APPENDIX AIR10-C
Technical Data Reports Containing Habitat Maps at Local and Regional Scales

TDR MI-4- Marine Invertebrates
Dungeness Crab Productivity TDR

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ROBERTS BANK TERMINAL 2
TECHNICAL DATA REPORT
Marine Invertebrates
Dungeness Crab Productivity

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Technical Report / Technical Data Report Disclaimer

The Canadian Environmental Assessment Agency determined the scope of the proposed Roberts Bank Terminal 2 Project (RBT2 or the Project) and the scope of the assessment in the Final Environmental Impact Statement Guidelines (EISG) issued January 7, 2014. The scope of the Project includes the project components and physical activities to be considered in the environmental assessment. The scope of the assessment includes the factors to be considered and the scope of those factors. The Environmental Impact Statement (EIS) has been prepared in accordance with the scope of the Project and the scope of the assessment specified in the EISG. For each component of the natural or human environment considered in the EIS, the geographic scope of the assessment depends on the extent of potential effects.

At the time supporting technical studies were initiated in 2011, with the objective of ensuring adequate information would be available to inform the environmental assessment of the Project, neither the scope of the Project nor the scope of the assessment had been determined.

Therefore, the scope of supporting studies may include physical activities that are not included in the scope of the Project as determined by the Agency. Similarly, the scope of supporting studies may also include spatial areas that are not expected to be affected by the Project.

This out-of-scope information is included in the Technical Report (TR)/Technical Data Report (TDR) for each study, but may not be considered in the assessment of potential effects of the Project unless relevant for understanding the context of those effects or to assessing potential cumulative effects.

EXECUTIVE SUMMARY

Port Metro Vancouver (PMV) is assessing the potential to develop the Roberts Bank Terminal 2 Project (RBT2 or the Project), a new three-berth marine terminal at Roberts Bank in Delta, B.C. The Project is part of PMV's Container Capacity Improvement Program (CCIP), a long-term strategy to deliver projects to meet anticipated growth in demand for container capacity to 2030.

Hemmera has been retained by PMV to undertake environmental studies related to the Project. This technical data report examines mid- to long-term trends in Dungeness crab population dynamics within the vicinity of the proposed Roberts Bank Terminal 2 Project (RBT2 or Project), specifically in DFO Fishery Management Area 29, and Sub-areas 29-6 and 29-7. Commercial crab fisheries are active at this site and are passively managed by DFO through measures that restrict harvest by sex, size, and season, such that only males larger than the minimum size limit are allowed to be retained during the open season. The major objective of the study was to create a model to estimate Dungeness crab productivity in the vicinity of the Project in order to gain a better understanding of the health and status of the population in this area. All data and results presented in this report relate only to male crabs because harvest of females is prohibited by regulation; therefore, the only relevant production assessment is of male crabs.

DFO's Shellfish Data Unit maintains long-term time-series of i) fishery dependent data, including landings and other catch statistics and ii) fishery-independent data from research surveys in Area 29, including indices of crab abundance and size-composition measured before and after the fishing season as well as information on crab growth and mortality from Vancouver Harbour. Relevant datasets were collated and used to develop a Bayesian size-structured model of crab population dynamics that estimates adult recruitment, biomass, and production. Bayesian techniques are particularly advantageous in that existing knowledge of crab biology (termed "priors") can be merged with detailed fishery and survey size composition data to generate a more robust model.

Model predictions indicate that, over a 21 year time series, annual legal-sized male standing stock biomass in Area 29 averaged 752 tonnes with biomass in Sub-areas 29-6 and 29-7 making up 37% and 6% of this total, respectively. Annual recruitment of male crabs in the Area 29 fishery averaged 6 million, and ranged from a low of 2.7 million to a high of almost 17 million. This recruitment resulted in annual production of harvestable crabs that averaged 629 tonnes with proportional contributions of 36% and 5% by areas 29-6 and 29-7, respectively.

Results also demonstrate that crab abundance in the Fraser River estuary (i.e., Area 29 overall) fluctuates widely, and can greatly increase or decrease over short intervals of time and space, consistent with observations of Dungeness crab dynamics from other parts of the Pacific Northwest. Mechanistic causes underlying such fluctuations are hypothesised to be both biological (e.g., competition, cannibalism) and physical (e.g., temperature, winds, currents) in nature, and tied to large-scale climactic forcing regimes such as the Pacific Decadal Oscillation.

As expected, the precision of estimated model parameters as well as estimated crab abundance, recruitment, and production all decrease as the spatial scale decreases from Area 29 overall to Sub-areas 29-6 and Area 29-7.

GLOSSARY

Bayesian Estimation	Statistical methods used in this report to compute probability distributions for parameters and other quantities of interest derived from crab abundance estimation models. The approach combines existing knowledge about the parameters with likelihoods of observed data.
Catch	A measure of all marine species removed from the environment, including bycatch, fish released, at-sea discards and species not sold.
Conspecifics	Individuals belonging to the same species.
Credible Interval	The Bayesian equivalent of a confidence interval around a model parameter or estimate. The term "credible" originates from the literal Bayesian interpretation of probability as "degrees of belief".
Discrepancy Statistic	A quantitative measure of disagreement between model estimates and observed data.
Fishery Dependent	Data sampled directly from the non-random harvesting process. Samples typically obtained via service providers include fishing activity information such as gear type, total catch, landings, effort, sales, date and place of harvest etc., but also can include biological attributes of the catch such as, size-composition, age structure, and sex ratio.
Fishery Independent	Data sampled according to a scientific survey design. Samples typically collected by scientists include biological information such as abundance, size composition, moult timing, injury rates, shell condition, and sex ratio.
Landings	A measure of the total number or weight of all marine species captured and accounted for in shore-based catch sampling.
Markov Chain Monte Carlo (MCMC)	A computer simulation approach to sampling from Bayesian joint posterior distributions for model parameters.
Posterior Distribution	A probability distribution function (PDF) summarizing what is known about a parameter or other quantity derived from an estimation model. A posterior PDF combines prior knowledge with new data. Samples from posterior PDFs obtained via MCMC can be summarised using basic statistics such as the mean, median, and standard deviation.
Prior Distribution	A PDF summarising what is known about a parameter before considering any new data.
Production	The difference between legal crab biomass remaining after fishing in year *t*-1 (adjusted for over-winter mortality) and legal crab biomass just prior to fishing in year *t.*
Recruitment	The number of new crabs entering the smallest sizes classes of the crab stock each year. Recruitment of crabs to the fishery and surveys later via processes of growth and gear selectivity.
Vancouver Harbour	The waters of English Bay and Burrard Inlet, northeast of the Fraser delta and southeast of Howe Sound.

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1.0 INTRODUCTION

This section provides Project Background information and an overview of the Dungeness Crab (*Metacarcinus magister*) Productivity Study.

1.1 PROJECT BACKGROUND

The Roberts Bank Terminal 2 Project (RBT2 or Project) is a proposed new three-berth marine terminal at Roberts Bank in Delta, B.C. that could provide 2.4 million TEUs (twenty-foot equivalent unit containers) of additional container capacity annually. The project is part of Port Metro Vancouver's Container Capacity Improvement Program, a long-term strategy to deliver projects to meet anticipated growth in demand for container capacity to 2030.

Port Metro Vancouver has retained Hemmera to undertake environmental studies related to the Project. This technical data report describes the results of the Dungeness Crab Productivity Study. The overall objective of this report is to ensure that sufficient information is available to inform a future effects assessment of the proposed Project.

1.2 DUNGENESS CRAB PRODUCTIVITY OVERVIEW

A review of the existing state of knowledge was completed for Dungeness crabs to identify key data gaps and areas of uncertainty, with a focus on crab resources in the Roberts Bank area. This technical data report describes the findings of studies completed to address some of the key knowledge gaps. Study components, major objectives and a brief overview are provided in **Table 1-1**.

Table 1-1 Dungeness Crab Productivity Study Components and Major Objectives

Component	Major Objective	Brief Overview
Size-structured Population Dynamics Model	• Estimate recent abundance dynamics and production of harvestable Dungeness crabs in DFO Management Area 29, and Sub-areas 29-6 and 29-7 where possible. • Verify robustness of model using simulation tests.	A Bayesian size-structured (length-based) model of Dungeness crab population dynamics was developed that merges existing knowledge of crab biology with detailed fishery dependent and fishery independent monitoring data.

The crab fishery, managed by DFO, is based on a "three-S" model, of which management measures include a minimum size limit for retention (165 mm carapace width (CW)), sex restriction (harvest is restricted to males only), non-retention of recently molted soft-shell crabs and, seasonal closures during the spring male moult (Zhang and Dunham 2013). As such, there are no quantitative stock assessment studies or data at Roberts Bank to inform the status of the population; therefore, to understand crab productivity at Roberts Bank a population dynamics model was developed, and validated against existing **catch** information.

For definitions of technical terms referred to throughout this document, please refer to the Glossary.

2.0 REVIEW OF AVAILABLE LITERATURE AND DATA

This section provides a review of available literature and data considered in the Dungeness Crab Productivity Study.

2.1 LIFE HISTORY AND BEHAVIOUR

Dungeness crab life history involves distinct stages of development, including: pelagic larvae, megalopae[1], instars[2], older juveniles, and mature adults (Armstrong et al. 1989). Adults migrate to shallow waters in spring (March through June) to reproduce. Males embrace females and mate shortly after the female crab moults and is in a softshell state (Jensen et al. 1996). Male crabs often mate with multiple females in the same season (Orensanz and Gallucci 1988), and females can also mate with more than one male in a season (Jensen et al. 1996). Females produce 200,000 to two million eggs, depending on their size, and can store sperm to fertilise their eggs at a later date when their carapace has hardened, usually around October or November (Wild 1980, Rasmuson 2013). Some female crabs "skip-moult", where they breed every second year, and can store sperm up to two and a half years to fertilise their eggs (Hankin et al. 1989). The eggs adhere to the abdomen and are protected and aerated by the female throughout the winter (approximately three months of embryonic development); during this time, female crabs are relatively inactive – they seldom feed and remain buried in bottom sediments (Dunham et al. 2011). Eggs hatch late winter/early spring, depending on location (latitude) and water temperature.

Dungeness crab larvae emerge into the water as pre-zoeae, but moult quickly (within one hour) to the first zoea stage. After an extended (four to five month) pelagic period entailing five zoeal stages, the megalopae settle in intertidal habitats within shallow coastal zones or estuaries (Gunderson et al. 1990, McConnaughey et al. 1992). Settlement occurs progressively later at higher latitudes, except in the Strait of Georgia where, in most years, settlement extends from late June through September, peaking in August (Dunham et al. 2011). In some years, multiple pulses of settlement are reported for inland waters, corresponding to cohorts of early settling coastal stocks and later settling inland stocks (McMillan et al. 1995).

Megalopae settle into complex substrates, such as oyster shell or eelgrass beds and metamorphose into first instar juveniles after settlement (Pauley et al. 1989). They are reclusive during this time, and appear to remain in the area of initial settlement throughout the first year of life. Upon reaching a carapace width of approximately 30 mm, considered a size refuge from predation, age 0+ crabs migrate to sub-tidal areas (Dumbauld and Armstrong 1987, Fernandez et al. 1993). Age 1+ crabs most commonly use sub-tidal areas, but migrate from these deeper refugia into intertidal habitats during flood tides to forage for food (Gunderson et al. 1990, Fernandez et al. 1993, Holsman et al. 2003).

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[1] Final larval stage in decapod crustaceans where behaviour, morphology and physiology is transitional between the larval and early juvenile stages (Brown and Terwilliger 1992).

[2] Developmental stage between each moult until sexual maturity is reached.

Like other crustaceans, Dungeness crabs grow discontinuously by moulting, a process whereby the old shell is shed as a new shell underneath absorbs water and swells to a new size 15 to 30% larger, and hardens over several months (Dunham et al. 2011). Each moult stage, or instar, cannot accurately be aged as no hard structures which might show growth rings are carried through a moult. Juvenile crabs moult multiple times annually and it takes approximately two years – and more than 10 moults – for a juvenile crab to reach sexual maturity (DFO 2012).

2.2 DENSITY AND ABUNDANCE

Dungeness crab larval dispersal and abundance in the plankton is highly variable at both regional and local spatial scales (McConnaughey and Armstrong 1995). Whether larvae are transported towards the open ocean or retained in the near-shore estuarine environment is governed by the strength of northward estuarine currents, coastal upwelling, and complex wind and tidal processes (Gunderson et al. 1990, Jamieson and Phillips 1993, McConnaughey et al. 1994, Roegner et al. 2007). In a ten-year study, Mackas et al. (2013) suggested that interannual variability in crab larval density in the Strait of Georgia can be partly explained by oceanic processes affecting deep water estuarine exchanges, such as variation in the Northern Pacific Gyre Oscillation (NPGO), warm currents produced by El Niño Southern Oscillation (ENSO) events, and wind processes that influence the timing of the spring phytoplankton blooms (Hobbs et al. 1992, Mackas et al. 2013, Rasmuson 2013).

Life span estimates for Dungeness crabs range from eight to ten years (DFO 2013). The major source of adult Dungeness mortality in the Strait of Georgia are commercial, recreational, and Aboriginal (CRA) fisheries, with exploitation rates over 90% for legal sized males in the Fraser River estuary (Zhang et al. 2002, MacKenzie 2010, DFO 2013, Zhang and Dunham 2013). Other sources of Dungeness mortality may be related to increased pathogen loads; while adult Dungeness crabs are hosts to a multitude of disease causing parasites, most infections have not been reported to have a detrimental effect on natural population abundance (Fisher and Velasquez 2008, Rasmuson 2013).

Increasing ocean temperatures associated with climate change may affect Dungeness crab populations in several ways (McConnaughey and Armstrong 1995, Rasmuson 2013). Warming of the sea-surface temperatures is predicted to result in northward movement in species that are competitors or predators of Dungeness crabs, such as mackerel that feed on zooplankton and are likely to prey on crab larvae (McConnaughey and Armstrong 1995, DFO 2013). Warming of semi-enclosed estuarine habitats like the Strait of Georgia may also influence egg development (Wild 1980) and can lead to shifts in the timing of larval release which, in turn, may lead to mismatches with the timing of phytoplankton blooms and thus have direct implications for Dungeness larval survival and **recruitment** into the fishery (McConnaughey and Armstrong 1995). More complex sources of Dungeness mortality as ocean temperature increases may involve near-shore habitat loss due to sea-level changes, potentially lethal effects associated with lower coastal salinity, changes in oceanic processes, and increased ocean acidification, which may pose a threat to crustaceans by inhibiting their ability to maintain calcareous (calcium carbonate based) shells (McConnaughey and Armstrong 1995, DFO 2013).

2.3 HABITAT REQUIREMENTS AND LIMITING FACTORS

While Dungeness crab settle broadly along the coast, the highest densities of juveniles are found in coastal estuaries; larval distribution patterns suggest that this is the result of active migration or directed transport toward estuarine areas for settlement (Fernandez et al. 1993). Advantages attributed to estuarine areas include warmer temperatures, greater standing stock biomass of food organisms, and refuge from predation (Gunderson et al. 1990). Growth rates of juvenile crabs are nearly twice as high in estuaries compared to **conspecifics** of the same year class found in adjacent coastal regions (Gunderson et al. 1990). Estuaries are deemed to provide essential nursery habitat for juveniles (McMillan et al. 1995, Armstrong et al. 2003, Martel 2009).

Due to their role in providing nursery habitat for juvenile Dungeness crabs, estuaries are, by extension, considered important for regional population **production** and fisheries (Eggleston and Armstrong 1995, McMillan et al. 1995, Triton 2004, Martel 2009). Tasto (1983) considered high recruitment of juveniles to estuaries as a sizeable future contribution to the coastal fishery while Stevens and Armstrong (1984) later concluded that total estuarine production could account for most of Washington’s coastal **landings**. Armstrong et al. (2003) highlight the role of estuarine production in helping to stabilise coastal landings, given the uncertainties created by physical and biotic forcing on larval survival, transport, and recruitment. Overall, there is compelling evidence that Dungeness crab fisheries rely on estuaries to produce future adult stocks for fisheries.

Predation is regarded as a key force in controlling population size of many crustacean species, and density of juveniles is correlated with three-dimensional structures that provide refuge (Heck and Wilson 1987, Doty et al. 1990, Dumbauld et al. 1993). Within estuarine regions, three dimensional structures occur as shell middens and vegetation, and harbour greater densities of juvenile Dungeness crabs than less complex habitats such as flat mud and sand (Henrys et al. 1986, Fernandez et al. 1993, McMillan et al. 1995). Protection from predators is particularly important following settlement from the water column, as frequent moulting at this time renders crab highly vulnerable to predation (Dumbauld et al. 1993). In addition to providing refuge, such complex habitats may also shelter infaunal and epifaunal species that are prey items for juvenile Dungeness crab (Armstrong et al. 1991).

Patterns in estuarine habitat use by juvenile Dungeness crabs are also governed by competitive interactions with other crab species. For example, the abundance of juvenile crabs in refuge shell habitats is negatively influenced by competition and displacement from other species, such as the European green crab (*Carcinus maenas*) and the yellow shore crab (*Hemigrapsus oregonensis)* (McDonald et al. 2001, Visser et al. 2004).

Sub-adult Dungeness crabs (40 to 100 mm) are largely absent from intertidal habitats at low tide but continue to forage there throughout the estuarine portion of their life history. Intertidal foraging is necessary to account for the large numbers of individuals present in estuaries since sub-littoral prey resources are insufficient to support observed abundances of crabs concentrated in shallow channels at low tide (Holsman et al. 2003). Generally, sub-adults most frequently utilise soft substrates such as mud and sand flats, and are found to a lesser extent in dense eelgrass beds and oyster shell deposits (Holsman et al. 2003). Sub-adults reach sexual maturity at around 2 years of age (>100mm carapace width), when they descend to deeper subtidal adult habitats (Rasmuson 2013).

2.4 DUNGENESS CRAB FISHERIES

2.4.1 Recreational Fishery

The B.C. recreational Dungeness crab fishery occurs year-round, coast-wide (DFO 2010). Key harvest restrictions include daily bag limits (limit is specific to fishing area), mandatory release of female crabs, and a minimum legal size (165 mm carapace width) (Dunham et al. 2011, DFO 2013, Zhang and Dunham 2013). Fishing occurs from shore or boat through the use of traps, ring nets, dip nets, and SCUBA (DFO 2010, Chudnow 2013). On average, more than 300,000 B.C. Tidal Water Sport Fishing licenses are sold each year with each license including access to numerous species (DFO 2010, MacKenzie 2010). At present, there is no catch monitoring program for the recreational Dungeness crab fishery; as a result, it is not currently possible to determine the total number of recreational harvesters targeting Dungeness crab or the impact of recreational fishing on crab stocks (DFO 2010).

2.4.2 Aboriginal Fishery

The Aboriginal Dungeness crab fishery occurs in two parts: harvest for Food, Social, and Ceremonial purposes (FSC) and as a part of the commercial fishery (DFO 2010). As outlined in the *R. v. Sparrow* (1990) decision, the Supreme Court of Canada found that fishing for FSC purposes takes priority, after conservation, over other uses of the resource (DFO 2007). Harvest of Dungeness crab for FSC is regulated through the *Aboriginal Communal Fishing Licenses Regulations*, SOR/93-332 under the *Fisheries Act*, RSC 1985, c. F – 14 (DFO 2010, 2013). FSC harvest occurs year-round using the same gear as the recreational fishery and, as with the recreational fishery, a minimum size limit of 165 mm carapace length applies to First Nations harvest (DFO 2010, 2013). Until recently, First Nations harvesters were able to retain female crab over the 165 mm size limit (DFO 2010); however, in support of sustainable fishing, DFO has requested First Nations to release all female crab, in a manner that causes the least possible harm (DFO 2013).

First Nations harvest within the commercial fishery also occurs under communal licenses, which hold no annual license fee (DFO 2010). Licenses are distributed by First Nation's organizations that designate license eligibility on an annual basis to vessels meeting license requirements (DFO 2010). Management, research, and monitoring within the fishery occur through collaborative management between First Nations groups and the federal government (DFO 2010).

