CL_i):

$$CL_i = NL_i \times \bar{E}_i \tag{A.12}$$

   where $\bar{E}_i$ is the estimated mean exploitation rate in the fishing period (Table A.3).

4. The corresponding catch of soft legal-sized crabs was calculated:

$$CSL_i = CL_i \times PSL_i \tag{A.13}$$

5. We estimated the number of soft legal-sized crabs that survived to the next fishing period, and thus became old-soft ($d \geq 2$), by removing crabs that died due to fishing or natural mortality:

$$NS_{d \geq 2,i+1} = \mathrm{e}^{-M \times \frac{15}{365}} \times (NS_{d-1,i} - CSL_i) \times \frac{NS_{d-1,i}}{\sum_h NS_{d-1,i}} \tag{A.14}$$

6. We converted this number to a proportion of old-soft crabs in all legal-sized crabs in the next fishing period:

$$POS_{i+1} = \frac{\sum_d NS_{d \geq 2,i}}{(NL_i - CL_i) \times \mathrm{e}^{-M \times \frac{15}{365}}} \tag{A.15}$$

7. We removed this proportion from the independently estimated (in Section A.1) proportion of all soft, legal-sized crabs in the next fishing period ($PSL_i + 1$, Table A.2), to estimate the proportion of new-soft legal-sized crabs in the next fishing period:

$$PNS_{i+1} = \begin{cases} PSL_{i+1} - POS_{i+1}\,, & PSL_{i+1} \geq POS_{i+1} \\ 0\,, & PSL_{i+1} < POS_{i+1} \end{cases} \tag{A.16}$$

8. We estimated the number of new-soft legal-sized males in the next fishing period:

$$NS_{1,i+1} = \mathrm{e}^{-M \times \frac{15}{365}} (NL_i - CL_i) \times \frac{PNS_{i+1}}{1 - PNS_{i+1}} \tag{A.17}$$

9. We estimated the number of legal-sized male crabs in the next fishing period by removing deaths due to fishing and natural mortality, and adding newly moulted crabs:

$$NL_{i+1} = (NL_i - CL_i) \times e^{-M \times \frac{15}{365}} + NS_{1,i+1} \tag{A.18}$$

The values for $NS_{d,i+1}$ and NL_{i+1}, were used to repeat steps 3-9 until the end of the fishing season had been reached.

A.4. PROPORTION OF FEMALES THAT ARE NEW RECRUITS

To determine the increase in the female population each fishing period due to moulting, we calculated the proportion of the size-distribution caught in the fishery that was newly vulnerable to the traps. We took three steps to determine this proportion:

1. We determined the size-distribution of female crabs using service provider commercial catch data;
2. We calculated the threshold where a new soft female crab becomes vulnerable to traps prior to moulting, using a regression equation from Hankin et al. (1989) ($y = 32.93 - 0.1374x$ where x is the moult increment (size increase due to moulting) and y is the pre-moult carapace width); and
3. We determined what proportion of soft female crabs in the commercial catch were newly vulnerable to traps.

Less than 5% of the female crabs caught in commercial traps are smaller than 110 mm, and less than 5% are larger than 153 mm. Between these limits, the cumulative percent of female crabs in the traps increases exponentially. Therefore, it is assumed that soft-shell crabs larger than 109 mm, but smaller than the maximum size of a newly recruited female crab (i.e., threshold size), have recently recruited into the population that is vulnerable to commercial traps.

A female crab that was 109 mm pre-moult would be 127 mm post-moult. This is the threshold size, the maximmum size of a newly recruited female crab. From the service provider commercial catch data, approximately 21% of soft crabs are in this size range. To account for crabs being soft for multiple fishing periods, we divided this percentage by the time it takes a soft crab to harden, which we assumed is four fishing periods, based on the DFO sampling protocol (Dunham et al. 2011). Therefore, for each fishing period, the proportion of the female population that are new recruits is 0.0525 times the proportion soft.

A.5. HANDLING MORTALITY

The current study follows Zhang and Dunham (2013) in using a handling mortality of 5% for hard female crabs and 25% for soft female crabs. Handling mortality rates are affected by shell hardness, size, sex, injuries, time since release, and how closely the study emulates the fishery, making direct comparisons difficult and care should be used when applying them. These issues are further compounded by the fact that tagging studies are only able to examine the relative return rate of hard versus soft crabs and are unable to differentiate between handling mortality and natural mortality following release (Kruse et al. 1994). The handling mortalities used in the current study do however fall within the range of available published values. A recent study found a total handling mortality for female crabs (both hard and soft) of 8%; however, they were not able to differentiate between hard and soft female crabs due to the small sample size for soft females (Yochum et al. 2017). Tegelberg and Magoon (1971) found a handling mortality of untagged soft crabs of 16% and untagged hard crabs of 4%. Although there was no mention of the sex of the crabs, they are referred to as 'legal-sized' and it can be assumed that they were male, as there is no retention of females in the fishery. Stewart (1974) summarized a number of earlier studies by Tegelberg (1970, 1972a, 1972b, cited therein) and reported that 'legal-sized' soft-shell crabs handled similarly to the commercial fishery, and subsequently held at depth in commercial traps, experienced mortalities of 10-15% after 2 days, 15-16% after 4 days, and 22-25% after 6-7 days. These mortality rates were exacerbated (> 40% mortality) when crabs experienced limb loss or were dropped on the deck during handling. Murphy and Kruse (1995) present an annotated bibliography of the handling effects on crabs and lobsters and a technical report cited therein (Barry 1981) reports handling mortalities for soft-shell Dungeness crab ranging from 11-50%. We therefore used handling mortalities of 5% and 25% to be consistent with previous DFO research and with the scientific literature.

APPENDIX B. SIMULATION MODEL

We set up the simulation with eleven fishing periods, each equal to half a month, between June 15th and November 30th (i.e., June 15-30, July 1-15, etc.). We used the Beverton-Holt stock-recruitment relationship with a four-year lag between female CPUE (spawners) and sublegal-sized male CPUE (recruits), and assumed a fixed annual natural mortality rate (M) of 0.97 (Zhang et al. 2004), as the simulations were relatively insensitive to the natural mortality parameter. We also estimated the mean exploitation rate ($\bar{E}_i$), mean proportion of soft-shell females (PSF_i), mean proportion of new-soft legal-sized males (PNS_i), and mean proportion of females among captured female and legal-sized males (PF_i) at each fishing period from the commercial catch data (see Sections A.2-A.3 for details). Additionally, although captured females are released, some released females die from handling. The handling mortality rates were set to 25% and 5% for soft (h_1) and hard (h_2) females, respectively, based on independent estimates of handling mortalities (see Appendix A). The ratio of the number of female crabs to the number of legal-sized male crabs at the beginning of the fishing season was set at 1.5, which approximately equals the median ratio observed in the spring fishery-independent surveys. We assumed 5.25% of soft females in each fishing period were new spawners (see Appendix A). To estimate the total number of females from female CPUE, a catchability coefficient (fq) of 0.0001 was assumed. Using a different value for fq did not alter the simulation outputs, as this value was applied at both the beginning and end of the simulations (see Appendix C).

Each simulation was initialized by setting an initial female CPUE at the end of the fishing season ($UF0$), from the series: $UF0 = [0.1, 0.2, .., 2.5]$. This range of female CPE values represents scenarios where population size is expected to be low (i.e., where the LRP is most likely to be set).

B.1. UNFISHED EQUILIBRIUM

1. We estimated the number of females at the end of the fishing season (fishing period 12). While the empirical data are primarily CPUE-based, converting to numbers (abundance) simplifies accounting for catch and mortality in the simulations.

$$NF0_{12} = \frac{UF0}{fq} \tag{B.1}$$

2. We back-calculated the number of females ($NF0_i$) at the beginning of the season ($NF0_1$), assuming no fishing, using the following step-wise equation:

$$NF0_i = \frac{NF0_{i+1} \times \mathrm{e}^{M \times \frac{15}{365}}}{1 + 0.0525 \times PSF_i} \tag{B.2}$$

   where 5.25% of females were assumed to be new spawners (see Appendix A). This step was repeated until the beginning of the season was reached (fishing period 1).

3. The number of females at the beginning of the fishing season was used to estimate the number of legal-sized males at the beginning of the fishing season, based on the ratio of females to legal-sized males observed in the spring fishery-independent survey (ratio = 1.5:1):

$$NL0_1 = \frac{NF0_1}{1.5} \tag{B.3}$$

4. We estimated the CPUE for male sublegal-sized crabs from the initial female CPUE using the stock-recruitment relationship (Equation 3).
5. We calculated the ratio (r) of the number of legal-sized males to the sublegal-sized male CPUE, from the stock-recruit relationship in step 1:

$$r = \frac{NL0_1}{USL0} \tag{B.4}$$

The r value was used in subsequent steps of each simulation, as a link between annual time steps. The ratio is applied to sublegal-sized male CPUE (USL), to create lower recruitment rates than would be expected from the estimated Beverton-Holt stock-recruit relationship. Lower values of $UF0$ result in less compensatory recruitment at lower spawning stock sizes (see Appendix C for further explanation of r values and how they are applied).