2.4.3 Commercial Fishery

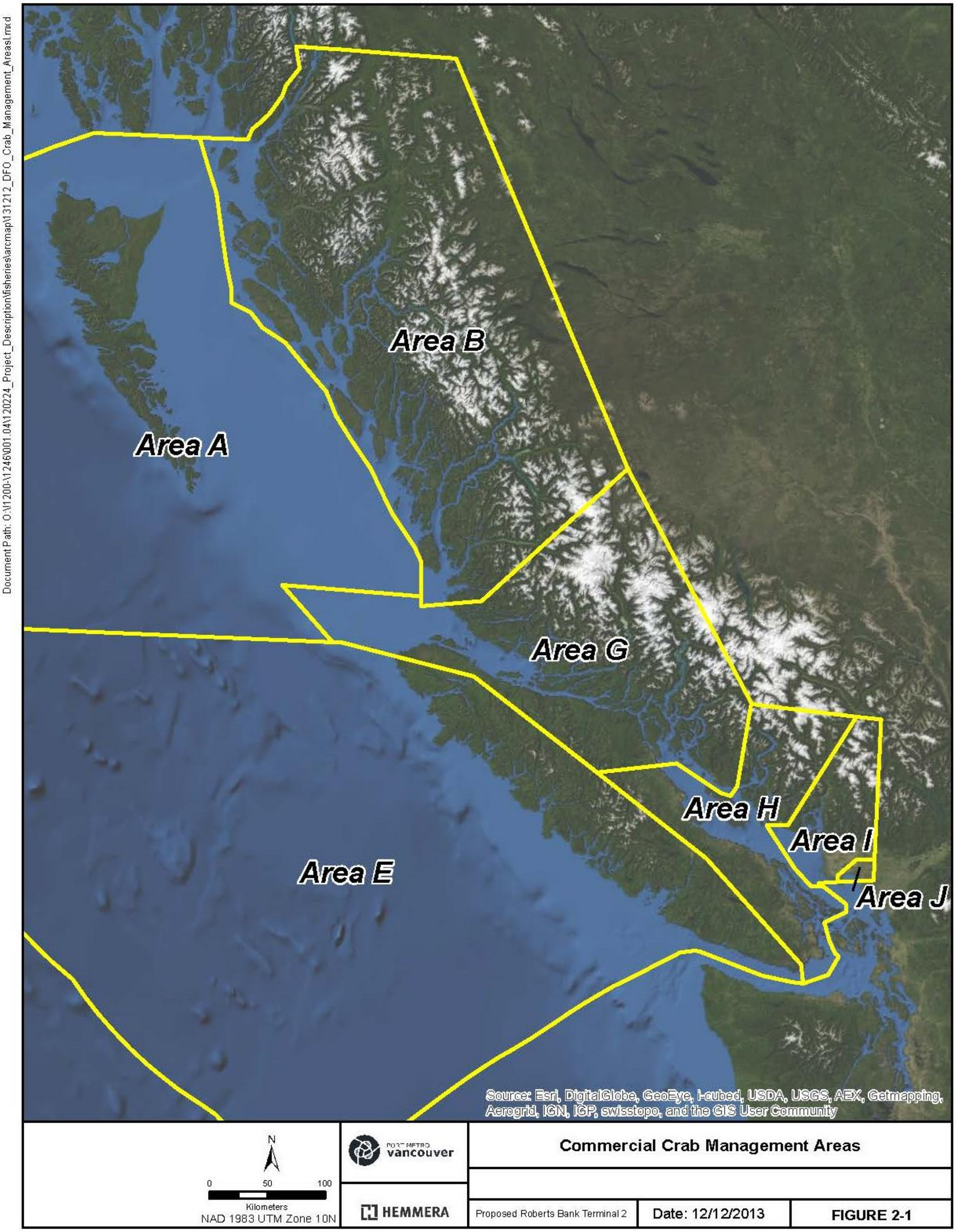
The B.C. commercial Dungeness crab fishery is divided into seven Crab Management Areas (CMAs) which, in turn, are divided into several Fishery Management Areas and Sub-areas. The Fraser River estuary is located in CMA I, within Fishery Management Area 29 (**Figure 2-1**); the proposed Project straddles management Sub-areas 29-6 and 29-7 (**Figure 2-2**).

The Dungeness crab fishery accounts for 11.6% of all total landed value of wild B.C. commercial fisheries (BC Ministry of Environment 2007). Fishing occurs through the use of baited traps, which are set on the ocean bottom for a period of 0 to 18 days (DFO 2010). Traps are then hauled to the surface and crabs are held live in seawater holding tanks, then delivered to processors and/or buyers across the coast (DFO 2010, Chudnow 2013). Approximately 36 to 51 vessels have been licensed to fish for Dungeness crab in Area 29 during each fishing season, and crew size ranges from 2 to 6 fishermen per vessel; as of 2005, the total number of active commercial fishermen along the B.C. Coast was estimated to be less than 1,000 individuals (DFO 2010).

Typically, male crabs in the Fraser River estuary moult in the spring and are sufficiently hard to allow commercial harvest to begin in mid- to late June. Legal sized male crabs are rapidly fished down over a periods of about six weeks after the opening of the fishery; thereafter, catch remains low and relatively stable until the close of the fishery in October (Zhang et al. 2002). The Area 29 fishery is highly intensive, with exploitation rates well over 90%; meaning that nearly all legal-sized males are removed during the fishing season (Zhang et al. 2002). Area 29 landings (obtained from harvest logbooks) have averaged 605 tonnes per year 1990 and 2011, with an average contribution of 157 tonnes from Sub-areas 29-6 (offshore Roberts Bank) and 34 tonnes from Sub-area 29-7 (onshore Roberts Bank) (**Table 3-2**). In 2010, Area 29 commercial landings were valued at $5.53 million CAD (Zhang and Dunham 2013).

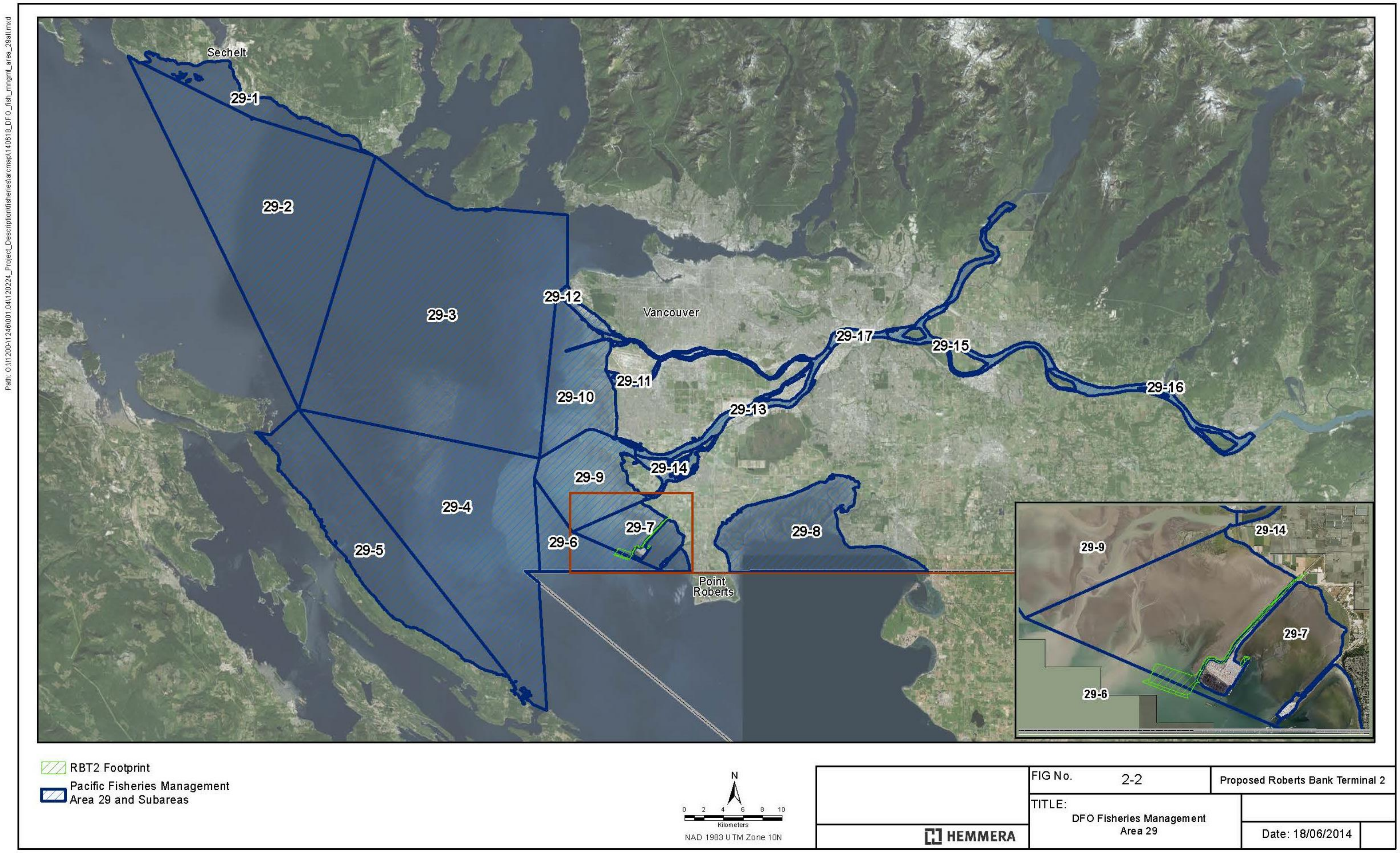
Commercial Dungeness crab fisheries in B.C. do not rely on estimates of abundance for management, but are instead managed using a "3-S" strategy that restricts harvest by sex, size, and season: only males larger than the minimum size limit are allowed to be retained during the open season, which extends from late-June to late-November. The 3-S strategy aims to maintain the reproductive potential of crab stocks by prohibiting harvest of females and allowing sexually mature males to mate at least once prior to harvest (Harbo and Wylie 2006). Some mortality of females and sub-legal males undoubtedly occurs; however, as part of normal fishery operations, a substantial number of non-legal crabs are captured and released repeatedly during the course of a fishing season.

Figure 2-1 **Fisheries and Oceans Pacific Commercial Crab Management Areas (CMA, The Proposed RBT2 Footprint is Located in CMA I)**



Source: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Figure 2-2 DFO Pacific Fishery Management Area 29 and Sub-areas in Relation to Proposed RBT2 Footprint



3.0 METHODS

Descriptions of the spatial and temporal scopes of the Dungeness Crab Productivity Study, plus study methods are provided below.

3.1 STUDY AREA

Because this study is built upon DFO fisheries data, the study area was selected to correspond to the same spatial scale on which the data was collected. The study area encompasses DFO Fishery Management Area 29, which extends roughly from the BC Ferries terminal at Roberts Bank north to Sechelt (**Figure 2-1**). There are gaps in the data at smaller spatial scales (typically a result of privacy concerns); however, where data allowed, focus was placed on assessing Sub-areas 29-6 and 29-7, as these are the specific areas that encompass the RBT2 footprint (**Figure 2-2** inset).

3.2 TEMPORAL SCOPE

This study examines mid- to long-term trends (i.e., over the past two decades) in commercial landings within the study area. Substantial and unexplained variations in abundance appear to characterise west coast Dungeness crab populations (McConnaughey et al. 1994) and, as such, populations are expected to show appreciable variation in size over multiple time scales, both inter-annually and over decadal timescales. To account for such temporal variability, long-term DFO time series data (dating as far back as 1982) were evaluated.

3.3 STUDY METHODS

3.3.1 DFO Data Collation and Summary

Assessment of Fraser River estuary crab production in Area 29 involved the collation of both fishery-dependent and fishery-independent data from different datasets, outlined in **Table 3-1** below. All data were acquired from the Shellfish Data Unit, Marine Ecosystem and Aquaculture Division, Science Branch, DFO in July 2013.

Table 3-1 Summary of Data Types and Datasets used to Model Dungeness Crab Productivity

Data Type	Description	Associated DFO Datasets
1. Fishery- Dependent	Data sampled directly from the non-random harvesting process. Samples typically obtained via service providers include fishing activity information such as gear type, total catch, landings, effort, sales, date and place of harvest etc., but also can include biological attributes of the catch such as, size-composition, age structure, and sex ratio.	• Fish Slip Program • Onboard Logbook
2. Fishery-Independent	Data sampled according to a scientific survey design. Samples typically collected by scientists includes biological information such as abundance, size composition, moult timing, injury rates, shell condition, and sex ratio.	• Fraser Delta Research Surveys • Vancouver Harbour Research Surveys

1. Fishery Dependent Datasets

a) Fish Slip Data

The first source for commercial catch data is DFO's fish slip program, which summarises dockside sales records generated at vessel offloading sites. According to these data, crab landings from Area 29 increased steadily from 1982 to 2006, gaining an average of 11.6 tonnes per year. In 2006, landings increased to 1,264 tonnes (more than doubling the previous year's catch), remained elevated from 2006 to 2009, and then decreased to levels similar to those experienced prior to 2006 (**Figure 3-1**). Landings data from Area 28 (which includes Howe Sound, English Bay, Burrard Inlet, and Indian Arm) are also presented for context, and similarly show a steady increase over time, without a corresponding decrease post-2009.

b) Onboard Logbook Data

The second source for commercial catch data is the onboard logbook ("logbook data"), maintained by the vessels. This dataset covers the period 1990 to 2011 and is divided into management sub-areas (**Table 3-2; Figure 3-2**). Fisheries-specific privacy restrictions precluded sub-area catch information from years in which less than three vessels reported catch and, as such, total catch data for Area 29 for the years 1996, 2002, 2003, and 2005 were omitted. In spite of these restrictions, approximately 95% of the data were available and show that, since 1990, the largest landings within Area 29 have consistently come from sub-area 29-8 (Boundary Bay). Sub-areas 29-6 (offshore Roberts Bank) and 29-3 (offshore Sturgeon Bank to entrance of Howe Sound) have also contributed a large proportion of the total landings since 1999 (**Figure 2-2**). The sub-areas that encompass the Project footprint, 29-7 (nearshore Roberts Bank) and 29-6 (offshore Roberts Bank), experienced opposite trends since 1990, with landings decreasing in Sub-area 29-7 and increasing in Sub-area 29-6 (**Figure 3-3**).

c) *Onboard Biological Sampling*

Size composition covering the period 2005 to 2012 was obtained from biological sampling of crabs brought onboard commercial vessels, including sub-legal size male crabs. This information is useful for estimating size selectivity of commercial fishing gear. It is assumed that all sub-legal size male crabs (notch width[3] (NW), < 155 mm) are released subject to a discard mortality rate[4].

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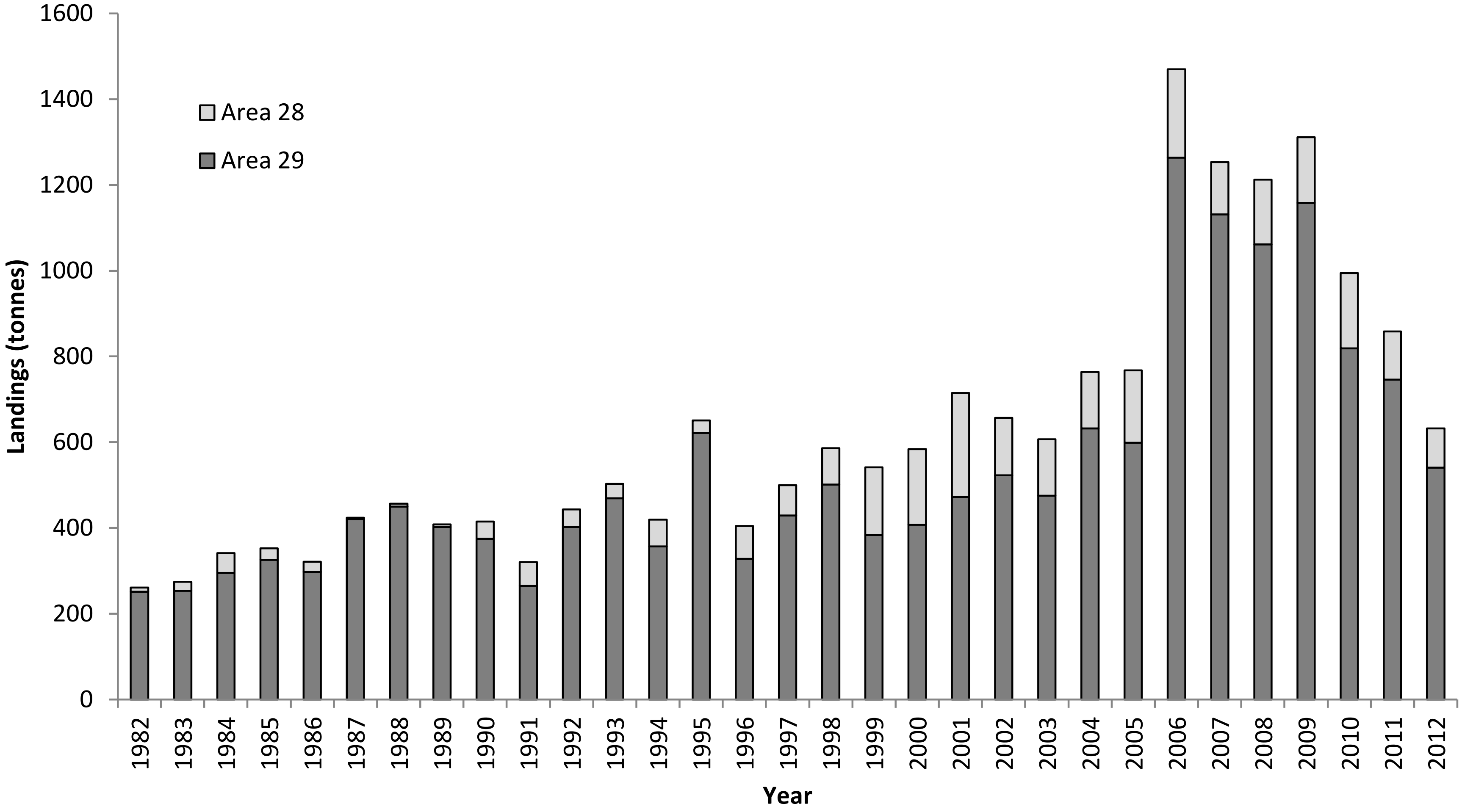
[3] Notch width (NW) refers to carapace width just anterior to the 10th anterio-lateral spine.

[4] Discard mortality rate refers to the proportion of discarded catch that dies as a result of catching or handling processes

Figure 3-1 Annual Commercial Landings of Dungeness Crab in Fishery Management Areas 28 and 29



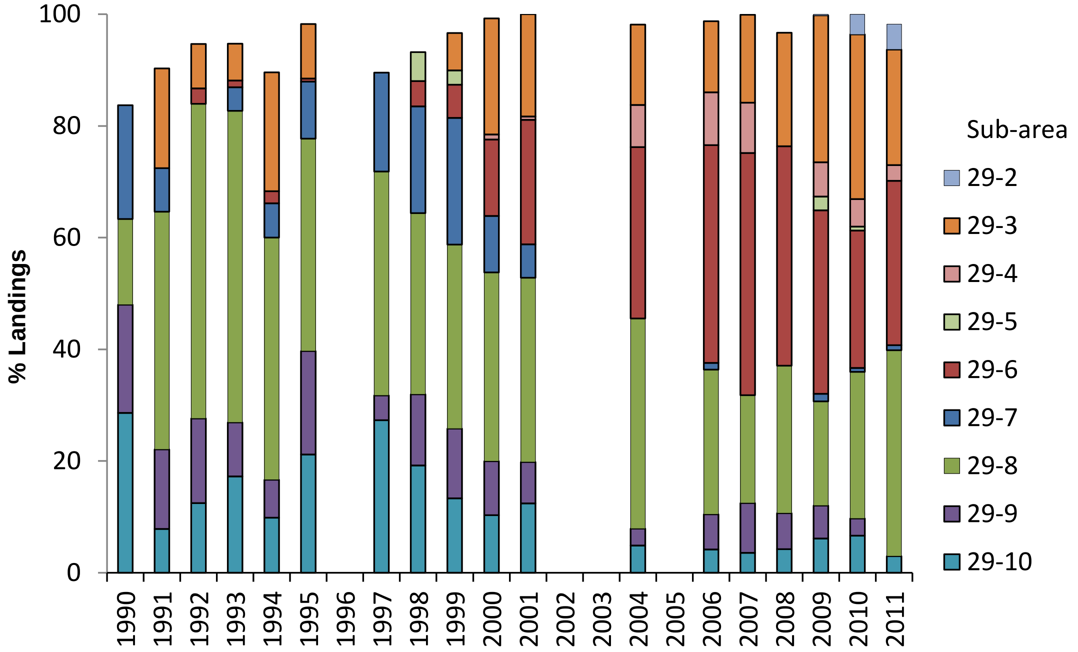
Note: Data Collected from DFO's "fish slip" program.

Table 3-2 Annual Commercial Dungeness Crab Landings (metric tonnes) for Management Area 29 broken down by Sub-area

Year	Sub-area														Total
	29-1	29-2	29-3	29-4	29-5	29-6	29-7	29-8	29-9	29-10	29-11	29-12	29-13	29-14	
1990						*	32.6	24.6	31.0	45.8			*		160.0
1991	*		34.6	*	*	*	15.1	82.3	27.6	15.1			*		193.4
1992			19.8	*		7.0	*	140.1	37.7	31.0					248.9
1993			25.7	*	*	4.7	16.5	218.1	37.9	67.4			*		391.0
1994			65.6	*	*	6.7	18.9	133.6	20.9	30.4			*		308.2
1995			53.8		*	3.0	56.0	208.9	101.8	116.2	*				549.3
1996			9.6		*	8.4	56.4	116.4	30.2	105.9					*
1997			*		*	*	71.1	160.8	17.6	109.6		*			401.0
1998			*		23.9	20.7	87.8	148.9	58.4	88.3	*		*		459.2
1999			25.5		9.9	22.6	86.4	125.8	47.4	50.9			*	*	381.3
2000		*	90.0	4.0	*	59.2	43.8	146.3	41.7	44.7	*				432.7
2001			90.8	3.0		110.5	29.7	163.6	36.6	61.6					495.7
2002			88.8	11.8	*	96.6	13.6	210.2	57.9	45.9					*
2003			88.3	22.1	*	69.9	29.6	237.5	38.9	17.6					*
2004		*	94.5	49.8	*	202.1	*	247.9	19.8	32.1		*			658.5
2005			104.1	39.8	*	160.6	11.1	240.6	48.8	8.0					*
2006		*	160.5	119.3	*	491.5	15.3	326.7	78.7	52.8		*			1260.7
2007		*	186.1	106.9		512.6	*	228.3	104.8	42.3					1181.9
2008			207.0	*	*	400.4		269.0	65.6	43.1	*				1018.8
2009		2.4	310.4	72.2	29.5	387.5	16.2	220.1	69.5	72.4					1180.3
2010		29.6	241.1	40.0	6.0	201.2	5.6	214.8	25.0	54.1					817.5
2011	*	34.2	156.0	21.3	*	222.0	6.9	278.5	*	22.2					754.6
Average		22.1	108	44.6	17.3	157.2	34	188.3	47.5	52.6					605.2

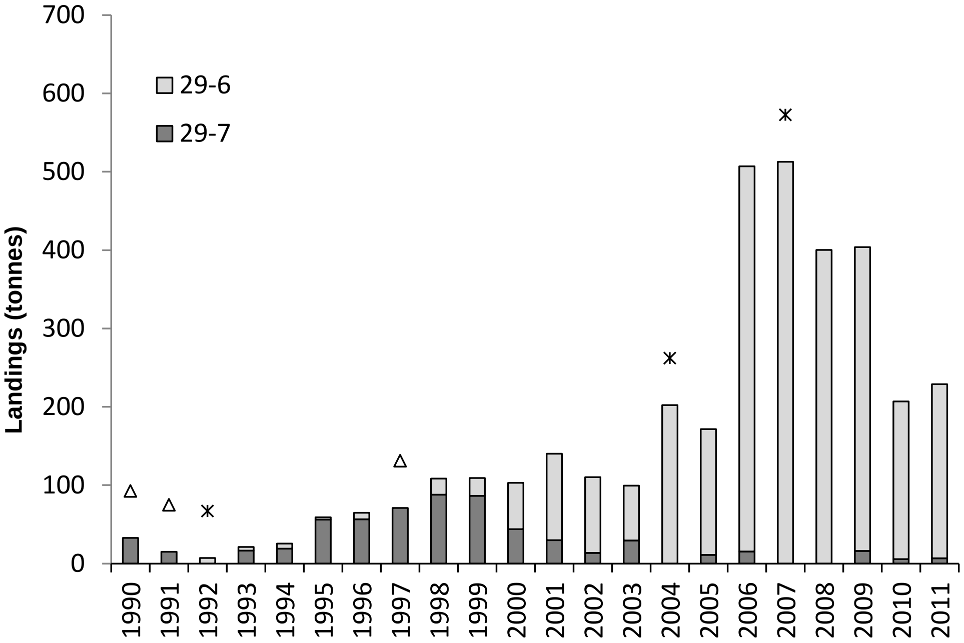
Note: Stars indicate omitted data due to privacy concerns. Shading indicates focal sub-areas in RBT2 vicinity. Data collected by vessels in logbooks.

Figure 3-2 Percent Contribution of Management Sub-area Landings to Area 29 Annual Landings from 1990 to 2011



Note: Missing data indicates where data were omitted due to privacy concerns**.**

Figure 3-3 Total Annual Landings in Sub-areas 29-6 (offshore Roberts Bank) and 29-7 (nearshore Roberts Bank) from 1990 to 2011



Note: Omitted data due to privacy concerns are indicated by triangles and stars for area 29-6 and 29-7, respectively.

2. Fishery-Independent Datasets

a) Area 29 Research Surveys

Since 1988, DFO has conducted fishery-independent trap surveys in CMA I/Area 29, including the Fraser River estuary, Indian Arm, and Boundary Bay, both before and after the commercial fishing season. Within a single year, surveys occurring between April and August are defined as “pre-season surveys” and those occurring between September and December are defined as “post-season surveys”, wherein ‘season’ refers to the commercial harvesting time period. Surveys in January and February (i.e., years 1989, 2000, and 2006) were excluded from further analysis because these tend to occur during the moult and therefore contain both pre- and post-moult individuals. Data on female crabs were also excluded because their harvest is prohibited by regulation, so the only relevant production assessment is of male crabs (Zhang and Dunham 2013).

Data collected in these pre- and post- season **fishery independent** surveys include catch, abundance, sex, shell condition, injuries, mating marks, and size composition (DFO 2013). Size composition data is particularly important for this model because it is length-based, and needs to reflect the size range of male crabs available to trap fisheries and surveys (Zhang et al. 2002). Crab sizes, measured using NW, were aggregated into 50 mm classes ranging from 102.5 mm to 207.5 mm, where each size represents the mid-point of the class. Males with NW ≥ 155 mm were defined as legal sized crabs. The final size class is a "plus group" representing the accumulation of crabs that are 207.5 mm and greater in size, although the number of crabs observed in this final size class has been very low and the contribution to the overall size frequency distribution inconsequential. The size composition of pre-season surveys ranges from 127.5 mm to about 192.5 mm, with small proportions of larger and smaller crabs occasionally observed. During 2007 to 2010, while survey catch per unit effort (CPUE) was at an all-time low, size composition was shifted toward larger sized crabs in both pre-season and post-season surveys.

b) Vancouver Harbour Research Surveys

Research surveys in **Vancouver Harbour** were conducted at several different periods during the years 1991 and from 1993 to 2001. These survey data were used to estimate some important parameters on the population dynamics, such as natural mortality rates, proportion of moulting, and moulting survival rate (Zhang et al. 2002).

In addition to size-composition as input into the model, fishery-dependent (fish slip program, onboard logbook) and independent (pre- and post-season survey) catch data are summarised in **Table 3-3**, and broken down by year for Area 29, covering the fishing seasons from 1982 to 2012.

Table 3-3 Annual Dungeness Crab Catch (metric tonnes) for Area 29, Aggregated by Data Type

Year	Fishery Dependent	Fishery Independent	
	Commercial Landings	Pre Season Catch	Post Season Catch
1982	251.2	-	-
1983	253.5	-	-
1984	295.0	-	-
1985	325.7	-	-
1986	297.3	-	-
1987	420.5	-	-
1988	450.0	-	0.51
1989	402.3	-	0.58
1990	374.7	-	0.54
1991	264.5	1.40	0.60
1992	402.1	2.68	1.06
1993	469.4	3.05	1.34
1994	357.1	3.05	1.26
1995	621.5	5.59	0.80
1996	327.8	2.91	1.15
1997	429.4	2.17	1.27
1998	501.3	3.30	0.31
1999	383.7	2.41	0.66
2000	407.5	2.25	0.76
2001	472.3	2.60	0.36
2002	523.1	-	1.84
2003	475.3	3.28	1.25
2004	632.4	1.56	0.70
2005	598.4	2.14	-
2006	1264.0	1.09	0.46
2007	1131.1	1.50	0.45
2008	1061.6	0.86	0.36
2009	1158.6	0.51	0.22
2010	819.1	0.65	0.34
2011	746.2	0.63	0.33
2012	540.7	0.80	0.42

3.3.2 Model Structure

Bayesian statistical methods are used to compute a probability distribution of parameters (or quantities of interest, regarded as random variables), using previous knowledge about the parameters and new data. Two probability distribution functions are used to make statements about the parameter, called the prior and **posterior distributions**. The **prior distribution** (or simply, the prior) summarises what is known about the ranges and associated probabilities for the parameter without reference to the data. The posterior distribution (the posterior) provides the same summaries, but as informed by the data; in other words, the additional information provided by the data modifies the probabilities. A third probability function, called the likelihood, is the probability of obtaining the observed data if the parameter value is true.

In a Bayesian analysis, inference about the parameter is based on the posterior distribution, obtained by applying Bayes' theorem to the prior and the likelihood. Thus, the posterior distribution describes the ranges of possible values for a parameter and their probabilities as indicated by the combination of data and prior knowledge. When drawing inferences from model predictions, the main feature considered is the difference between the prior and posterior: if they are very similar one may conclude that the data did not provide new information about the parameters.

A Bayesian length-based model was developed by Dr. Sean Cox of Simon Fraser University and Cameron Mackenzie of Atwater Resources Corporation. The model uses a combination of **fishery dependent** and independent data as inputs to estimate annual Dungeness crab production in Management Area 29, and Sub-areas 29-6 and 29-7 where possible. A Bayesian approach was chosen because, as discussed above, it enables incorporation of existing knowledge about crab biology (gleaned from DFO studies in Vancouver Harbour) to generate a more accurate predictive model. The model has five primary components, including: (i) Parameters; (ii) Data; (iii) Dynamic Model; (iv) Prior Distributions; and, (v) Likelihood Function.

(I) ***Parameters***, Θ, are a set of model coefficients that determine crab population abundance, fishery catch, and size-composition in fishery dependent and fishery independent sampling programs. The model parameters, combined with the assumptions about crab population dynamics (i.e., growth, recruitment, and mortality) are used in this study to assess Dungeness crab population abundance in Area 29. Parameter values are estimated using a Bayesian approach, which estimates the plausible ranges for each parameter. Parameters estimated by the model are transformed to suit various biological and numerical constraints, as well as prior distribution forms (see IV Prior Distributions below). Throughout this report, the index g is used to represent the fishery ($g = 1$), DFO pre-season survey ($g = 2$), and DFO post-season survey ($g = 3$). Model parameters are as follows:

1. $\hat{N}_{1,i}$ (i = 6, 7...22) - male crab abundance in size classes 127.5 to 207.5 mm for the first model year t = 1. Note that "time" in this model is indexed by t = 1, 2...22 corresponding to years 1991 – 2012 and size classes are indexed i = 1,2…22 corresponding to size classes 102.5 to 207.5 mm;
2. R_t (t = 1, 2...22) – annual total male crab recruitment to the population;
3. ρ_i (i = 1, 2...5) – proportional allocation of new male recruitment across the five smallest size classes (102.5 – 122.5 mm) to represent the size distribution of incoming recruits;
4. P_t^{95}, P_t^{50} - sizes at 95% and 50% annual moulting probability. The time index "t" reflects possible year effects on the size-at-moulting;
5. $\beta_0, \beta_1, \sigma_G$ - linear growth model parameters representing absolute carapace width increment per moult, relative moult increment multiplier, and standard deviation of final sizes around the expected final size per moult. Growth model parameterisation and prior distributions (both given below) are based on Zhang et al. (2004);
6. M_1 and M_2 - instantaneous annual natural mortality rates for non-moulting and moulting periods, respectively. The post-moult mortality rate M_2 is only applied for the month following the spring moult;
7. $S_{g,t}^{50}, S_{g,t}^{95}$ - sizes at 50% and 95% selectivity in the commercial fishery (g = 1), the pre-season survey (g = 2), and the post-season survey (g = 3). The gear and time indices reflect possible gear-specific year effects on the size selectivity relationships;
8. $\tau_{I,g}^2$ - measurement error variances for DFO abundance indices (g = 2, 3);
9. $\tau_{L,g}^2$ - measurement error variances for length composition (g = 1, 2, 3);
10. q - catchability (scaling) coefficient for DFO abundance survey.

(II) ***Data***, Y, consist of the datasets discussed in Section 3.3.1, including fishery-dependent and fishery-independent (i.e., pre-season and post-season) size composition and fishery-dependent and fishery-independent catch data (i.e. commercial landings weight and pre- and post-season catch weights, respectively). In Areas 29-6 and 29-7, missing catch data were estimated using the average of adjacent years.

(III) ***Dynamic Model,*** is a length-based population dynamics model that describes the relationship between the Parameters and Data. The model consists of the mathematical rules describing how male crab population abundance and size-structure changes over time in response to recruitment, growth, natural mortality and fishery removals. This model generates a set of predictions about proportions-at-length for each data set, $\hat{\mathbf{Y}}$, that should agree reasonably well with the observed data **Y** if model parameters are well determined.

(IV) ***Prior Distribution***, $\pi_j(.)$, refers to the probability distribution of a parameter prior to analysing the data; in other words, priors summarise what is known about each of the parameters, Θ, before examining the data, **Y**. In a Bayesian statistical analysis, each parameter requires a prior distribution, which can be derived from any data source or expert opinion not included in **Y;** in this case, prior distributions for crab natural mortality, growth, and moulting rates were derived from crab biological studies in Vancouver Harbour (Zhang et al. 2002, Zhang and Dunham 2013). Vancouver Harbour is closed to commercial crab fishing due to navigation concerns, so the crab population remains virtually unfished – therefore, natural mortality can be estimated there because it is not confounded with fishing mortality. Vancouver Harbour is bounded by the Fraser River estuary commercial fishery to the southwest and the Howe Sound commercial fishery to the northwest and therefore represents a population of crabs that is directly comparable to those adjacent areas in terms of the parameters under investigation (Zhang et al. 2002). All parameters prior distributions are described in **Appendix A**. Parameters that were not defined by previous studies were given the least informative priors possible.

(V) ***Likelihood Function***, $L(\Theta|\boldsymbol{Y}) = p(\boldsymbol{Y}|\Theta)$, gives the probability of obtaining the data if the model parameters were true or correct. The conventional notation $p(\boldsymbol{Y}|\Theta)$ is used here to represent the statistical sampling distribution of the data given the model parameters. The joint *likelihood function* is factorable into components, one for each data set, e.g.:

$$p\left(\mathbf{Y}_L \mid \Theta\right) = \prod_{g=1}^{g=3} MNL\left(\mathbf{Y}_{L,g} \mid \hat{\mathbf{Y}}_{L,g}, \tau^2_{L,g}\right)$$

where *MNL*() are multinomial logistic probability density functions (Schnute and Richards 1995, Cox and Kronlund 2008), respectively, that are used to model abundance and composition data, and $\tau^2_{L,g}$ are measurement error variances specific to each dataset. Note that the predicted values $\hat{\mathbf{Y}}_{L,g}$ are generated by *Parameters* Θ via the *Dynamic Model* (these predictions are shown to simplify the notation). For this formulation, the joint Bayes posterior distribution for all the parameters would be:

$$p\left(\Theta \mid \mathbf{Y}_L\right) \propto \pi\left(\Theta\right) p\left(\mathbf{Y}_L \mid \Theta\right)$$

where the symbol "$\propto$" implies proportionality between the above product and actual posterior distribution function. The missing normalisation constant required to make $p\left(\Theta \mid \mathbf{Y}_L\right)$ an actual probability density function is not obtainable in closed form because the full model is non-linear and of high dimension (e.g. up to 80+ parameters). Therefore, a **Markov Chain Monte Carlo** (MCMC)[5] simulation (Gelman et al. 1995) is used to obtain an approximation to the true posterior distribution.

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[5] Markov Chain Monte Carlo is a sampling approach to approximating the full posterior distribution for the model parameters that uses a matrix of sampling points, rather than an equation, to compute the posterior.

3.3.3 Dynamic Model Specifications

The Dynamic Model tracks annual abundance of male crabs in J = 22 size classes ranging from 102.5 mm to 207.5 mm, assuming a calendar year beginning 1 April and ending on 31 March. A brief summary of the order of processes in the model are outlined below, while detailed mathematical specifications for each process are provided in **Appendix A**:

1. Update crab abundance in each size class i= 1, 2...L (L = 22) to 1 April of year t from crabs surviving over-winter from the previous year (t-1), moulting (or not) into larger sizes, and new recruitment;
2. Account for post-moult mortality of moulting crabs between 1 April and 1 May;
3. Compute predicted crab abundance-at-length $N_{t,l}^{pre}$ available to the pre-season survey (assumed to occur on 1 May) and proportional survey size composition $\hat{p}_{2,t,l}$. Note that the gear index is g = 2 for this survey;
4. Compute predicted mid-season (assumed to be 15 August) crab abundance- and biomass-at-length available to the fishery $N_{t,l}^{mid}$ and proportional size composition $\hat{p}_{1,t,l}$. Note that the gear index is g = 1 for the fishery;
5. Compute exploitation rate for fully selected crabs as total landed catch weight divided by legal biomass available to the fishery. Then compute sub-legal catch that is brought onboard fishing vessels and subsequently discarded. Remove landed crab catch from the population and apply discard mortality to discarded under-sized crabs;
6. Compute predicted crab abundance-at-length $N_{t,l}^{post}$ just after the fishery when the post-season survey is assumed to occur (1 November) and proportional survey size composition $\hat{p}_{3,t,l}$.

3.4 DATA ANALYSIS

3.4.1 Model Diagnostics and Checking

Model performance was checked in several ways. First, model fits to observed data were examined for each input data source. This provides an immediate visual indication of model agreement with each individual survey index or length frequency observation. Second, scatterplots of predicted and observed mean lengths were created, which should be closely correlated if the model performs well, on average, across a whole data set. Third, **discrepancy statistics** between the predicted and observed means lengths were computed for each length composition data set as:

$$D_g = \sum_{t=1}^{t=T} \frac{\left(l_{g,t}^{obs} - l_{g,t}^{rep}\right)^2}{l_{g,t}^{rep}} .$$

The discrepancy statistics provide a quantitative indication of overall model fits to each length dataset, where lower values indicate a better fit. Note that missing length observations for sub-areas limit the utility of these statistics. The posterior distributions for each parameter were shown along with their corresponding prior distributions. Where these two do not substantially overlap, the model and data provide new information about the parameter compared to prior knowledge from Vancouver Harbour and other crab populations. Similarity in the location and/or shape (e.g., spread of the distribution) of posteriors and priors indicate that the data provide no new information about a parameter. In cases where the data and prior provide similar information about the location of a parameter (e.g., the mean or mode), the posterior variance should be smaller than the prior variance, indicating a reduction of uncertainty.

4.0 RESULTS

Model fits to the size composition data for Area 29 crabs are described, followed by posterior distributions for crab recruitment, legal-sized crab biomass, and legal-sized crab production available to fisheries in each of these areas. Overall, as expected, some parameters were well estimated by the model while others could not be improved beyond their prior values. Tabular summaries of all model parameters, as well as biomass and production estimates in each area are presented in **Appendix B**.