B.2. FISHED EQUILIBRIUM

1. To initialize the simulation under continued fishing, we set the sublegal-sized male CPUE (USL) equal to the unfished equilibrium value ($USL0$). This only occurs in the first annual time step of the simulation. In subsequent time steps, USL was estimated at the end of the previous time step. This process repeated until the new equilibrium was reached.

$$USL = USL0 \tag{B.5}$$

2. We estimated the number of legal-sized males at the beginning of the fishing season (not including newly moulted males) from the ratio in the unfished scenario (r).

$$NLo_1 = r \times USL \tag{B.6}$$

3. We estimated the number of female crabs (not including newly moulted female crabs) from the ratio of females to males in the spring survey (mean ratio of ~1.5:1):

$$NFo_1 = 1.5 \times NLo_1 \tag{B.7}$$

4. Newly moulted crabs were added to the number of legal-sized male crabs, based on the estimated proportion of newly-soft legal male crabs in that fishing period. This represents crabs that have recently reached the legal size limit:

$$NL_i = NLo_i \times (1 + \frac{PNS_i}{1 - PNS_i}) \tag{B.8}$$

5. We calculated catch from the exploitation rate in that fishing period, averaged over the years from 2009-2019:

$$CL_i = NL_i \times \bar{E}_i \tag{B.9}$$

6. We estimated the number of legal-sized crabs that survived to the next fishing period by removing catch and accounting for natural mortality in that period (i.e., 15 days):

$$NLo_{i+1} = (NL_i - CL_i) \times \mathrm{e}^{-M \times \frac{15}{365}} \tag{B.10}$$

7. We estimated the number of female crabs, including newly moulted crabs from the estimated proportion of new-soft female crabs in that fishing period, and assuming 5.25% of these were new recruits:

$$NF_i = NFo_i \times (1 + 0.0525 \times PSF_i) \tag{B.11}$$

8. We estimated the total catch of females using the proportion of female crabs in the fishing period and the catch of legal-sized crabs in that period:

$$CF_i = \frac{CL_i \times PF_i}{1 - PF_i} \tag{B.12}$$

9. We estimated handling mortality by applying different rates of handling mortality (h_1, h_2) to the proportion of females that were soft and hard, respectively.

$$MF_i = CF_i \times (PSF_i \times h_1 + (1 - PSF_i) \times h_2) \tag{B.13}$$

10. We estimated the number of females that survived to the next fishing period by removing the number of females that died due to handling mortality and natural mortality in that fishing period (15 days):

$$NFo_{i+1} = (NF_i - MF_i) \times \mathrm{e}^{-M \times \frac{15}{365}} \tag{B.14}$$

11. Steps 4-10 were repeated until after the 11th fishing period had been completed (i.e., $i = 12$).
12. We estimated female CPUE, from the estimated number of females and the assumed catchability:

$$UF = fq \times NF_{12} \tag{B.15}$$

13. We estimated sublegal-sized male CPUE based on the female CPUE and the stock-recruitment relationship (Equation 3).
14. We used the sublegal-sized male CPUE to repeat steps 2-13, representing continued generations of fishing at current levels. We repeated until the change in two consecutive end-of-season female CPUEs was less than 1%, at which point a new equilibrium was assumed to be reached. This equilibrium female CPUE was estimated for each initial female CPUE.

Table B.1. Description of mathematical symbols used, in order of appearance.

Symbol	Description
$NF0_i$	Number of females at initial unfished equilbrium in period i
$UF0$	Initial female CPUE
fq	Assumed catchability of females
M	Natural mortality
PSF_i	Proportion of females that are soft in period i
$NL0_i$	Number of legal male crabs at unfished equilibrium, in period i
r	Ratio used to scale the number of legal male crabs, and reduce compensatory growth
$USL0$	Sublegal-sized male CPUE under initial equilibrium, from stock recruit relationship

Symbol	Description
USL	Sublegal-sized male CPUE under fishing, from stock recruit relationship
NLo_i	Number of legal-sized male crabs in period i, excluding newly moulted crabs
NL_i	Number of legal-sized male crabs in period i
NFo_i	Number of females crabs in period i, excluding newly moulted crabs
PNS_i	Proportion of legal-sized male crabs that are new soft in period i
NF_i	Number of female crabs in period i
CF_i	Catch of female crabs in period i
MF_i	Number of female crabs that die from handling mortality in period i
h_1	Handling mortality rate for soft crabs
h_2	Handling mortality rate for hard crabs
UF	Estimated female CPUE at end of simulation year
PR	Percent reduction in female CPUE from unfished equilibrium to fished equilibrium
R	Beverton-Holt recruitment (sublegal CPUE)
S	Beverton-Holt spawners (Female CPUE)
α	Beverton-Holt alpha parameter (asymptotic recruitment)
β	Beverton-Holt beta parameter (spawners that produce recruitment 0.5 x α)
ϵ	Beverton-Holt error term
$N0_{y,1}$	Estimated initial number of legal-sized male crabs in year y
$CPUE_{y,1}$	Commercial crabs per trap (CPUE) in the first period of year y
q_y	Catchability estimated from slope of regression with commercial CPUE over time
$E_y, 1$	Exploitation rate in first period of year y
$C_{y,1}$	Observed catch in first period of year y
$\bar{E_1}$	Average estimated exploitation rate in the first period
NY	Number of years, y, for which the average exploitation rate is calculated
$\bar{E_i}$	Average exploitation rate in period i
H_i	Effort in period i relative to the effort in period 1
c_i	Scaling parameter to represent changes in catchability through the fishing season
$N_{y,i}$	Number of soft legal-sized male crabs in year y, period i
$TN_{y,i}$	Total number of legal-sized male crabs in year y, period i
YE_y	Effect of year y on probability of crab being soft
$PE_{y,i}$	Effect of period i on probability of crab being soft

Symbol	Description
$\phi_{y,i}$	Error term for probability of crab being soft
γ	Mean of the year effect on the probability of crab being soft
σ_{γ}^2	Variance for year effect on the probability of crab being soft
ψ_i	Mean of period effect on the probability of crab being soft
σ_{ψ}^2	Variance for period effect on the probability of crab being soft
$NS_{d,i}$	Number of soft crabs in period i, in hardening stage h
PSL	Proportion of legal-sized male crabs that are soft
PSS_1	Proportion of initial soft male crabs that are new soft
CL_i	Catch of legal-sized male crabs in period i
CSL_i	Catch of legal-sized soft male crabs in period i
POS_{i+1}	Proportion of old soft male crabs in period $i+1$

APPENDIX C. EXPLANATION OF PRODUCTIVITY SCALING VARIABLE

In the simulations, the ratio of the number of legal-sized male crabs to the sublegal-sized male CPUE at the beginning of the season (r value) (assumed to be at unfished equilibrium), is used to reduce compensation at low stock sizes in the stock-recruitment relationship. This ratio is calculated based on the initial female CPUE used to initialize the simulation and is therefore unique to each initial female CPUE value. The r value is used within the model simulations to convert the sublegal-sized male CPUE, from the Beverton-Holt stock recruitment relationship, to number of legal-sized males. Using a unique r value for each initial female CPUE, increases the linearity of the relationship between the number of legal-sized males at the beginning of the season (unfished equilibrium number) for each value of low initial female CPUE (CPUE ≤ 2.5). If the value of r was instead independent of the initial female CPUE, the plot of initial female CPUE to number of legal-sized males at the beginning of the season would show the expected Beverton-Holt curve (Figure C.1) .

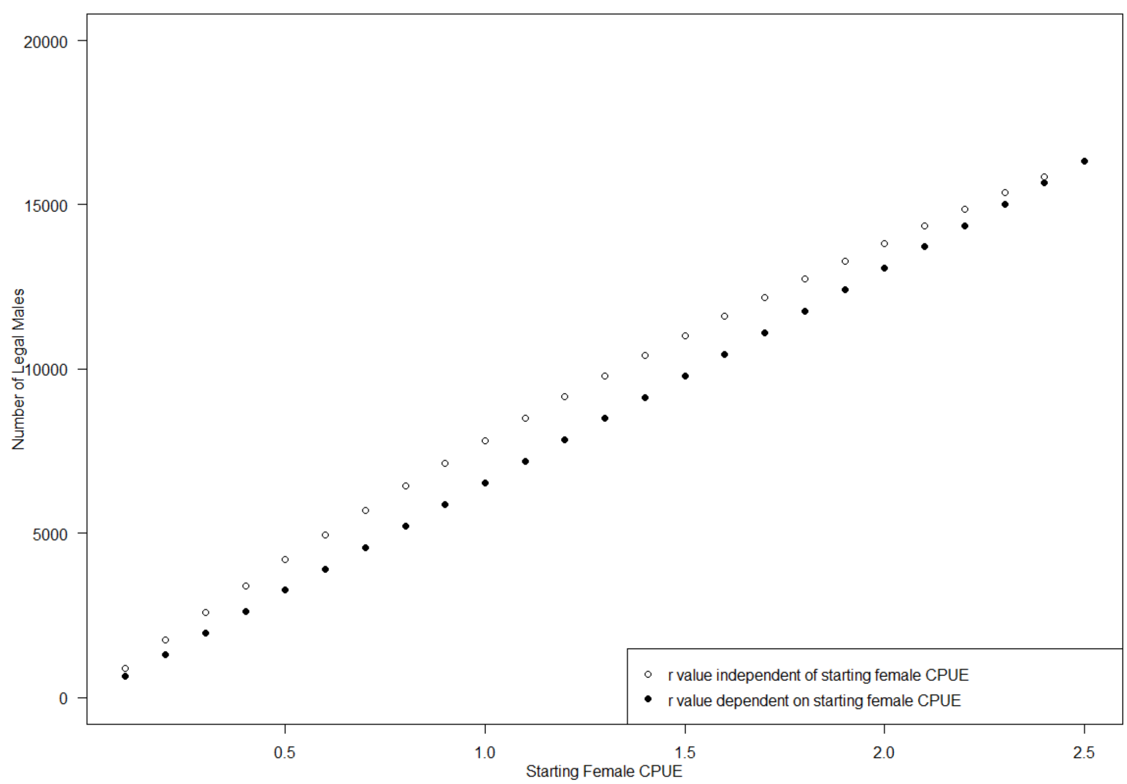

Figure C.1. The number of legal-sized males (sublegal-sized CPUE x r) produced at the beginning of the fishing season based on a initial female CPUE value. The open circles indicate number of legal males calculated with a fixed value of r across initial female CPUE. The closed circles indicate number of legal males calculated with an r specific to each initial female CPUE. The number of legal males produced is lower or equal for all initial female CPUE values when an r value dependent on initial female CPUE is used.

There are no data for the stock-recruitment relationship at low female CPUE values and inferring the curve from the stock-recruitment relationship assumes compensation at these low values.

It is more conservative to assume that in scenarios with a low initial female CPUE the number of legal-sized males is likely to trend towards zero over time. The assumed productivity is lower under a linearizing assumption than under a Beverton-Holt relationship. In other words, a low initial female CPUE value would result in a lower r value and lower productivity, than a higher initial female CPUE value. The r value was therefore introduced in order to include this assumption about productivity and "linearize" the Beverton-Holt relationship by removing compensation at low initial female CPUE values (see Figure C.1). One potential issue with this approach is that the productivity proxy (r value) remains constant over time and between simulation years even as the spawning stock (female CPUE) decreases. This means that simulations that started with a higher female CPUE value would have higher productivity over time than a simulation that started at a lower female CPUE value even if the more productive stock declines to the size of the smaller one.