4.1 MODEL FIT TO LENGTH COMPOSITION DATA

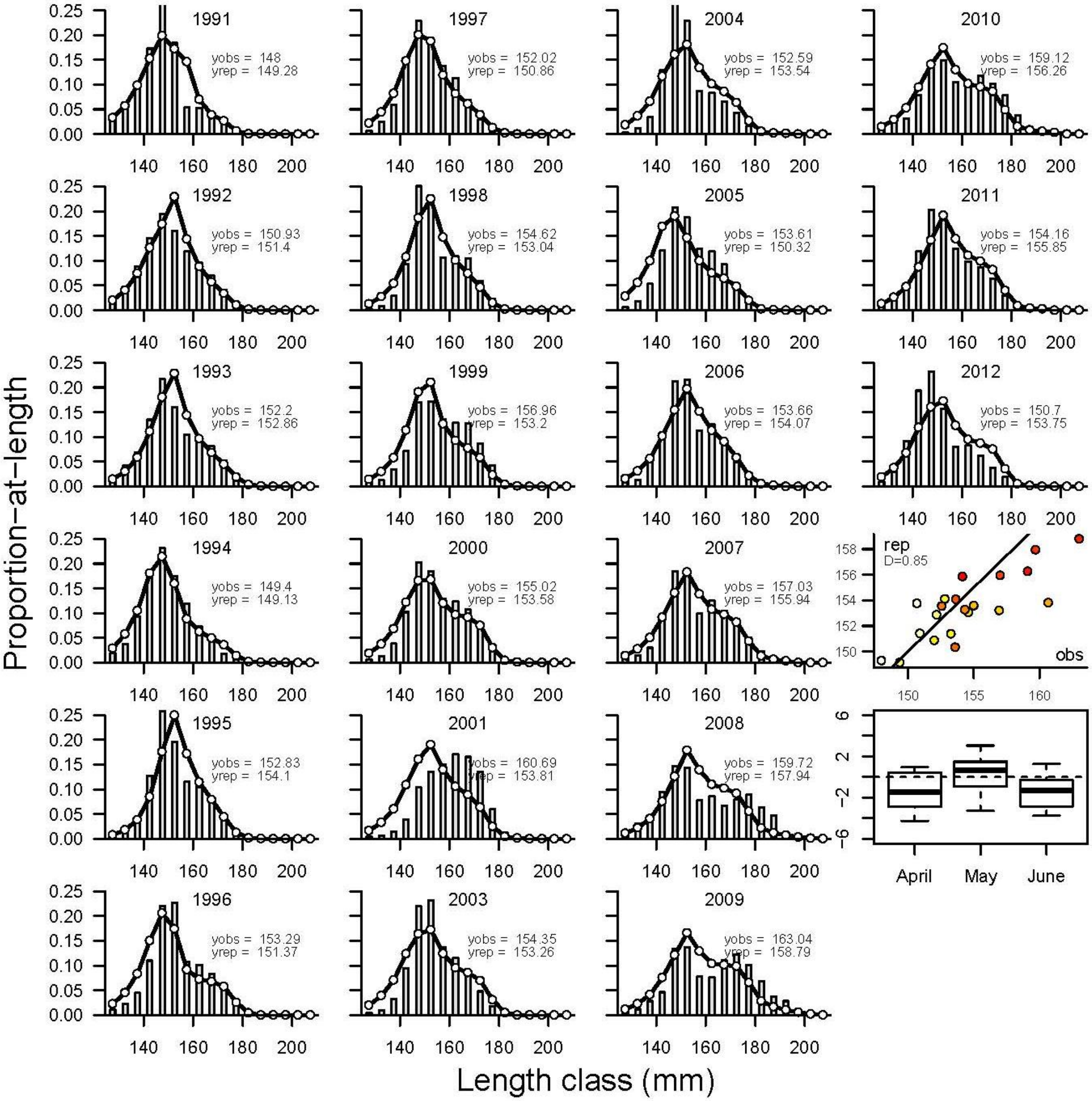
In a Bayesian analysis, inference about the parameter is based on comparing the posterior distribution to the prior. For size selectivity in fisheries and research surveys, no independent measurements are taken and therefore there were no values to compare to the prior. Therefore, uninformative priors were used and relied on the length composition data to provide information about these parameters. **Figure 4-1a**, **b**, **c** show the model fits to length composition from DFO's pre-season survey (**Figure 4-1a**), in-season fishery samples (**Figure 4-1b**), and DFO's post-season survey (**Figure 4-1c**). In general, the model does a reasonable job of matching the overall shape of the length distributions, particularly the increasing abundance between length 140 to 155 mm (i.e., increasing selectivity for large sizes), peak abundance at lengths just below the fishery size limit, and the "shoulder" to the right of the size limit where abundance is lower because of fisheries removals.

Initially, DFO pre-season survey selectivity was allowed to change in seven time blocks to capture the differences in survey timing (April, May, or June) among years; however, such freedom degraded the model fits to other length composition datasets. Ultimately three selectivity time blocks 1991 to 1997, 1998 to 2001, and 2002 to 2012 were chosen based on the fits to all three datasets. Residual deviations between predicted and observed mean lengths indicated that the model tends to underestimate mean crab length, particularly for larger sizes (**Figure 4-1a** obs vs rep scatterplot). Grouping these residuals by the months in which surveys occurred showed that the model underestimated crab sizes when surveys occurred in April and June, and accurately matched crab sized for surveys that occurred in May (**Figure 4-1a**; last panel). Note that the discrepancy statistics indicated in the obs vs rep scatterplots are only comparable within a dataset; they were used during model fitting and provide no additional information to the final model interpretation.

Model fits to fishery size composition (**Figure 4-1b**) captured the general pattern of length distributions, although in most years proportions-at-length in the 152.5 to 177.5 mm size range were largely overestimated (obs vs rep plot in lower right corner of the page). No attempt was made to further improve the fit of predicted length distributions because information on the timing of observer sampling of fishery catches was not available and sampling catches later in the season would create larger discrepancies between the predicted and observed frequencies because no account of catch prior to sampling was taken. Sampling catches early in the fishery seemed more representative of model predictions.

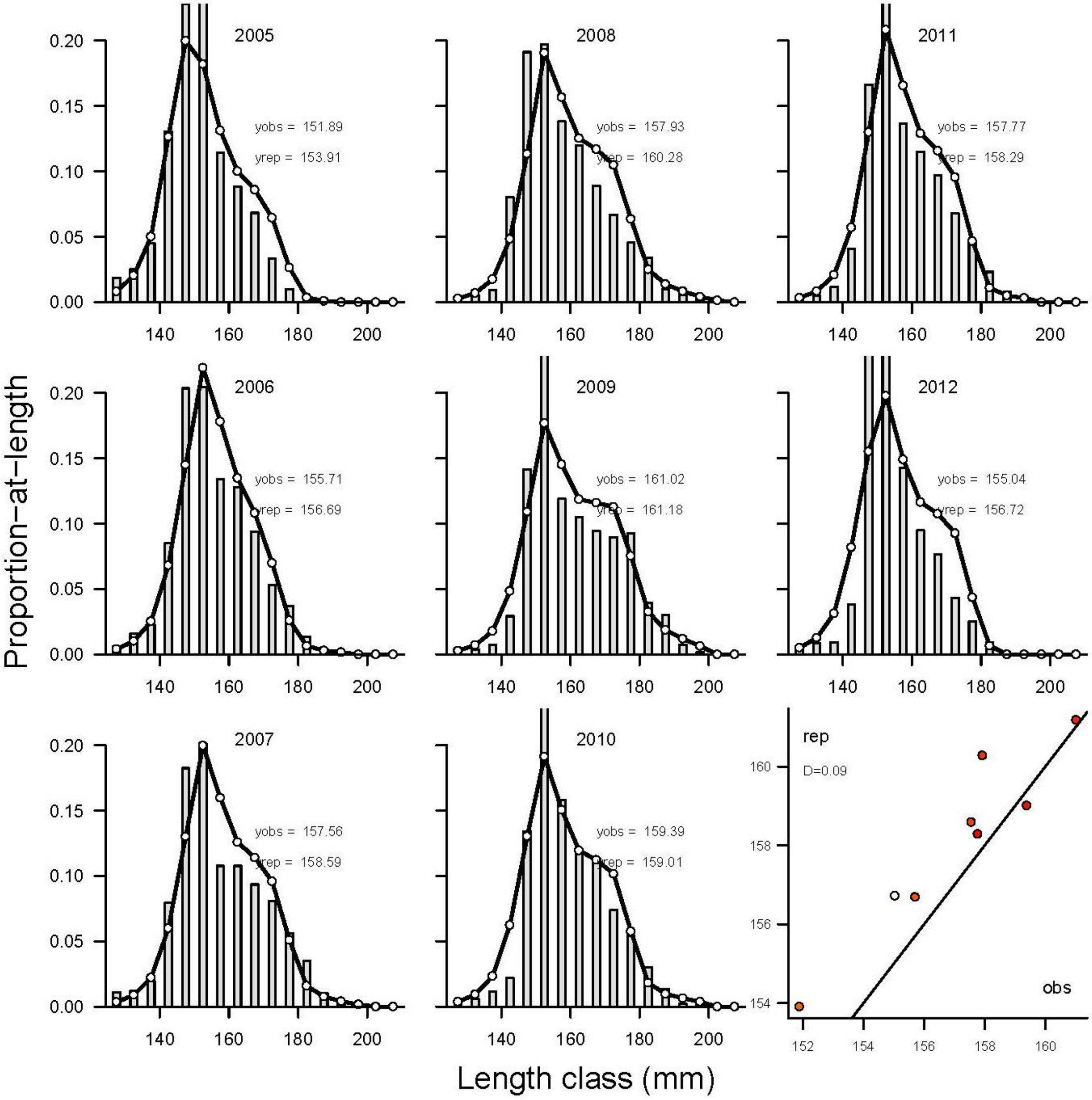
DFO post-season surveys provide clear patterns of legal-sized crab depletion relative to pre-season levels (**Figure 4-1c**). Length-based model fits to these surveys showed consistent agreement, except for 2009 and 2010, where predicted size distributions were shifted toward larger crabs than observed in the survey. During the period of highest crab production (2007), both the model and data indicated substantial amounts of crabs remaining after the fishery, which suggests that exploitation rates on these high abundances were lower than usual or that there was an influx of legal-sized crabs from outside of the management area to these populations.

Figure 4-1a Bayesian Length-based Model Fits (lines and circles) to Fishery-Independent Pre-season Surveys Size Composition Data (bars) from 1991 – 2012



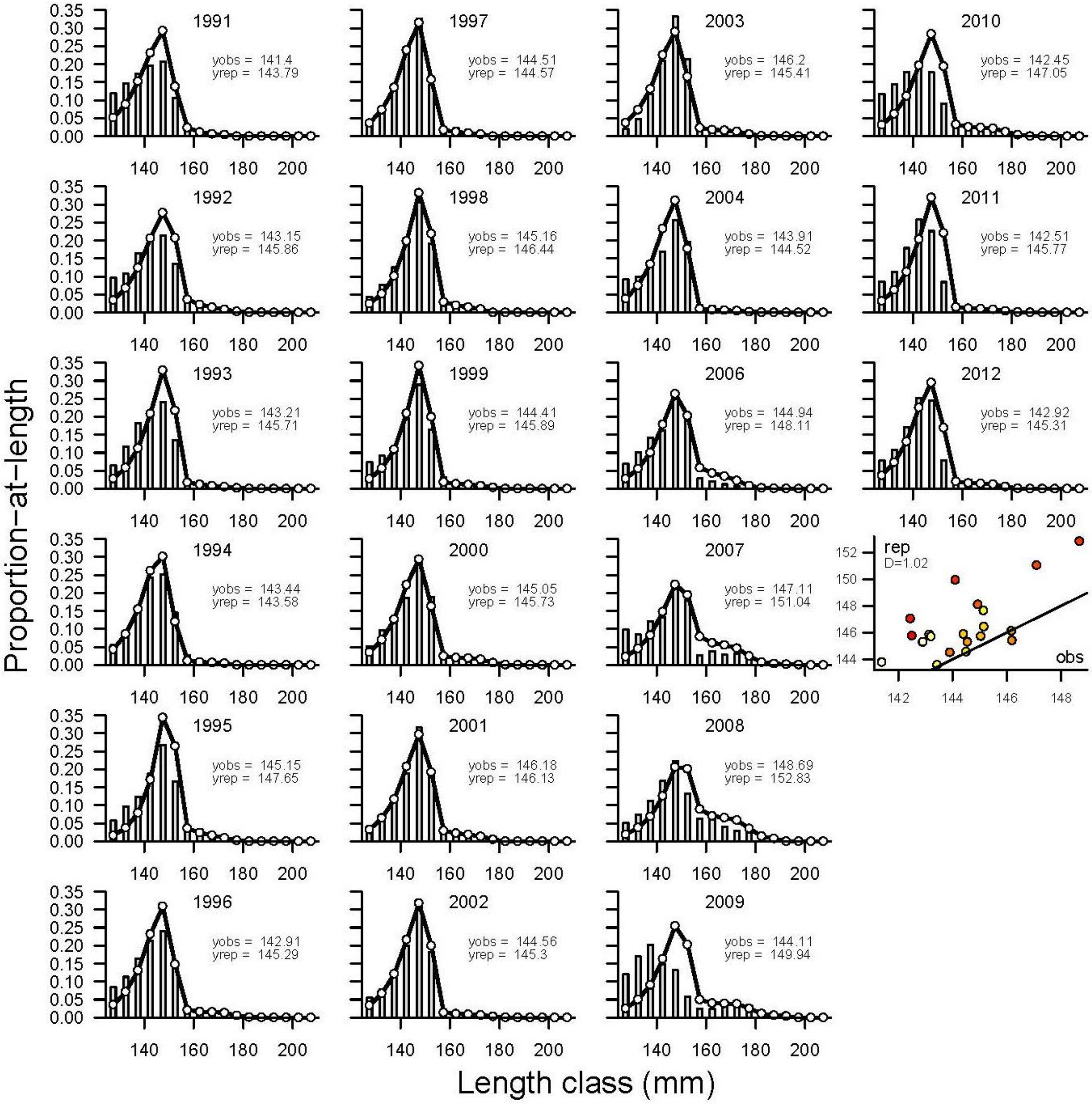
Note: This figure is based on maximum posterior density parameters. Each panel indicates the year, observed mean crab length in the sample (yobs), and predicted length from the model (yrep). Scatterplots compare predicted mean size (rep) with the observed mean size (obs) for each year as an indicator of overall model fit. The discrepancy statistic D provides a quantitative measure of how well the model fits with the observed data; with lower values indicating a better fit.

Figure 4-1b Bayesian Length-based Model Fits (lines and circles) to Fishery-Dependent Size Composition Data (bars) from 2005 – 2012



Note: The figures are based on maximum posterior density parameters. Legends in each figure indicate the year, observed mean crab length in the sample (yobs), and predicted length from the model (yrep). Scatterplots compare predicted mean size (rep) with the observed mean size (obs) for each year as an indicator of overall model fit. The discrepancy statistic D provides a quantitative measure of how well the model fits with the observed data; with lower values indicating a better fit.

Figure 4-1c Bayesian Length-based Model Fits (lines and circles) to Fishery-Independent Post-season Size Composition Data (bars) from 1991 – 2012



Note: The figures are based on maximum posterior density parameters. Legends in each figure indicate the year, observed mean crab length in the sample (yobs), and predicted length from the model (yrep). Scatterplots compare predicted mean size (rep) with the observed mean size (obs) for each year as an indicator of overall model fit. The discrepancy statistic D provides a quantitative measure of how well the model fits with the observed data; with lower values indicating a better fit.

4.2 POSTERIOR DISTRIBUTION SUMMARIES

4.2.1 Annual Recruitment

Model estimates of recruitment are insensitive to the prior on $\overline{\log R}$ because there is sufficient information in the total Area 29 data to estimate this quantity. Overall annual recruitment of male crabs to the Area 29 fishery (i.e., recruitment into legally harvestable size classes) ranged widely over a 30 year time-series (1982 to 2012) from a low of 2.7 million to a high of almost 17 million crabs. Average recruitment in Area 29 had a posterior mean of 6.03 million crabs per year and a 95% **credible interval**[6] ranging from 4.81 to 6.81 million crabs (**Figure 4-2a**). Sub-area 29-6 had a posterior mean of 1.39 million crabs per year (1.26 to 1.54 million) (**Figure 4-2b**) and 29-7 had a posterior mean of 300,000 crabs per year (210,000 to 500,000) (**Figure 4-2c**), showing the expected pattern of decreasing recruitment at smaller spatial scales. The time period from 2004 to 2006 appeared to support crab recruitment several times higher the annual average in Area 29 and Sub-area 29-6, whereas Sub-area 29-7 appeared to have highest recruitment during the period 1993 to 1996 (**Figure 4-3**).

Estimated average recruitment in each area is strongly correlated with the estimate of non-moulting natural mortality rate, M_1, where higher M_1 values result in higher recruitment estimates **(Figure 4-4**; avgR and M1 for Area 29 only). Such a correlation is expected when estimating recruitment from catch data because, if crab survival from recruitment to legal sizes is low, then very high initial recruitment levels are needed to support a fixed amount of legal-sized crab catch. Unfortunately, there is little information in the observed data to inform the estimate of M_1, so the posterior distribution closely mimics the prior (**Figure 4-2**, Non-moulting mortality).

4.2.2 Crab Biomass and Production

Posterior distributions for legal crab biomass before and after fishing suggested that model estimates were precise for Area 29 and Sub-area 29-6 (**Figure 4-5 a, b**), as indicated by narrow 95% credible intervals (**Table 1, Appendix B**). The pattern and scale of legal crab biomass was consistent despite the inability of the model and data to provide unique estimates for some biological parameters (e.g. mortality, M_1, and growth model, b_1) as described below.

Posterior means calculated by the model show that annual legal-sized crab biomass in Area 29 ranged from a low of 272 tonnes in 1991 to a high of 1,865 tonnes in 2007, and averaged 760.12 tonnes per year between 1982 and 2012 (**Figure 4-5a (A)**). Biomass in Sub-area 29-6 ranged from 93 to 797 tonnes, averaging 279.82 tons (**Figure 4-5a (B)**) and ranged from 20 to 105 tonnes, averaging 42 tons in Sub-area 29-7 (**Figure 4-5a (C)**). This corresponds to Sub-areas 29-6 and 29-7 making up 37% and 6% total standing stock biomass in Area 29, respectively.

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[6] In Bayesian inference, a credible (or probability) interval is a probabilistic region around a posterior moment and is similar in use to a confidence interval. The difference is that the Bayesian interval incorporates information from the prior distribution into the estimate, while confidence intervals are based solely on the data.

Annual crab production was estimated as the difference between legal crab biomass remaining after fishing in year *t*-1 (adjusted for over-winter mortality) and legal crab biomass just prior to fishing in year *t*. These estimates are higher than what is actually available to fisheries because, over a 6-month fishing season, natural mortality will occur. Production in Area 29 averaged 629.79 tonnes per year over the 21 year time-series, with proportional average contributions of 223.65 tons from Sub-area 29-6 and 32.93 tons from Sub-area 29-7, comprising 36% and 5% of the Area 29 total, respectively. The production patterns in **Figure 4.5b (D, E, F)** suggest that there were three years of exceptional crab production in Area 29 and Sub-area 29-6 that appeared to follow recruitments from 2004 to 2006 and, subsequently, influenced biomass and fishery catch for the five-year period 2006 to 2009. One reason for protracted high biomass and catch values compared to recruitment is that exploitation rates in these high abundance years were lower (62 to 78%) than typical (85 to 96%). An indication of above average legal crab survival owing to this low exploitation is evident in the post-season size compositions for 2007 to 2010 (**Figure 4-1c**).

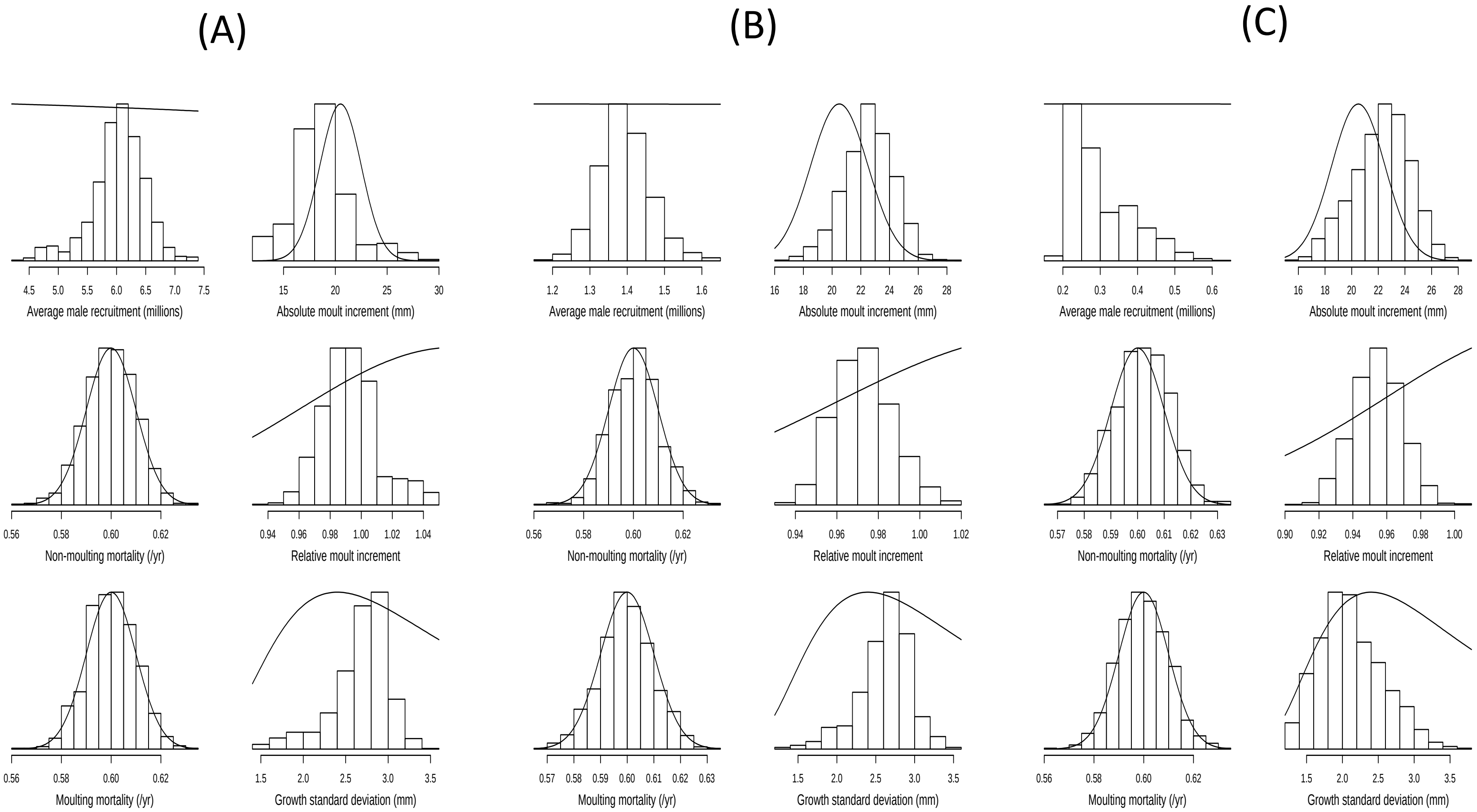
4.2.3 Growth Parameters

Only relative growth increment and growth spread parameters were moderately estimable from the length-composition data. These appear in the second column of **Figure 4-2 A-C** as narrower posterior histograms compared to the prior distributions. In all areas, the centre of the relative moult increment distribution was shifted slightly lower than the prior distribution (**Figure 4-2 A-C**, column 2, row 2). The absolute growth increment (**Figure 4-2 A-C**, column 2, row 1) was shifted either upward toward faster growth, or lower, depending on the area, but all showed similar posterior variances as the priors indicating that there is little information in the size composition data to further inform these estimates.

The shift in location of the posterior distribution for absolute growth rate compared to the prior suggested correlation with another model parameter, which turns out to be the relative growth increment (**Figure 4-4**, beta1 and beta2). These two parameters are used to model carapace width via the linear growth model $l_{t+1} = \beta_0 + \beta_1 l_t$ (**Appendix A**), where the absolute growth rate beta1 = β_0 and the relative growth rate beta2 = β_1.

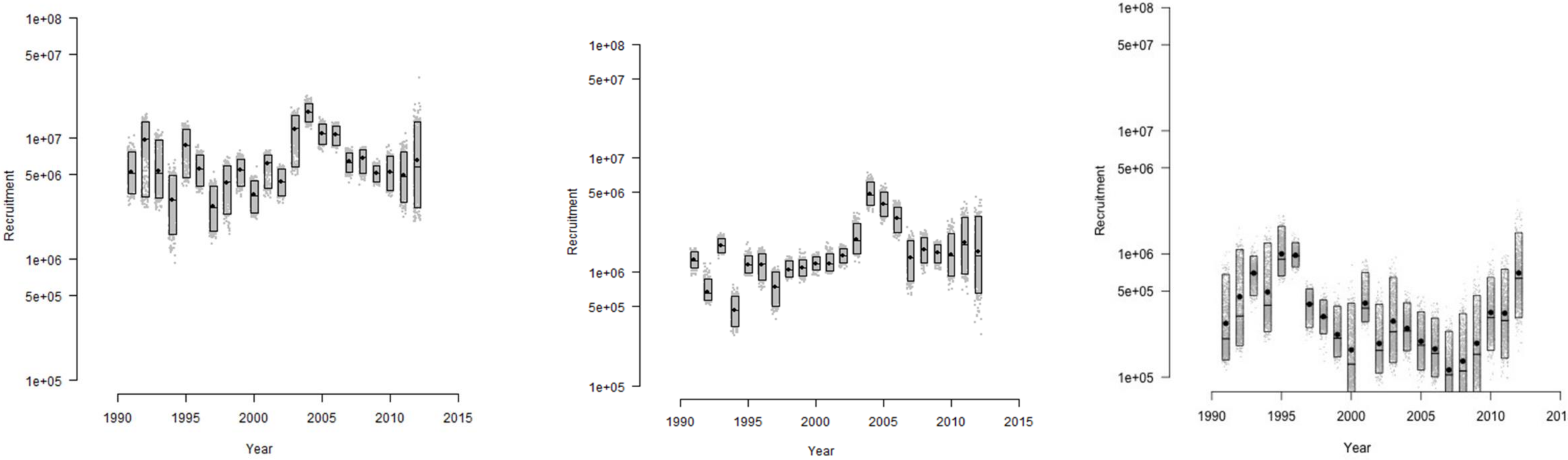
Negative correlation between these two parameters occurs because high absolute growth rates can be offset by low relative growth rates to give similar expected final carapace width. The prior distribution for either parameter was not changed because there is not much effect on estimates of absolute crab abundance and production, as was the case for M_1. There appears to be a limit to how low the relative growth rate can be – very low values would generate "shrinking" of crab body size, which is unlikely given the length frequencies; this best explains why the posterior variance of the relative growth increment was much smaller than the prior variance.

Figure 4-2 **Posterior Sample Histograms (bars) for Recruitment, Natural Mortality, and Growth Parameters for (A) Area 29 Overall, (B) Sub-area 29-6, and (C) Sub-area 29-7**



Note: Prior density functions are shown for each parameter (lines) to indicate the extent of information gained from fitting the model to size composition data.

Figure 4-3 Model-Predicted (Posterior) Distributions for Total Annual Crab Recruitment to 102.5 to 122.5 mm Size Classes in Area 29 Overall (A), and Sub-areas 29-6 (B) and 29-7 (C)



(A) **(B)** **(C)**

Notes: Boxes delimit 1.5 times the inter-quartile range, the horizontal lines and circles in each box are posterior medians and means, respectively. Small dots (light grey shading) are the 1,000 individual posterior sample points.

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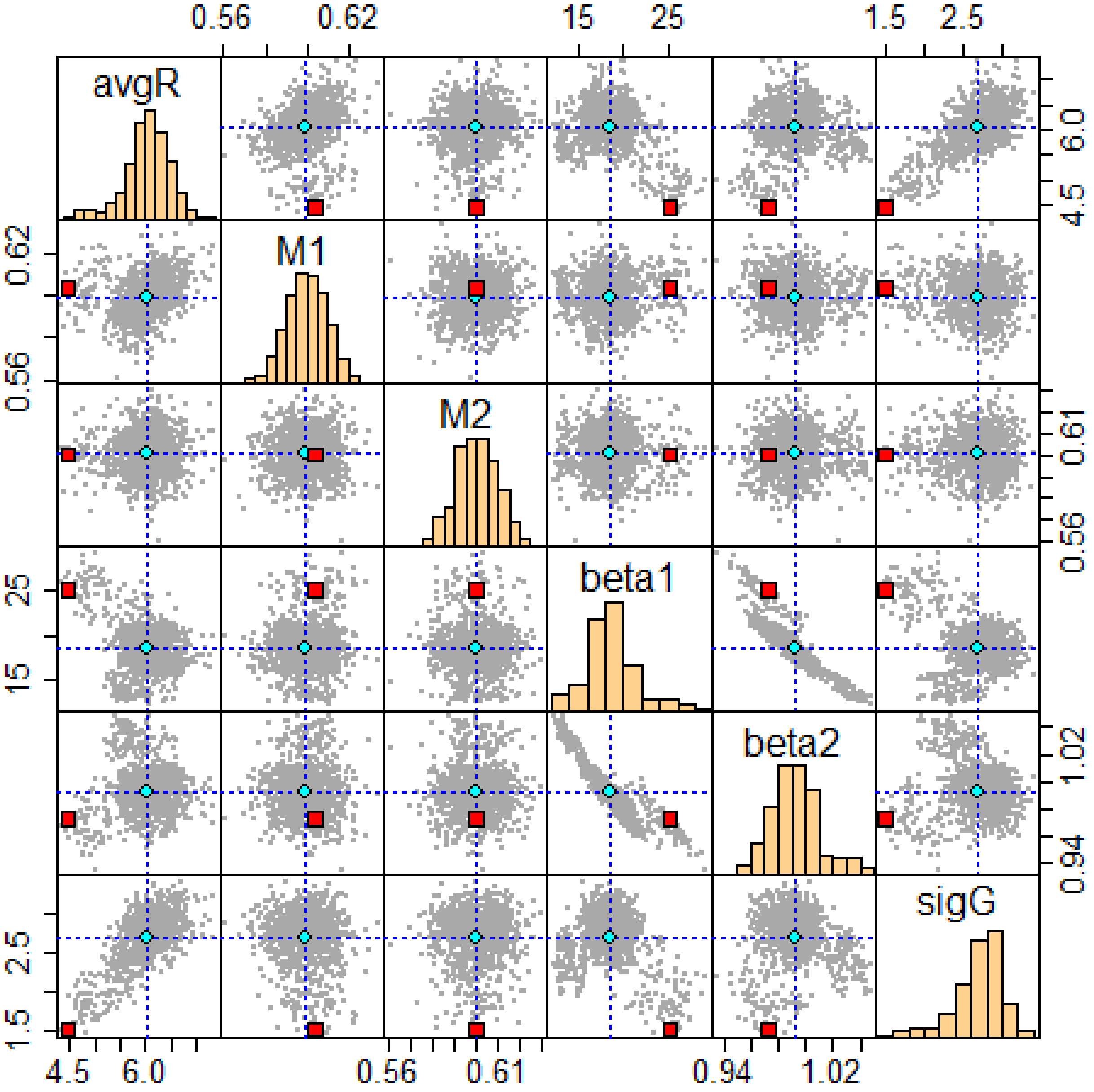
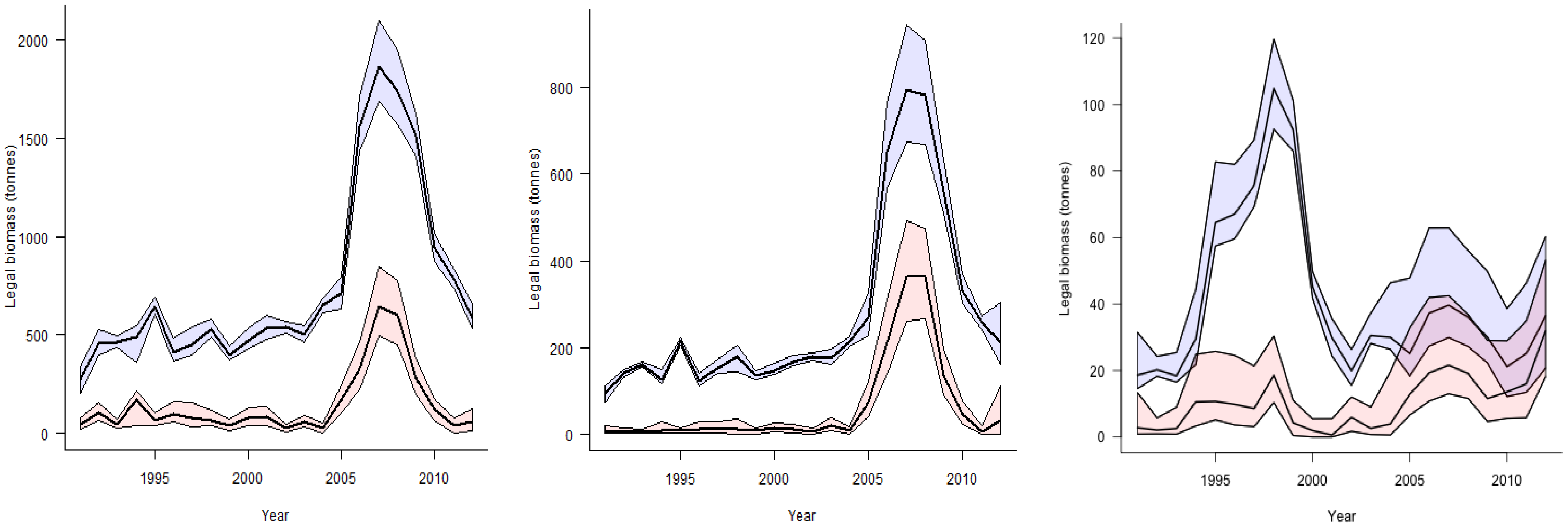
Figure 4-4 Pairwise Joint Posterior Distributions for Six Model Parameters



Note: Histogram plots along the diagonal are the marginal posterior distributions for each parameter. Off-diagonals are pairwise scatterplots of Markov Chain Monte Carlo (MCMC) sample points, which represent the joint pairwise distributions used to test for parameter correlations. Parameters are average annual recruitment (avgR, millions), non-moulting mortality rate (M_1, yr^{-1}), post-moult mortality rate (M_2, yr^{-1}), absolute growth increment (beta1, mm), relative growth increment (beta2, unitless), and the growth spread (sigG, mm).

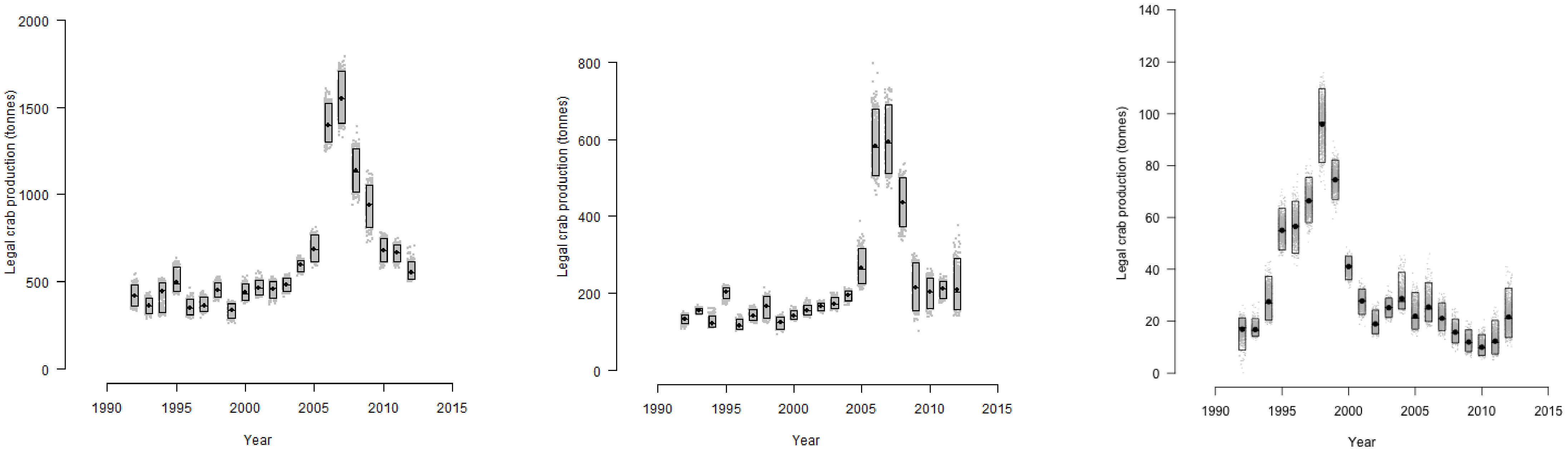
Figure 4-5a **Model-Predicted (posterior) Distributions for Legal Crab Biomass Before (blue) and After (red) the Commercial Fishing Season for A) Area 29 overall, and B) Sub-area 29-6, and C) Sub-area 29-7**



(A) **(B)** **(C)**

Note: Tabular summaries are provided in **Appendix B**.

Figure 4-5b Model-Predicted (posterior) Distributions for Legal Size Crab Annual Production (bottom row) in D) Area 29 overall E) Sub-area 29-6 and F) Sub-area 29-7



(D) **(E)** **(F)**

4.2.4 Natural Mortality Rates

Natural mortality rates could not be estimated from the length data. Preliminary results showed that the posterior distribution for non-moulting natural mortality (for all months except April) was shifted toward higher values compared to the prior distribution, but that the posterior and prior variances were similar. As described above, this lack of variance reduction is caused by correlation with average recruitment. Thus, both natural mortality rate posterior distributions (M_1 and M_2) are nearly identical to the priors for all areas (**Figure 4-2 A-C**, column 1, rows 2 to 3), suggesting that there is no information in the data to estimate this parameter.

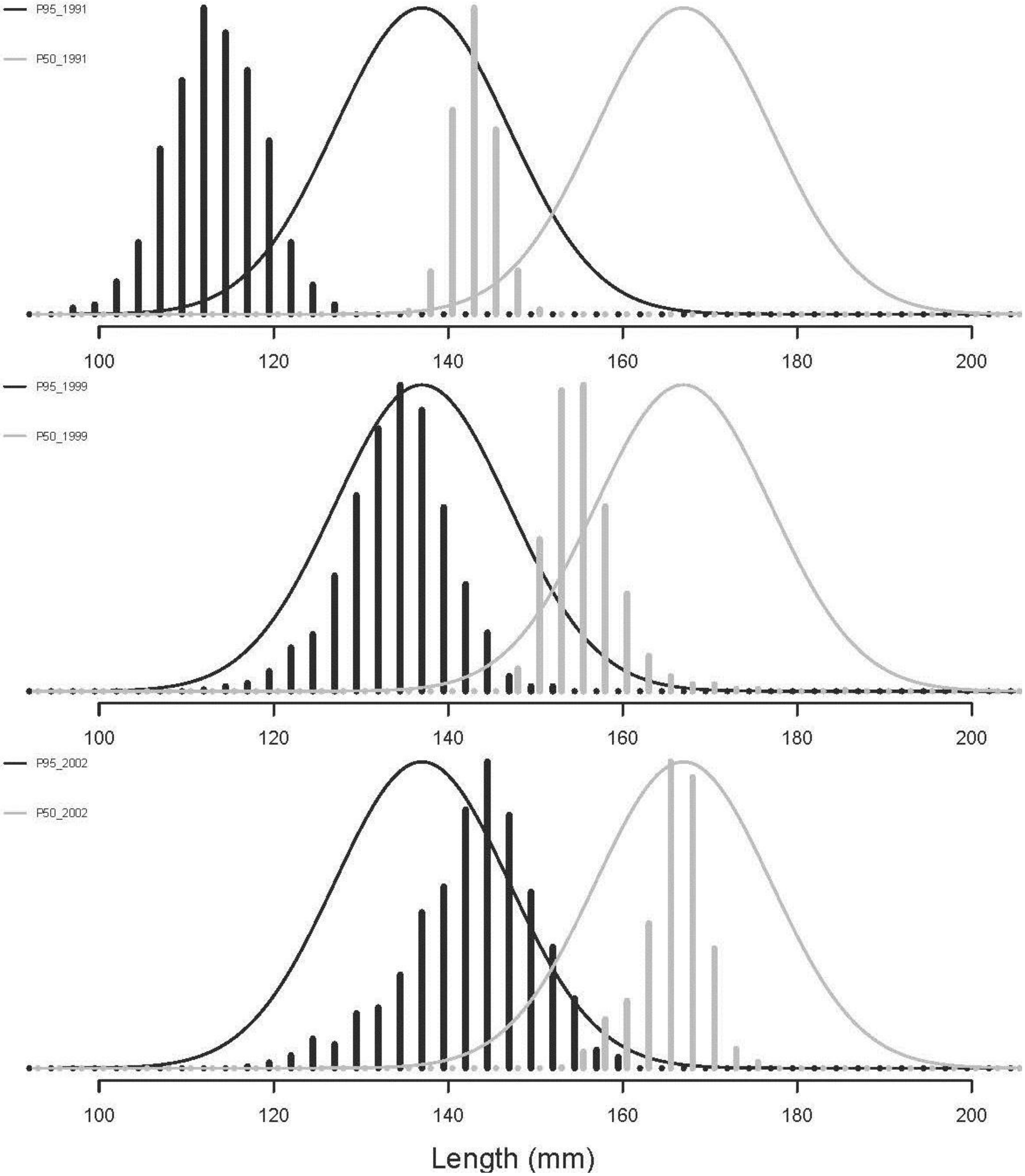
4.2.5 Size-Dependent Moulting and Selectivity Functions

A great amount of inconsistency is typically observed in crab moulting: entire size frequency distributions can shift to larger or smaller sizes from year to year, and size classes that should be present in the data may be absent. This suggests that the timing of moulting, for example, may differ from year to year. Grouping moulting parameters into time-blocks, or blocks of years, attempts to account for this kind of interannual variation. A range of temporal changes in the moulting relationship to size were examined for Area 29, which was the only spatial scale at which moulting parameters were estimable. Preliminary models involved up to seven time-blocks for these functions; however, for the final model, three main time blocks were identified: 1991 to 1997, 1998 to 2001, and 2002 to 2012. Moulting probability functions were shifted toward smaller sizes in earlier time periods compared to later ones (**Figure 4-6**). The best estimated block of parameters was the earliest, 1991 to 1997, while latter periods were similar to the priors.

Timing of DFO research (fishery-independent) surveys has varied over the years from beginning in February/March to May/June; therefore, the sizes of crabs available to be sampled in these surveys will also vary from year to year. Like moulting, the time-blocking of selectivity is an attempt to account for changes in survey timing that could cause large differences in model estimates. Preliminary models used up to three time blocks for commercial fishery selectivity in an attempt to capture changes resulting from different management regimes; however, selectivity in the periods prior to available commercial catch sampling (2005 to 2012) mimicked the priors because of the lack of size composition data; therefore, selectivity blocks were reduced to one for the fishery (**Figure 4-7a, b, c; left column**).