Compensation is not completely removed from the model. Within a given simulation with a initial female CPUE and r value there is a stock-recruitment relationship included to calculate the sublegal-sized CPUE over time. This sublegal-sized CPUE is then converted to number of legal-sized males using the r value calculated for the beginning of the season.

The fished equilibrium CPUE of the model is dependent on these productivity assumptions of r. When the r value is fixed, the system, regardless of initial female CPUE, converges to the same equilibrium number of legal-sized males (Figure C.3), and this equilibrium value is set based on the r value of the system. However, when r changes depending on initial female CPUE, there is a distinct equilibrium for each initial female CPUE value (Figure C.3).

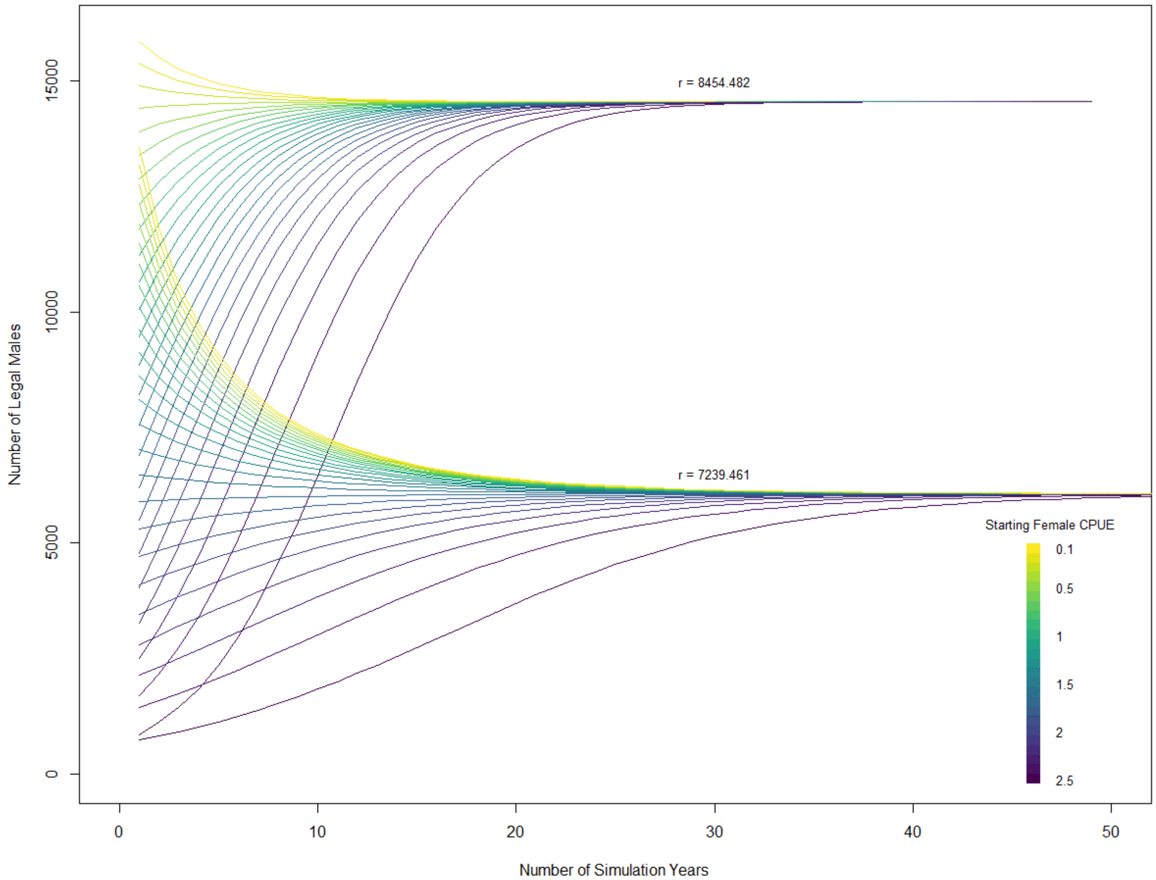

Figure C.2. Number of legal-sized males over simulation years when the system is initialized with a single r value for each initial female CPUE value. Two model runs are shown, one where r was set to 8454.482 and one where it was set to 7239.461. Colour denotes the initial female CPUE value used by each curve. The equilibrium number of legal-sized males for each model run is determined by the assumed value of r.

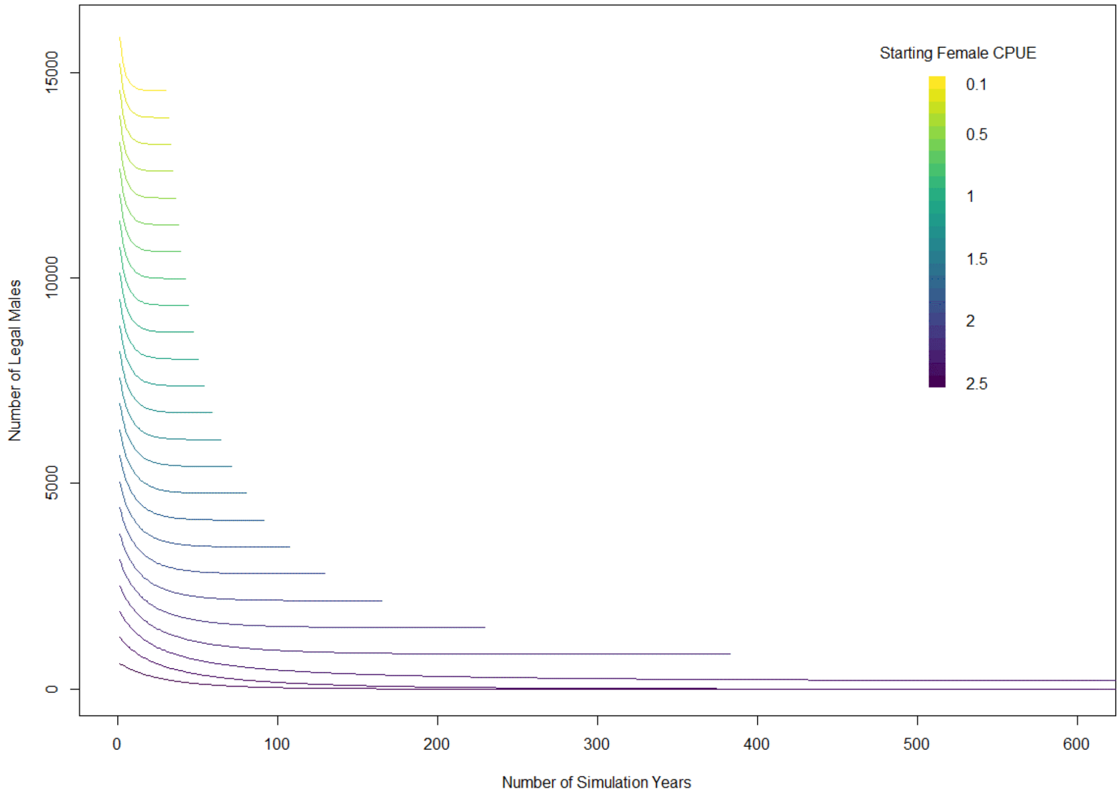

Figure C.3. Number of legal males over simulation years when the system is initialized with a unique r value for each initial female CPUE value. Colour denotes the initial female CPUE value used by each curve. The equilibrium number of legal males is unique for each initial female CPUE and depends on the r value.

APPENDIX D. SENSITIVITY ANALYSES

We tested the sensitivity of the simulation modeling outputs to different parameter values, including those for the natural mortality rate (M), catchability (fq), handling mortality ($h2$) and ratio of females to legal-sized males at the start of the fishing season. The percent reduction in the equilibrium female CPUE was sensitive to changes in the ratio of females to legal-sized males at the start of the fishing season (Figure D.1), and to changes in handling mortality (Figure D.2). The simulation was insensitive to changes in natural mortality (Figure D.3) and female catchability (Figure D.4).