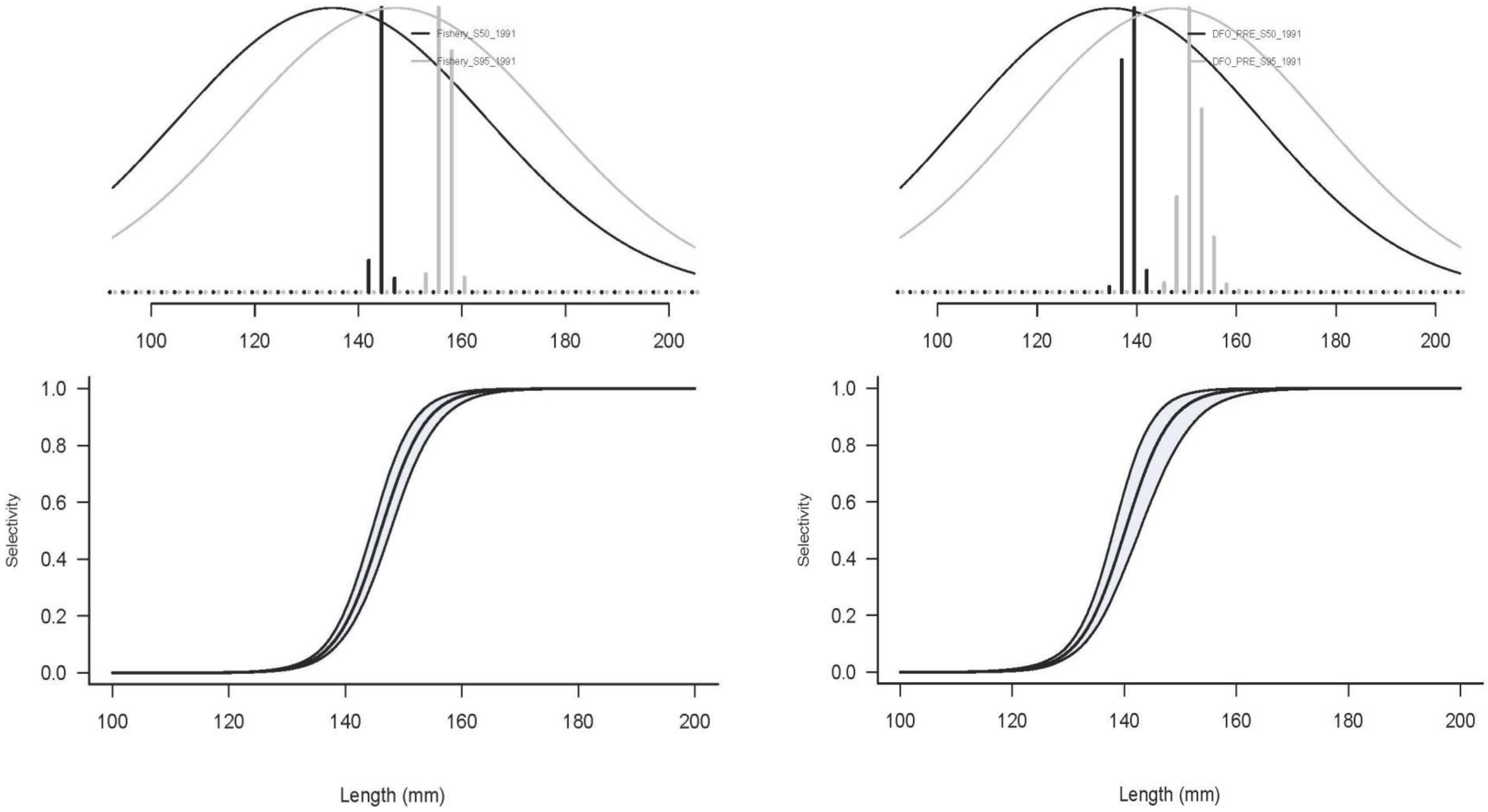
Preliminary models for pre-season fishery-independent surveys used up to 11 time-blocks to capture variation from year-to-year in survey timing. In many cases, the selectivity functions looked to be well-estimated from the data, but overall there was little effect on estimates of biomass and production. Initial estimates of post-season fishery-independent survey selectivity were also sensitive to time-blocking and were strongly correlated to moulting probability functions. Therefore, in the final model, time-blocks were reduced to one overall function that applied to both pre-season and post-season surveys (**Figure 4-7a, b, c; right column**).

Figure 4-6 **Posterior Distributions for Parameters $\tilde{P}_k^{95}$ and $\tilde{P}_k^{50}$, which are the Lengths at which 95% (black) and 50% (grey) of Male Crabs Moult**



Note: The subscript *k* indicates year blocks (top) 1991 to 1997, (middle) 1998 to 2001, and (bottom) 2002 to 2012.

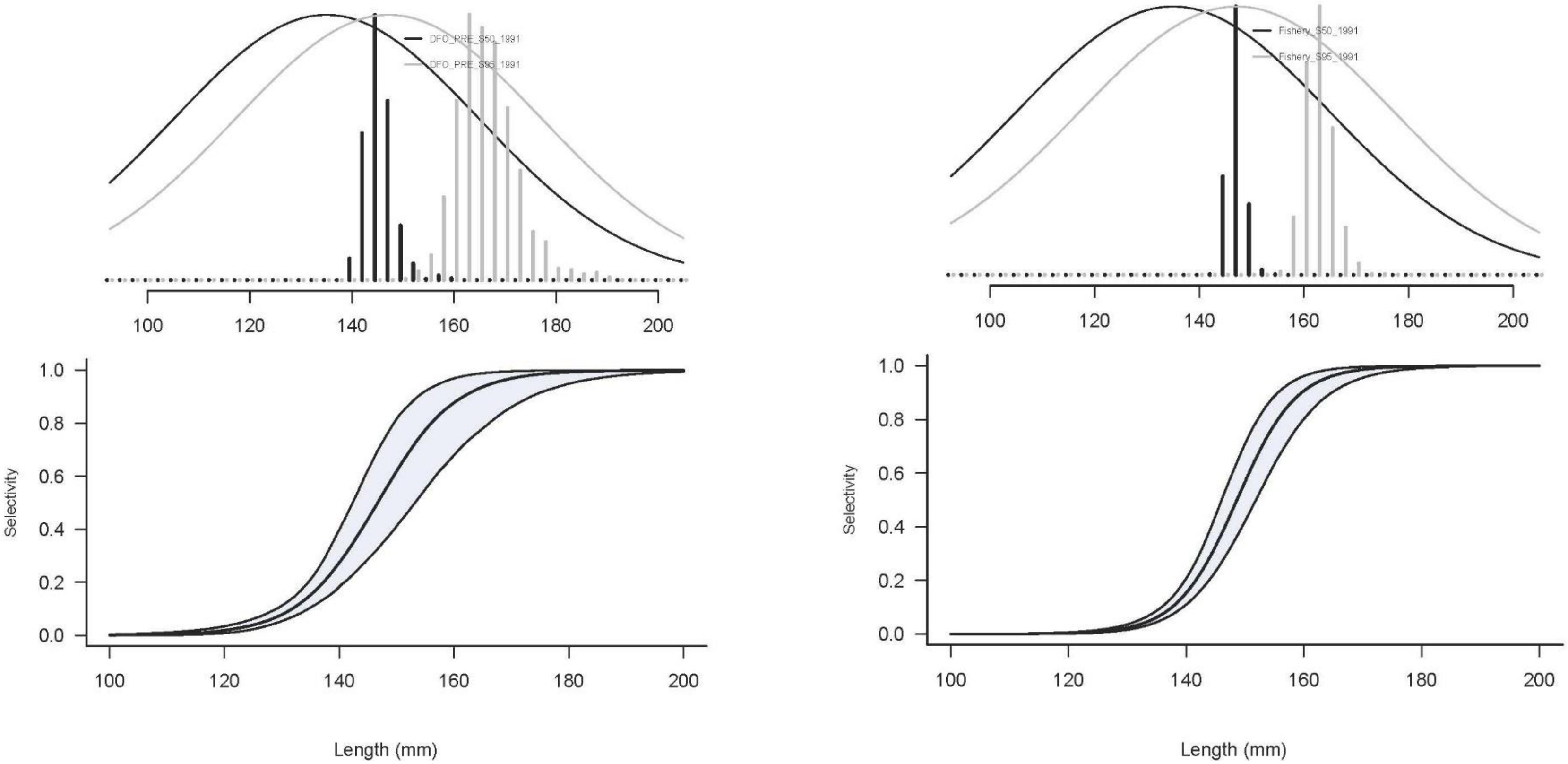
Figure 4-7a Model-Predicted (posterior) Distributions for Size Selectivity in (A) Fishery-Dependent Surveys and (B) Fishery-Independent Surveys in Area 29



(A) **(B)**

Note: Top panels show distributions for parameters S50 (black) and S95 (gray) overlayed on prior distributions (lines). Lower panels show total uncertainty in each selectivity function.

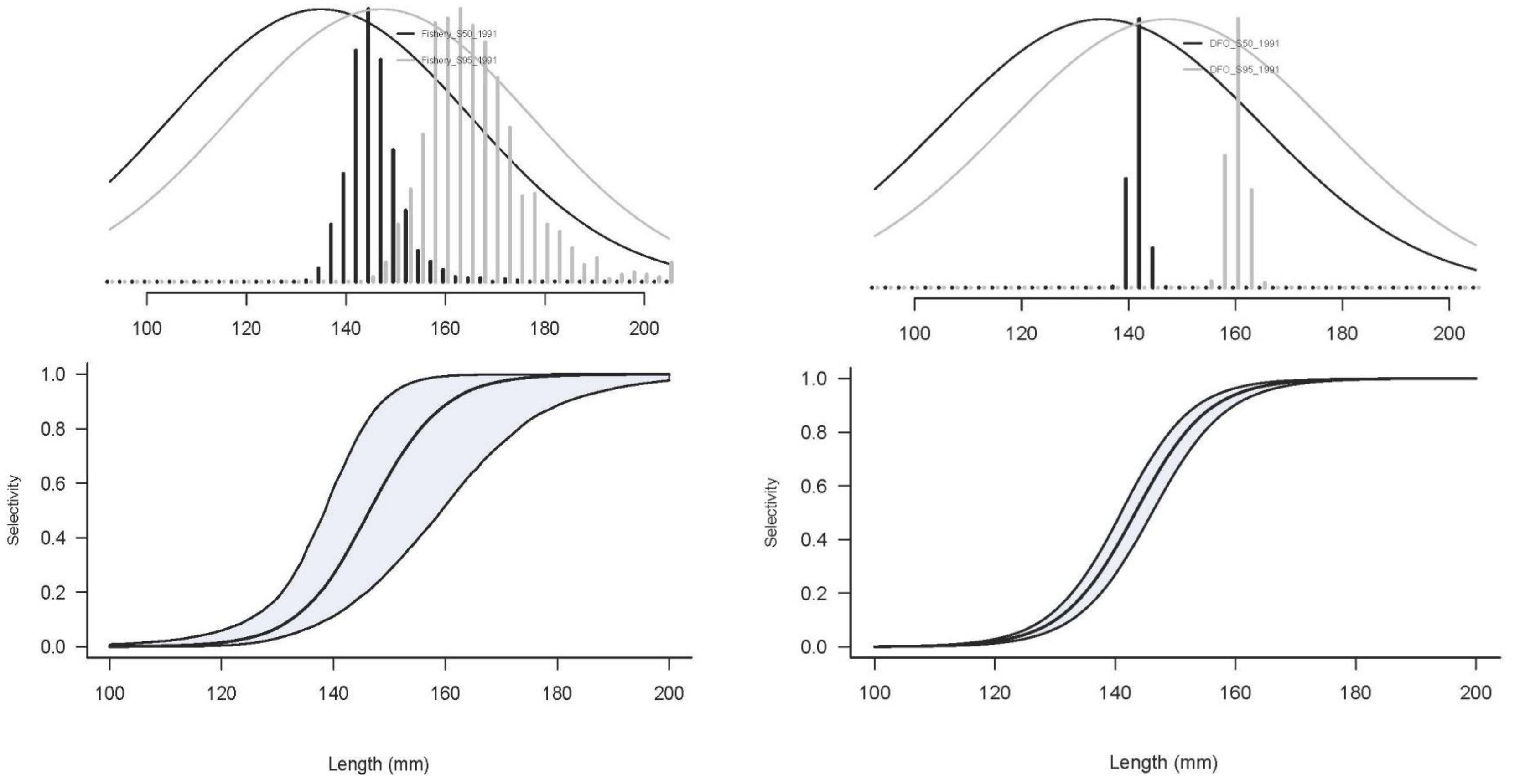
Figure 4-7b **Model-Predicted (posterior) Distributions for Size Selectivity in (C) Fishery-Dependent Surveys and (D) Fishery-Independent Surveys for Sub-area 29-6**



(C) **(D)**

Note: Top panels show distributions for parameters S50 (black) and S95 (gray) overlayed on prior distributions (lines). Lower panels show total uncertainty in each selectivity function.

Figure 4-7c Model-Predicted (posterior) Distributions for Size Selectivity in (E) Fishery-Dependent Surveys and (F) Fishery-Independent Surveys for Sub-area 29-7



(E)

(F)

Note: Top panels show distributions for parameters S50 (black) and S95 (gray) overlayed on prior distributions (lines). Lower panels show total uncertainty in each selectivity function.

5.0 DISCUSSION

Intensive fishing on Fraser River estuary crabs generates variation in crab size composition that enables estimation of annual recruitment and production. Removal rates for Area 29 legal sized crabs are in the range of 65 to 99% per year, which provides relatively precise estimates of the total amount of crab biomass available prior to the fisheries. Model predicted annual recruitment of male crabs to the Area 29 fishery averaged 6 million, and ranged from a low of 2.7 million to a high of almost 17 million. Annual recruitment in Sub-area 29-6 recruitment averaged 1.39 million crabs while Sub-area 29-7 recruitment averaged 300,000 crabs (**Appendix B**). This corresponds to a mean annual production of legal-sized crabs of 629 tonnes, with proportional contributions of 36% and 5% by Sub-areas 29-6 and 29-7, respectively (**Appendix B**). As expected, the precision of estimated model parameters as well as estimated crab abundance, recruitment, and production all decrease as the spatial scale decreases from Area 29 overall to Sub-areas 29-6 and Area 29-7.

According to fishery-dependent landings data, the relative contribution of each Sub-area to overall Area 29 landings appears to undergo episodic shifts (**Figure 3-2** and **Table 3-2**). Sub-area 29-7 currently contributes about 5% of total Area 29 crab landings; however, during the 1990s, when total Area 29 landings were lower, Sub-area 29-7 contributed four to five times more crab landings than it does now, which amounted to as much as 18% of Area 29 overall. Conversely, Sub-area 29-6 catches were a very minor portion of Area 29 landings in the 1990s, but have comprised as much as 43% of Area 29 landings in recent years. The highest landings, on average, for Area 29 have consistently come from Sub-area 29-8 (Boundary Bay; 188.3 tons; 43%), with appreciable contributions from Sub-area 29-3 (offshore Sturgeon Bank to entrance of Howe Sound; 108 tons; 24%) (**Figure 3-2**).

Though the model was able to estimate crab biomass and recruitment relatively precisely at the Area 29 scale, estimated temporal patterns of crab abundance were inconsistent with predictions reported by Zhang and Dunham 2013, who also standardised fishery-dependent and fishery-independent catch rates (but did not use a model linking sub-legal to legal crabs). They showed that Area 29 legal male crab abundance prior to fisheries generally increased from the early 1990s to 2003 and declined over the period 2006 to 2009, which is the period during which our model estimates a large short-term increase in legal crab biomass both before and after fisheries. Zhang and Dunham's result implies that the fishery-independent survey of crab abundance did not indicate the increase in male crab biomass over the period 2005 to 2007 that would have been necessary to explain the high fishery catches in 2006 to 2009. This discrepancy may be the result of DFO's spring fishery-independent surveys simply missing a large biomass of crabs prior to fisheries, either by coincidence or because of shifts in survey timing and gear. Alternatively, a large influx of crabs over 2005 to 2007 could be a result of immigration from surrounding areas, although DFO's spring and fall survey should both have indicated the change in biomass.

Results also demonstrate that crab abundance in the Fraser River estuary (i.e., Area 29 overall) fluctuates widely, and can greatly increase or decrease over a very short period of time. Dungeness crab population dynamics in the Fraser River estuary thus appear to be characterised by a “boom and bust” pattern typified by low production (1982 to 2005), with occasional, but sizeable, bursts (2006 to 2009). These observations are corroborated by reports from elsewhere in the Pacific Northwest. Catch figures in California, for instance, plunged from 7,000 tonnes to 130 tonnes within a four year timespan (Higgins et al. 1997). The literature characterises Dungeness crab population dynamics as notoriously erratic, dramatically increasing/decreasing from one year to the next and at different geographic scales, with consequent economic implications that compel ongoing scrutiny of mechanistic causes underlying such fluctuations (McConnaughey et al. 1994, Higgins et al. 1997, Armstrong et al. 2003).

Conclusive linkages to causal factors governing Dungeness crab recruitment and biomass are lacking. Several hypotheses have been proposed to explain these cycles, including density-dependent biological mechanisms such as competition, egg and larval predation, and cannibalism of young. External environmental mechanisms such as changes in water temperature, ocean currents, wind stress, and other aspects of crab habitat that might affect larval advection, survival, and settlement have also been proposed (Johnson et al. 1986, Berryman 1991, McConnaughey et al. 1992, Botsford 2001).

In California, legal male crab abundance was shown to be primarily determined by the abundance of returning megalopae, and not correlated with the corresponding spawning biomass of females (Shanks and Roegner 2007). This implies Dungeness crab recruitment success may vary primarily due to physical or climatic forcing, embodied in such recurrent meteorological variations as the Pacific Decadal Oscillation (PDO) and the El Nińo Southern Oscillation (ENSO) (Shanks and Roegner 2007). Zhang and Dunham (2013) argue that this explanation may not hold entirely true in the Strait of Georgia because it is a different kind of oceanographic system compared to the open coast.

Unlike the open coast, the Strait of Georgia is largely enclosed, bordered by archipelagos and shallow depths, and bounded by strong tidal fronts to the north and south (Powles et al. 2004). Tides, winds, and freshwater runoff are primarily responsible for water movements and, a counter-clockwise gyre exists in the southern Strait, where the Fraser River estuary is located (Harris and Rattray Jr. 1954). These unique oceanographic and geographic properties may help retain crab larvae in the Strait. Jamieson and Phillips (1993) hypothesised the Juan de Fuca Strait may act as a physical barrier to dispersing larval crabs, based on evidence of regional differences in size and behaviour between megalopae in the southern Strait of Georgia compared with those on the west coast of Vancouver Island. However, genetic differentiation between southern Strait of Georgia and outer coastal Vancouver Island crab populations was substantially less than other populations surveyed in B.C., suggesting some degree of mixing of larval crabs exists between these two regions (Beacham et al. 2008). Dinnel et al. (1993) posited that, on occasion, oceanographic conditions allow influx of Pacific Ocean Dungeness crab larvae through the

Strait of Juan de Fuca into Puget Sound (and, by extension, the Strait of Georgia), such that inner coast Dungeness populations may not be as susceptible to the vagaries of large-scale climatic forcing on larval advection and settlement as those on the open coast. This notion is evidenced in two ways in Area 29. First, since these forcing regimes affect egg and larval stages, for the most part, their effects should be reflected in fisheries data four years later (Armstrong et al. 2003); however, fishery dependent and independent time series for Area 29 show no sign of such cyclical patterns. Second, unlike California, the presence of a strong stock recruitment relationship has been documented between the abundance of female crabs at the end of the fishing season and subsequent legal male crab abundance at the beginning of the fishing season five years later (Zhang and Dunham 2013).

Dungeness crab populations undergo fluctuations due to varying environmental and biological conditions. The Bayesian population dynamics model developed here demonstrates that it is difficult to accurately estimate productivity for Dungeness crab populations that fluctuate dramatically over short intervals of time and space. Population fluctuations observed in the Fraser River estuary are consistent with observations about Dungeness crab dynamics from other areas.

5.1 DATA GAPS AND LIMITATIONS

The model provided relatively accurate predictions of biomass and recruitment in Area 29. Unfortunately, predictions for finer scales of spatial resolution, particularly for Sub-areas 29-6 and 29-7, were less precise: the posterior distributions clearly show how uncertainty increases as the spatial scale gets smaller to the point where small spatial scale inferences are more dependent on the prior information.

Overall, while Bayesian models have a high degree of biological realism, they are computationally complex and need a high level of technical expertise to develop (Smith and Addison 2003). They also require considerably more data and biological assumptions than most other methods. This technical complexity may result in a lack of transparency (Hilborn 1997), as those without extensive modelling experience may have difficulty interpreting the methods and results.

Despite the above mentioned limitations, the overall objective of estimating recent abundance dynamics and production of harvestable Dungeness crabs in Area 29, and ensuring that sufficient information is available to inform a future effects assessment of the proposed Project have effectively been achieved.

6.0 CLOSURE

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8.0 STATEMENT OF LIMITATIONS

This report was prepared by Hemmera, based on work conducted by Atwater Resources Corporation, for the sole benefit and exclusive use of Port Metro Vancouver. The material in it reflects Hemmera's best judgment in light of the information available to it at the time of preparing this Report. Any use that a third party makes of this Report, or any reliance on or decision made based on it, is the responsibility of such third parties. Hemmera accepts no responsibility for damages, if any, suffered by any third party as a result of decisions made or actions taken based on this Report.

Hemmera has performed the work as described above and made the findings and conclusions set out in this Report in a manner consistent with the level of care and skill normally exercised by members of the environmental science profession practicing under similar conditions at the time the work was performed.

This Report represents a reasonable review of the information available to Hemmera within the established Scope, work schedule and budgetary constraints. The conclusions and recommendations contained in this Report are based upon applicable legislation existing at the time the Report was drafted. Any changes in the legislation may alter the conclusions and/or recommendations contained in the Report. Regulatory implications discussed in this Report were based on the applicable legislation existing at the time this Report was written.

In preparing this Report, Hemmera has relied in good faith on information provided by others as noted in this Report, and has assumed that the information provided by those individuals is both factual and accurate. Hemmera accepts no responsibility for any deficiency, misstatement or inaccuracy in this Report resulting from the information provided by those individuals.

APPENDIX A

Dynamic Model Mathematical Specifications

1.0 DYNAMIC MODEL SPECIFICATIONS

A length-based population dynamics model is used to track annual abundance of male crabs in J = 22 size classes ranging from 102.5 mm to 207.5 mm. The model assumes a calendar year beginning 1 April and ending on 31 March. A brief summary of the order of processes in the model is as follows (detailed mathematical specifications for each process is given below):

1. Update crab abundance in each size class l = 1, 2...L (L = 22) to 1 April of year t from crabs surviving over-winter from the previous year (t-1), moulting (or not) into larger sizes, and new recruitment.
2. Account for post-moult mortality of moulting crabs between 1 April and 1 May.
3. Compute predicted crab abundance-at-length $N_{t,l}^{pre}$ available to the pre-season survey (assumed to occur on 1 May) and proportional survey size composition $\hat{p}_{2,t,l}$. Note that the gear index is g = 2 for this survey.
4. Compute predicted mid-season (assumed to be 15 August) crab abundance- and biomass-at-length available to the fishery $N_{t,l}^{mid}$ and proportional size composition $\hat{p}_{1,t,l}$. Note that the gear index is g = 1 for the fishery.
5. Compute exploitation rate for fully selected crabs as total landed catch weight divided by legal biomass available to the fishery. Then compute discard catch brought onboard fishing vessels. Remove landed crab catch and apply discard mortality to under-sized crabs incidentally caught and released during fishing.
6. Compute predicted crab abundance-at-length $N_{t,l}^{post}$ just after the fishery when the post-season survey is assumed to occur (1 November) and proportional survey size composition $\hat{p}_{3,t,l}$.

(1) Update crab abundance at 1 April: Crab abundance is initialised in each size class as of 1 April 1991 by estimating their values as free parameters $\hat{N}_{t,i}$ (i = 6, 2,...17). Annual recruitment of new male crabs (R_t) is spread over the first five size classes from 102.5 to 122.5 mm according to proportions ρ_i (l = 1, 2,...5). Combining survival, recruitment, and growth processes, the model for updating abundance of male crabs in each size class j at the beginning of each year t is:

$$\boldsymbol{N_{t,j}^{pre}} = \begin{cases} \boldsymbol{\widehat{N}_{t,j}} & \boldsymbol{t = 1} \\ \boldsymbol{N_{t-1,j}^{post}(1 - P_{t,j})e^{-6,M_t} + \rho_i R_t + \sum_{i=1}^{i=j-1} P_{t,i}\theta_{t,j} N_{t-1,j}^{post} e^{-5M_t M_2}} & \boldsymbol{t > 1} \end{cases} \qquad \text{[Equation 1]}$$

for all initial size classes j = 1, 2...J. The main idea behind this model (i.e. for t > 1) is that crab abundance in size class j is made up of crabs surviving from the previous year that did not moult (first term), plus new recruitment to the size class (second term), plus crabs surviving from the previous fall and growing into size class j from all smaller sizes (third term). The sub-model describing transition probabilities $q_{i,j}$ is given below along with an example.

It is important to note the assumption that the Area 29 crab population is closed to immigration from neighbouring areas. This is reflected in Equation 1 where the recruitment term R_t is the only source of new individual crabs entering the model population. A more detailed spatial model would be needed to account for immigration of crabs (of all sizes) from other areas.

(2) Account for post-moult mortality: Updating crab abundance to account for post-moult mortality occurs in Equation 1 via one month of mortality rate M_2.

(3) Compute abundance available to the pre-season survey: Equation 1 gives the prediction for the total number of crabs in each length class that are potentially available to the fishery. To get the actual number of vulnerable crabs, the numbers-at-length in Equation 1 are adjusted for size selectivity of the pre-season survey and normalised to give the predicted proportion of the pre-season survey catch that is in length-class j:

$$\hat{P}_{t,j}^{pre} = S_{2,t,j} N_{t,j}^{pre} / \sum_{j=1}^{j=J} S_{2,t,j} N_{t,j}^{pre}$$

Note that the range of length classes in the proportional size composition is limited to where crabs were actually observed in the fishery and surveys. Because this range varies by year, year-specific ranges of j are used in the sample size and likelihood calculations.

(4) Compute mid-season crab abundance and biomass available to the commercial fishery: Assuming that the fishery opens 1 June each year, and the mid-season date is 15 August, mid-season abundance and biomass, respectively, in each length class are:

$$N_{t,j}^{mid} = N_{t,j}^{pre} e^{-2.5M_1}$$

$$B_{t,j}^{mid} = w_j N_{t,j}^{mid}$$

where w_j is the average weight of crabs in the j^{th} length class. It is assumed the parameters of the crab weight-length relationship are known (see Size Transition model section).

(5) Compute catch-at-length by the fishery: Once the mid-season biomass is updated, the exploitation rate by the fishery is computed based on predicted legal crab biomass:

$$U_t = \frac{C_{t,.}}{\sum_{j=1}^{j=J} (1 - u_j) B_{t,j}^{mid}}$$

This assumes that reported catch includes only legal-sized crabs. The weights $1-u_j$ assigned to each size class are the proportions of the catch that would be retained. The release rates $u_j = 1$ for sub-legal sizes classes less than 152.5 mm, $u_j = 0.5$ for the 152.5 mm size class (given 155 mm size limit), and $u_j = 0$ for 157.5 mm and larger size classes. Biomass of landed catch-at-length and released catch-at-length, respectively, are:

$$C_{t,j} = U_t(1-u_j)B_{t,j}^{mid}$$

$$D_{t,j} = U_t u_j S_{1,t,j} B_{t,j}^{mid}$$

where the terms $S_{1,t,j}$ in the discard equation further account for size selectivity of the fishery in year *t*.

(6) Compute crab abundance after the fishery and just prior to the post-season survey: Biomass remaining after fishing and surviving the 2.5 months until the post-season survey is:

$$B_{t,j}^{post} = (B_{t,j}^{mid} - C_{t,j} - dD_{t,j})e^{-2.5M_1}$$

$$N_{t,j}^{post} = \frac{B_{t,j}^{post}}{w_j}$$

where *d* = 0.1 is the fraction of released crabs that die from handling. The predicted proportion of the post-season survey catch that is in length-class *j* is:

$$\hat{P}_{t,j}^{post} = S_{3,t,j} N_{t,j}^{post} / \sum_{j=1}^{j=J} S_{j,3} N_{t,j}^{post}$$

.

The above cycle of calculations is repeated for each year of the assessment using the final $N_{t,l}^{post}$ values in Equation 1 to start the seasonal calculations for the next year. The remainder of this section describes the growth, moulting, and size selectivity functions used in Equation 1.

1.1 SIZE TRANSITION PROBABILITIES $\theta_{i,j}$

The length-based model in Equation 1 requires a transition matrix giving the probability $\theta_{i,j}$ that a crab from initial size class *i* moults into final size class *j* during the spring moulting period. For crabs that moult to increase in size, growth rates or moult number within a year may vary among individual crabs, which will result in a spreading of final size for crabs that all start out at the same initial size. This variation means that crabs growing from a given size class *i* will, after moulting, end up in a range of size classes around an expected mean size. It was assumed that the mean size after moulting $E(l_{t+1})$ follows a linear model in which the growth increment is proportional to the initial size l_t (Zhang and Dunham 2013):

$$l_{t+1} = \beta_0 + \beta_1 l_t$$

where variation around the expected mean size has standard deviation s_G. This linear growth model represents the stochastic progression of crabs moulting through the length frequency distribution. To simplify the presentation, the linear growth model is compressed to matrix form $\mathbf{X}_i\mathbf{b}$ where the input matrix $\mathbf{X}_i = (1, l_i)$ and the growth coefficients are **b=**(β_0, β_1). The transition probabilities from initial size class l_i to final size class l_j are then:

$$\theta_{i,j} = \begin{cases} 1 - logit^{-1}(\boldsymbol{X}_i\boldsymbol{b}/\sigma_G^2) & i = j \\ \theta_{i-1,j} - logit^{-1}((\boldsymbol{X}_i\boldsymbol{b} - l_j)/\sigma_G^2) & j \le i < J \\ \theta_{i-1,j} & j = J \end{cases}$$

where logit^{-1}() is the inverse-logit function e^{u}/(1+e^{u}). The resulting values $\theta_{I,j}$ obey the rules of probability, namely that all $0 \le \theta_{I,j} \le 1$ and $\sum_{i=j}^{i=J} \theta_{i,j} = 1$. A visual example of this growth model is provided to show how crabs in each size class *i* grow and spread to new size classes *j* (**Figure 1** below).

Lengths (mm) are converted to weight (kg) via the length-weight conversion $w_i = c_1 l_i^{c_2}$ where the constants c_1 = 1.32e-7 and c_2 = 3.045 (Zhang et al. 2002).

1.2 MOULTING PROBABILITY

All crabs do not moult at every opportunity; therefore, crab moulting probability is modelled as a decreasing logistic function of initial size *l*. Variation in this relationship among years is allowed for, assuming that conditions affecting moulting could vary from year-to-year. The time-varying moulting probability function is:

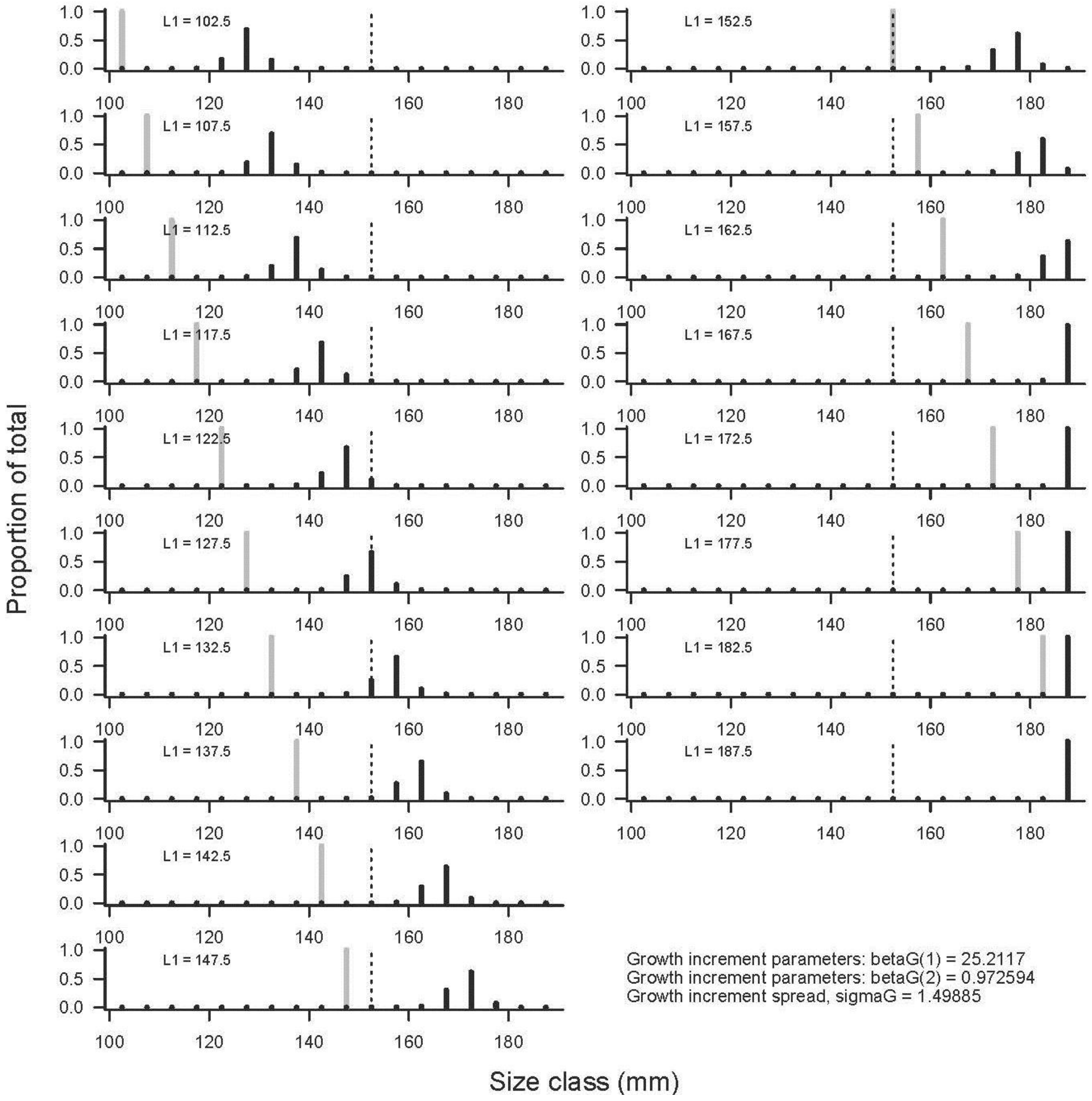
$$P_{t,l} = \frac{1}{1 + \exp[-\log(19)\,(l - P_t^{50})/(P_t^{50} - P_t^{95})]}$$

where P_t^{95}, P_t^{50} are lengths at 95% and 50%, respectively, probability of moulting in year *t*.

1.3 SIZE-SELECTIVITY ($S_{g,t,l}$) IN FISHERY AND SURVEYS

Size selectivity describes the relationship between crab size and relative vulnerability to fishery and survey trap gear. Typically, selectivity is near zero at very small sizes, mainly because small crabs (<75-90 mm) occur in nursery areas that are not sampled extensively either by the fishery or the biological survey.

Figure 1: **Dungeness crab linear growth model as estimated from length composition and catch data for Area 29. Each plot shows the resulting frequency distribution (black bars) of crabs following a moult from the initial size class (gray bars). The sum of the black bars is 1 in all cases. The last 4 size classes are omitted to fit the plot on a single page.**



Growth increment parameters: betaG(1) = 25.2117
Growth increment parameters: betaG(2) = 0.972594
Growth increment spread, sigmaG = 1.49885

There may also be behavioral reasons why small crabs do not enter traps as readily as larger crabs. Whatever the reasons, size selectivity of fishing gear is not directly observable and must be estimated from size-composition data.

Size selectivity in fisheries may vary in response to economic conditions, such as market preference for certain sizes or products, as well as ecological conditions affecting the spatial and temporal distribution of harvested populations. Therefore, fishery size selectivity is expected to change from year-to-year. Fishery-independent survey selectivity should typically be constant if the survey is properly designed to represent the entire stock at all times. Fixed station surveys, such as the ones used for Fraser River estuary crabs, could change selectivity if the spatial distribution of crabs changes from year-to-year with respect to the stations, or if the survey occurs at different times of year when different size classes are more or less available. For these reasons, size selectivity of each gear was allowed to vary in time blocks of various lengths.

Each combination of gear and time period requires two selectivity parameters, $S^{50}_{g,t}, S^{95}_{g,t}$, representing the sizes at which crabs are 50% and 95% selected by the gear, respectively. Given these parameters, the size selectivity function of crab length *l* for gear *g* in year *t* is of the form:

$$S_{g,t,l} = \frac{1}{1 + \exp[-\log(19)\,(l - S^{50}_{g,t})/(P^{95}_{g,t} - S^{50}_{g,t})]}$$

1.4 PRIOR DISTRIBUTIONS

Prior probability distributions on model parameters are used for two distinct reasons. First, priors representing existing knowledge of crab biology are needed for processes such as growth and mortality that cannot be uniquely determined from relative abundance and size composition data alone. Informative priors for these processes are based on fishery-independent studies of crab growth and mortality in Vancouver Harbour, which is closed to fishing, and possibly separate from the Fraser River estuary crab stock (Zhang and Dunham 2013).

The second reason for using prior distributions is to allow for random effects on certain parameters, including: annual recruitment, the spread of recruitment over the first five size classes, initial abundance in 1991, annual moulting probability, and annual selectivity. Prior distributions in these cases are typically uninformative, but the prior variances constrain the outcomes to produce uniquely identifiable parameter estimates. Each of these random effects models is explained in the following sections.

1.5 RECRUITMENT

Parameters that are allowed to vary over time are separated into random year effects as $N\left(0,\sigma\right)$ deviations from a stationary mean. For instance, annual crab recruitment R_t used in Equation (1) is parameterised in the following way:

$$
\begin{aligned}
R_t &= \exp\left(\overline{\log R} + \delta_{R,t}\right) \\
\exp\left(\overline{\log R}\right) &\sim N\left(5.\mathrm{e}6, 20.\mathrm{e}6\right) \\
\delta_{R,t} &\sim N\left(0, \sigma_R\right)
\end{aligned}
$$

This shows that the actual parameters estimated are the stationary average log-recruitment ($\overline{\log R}$) and annual random effects ($\delta_{R,t}$) representing log-normal variation in recruitment around the average. This specification implements a normal prior on average recruitment centered at 5 million crabs (spread across the 102.5 to 122.5 mm classes) with a standard deviation of 20 million. Annual variation in log-recruitment around this average has an expected mean of zero and standard deviation $\sigma_R = 0.4$, which allows sufficient range for recruitment to capture variability in the data. As shown in the results, model estimates of recruitment are insensitive to the prior on $\overline{\log R}$ because there is sufficient information in the total Area 29 data to estimate this quantity.

1.6 SPREAD OF RECRUITMENT AMONG SIZE CLASSES

The distribution of crab recruitment among the first five size classes is given by model parameters ρ_i , which are parameterised by:

$$
\rho_i = \frac{e^{\gamma_i}}{\sum_{j=1}^{j=5} e^{\gamma_j}}
$$

Each of these proportions are given identical uninformative normal priors $\mathrm{logit}^{-1}(\gamma_i) \sim N(0.2,1)$, which assumes that recruitment is evenly spread among the first five size classes.

1.7 INITIAL ABUNDANCE IN 1991

The crab population must be initialised in the first year using parameters $\hat{N}_{1,j}$ representing abundance in each size class. In this case, the log-abundances are estimated via $\log \hat{N}_{t,j} \sim N(14,4)$. As with recruitment, these parameters are well informed by the data, so the priors have little effect, except in Sub-area 29-7 where there are few large crabs.

1.8 ANNUAL MOULTING PROBABILITY

As mentioned above, not all crabs moult every year and the proportion moulting decreases as crabs grow larger. Empirical estimates of crab moulting probability suggest that interannual variation may be important. For instance, Zhang et al. (2002) found 89% of crabs moulting in the 162.5 mm size class in 1997, but only 21% in 1999. The moulting probability function was allowed to vary in time blocks of various lengths by creating time block lower boundaries T_k^P (*k* = 1, 2...*K*) and setting $P_t^{95} = \tilde{P}_k^{95}$ whenever the time step fell within the range $k \le t \le k+1$. For example, in a model with two time blocks for moulting probability with lower boundaries 1991 and 1999, all P_t^{95} values would be equal to $\tilde{P}_1^{95}$ in years 1991 to 1998, and then switch to $\tilde{P}_2^{95}$ values for 1998 to 2012. In preliminary models, switching was tested as frequently as every year. The time-blocked 95% moulting probability parameters are given relatively informative normal priors based on Zhang et al. (2002):

$$\tilde{P}_k^{95} \sim N\left(137.5,80\right)$$

In order to force moulting probability to be a decreasing function of length, the corresponding $\tilde{P}_k^{50}$ values are constrained to be greater than $\tilde{P}_k^{95}$ via

$$\tilde{P}_k^{50} = \tilde{P}_k^{95} + e^{d_k^P}$$
$$d_k^P \sim N\left(3.4,6\right)$$

This prior distribution implies a mean parameter set $\tilde{P}^{95} = 137.5, \tilde{P}^{50} = 167.5$, which is consistent with the observed average values. Note however, that the large prior standard deviations reduce the amount of information contributed by the existing data.