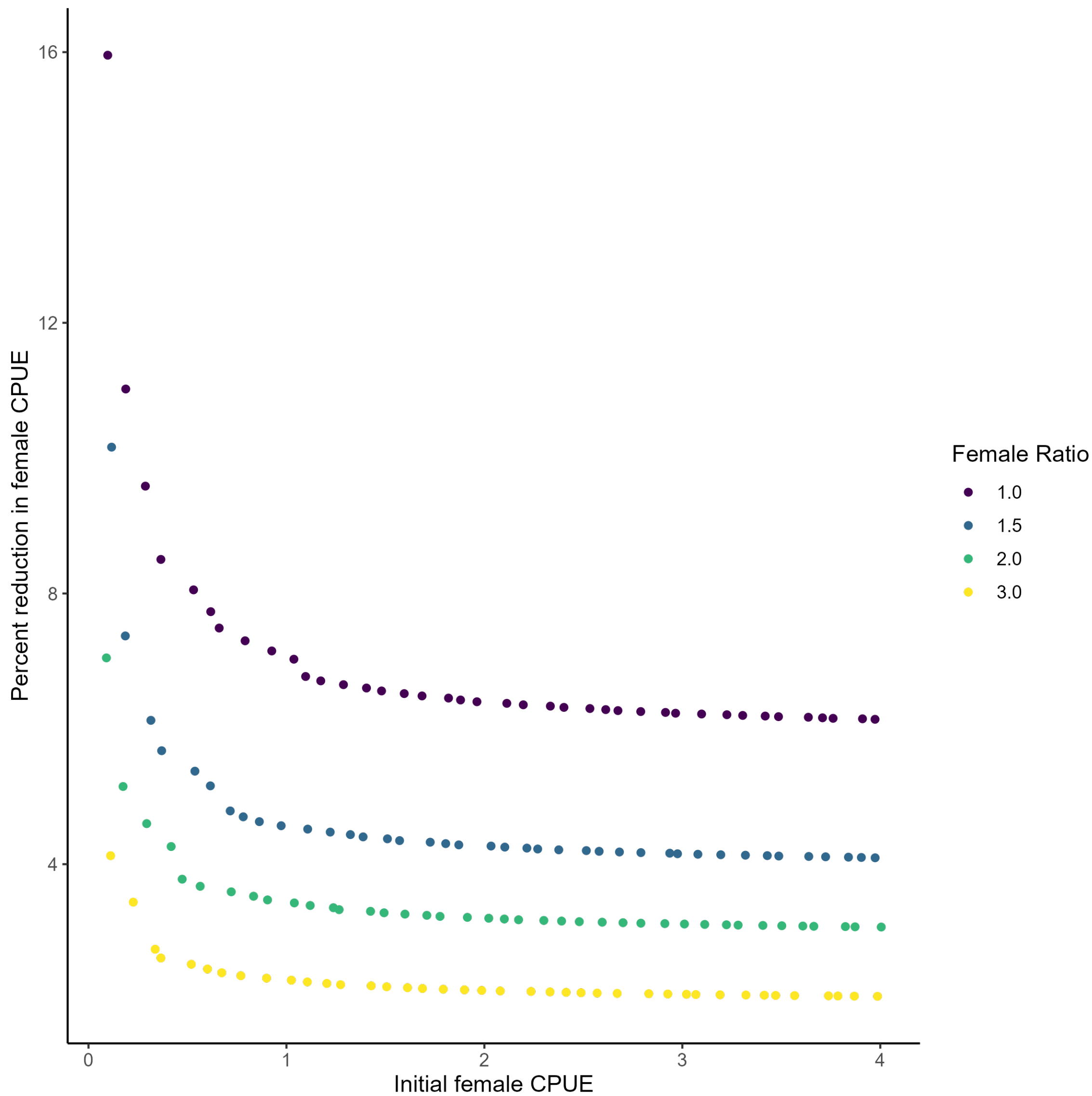

Figure D.1. Percent reduction in equilibrium female CPUE for each initial value of female CPUE at the end of the season given different assumptions for the ratio of female crabs to legal male crabs in the spring. Lower values for the ratio lead to higher reductions in equilibrium female CPUE. All points are jittered.

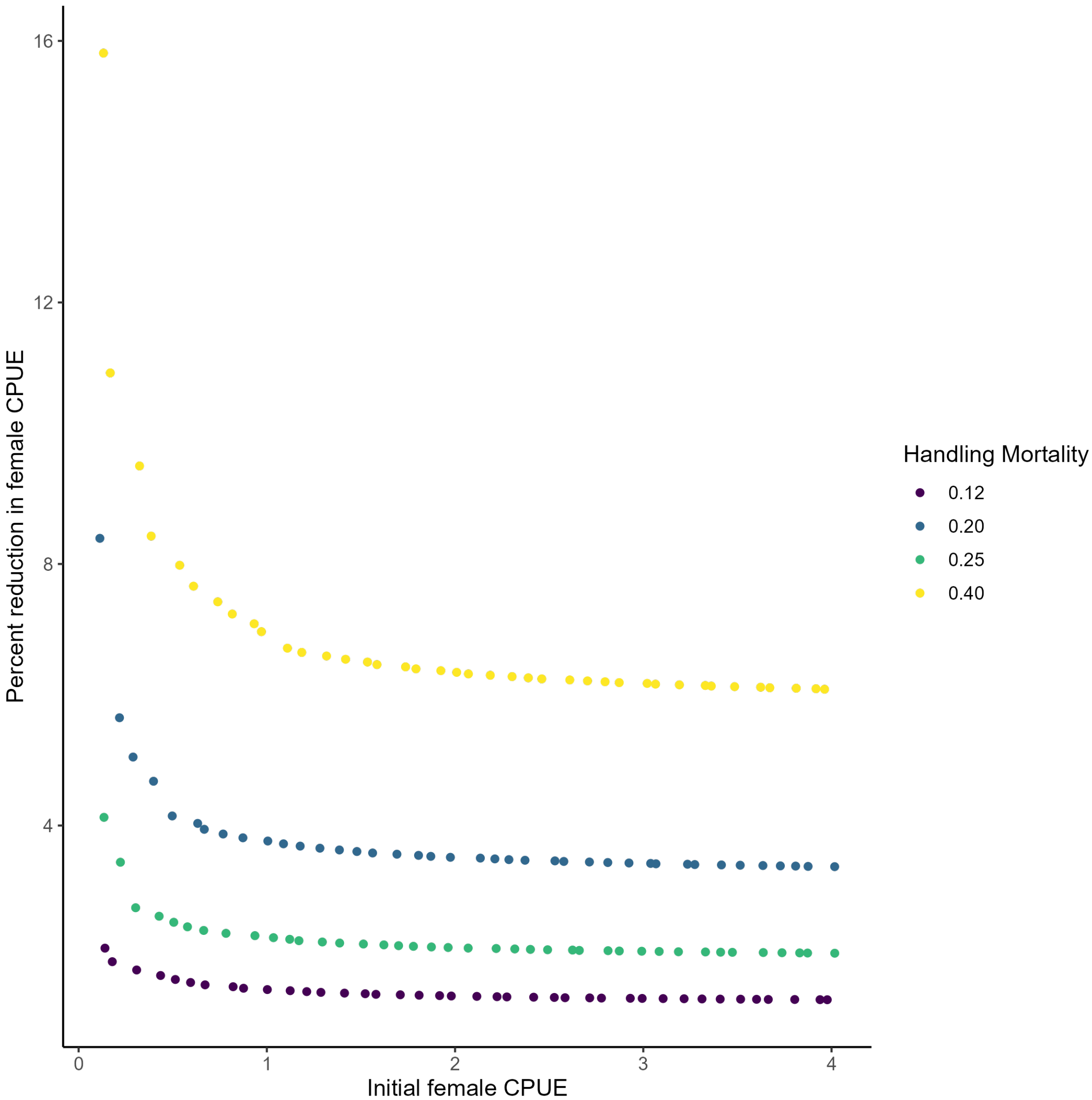

Figure D.2. Percent reduction in equilibrium female CPUE for each initial value of female CPUE, given different assumptions for handling mortality for soft-shell female crabs. Higher handling mortality leads to higher percent reductions in equilibrium female CPUE, particularly for low values of equilibrium female CPUE. All points are jittered.

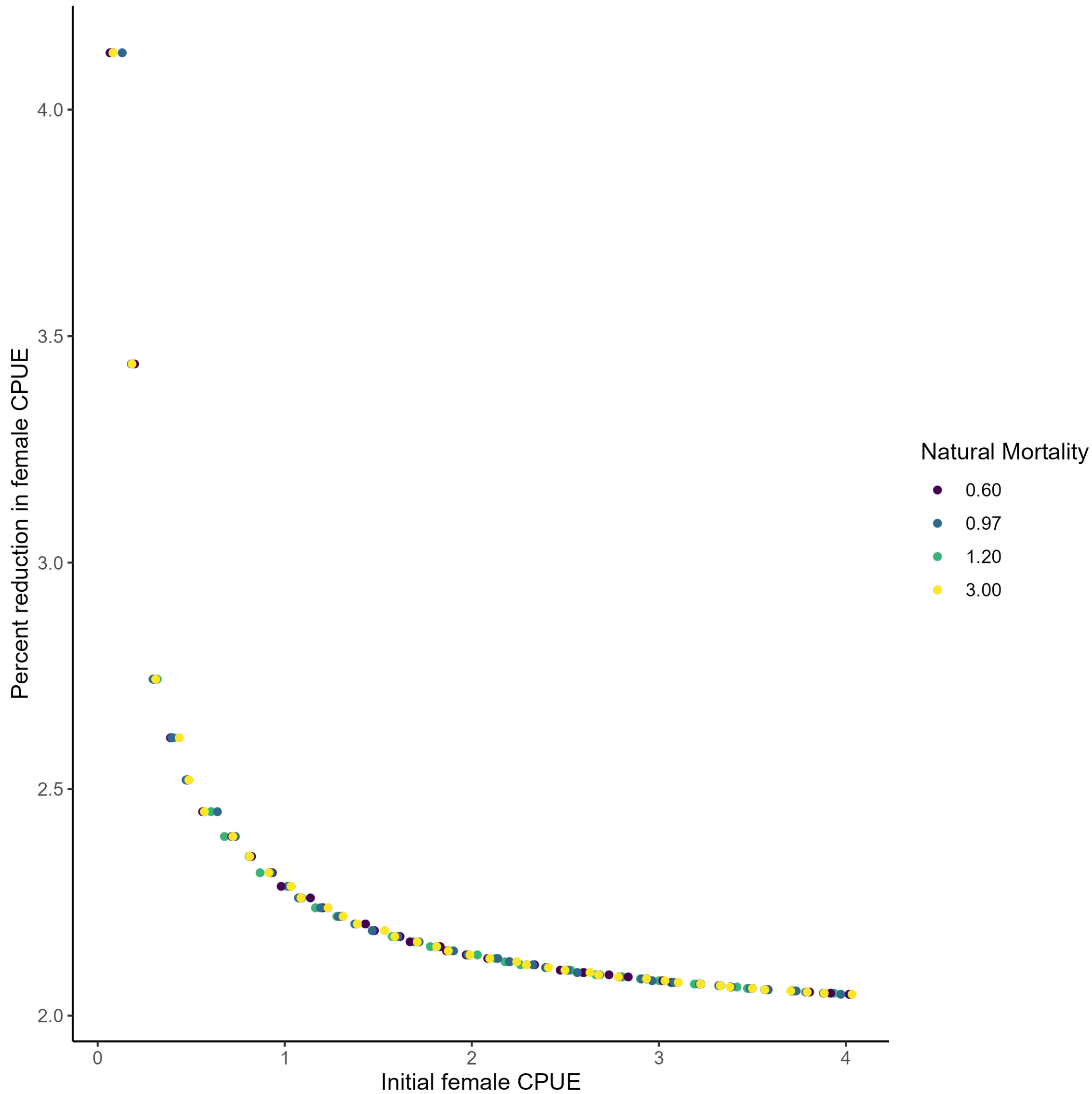

Figure D.3. Percent reduction in equilibrium female CPUE for each initial value of female CPUE, given different assumptions for natural mortality. The simulation output was insensitive to changes in natural mortality. All points are jittered.

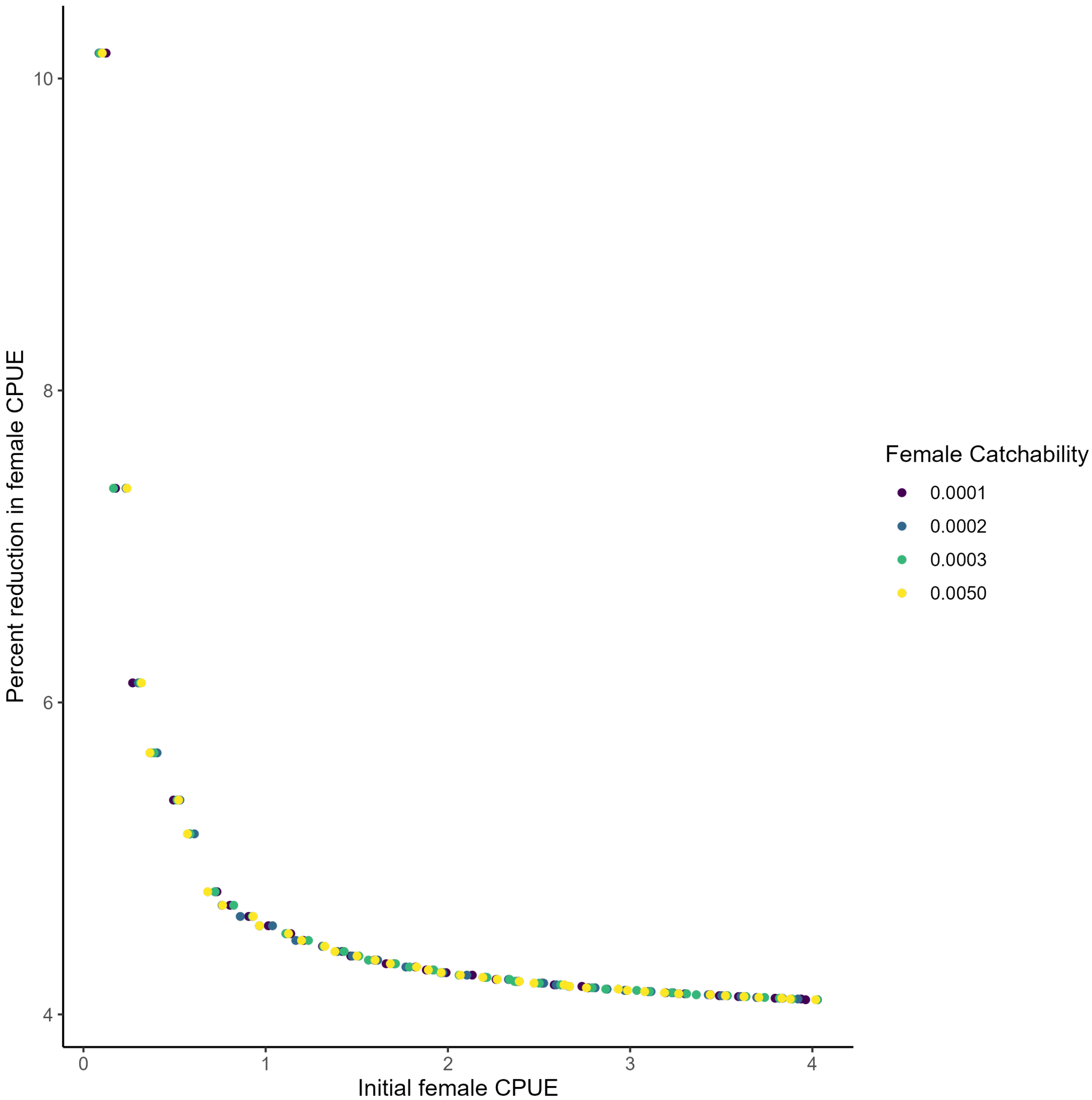

Figure D.4. Percent reduction in female CPUE for each initial value of female CPUE, given different assumptions for female catchability. The simulation output was insensitive to changes in catchability. All points are jittered.

APPENDIX E. STANDARDIZATION OF CRAB SURVEY CATCH PER UNIT EFFORT

In order to generate a standardized index of abundance for female and sub-legal male crabs using survey catch data, we attempted to account for changes in survey methods, environmental conditions and crab behaviour over the time series. This approach also better incorporated data from CMA I and J. Before fitting candidate standardization models, we gathered available data, filtered and formatted it. Each survey trap was treated as an independent observation, to account for trap effects that can effect crab catchability. This appendix describes the variables considered for use in the candidate standardization models, provides the candidate models, and outlines the process of selecting the best fitting model. We compared the standardized index to the unstandardized index to understand the effect of standardization on the proposed reference points. These methods were based on a similar approach used to standardize commercial groundfish CPUE indices (Anderson et al. 2019).

E.1. DESCRIPTION OF SURVEY CHANGES

Although the crab survey methods have been standardized for number of traps per line, trap size, trap type, and bait type, survey methods have varied since the survey began in 1988. The survey now consistently occurs in mid-May and mid-October. In earlier years the “spring” survey occurred between February and June, and the “fall” survey occurred September to November. There were also sparse observations in January, July, and December. The bait type used in the survey is usually herring, but other baits such as geoduck and fish frames (carcasses) have been used in the past. The survey follows a fixed station design where the same locations are consistently sampled. However, stations have been added and removed over time, mainly in the first ten years of the survey (i.e., 1988-1997). Target trap soak time in the survey is 24 hours, but this can vary due to weather events or other logistics. We can account for these changes in survey methods through time by including these variables as predictors in a standardization model. In addition to variation in methodology, survey CPUE may not change proportionally with crab abundance due to changes in the environment or crab behaviour. We attempted to account for some of this variability using the standardization models.

E.2. DEFINING STANDARDIZATION MODEL PREDICTORS

The candidate standardization model predictors included data collected during the survey (e.g., bait type, soak time, presence of legal male crabs, etc.) and environmental data collected post-hoc from recording stations. Weather data (e.g., wind, pressure) were collected from the Vancouver Airport weather stations (station IDs 889 and 51442). Tide data were collected from the Vancouver Harbour station (ID 07735). Fraser River outflow and air temperature data were not included due to correlation with day and month of year.

Predictors treated as continuous variables (Table E.1) were centered (i.e., the mean value was subtracted from each observation) and scaled (i.e., each observation was divided by the standard deviation) to improve estimation and interpretation of the posterior effects and to allow use of the same prior distribution for all fixed effects in the Bayesian models. Predictors treated as factors included survey year and latitude (binned into bands 0.1 degrees wide, Table E.1). Treating latitude as a factors allowed for a non-linear relationship with crab catch (Maunder and Punt 2004). Survey year was treated as a factor in order to generate the predicted standardized

CPUE index in each year. We used bands that were 0.1 degrees wide. A description of all predictors included in candidate models can be found in Table E.1.

In addition to the fixed effects mentioned above, the standardization models included spatial and spatiotemporal random effects. These random effects are intercepts that are allowed to vary from the overall model intercept spatially (in this case, by PFMA sub-area), and spatiotemporally (an interaction between year and PFMA subarea). The spatial random effects incorporated factors not included as fixed effects, that are constant through time, such as bottom substrate type. The spatiotemporal random effects incorporated factors that vary through time, such as ocean currents and changes in crab or fishery behaviour. This allows the catch trends to vary between areas, and for each area to have unique trends, while capturing the overall trend for CMA I and J combined.

E.3. DATA FILTERING

Survey observations that did not include data on geographic location, soak time, or trap position in string were not appropriate for fitting and were excluded from the model. Observations with usability codes that indicated the trap fished abnormally (e.g., fish in trap) were excluded. Observations without a trap usability code were included, as recording of trap usability began in 1999. Attempts to include trap usability as a predictor led to poor model convergence. In total, 308 trap observations were removed from the dataset, leaving a remaining 32,651.

It was possible to impute certain missing values. Observations with missing depth were assigned the mean value for their geographic location (i.e., fixed station name) for the entire time series. We did this for four sets of observations (i.e., four strings of traps).

E.4. A NEGATIVE-BINOMIAL GLMM INDEX STANDARDIZATION MODEL

The negative binomial distribution is used to model count data, and is more flexible than the Poisson distribution, which assumes the mean (μ) is equal to the variance. The negative binomial distribution uses an additional parameter (ϕ) to allow for additional variance. The variance of the negative binomial is given by $\mu + \frac{\mu^2}{\phi}$. We fit the negative binomial generalized linear mixed effects model as:

$$y_i \sim NegBinom(\mu_i, \phi) \tag{E.1}$$

$$\mu_i = \exp(X_i\beta + \alpha_{j[i]}^{\text{location}} + \alpha_{k[i]}^{\text{location:year}}) \tag{E.2}$$

$$\alpha_j^{\text{location}} \sim Normal(0, \sigma^2_{\alpha \text{ location}}) \tag{E.3}$$

$$\alpha_k^{\text{location:year}} \sim Normal(0, \sigma^2_{\alpha \text{ location:year}}) \tag{E.4}$$

where i represents a single survey trap, y_i is the number of crabs (either female or sublegal male), μ_i represents the mean of crabs (either female or sublegal male) in a survey trap, X_i represents a vector of fixed effect predictor variables, β represents a vector of fixed effect coefficients. Random effects are allowed to vary by PFMA sub area j ($\alpha_j^{\text{location}}$) and location:year combination k ($\alpha_k^{\text{location:year}}$).

The standardized survey index (I) in each year (y) was estimated by exponentiating the fixed effect (β) for each year:

$$I_y = \exp(\beta_y) \tag{E.5}$$

The stock status indicator is a three year running median of the standardized index (I_y) in the each year plus the two previous years.

Vague priors were used for the fixed and random effects included in the standardization model. Fixed effects (β) were assigned a normal distribution of the form $N(0, 20)$, and standard deviation for the random effects was assigned a student-t prior of the form $t(3, 0, 2.5)$. The software default $\mathrm{Gamma}(0.01, 0.01)$ prior was used for the shape parameter ϕ. The Bayesian analyses were performed using the R package “brms” (Bürkner 2017), which is an extension of the Stan programming language. Four chains were used, with 2000 samples each. The first 1000 samples in each chain were discarded as “warm up”, leaving a total of 4000 samples. These 4000 samples form the posterior distribution for each parameter estimate, and each represents a candidate model fit. Each posterior draw therefore provides a time-series of standardized CPUE. Thus, for each posterior sample, we can estimate the empirical LRP and stock status indicator (three-year running median). For ease of comparison, we divided each time series by its respective mean. This means the LRP (40% of the mean) for each series of B_y was equivalent to a CPUE 0.4. We estimated the probability of stock status in each year by determining the proportion of samples where the stock status indicator breached the LRP (or USR) in that year. This is shown graphically in Figure E.1, with the unstandardized index for comparison. The unstandardized time series was estimated by dividing the total number of crabs caught (efemale) by the total number of trap pulls in a given year. The index was then estimated as the three year moving median of this time series.

Table E.1. Predictor variables used in the standardization models, with descriptions.

Variable	Type	Definition
Year	Factor	Year in which survey observations were recorded
Soak Time	Continuous	Time between setting and hauling of traps, in hours. Treated as degree two polynomial
Depth	Continuous	Minimum depth recorded while setting traps
Bait	Factor	Bait type used in trap
Air pressure	Continuous	Mean air pressure on day of sampling as measured at Vancouver Airport weather station
Tidal Magnitude	Continuous	Difference between maximum and minimum tide recorded at Vancouver Harbour tide station on day of sampling
Wind Speed	Continuous	Mean wind speed on day of sampling as measured at Vancouver Airport weather station
Wind Direction	Cyclical	Mean wind direction on day of sampling as measured at Vancouver Airport weather station, broken into sin and cos components
Trap Position	Factor	Boolean indicating if a trap is at the end (first or last) of a string or not
Legal Male Crab Presence	Factor	Boolean indicating if at least one legal male crab was found in trap

Variable	Type	Definition
Latitude	Factor	Latitude of start of string, binned to nearest 0.1 degree
PFMA Area	Factor	PFMA stat and subarea in which the trap was set

E.5. MODEL SELECTION AND DIAGNOSTICS

We fit four candidate models each for sublegal male, legal male, and female crabs. These models were all specific to certain hypotheses about which variables may result in variation in crab survey catches. All models included spatial and spatiotemporal random effects. The most basic model is referred to as a null model, and includes only year as a fixed effect. The “full” model, included the entire suite of candidate fixed effects. We also fit a model that did not include environmental effects (i.e., pressure, tide, wind speed, wind direction), and a model that did not include “trap effects” (i.e., bait type, trap position in string, presence of legal male crabs). We assumed convergence in the models as all $\hat{R}$ values were $\leq$ 1.01 (Vehtari et al. 2021). Mixing of chains was confirmed by examining trace plots. Models were compared using the widely applicable information criterion (WAIC) (Vehtari et al. 2017), as seen in Tables E.2, E.3, and E.4. The model with the lowest WAIC is the best fit, and differences in WAIC are shown. Differences were calculated by subtracting a given model from the best fit model (i.e., larger negative values indicate a worse model fit). Model assumptions were checked using DHARMa simulated residuals (Hartig 2022), which uses a simulation approach to create interpretable scaled residuals for mixture models, and plots of observed vs predicted values.

The model including all possible predictors (i.e., the full model) was the most supported by WAIC for female, sublegal male, and legal male crabs. The model with environmental predictors excluded was next most supported, followed by the model without trap effects. The null model was least supported for males and females.

We conclude there are no years where the LRP is breached by either the unstandardized or standardized index. The stock is considered in the critical zone when there is greater than 50% probability that the index is below the LRP. There are some years where the USR is breached by the unstandardized index, but not breached by the standardized index. Survey CPUE should therefore always be standardized to ensure stock status is not determined by changes in survey methodology.

Table E.2. Table of model comparison with WAIC for models fit to female crab data.

Model	WAIC Difference
Full Model	0.0000
No Environment	-113.0963
No Trap	-250.9204
Null	-2,298.5347

Table E.3. Table of model comparison with WAIC for models fit to sublegal crab data.

Model	WAIC Difference
Full Model	0.00000
No Environment	-23.17317
No Trap	-462.06119
Null	-2,388.21741

Table E.4. Table of model comparison with WAIC for models fit to legal crab data.

Model	WAIC Difference
Full Model	0.000000
No Environment	-4.633263
No Trap	-152.830805
Null	-5,624.867807

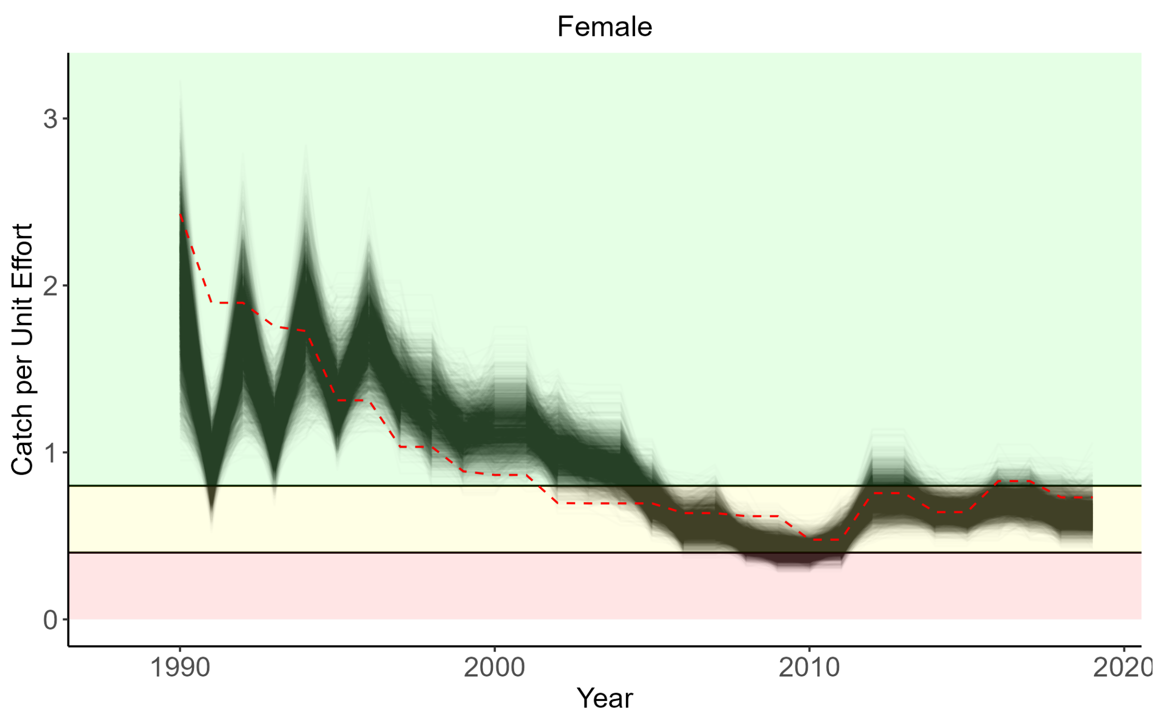

Figure E.1. Time series of female stock status indicator. Each black line represets a sample three-year running median from the Bayesian standardization model. The coloured background represents a stock status zone, delineated by the LRP (CPUE = 0.4) and USR (CPUE = 0.8). The red line represents the unstandardized estimate of the three year running median of female CPUE.

Table E.5. Summary statistics of fixed effects in best fit standardization model for female crabs.

	Estimate	Standard Error of estimate	Lower 95 confidence interval	Upper 95 confidence interval	Rhat	Bulk Effective Sample Size	Tail Effective Sample Size
Year1988	0.357	0.508	-0.662	1.323	1.006	772.058	1,300.418
Year1989	-0.925	0.493	-1.904	0.006	1.005	752.511	1,302.553
Year1990	0.097	0.519	-0.946	1.091	1.005	773.214	1,408.102
Year1991	-0.707	0.490	-1.702	0.221	1.007	711.597	1,325.585
Year1992	0.034	0.498	-0.983	0.984	1.007	776.833	1,365.107
Year1993	-0.486	0.483	-1.475	0.456	1.005	698.042	1,208.782
Year1994	0.184	0.484	-0.817	1.106	1.006	710.773	1,320.682
Year1995	-0.306	0.487	-1.292	0.642	1.009	714.038	1,243.767
Year1996	-0.065	0.485	-1.084	0.881	1.007	715.592	1,082.012
Year1997	-0.350	0.480	-1.323	0.561	1.008	726.774	1,139.428
Year1998	-0.823	0.486	-1.791	0.107	1.008	712.406	1,249.679
Year1999	-0.413	0.485	-1.384	0.531	1.007	720.875	1,399.968
Year2000	-0.280	0.489	-1.271	0.657	1.007	713.710	1,159.848
Year2001	-0.711	0.486	-1.695	0.240	1.007	705.097	1,216.706
Year2002	-0.607	0.484	-1.563	0.321	1.007	729.938	1,363.384
Year2003	-0.592	0.485	-1.578	0.339	1.006	725.525	1,020.269
Year2004	-0.925	0.485	-1.872	0.002	1.006	700.470	1,216.981
Year2005	-1.140	0.493	-2.113	-0.183	1.007	734.061	1,293.126
Year2006	-1.397	0.479	-2.380	-0.473	1.006	707.125	1,369.531
Year2007	-0.736	0.482	-1.695	0.201	1.008	711.105	1,196.387
Year2008	-1.431	0.483	-2.388	-0.511	1.006	695.714	1,183.421
Year2009	-1.756	0.480	-2.708	-0.835	1.008	703.433	1,201.115
Year2010	-1.339	0.482	-2.276	-0.406	1.007	697.835	1,239.932
Year2011	-0.536	0.477	-1.479	0.373	1.007	691.299	1,173.194
Year2012	-0.899	0.481	-1.877	0.019	1.007	699.498	1,129.363
Year2013	-1.136	0.474	-2.086	-0.228	1.007	710.407	1,303.563
Year2014	-1.003	0.475	-1.950	-0.092	1.006	667.998	1,280.335

	Estimate	Standard Error of estimate	Lower 95 confidence interval	Upper 95 confidence interval	Rhat	Bulk Effective Sample Size	Tail Effective Sample Size
Year2015	-0.946	0.485	-1.940	-0.024	1.007	683.638	1,210.039
Year2016	-0.790	0.480	-1.751	0.119	1.006	688.589	1,208.868
Year2017	-1.043	0.485	-2.037	-0.108	1.007	710.734	1,190.460
Year2018	-1.211	0.486	-2.191	-0.272	1.006	694.106	1,170.573
Year2019	-0.873	0.487	-1.838	0.055	1.008	703.618	1,408.257
polyHoursSoak21	5.835	1.340	3.253	8.490	1.001	4,595.164	2,816.476
polyHoursSoak22	-10.607	1.469	-13.484	-7.812	1.000	4,712.220	2,885.968
MinDepth	0.168	0.009	0.151	0.184	1.001	4,853.930	3,189.899
BaitCodeCLA	-0.084	0.226	-0.534	0.362	1.000	4,178.482	2,488.826
BaitCodeEUL	0.335	0.141	0.066	0.603	1.000	3,945.909	3,625.557
BaitCodeFRA	0.219	0.096	0.026	0.405	1.000	4,459.614	3,689.164
BaitCodeGEO	-0.759	0.102	-0.958	-0.559	1.001	3,785.312	3,146.888
BaitCodeGWH	-0.805	0.143	-1.082	-0.530	1.001	4,257.176	3,135.114
BaitCodeHCQ	0.114	0.321	-0.488	0.766	1.000	3,996.979	3,101.273
BaitCodeHDB	-0.224	0.196	-0.603	0.155	1.001	4,251.843	3,277.014
BaitCodeHER	-0.220	0.090	-0.398	-0.045	1.001	3,744.059	3,125.374
BaitCodeHWP	0.227	0.199	-0.168	0.619	1.001	4,168.580	2,349.000
BaitCodeHWQ	1.286	0.168	0.958	1.613	1.001	3,882.439	3,324.597
BaitCodePEL	-0.974	0.281	-1.529	-0.435	1.001	4,946.615	2,860.461
BaitCodePIL	0.052	0.107	-0.157	0.262	1.001	3,947.499	3,151.430
BaitCodeQID	-0.480	0.183	-0.830	-0.125	1.001	4,575.575	3,645.712
BaitCodeROC	-1.569	0.205	-1.956	-1.157	1.000	4,262.273	2,938.716
BaitCodeUNK	-0.315	0.105	-0.526	-0.104	1.001	3,838.291	2,620.790
pressure	0.108	0.010	0.088	0.127	1.001	5,172.255	3,394.146
Tidal.Magnitude	0.097	0.010	0.077	0.117	1.000	4,470.783	3,000.664
windSpeed	0.059	0.010	0.040	0.078	1.000	5,229.425	3,099.684
sinWindDir	-0.015	0.011	-0.037	0.007	1.001	4,555.941	3,224.766

	Estimate	Standard Error of estimate	Lower 95 confidence interval	Upper 95 confidence interval	Rhat	Bulk Effective Sample Size	Tail Effective Sample Size
cosWindDir	-0.076	0.021	-0.117	-0.036	1.001	5,116.158	3,325.796
Month2	1.307	0.454	0.424	2.235	1.008	705.046	1,297.412
Month3	2.757	0.494	1.799	3.784	1.007	790.080	1,277.853
Month4	2.550	0.457	1.654	3.490	1.008	699.397	1,240.019
Month5	2.526	0.458	1.633	3.462	1.009	697.368	1,196.465
Month6	1.667	0.455	0.771	2.604	1.010	695.485	1,174.446
Month7	1.783	0.461	0.906	2.721	1.009	705.440	1,289.383
Month9	2.672	0.457	1.782	3.608	1.009	696.166	1,168.224
Month10	2.157	0.456	1.260	3.096	1.009	695.047	1,199.357
Month11	1.399	0.457	0.504	2.338	1.007	700.601	1,200.326
Month12	0.840	0.463	-0.044	1.766	1.010	723.892	1,054.522
firstLastTRUE	-1.243	0.435	-2.050	-0.376	1.002	4,551.369	2,229.595
hasLegalMaleTRUE	-0.129	0.014	-0.158	-0.101	1.001	5,073.527	2,918.246
startLAT49.1	0.170	0.052	0.069	0.272	1.001	5,288.591	3,500.102
startLAT49.2	-0.553	0.058	-0.667	-0.439	1.000	5,477.029	3,561.241
startLAT49.3	-0.749	0.090	-0.928	-0.577	1.000	3,895.447	3,539.766
startLAT49.4	-2.408	0.176	-2.766	-2.065	1.002	3,831.654	3,263.937
startLAT49.5	-2.014	0.394	-2.798	-1.252	1.000	4,720.920	3,215.764
startLAT49.6	-2.324	0.544	-3.407	-1.280	1.000	4,759.713	3,408.570
startLAT49.7	-1.145	0.590	-2.321	0.031	1.002	5,110.830	2,818.223

Table E.6. Summary statistics of fixed effects in best fit standardization model for sublegal male crabs.

	Estimate	Standard Error of estimate	Lower 95 confidence interval	Upper 95 confidence interval	Rhat	Bulk Effective Sample Size	Tail Effective Sample Size
Year1988	0.942	0.265	0.427	1.461	1.002	1,255.084	2,116.419
Year1989	1.468	0.245	0.990	1.963	1.002	1,208.518	2,185.612
Year1990	0.951	0.283	0.403	1.509	1.002	1,291.491	2,003.600
Year1991	0.385	0.242	-0.079	0.874	1.003	964.837	1,832.789
Year1992	0.985	0.250	0.512	1.479	1.002	1,036.554	1,904.380
Year1993	1.274	0.233	0.820	1.752	1.003	983.175	1,698.863
Year1994	1.111	0.232	0.664	1.579	1.004	949.986	1,625.026
Year1995	0.800	0.235	0.335	1.263	1.001	945.575	1,670.849
Year1996	0.823	0.234	0.378	1.306	1.004	942.798	1,554.276
Year1997	0.967	0.230	0.527	1.443	1.002	932.010	1,553.962
Year1998	0.716	0.231	0.263	1.167	1.002	921.437	1,693.394
Year1999	0.683	0.227	0.240	1.136	1.002	974.193	1,629.399
Year2000	0.989	0.235	0.541	1.481	1.002	922.239	1,618.389
Year2001	0.877	0.238	0.413	1.348	1.003	998.712	1,715.589
Year2002	1.044	0.230	0.615	1.511	1.001	968.666	1,631.733
Year2003	1.023	0.229	0.599	1.494	1.002	933.478	1,440.707
Year2004	0.838	0.230	0.398	1.305	1.002	915.502	1,573.820
Year2005	0.520	0.240	0.054	0.992	1.003	970.143	1,557.265
Year2006	0.770	0.226	0.319	1.241	1.003	936.293	1,661.820
Year2007	0.733	0.227	0.289	1.195	1.002	897.834	1,512.374
Year2008	0.109	0.229	-0.334	0.560	1.003	890.087	1,696.398
Year2009	-0.055	0.227	-0.480	0.400	1.003	918.433	1,621.164
Year2010	0.400	0.226	-0.035	0.859	1.003	926.658	1,520.092
Year2011	0.286	0.228	-0.147	0.741	1.003	891.165	1,460.034
Year2012	0.469	0.225	0.032	0.925	1.003	936.034	1,702.109
Year2013	0.441	0.225	0.004	0.900	1.003	887.821	1,463.408
Year2014	0.723	0.222	0.298	1.168	1.002	935.439	1,534.555

	Estimate	Standard Error of estimate	Lower 95 confidence interval	Upper 95 confidence interval	Rhat	Bulk Effective Sample Size	Tail Effective Sample Size
Year2015	0.982	0.230	0.541	1.449	1.003	962.486	1,453.039
Year2016	0.725	0.226	0.287	1.184	1.002	898.218	1,582.699
Year2017	0.632	0.230	0.184	1.112	1.003	933.810	1,457.706
Year2018	0.387	0.232	-0.061	0.860	1.002	938.725	1,656.538
Year2019	0.700	0.230	0.246	1.171	1.002	958.367	1,407.856
polyHoursSoak21	13.250	1.007	11.282	15.182	1.001	4,613.314	3,103.083
polyHoursSoak22	-9.270	1.024	-11.245	-7.280	1.000	4,864.985	2,753.569
MinDepth	-0.350	0.007	-0.365	-0.336	1.001	4,373.095	3,037.849
BaitCodeCLA	0.599	0.151	0.307	0.896	1.000	4,232.256	3,164.649
BaitCodeEUL	-0.405	0.111	-0.620	-0.183	1.000	3,563.315	2,969.805
BaitCodeFRA	-0.275	0.081	-0.436	-0.120	1.001	3,634.265	3,508.158
BaitCodeGEO	-0.305	0.084	-0.468	-0.141	1.001	3,310.764	2,866.982
BaitCodeGWH	-0.438	0.107	-0.647	-0.226	1.000	3,843.585	3,358.518
BaitCodeHCQ	0.134	0.287	-0.415	0.696	1.001	4,601.465	3,434.746
BaitCodeHDB	-0.290	0.191	-0.655	0.090	1.002	4,038.521	3,264.890
BaitCodeHER	-0.433	0.077	-0.588	-0.280	1.001	3,098.002	2,932.752
BaitCodeHWP	-1.086	0.197	-1.463	-0.702	1.000	4,081.848	2,560.218
BaitCodeHWQ	-1.627	0.130	-1.876	-1.359	1.001	2,852.244	3,350.854
BaitCodePEL	-1.051	0.211	-1.473	-0.635	1.001	3,884.840	2,824.539
BaitCodePIL	-0.659	0.091	-0.843	-0.483	1.001	3,302.318	3,249.417
BaitCodeQID	-0.378	0.190	-0.761	-0.009	1.000	5,076.128	3,115.866
BaitCodeROC	-0.920	0.161	-1.233	-0.601	1.001	3,769.660	3,253.674
BaitCodeUNK	-0.804	0.088	-0.978	-0.631	1.001	2,972.475	3,177.633
pressure	0.004	0.008	-0.012	0.020	1.000	4,693.949	3,177.853
Tidal.Magnitude	-0.030	0.008	-0.046	-0.014	1.001	5,192.176	2,977.289
windSpeed	0.002	0.008	-0.012	0.017	1.001	4,865.484	3,180.868
sinWindDir	-0.023	0.009	-0.041	-0.005	1.001	4,900.439	3,152.149

	Estimate	Standard Error of estimate	Lower 95 confidence interval	Upper 95 confidence interval	Rhat	Bulk Effective Sample Size	Tail Effective Sample Size
cosWindDir	-0.103	0.017	-0.134	-0.070	1.000	5,741.824	3,278.960
Month2	0.368	0.177	0.004	0.717	1.003	1,047.163	1,665.760
Month3	-0.771	0.277	-1.306	-0.228	1.001	1,679.678	2,468.031
Month4	-0.220	0.182	-0.585	0.140	1.003	1,016.901	1,687.754
Month5	0.258	0.184	-0.111	0.622	1.003	1,007.418	1,563.118
Month6	0.133	0.181	-0.237	0.487	1.003	1,017.457	1,719.377
Month7	0.196	0.188	-0.181	0.559	1.003	1,115.301	1,703.346
Month9	0.389	0.183	0.019	0.752	1.003	1,021.262	1,588.079
Month10	0.257	0.182	-0.107	0.614	1.003	1,010.531	1,600.584
Month11	0.526	0.182	0.157	0.888	1.003	1,014.646	1,796.482
Month12	0.233	0.188	-0.145	0.608	1.002	1,096.666	1,951.343
firstLastTRUE	-1.964	0.703	-3.471	-0.750	1.000	4,004.859	2,186.473
hasLegalMaleTRUE	0.307	0.012	0.284	0.331	1.001	4,671.296	2,589.702
startLAT49.1	0.037	0.041	-0.042	0.117	1.001	4,914.909	3,465.026
startLAT49.2	0.406	0.047	0.316	0.499	1.001	5,063.133	3,335.865
startLAT49.3	0.513	0.067	0.386	0.644	1.000	4,011.305	3,194.795
startLAT49.4	0.173	0.125	-0.076	0.423	1.001	4,652.213	3,685.549
startLAT49.5	-0.357	0.345	-1.043	0.331	1.001	4,750.547	2,744.548
startLAT49.6	-0.638	0.431	-1.478	0.212	1.000	4,695.058	3,032.229
startLAT49.7	-0.027	0.556	-1.100	1.073	1.002	6,986.371	2,769.022

Table E.7. Summary statistics of fixed effects in best fit standardization model for legal male crabs.

	Estimate	Standard Error of estimate	Lower 95 confidence interval	Upper 95 confidence interval	Rhat	Bulk Effective Sample Size	Tail Effective Sample Size
Year1988	-1.024	0.429	-1.866	-0.167	1.019	195.143	441.994
Year1989	-1.015	0.392	-1.783	-0.244	1.021	183.364	461.309
Year1990	-0.343	0.456	-1.255	0.548	1.020	190.253	476.771
Year1991	-0.284	0.402	-1.087	0.501	1.028	151.617	356.737
Year1992	0.391	0.414	-0.405	1.256	1.028	165.315	391.909
Year1993	0.590	0.399	-0.163	1.370	1.023	145.686	277.386
Year1994	0.142	0.397	-0.619	0.946	1.033	136.741	419.460
Year1995	-0.314	0.397	-1.093	0.487	1.025	165.833	336.585
Year1996	-0.279	0.394	-1.052	0.526	1.025	155.639	378.501
Year1997	-0.199	0.383	-0.943	0.562	1.025	153.142	373.817
Year1998	0.243	0.385	-0.512	1.022	1.031	144.614	384.326
Year1999	0.191	0.389	-0.556	0.988	1.024	152.871	378.025
Year2000	-0.015	0.398	-0.783	0.775	1.024	162.336	447.275
Year2001	0.612	0.396	-0.162	1.391	1.021	154.814	324.143
Year2002	-0.055	0.397	-0.820	0.765	1.030	156.316	422.321
Year2003	0.170	0.392	-0.599	0.960	1.025	146.076	362.269
Year2004	0.064	0.387	-0.721	0.834	1.023	154.572	356.276
Year2005	0.305	0.403	-0.467	1.140	1.019	149.692	396.520
Year2006	0.473	0.391	-0.291	1.257	1.026	159.803	414.500
Year2007	0.405	0.400	-0.397	1.233	1.027	148.467	422.987
Year2008	0.082	0.391	-0.696	0.856	1.026	157.999	367.173
Year2009	0.101	0.387	-0.661	0.863	1.028	147.537	341.968
Year2010	0.096	0.390	-0.677	0.878	1.027	145.383	358.501
Year2011	-0.366	0.391	-1.123	0.421	1.023	153.089	375.496
Year2012	-0.395	0.391	-1.160	0.420	1.025	153.365	411.764
Year2013	0.031	0.388	-0.740	0.817	1.027	156.756	353.272
Year2014	-0.214	0.383	-0.964	0.566	1.028	149.899	327.872

	Estimate	Standard Error of estimate	Lower 95 confidence interval	Upper 95 confidence interval	Rhat	Bulk Effective Sample Size	Tail Effective Sample Size
Year2015	0.116	0.391	-0.645	0.947	1.024	158.491	403.843
Year2016	0.121	0.404	-0.674	0.933	1.026	149.237	391.339
Year2017	-0.460	0.393	-1.232	0.332	1.021	158.220	311.673
Year2018	-0.153	0.390	-0.931	0.636	1.032	143.138	353.297
Year2019	-0.250	0.402	-1.050	0.564	1.026	146.009	343.697
polyHoursSoak21	18.244	1.516	15.234	21.182	1.001	3,329.731	2,943.214
polyHoursSoak22	-23.445	1.571	-26.615	-20.391	1.002	3,002.433	2,844.323
MinDepth	-0.228	0.010	-0.248	-0.209	1.002	4,379.160	3,252.478
BaitCodeCLA	-1.192	0.230	-1.641	-0.746	1.001	1,625.150	2,246.502
BaitCodeEUL	0.749	0.162	0.432	1.066	1.003	787.289	1,552.729
BaitCodeFRA	0.004	0.134	-0.250	0.275	1.003	768.500	1,684.482
BaitCodeGEO	0.075	0.136	-0.191	0.347	1.003	647.171	1,194.579
BaitCodeGWH	-0.038	0.161	-0.342	0.277	1.003	812.160	1,626.465
BaitCodeHCQ	0.675	0.553	-0.424	1.718	1.002	3,017.928	2,605.760
BaitCodeHDB	-0.579	0.450	-1.524	0.253	1.002	2,966.486	3,037.549
BaitCodeHER	0.029	0.125	-0.219	0.283	1.004	599.077	1,052.420
BaitCodeHWP	0.051	0.267	-0.459	0.562	1.001	1,598.342	2,032.139
BaitCodeHWQ	0.640	0.248	0.155	1.112	1.003	947.426	2,110.971
BaitCodePEL	-1.135	0.578	-2.382	-0.114	1.002	3,132.851	2,450.280
BaitCodePIL	-0.976	0.150	-1.272	-0.682	1.002	762.944	1,306.741
BaitCodeQID	-1.543	0.317	-2.193	-0.932	1.002	1,707.662	2,300.311
BaitCodeROC	0.804	0.283	0.239	1.355	1.000	1,794.203	2,312.072
BaitCodeUNK	0.223	0.146	-0.062	0.516	1.003	668.985	1,321.790
pressure	0.012	0.012	-0.011	0.034	1.001	2,555.929	3,033.129
Tidal.Magnitude	0.026	0.012	0.003	0.048	1.000	2,878.364	2,840.871
windSpeed	-0.002	0.010	-0.022	0.019	1.002	2,675.681	2,430.551
sinWindDir	-0.040	0.014	-0.067	-0.013	1.001	3,257.136	2,961.663

	Estimate	Standard Error of estimate	Lower 95 confidence interval	Upper 95 confidence interval	Rhat	Bulk Effective Sample Size	Tail Effective Sample Size
cosWindDir	0.041	0.026	-0.011	0.090	1.000	2,690.562	2,766.973
Month2	-0.251	0.366	-0.996	0.481	1.017	186.001	328.026
Month3	1.865	0.479	0.927	2.783	1.011	275.167	606.506
Month4	0.338	0.370	-0.422	1.070	1.017	181.374	322.610
Month5	0.590	0.373	-0.183	1.331	1.018	180.979	329.576
Month6	1.195	0.370	0.423	1.926	1.017	181.012	322.090
Month7	1.656	0.374	0.899	2.392	1.017	186.750	343.586
Month9	-1.204	0.374	-1.970	-0.458	1.018	184.210	323.124
Month10	-0.868	0.371	-1.628	-0.135	1.017	181.687	321.576
Month11	-0.679	0.372	-1.453	0.061	1.017	185.076	319.550
Month12	-0.721	0.384	-1.490	0.025	1.018	190.515	355.092
firstLastTRUE	-18.183	11.331	-45.229	-3.466	1.002	2,704.804	2,180.846
startLAT49.1	-0.136	0.061	-0.257	-0.018	1.005	1,496.032	2,093.369
startLAT49.2	0.217	0.070	0.082	0.352	1.005	1,405.146	1,962.964
startLAT49.3	0.166	0.098	-0.028	0.355	1.006	1,295.621	2,044.423
startLAT49.4	-0.036	0.186	-0.412	0.327	1.002	2,311.921	2,900.546
startLAT49.5	0.114	0.449	-0.744	1.007	1.004	1,114.121	1,817.638
startLAT49.6	-0.638	0.546	-1.692	0.406	1.002	1,423.910	2,463.005
startLAT49.7	0.251	0.770	-1.303	1.736	1.001	1,817.496	1,983.253