1.9 SIZE SELECTIVITY IN FISHERIES AND SURVEYS

Similar to moulting, there are numerous reasons to expect size selectivity of crab fishing gear and surveys to vary from year-to-year. Because of the similar logistic form, parameterization of time-varying selectivity is similar to moulting where fundamental parameters $\tilde{S}_k^{50}$ are used for each time block *k* and the length at 95% selection is constrained to be larger than the length at 50% selection (unlike moulting, increasing selectivity with size is expected, so the order of 95% and 50% sizes are reversed). This is accomplished via:

$$\tilde{S}_k^{50} \sim N\left(135,80\right)$$
$$\tilde{S}_k^{95} = \tilde{S}_k^{50} + \mathrm{e}^{d_k^S}$$
$$d_k^S \sim N\left(2.5,0.5\right)$$

These priors imply mean $\tilde{S}_k^{50}, \tilde{S}_k^{95}$ values of 135 and approximately 147, respectively. Unlike moulting, it cannot be confirmed whether these prior values are consistent with actual values for the fishery or surveys. In the absence of independent measurements, they can only be determined from fitting the model to length composition data.

1.10 NATURAL MORTALITY

Natural mortality rates in length-based stock assessments are difficult to determine from size composition data because of severe confounding with recruitment, catchability, growth rates, and possibly moulting probabilities. Therefore, identical, informative priors are assigned for non-moulting period and moulting period mortality rates:

$$M_1 \sim N\left(0.60,0.01\right)$$
$$M_2 \sim N\left(0.60,0.01\right).$$

Both of these are instantaneous annual mortality rates, but are converted to monthly values prior to use in the population dynamics model.

1.11 GROWTH PARAMETERS

Zhang et al. (2004) report growth model values of $b_0 = 18.07$ and $b_1 = 1.07$. Separate models were run under each parameterization and the results were nearly identical, so a compromise prior with specifications was employed:

$$
\begin{aligned}
&b_0 \sim N(18.07, 2) \\
&b_1 \sim N(1.06, 0.1) \\
&s_G^2 \sim IG(4, 12)
\end{aligned}
$$

The growth model standard deviation implied by the prior is approximately 4 mm.

1.12 MEASUREMENT ERROR VARIANCES

Non-informative inverse-gamma prior distributions were used for measurement error variances $t_{L,1}^2, t_{L,2}^2, t_{L,3}^2$

1.13 LIKELIHOOD FUNCTIONS FOR FISHERY AND SURVEY SIZE COMPOSITION DATA

Proportion-at-length data for Area 29 correspond to the fishery (2005 to 2012), the pre-season survey (1991 to 2012, missing 2002), and post-season (1991 to 2012, missing 2005) surveys. Missing data increase as spatial scale decreases from Area 29 to 29-6 to 29-7. For each data type and year, it is assumed that the predicted proportion in length-class *i* (e.g., $\hat{p}_{t,l}^{post}$) follows a logistic-normal probability density function (Schnute and Richards 1995) for which the length-proportion residuals are defined by (using the post-season as an example):

$$
h_{g,t,l}^{post} = \log \hat{p}_{g,t,l}^{post} - \log p_{g,t,l}^{post} - \frac{1}{L} \sum_{l=1}^{L} \left[\log \hat{p}_{g,t,l}^{post} - \log p_{g,t,l}^{post} \right]
$$

where the predicted values $\hat{p}_{g,t,l}^{post}$ are given above. The negative log-likelihood component for this particular length composition data set is:

$$
\ell_{L,g} = \frac{1}{(J - 1) n_{L,g}} \log\left(\hat{t}_{L,g}\right) + \frac{1}{2\hat{t}_{L,g}^2} \overset{t=n_{L,g}}{\underset{t=1}{\text{å}}} \overset{i=J}{\underset{i=1}{\text{å}}} h_{g,t,i}^2 \ .
$$

The same process is repeated for the fishery and pre-season survey length compositions giving a total negative log-likelihood for length compositions

$$
\ell_{L,.} = \ell_{L,1} + \ell_{L,2} + \ell_{L,3} \ .
$$

1.14 JOINT POSTERIOR DISTRIBUTION

The total negative log-posterior distribution is given by sum of the data log-likelihoods and the log-priors, all multiplied by -1:

$$\ell_{\mathrm{posterior}} = \ell_{L,\cdot} + \ell_{\Theta} \; .$$

where all of the negative log-priors described above have been added together to give the single joint prior value ℓ_{Θ}. An approximation of the full joint posterior distribution of the parameters is obtained by Markov Chain Monte Carlo (MCMC) simulation (Gelman et al. 2005). Minimization of the negative log-posterior distribution and MCMC are done in AD Model Builder software (Fournier et al. 2012).

2.0 DATA ANALYSIS

2.1 MODEL DIAGNOSTICS AND CHECKING

Model performance was checked in several ways. First, model fits to observed data were examined for each input data source. These provide an immediate visual indication of model agreement with each individual survey index or length frequency observation. Second, scatterplots of predicted and observed mean lengths were created, which should be closely correlated if the model performs well on average across a whole data set. Third, discrepancy statistics between the predicted and observed means lengths were computed for each length composition data set as:

$$D_g = \sum_{t=1}^{t=T} \frac{\left(l_{g,t}^{obs} - l_{g,t}^{rep} \right)^2}{l_{g,t}^{rep}} \; .$$

The discrepancy statistics provide a quantitative indication of overall model fits to each length dataset where lower values are better. Note that missing length observations for areas other than Area 29 limit the utility of these statistics. Fourth, the posterior distributions for each parameter were shown along with their corresponding prior distributions. Where these two do not substantially overlap, the model and data provide new information about the parameter whereas similarity between posteriors and priors potentially indicate that the data provide no information about a parameter. In cases where the data and prior provide similar information about the location of a parameter (e.g. the mean or mode), the posterior variance should be smaller than the prior variance.

3.0 APPENDIX A REFERENCES

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APPENDIX B

Tabular Summaries of Model Parameters with Biomass and Production Estimates

Table 1 Posterior Distribution Summary Statistics for Legal Crab Biomass (tonnes) in Area 29 and Sub-areas 29-6 and 29-7

Area	Parameter	2.50%	Median	Mean	97.50%
Area 29	Legal_B_1991	203.11	272.8	272.58	339.93
	Legal_B_1992	401.08	459.94	462.11	530.48
	Legal_B_1993	438.7	466.41	467.46	497.62
	Legal_B_1994	360.6	490.23	484.7	545.02
	Legal_B_1995	603.52	647.65	647.38	690.73
	Legal_B_1996	366.52	410.36	414.03	482.58
	Legal_B_1997	400.82	450.25	455.43	542.12
	Legal_B_1998	486.49	527.71	529.33	581.39
	Legal_B_1999	370.05	401.17	401.64	440.88
	Legal_B_2000	428.23	469.22	472.07	533.95
	Legal_B_2001	479.45	532.41	535.52	601.67
	Legal_B_2002	510.84	538.68	538.38	565.95
	Legal_B_2003	463.67	504.6	505.38	546.31
	Legal_B_2004	613.11	652.99	651.57	686.89
	Legal_B_2005	631.64	709.72	711.62	797.86
	Legal_B_2006	1431.04	1554.61	1559.24	1710.85
	Legal_B_2007	1686.2	1861.3	1865.68	2093.95
	Legal_B_2008	1570.11	1741.17	1749.33	1948.63
	Legal_B_2009	1406.72	1510.24	1512	1624.26
	Legal_B_2010	876.41	945.75	945.75	1017.03
	Legal_B_2011	733.57	781.16	781.37	833.56
	Legal_B_2012	535.55	584.6	588.57	658.11
Area 29-6	Legal_B_1991	74.62	94.2	93.75	111.07
	Legal_B_1992	133.56	140.95	141.22	150.53
	Legal_B_1993	155.08	160.36	160.57	166.88
	Legal_B_1994	117.63	125.47	127.23	150.15
	Legal_B_1995	204.84	214.06	214.17	223.64
	Legal_B_1996	113.22	122.14	123.46	142.19
	Legal_B_1997	141.57	152.29	153.68	173.28
	Legal_B_1998	142.86	179.45	178.43	206.46
	Legal_B_1999	127.59	135.59	135.89	146.67
	Legal_B_2000	137.43	147.86	148.48	163.82
	Legal_B_2001	157.45	167.34	168.35	183.24

Area	Parameter	2.50%	Median	Mean	97.50%
Area 29-6	Legal_B_2002	169.69	178.26	178.33	188.3
	Legal_B_2003	162.5	176.9	177.8	197.81
	Legal_B_2004	203.72	214.35	214.72	227
	Legal_B_2005	229.49	269.32	272.17	325.18
	Legal_B_2006	566.28	650.71	655	765.41
	Legal_B_2007	673.49	794.24	797.89	942.17
	Legal_B_2008	668.71	781.24	783.37	908.37
	Legal_B_2009	508.62	560.49	562.78	633.46
	Legal_B_2010	302.78	331.29	331.79	368.05
	Legal_B_2011	241.86	257.15	257.26	272.89
	Legal_B_2012	161.82	211.92	215.84	306.07
Area 29-7	Legal_B_1991	14.55	18.61	19.68	31.5
	Legal_B_1992	18.28	20.22	20.5	24.23
	Legal_B_1993	16.51	18.41	19.07	25.38
	Legal_B_1994	21.74	29.53	30.61	44.42
	Legal_B_1995	57.44	64.52	66.19	82.74
	Legal_B_1996	59.65	67.05	67.96	81.95
	Legal_B_1997	69.22	75.7	76.68	89.38
	Legal_B_1998	92.59	104.85	105.23	119.68
	Legal_B_1999	86.02	92.38	92.7	101.22
	Legal_B_2000	41.72	45.27	45.42	49.82
	Legal_B_2001	24.33	29.85	29.83	35.57
	Legal_B_2002	15.52	19.9	20.12	26.32
	Legal_B_2003	28.13	30.55	31.04	37.26
	Legal_B_2004	26.34	30.02	31.72	46.41
	Legal_B_2005	18.37	25.06	27.41	47.78
	Legal_B_2006	27.32	37.22	39.61	62.87
	Legal_B_2007	29.93	39.61	41.56	62.9
	Legal_B_2008	27.21	36	37.87	56.06
	Legal_B_2009	22.23	30.04	31.71	49.79
	Legal_B_2010	12.17	21.13	22.37	38.56
	Legal_B_2011	13.47	25.1	26.24	46.31
	Legal_B_2012	20.73	36.45	37.86	60.29

Table 2 **Posterior Distribution Summary Statistics for Legal Crab Production (tonnes) in Area 29 and Sub-areas 29-6 and 29-7**

Area	Parameter	2.50%	Median	Mean	97.50%
Area 29	Prod_1992	359.84	416.39	417.84	481.04
	Prod_1993	316.58	362.21	362.63	405.58
	Prod_1994	324.56	446.43	441.22	493.36
	Prod_1995	443.88	484.8	490.05	580.71
	Prod_1996	306.04	346.23	347.94	398.75
	Prod_1997	324.96	359.81	360.65	409.77
	Prod_1998	409.55	451.71	451.48	495.49
	Prod_1999	289.21	334.41	333.83	372.52
	Prod_2000	394.61	431.81	433.23	486.31
	Prod_2001	420.58	458.95	460.17	503.88
	Prod_2002	403.32	458.91	456.81	499.4
	Prod_2003	445.37	481.32	481.48	517.96
	Prod_2004	555.99	593.13	592.45	622.94
	Prod_2005	615.62	686.57	686.87	766.61
	Prod_2006	1298.91	1393.17	1397.22	1524.57
	Prod_2007	1407.01	1547.23	1548.51	1707.57
	Prod_2008	1011.97	1128.58	1132.03	1261.31
	Prod_2009	809.21	941.43	937.02	1053.39
	Prod_2010	611.9	678.01	678.24	747.86
	Prod_2011	611.78	664.99	664.27	711.68
	Prod_2012	514.02	547.75	551.67	615.14
Area 29-6	Prod_1992	121.23	132.54	132.21	142.63
	Prod_1993	145.42	153.54	153.42	160.36
	Prod_1994	112.25	119.27	120.92	141.58
	Prod_1995	184.57	204.66	203.85	214.64
	Prod_1996	106.26	113.89	115.11	131.42
	Prod_1997	128.2	141.22	141.71	158.02
	Prod_1998	134.33	167.18	165.72	192.14
	Prod_1999	106.39	124.38	123.73	137.29
	Prod_2000	131.06	139.82	140.58	153.87
	Prod_2001	142.38	154.21	154.65	168.03

Area	Parameter	2.50%	Median	Mean	97.50%
Area 29-6	Prod_2002	155.83	167.31	166.7	174.66
	Prod_2003	159.14	170.58	171.59	189.12
	Prod_2004	180.68	195.95	195.06	205.89
	Prod_2005	224.28	261.86	264.08	316.97
	Prod_2006	506.7	579.49	582.35	678.77
	Prod_2007	511.88	591.46	593.35	690.26
	Prod_2008	372.72	434.83	434.93	498.82
	Prod_2009	153.45	215.27	214.74	277.98
	Prod_2010	161.08	203.23	202.22	239.68
	Prod_2011	186.25	212.65	211.87	230.96
	Prod_2012	157.9	203.25	207.94	290.15
Area 29-7	Prod_1992	8.85	17.4	16.84	21.28
	Prod_1993	14.16	16.41	16.72	21.03
	Prod_1994	20.34	26.96	27.57	37.23
	Prod_1995	47.49	54.89	55.06	63.5
	Prod_1996	46.3	56.68	56.55	66.2
	Prod_1997	57.98	66.33	66.36	75.47
	Prod_1998	81.21	96.64	96.01	109.58
	Prod_1999	66.94	74.62	74.58	82.14
	Prod_2000	36.05	41.18	41.03	44.94
	Prod_2001	22.68	27.86	27.81	32.38
	Prod_2002	15.13	18.67	18.91	24.3
	Prod_2003	21.54	25.31	25.25	28.93
	Prod_2004	24.74	27.64	28.75	38.81
	Prod_2005	16.86	21.31	21.99	31.1
	Prod_2006	19.81	24.77	25.52	34.83
	Prod_2007	16.32	20.94	21.11	27.09
	Prod_2008	11.6	15.45	15.72	20.73
	Prod_2009	8.25	11.71	11.94	16.63
	Prod_2010	6.81	9.69	9.96	14.79
	Prod_2011	7.37	11.82	12.28	20.21
	Prod_2012	13.67	21.13	21.63	32.73

Table 3 Posterior Distribution Summary Statistics for Model Parameters in Area 29

Area	Parameter	2.50%	Median	Mean	97.50%
Area 29	avgR	4.81	6.07	6.03	6.81
	M1	0.58	0.6	0.6	0.62
	M2	0.58	0.6	0.6	0.62
	beta1	13.29	18.49	18.63	25.83
	beta2	0.96	0.99	0.99	1.04
	sigG	1.78	2.74	2.68	3.19
	P95_1991	104.72	114.95	114.94	124.73
	P50_1991	138.87	143.74	143.73	148.58
	P95_1999	123.21	136.03	135.69	146.49
	P50_1999	150.35	155.69	156.29	165.66
	P95_2002	127.37	145.31	144.49	156.46
	P50_2002	158.07	166.93	166.53	172.5
	Fishery_S50_1991	144.56	146.06	146.08	147.73
	Fishery_S95_1991	154.85	157.36	157.38	160.06
	DFO_S50_1991	138.1	140.17	140.25	142.79
	DFO_S95_1991	147.97	151.89	152.06	156.95
	Rec_1991	3.47336775	5.1309	5.25861338	7.7647985
	Rec_1992	3.24769625	9.900695	9.64710505	13.6004525
	Rec_1993	3.22281975	5.102275	5.37558579	9.60685575
	Rec_1994	1.592484	3.050805	3.09502119	4.90388125
	Rec_1995	4.776321	8.81486	8.78541162	11.91977
	Rec_1996	4.0469225	5.520905	5.57282301	7.3090425
	Rec_1997	1.691918	2.6651	2.70422301	4.0217295
	Rec_1998	2.382003	4.341245	4.30352048	5.92670325
	Rec_1999	3.9836595	5.491245	5.48238171	6.7518565
	Rec_2000	2.40133175	3.361815	3.38046187	4.430718
	Rec_2001	3.83666525	6.357825	6.19963763	7.27119075
	Rec_2002	3.32450675	4.34694	4.36308127	5.54171925

Area	Parameter	2.50%	Median	Mean	97.50%
Area 29	Rec_2003	5.81289875	12.10105	11.79198395	15.540155
	Rec_2004	13.7924975	16.5646	16.5969691	19.449305
	Rec_2005	9.00283625	10.88455	10.96011146	13.147125
	Rec_2006	8.77622225	10.62035	10.63628754	12.518845
	Rec_2007	5.21712875	6.332715	6.3697826	7.63235525
	Rec_2008	5.16655475	6.945835	6.86565499	7.9860745
	Rec_2009	4.3863375	5.15742	5.16765267	5.983866
	Rec_2010	3.73051775	5.20479	5.26280087	7.054102
	Rec_2011	2.94599275	4.78874	4.95747494	7.74711575
	Rec_2012	2.64647825	5.863705	6.49952549	13.83089
	rho_102.5	0	0.03	0.12	0.58
	rho_107.5	0.13	0.89	0.81	0.99
	rho_112.5	0	0.01	0.02	0.15
	rho_117.5	0	0.02	0.04	0.18
	rho_122.5	0	0	0.01	0.09
	init_N_127.5	1140797.75	2335535	2359861.54	3626329.25
	init_N_132.5	495831.03	979394	1039378.82	1899788.75
	init_N_137.5	296035.75	678474	711512.15	1288598.75
	init_N_142.5	226254.27	485127.5	510097.39	919812.02
	init_N_147.5	215132.45	460566.5	476692.91	831480.97
	init_N_152.5	152707.95	344518	358784.34	649114.18
	init_N_157.5	86874.16	172176.5	180753.97	324599.92
	init_N_162.5	43287.05	97679.25	102207.07	191696.1
	init_N_167.5	23725.29	53512.95	58065.42	119761.02
	init_N_172.5	15879.93	38959.5	42588.14	92375.17
	init_N_177.5	3573.88	12239.55	15243.78	44247.11
	init_N_182.5	270.43	974.46	1217.44	3359.4
	init_N_187.5	256.44	940.7	1157.93	3612.26

Note: The units for average crab recruitment (avgR and Rec_YEAR) are millions.

Table 4 Posterior Distribution Summary Statistics for Model Parameters in Sub-area 29-6

Area	Parameter	2.50%	Median	Mean	97.50%
Area 29-6	avgR	1.26	1.39	1.39	1.54
	M1	0.58	0.6	0.6	0.62
	M2	0.58	0.6	0.6	0.62
	beta1	18.93	22.61	22.52	25.58
	beta2	0.95	0.97	0.97	1.01
	sigG	1.81	2.67	2.62	3.2
	P95_1991	122.47	140.9	140.45	154.7
	P50_1991	162.85	169.21	169.65	179.72
	Fishery_S50_1991	146.03	148.62	148.69	151.86
	Fishery_S95_1991	158.81	163.37	163.57	169.28
	DFO_S50_1991	142.34	146.71	146.94	153.19
	DFO_ S95_1991	157.57	166.67	167.23	180.25
	Rec_1991	1.086481	1.2589	1.26516758	1.49050075
	Rec_1992	0.56045278	0.655352	0.66902456	0.87411995
	Rec_1993	1.489096	1.700035	1.7044834	1.95032775
	Rec_1994	0.33176783	0.457572	0.45966935	0.61120953
	Rec_1995	0.97695297	1.142185	1.15525865	1.397226
	Rec_1996	0.84719465	1.176715	1.16455976	1.44573725
	Rec_1997	0.495669	0.731491	0.74007402	1.00104075
	Rec_1998	0.9078409	1.045115	1.05132661	1.244244
	Rec_1999	0.91701865	1.080045	1.08214052	1.26531725
	Rec_2000	1.03956025	1.179	1.18265577	1.35322775
	Rec_2001	1.0256705	1.1736	1.18706796	1.4372655
	Rec_2002	1.20287775	1.396075	1.40029213	1.596909
	Rec_2003	1.449766	1.90277	1.93277077	2.66188
	Rec_2004	3.887671	4.772955	4.82519299	6.11328225
	Rec_2005	3.08206025	3.92664	3.95527999	4.9801425
	Rec_2006	2.2409515	2.94771	2.96370128	3.7224255

Area	Parameter	2.50%	Median	Mean	97.50%
Area 29-6	Rec_2007	0.83070503	1.326815	1.33049178	1.866958
	Rec_2008	1.199217	1.57646	1.58359196	1.99857
	Rec_2009	1.1956075	1.460895	1.46149415	1.7327275
	Rec_2010	0.92659522	1.377395	1.42036568	2.1719975
	Rec_2011	0.95804835	1.744225	1.80405163	3.03712125
	Rec_2012	0.64708283	1.38474	1.49300685	3.0546865
	rho_102.5	0	0.01	0.02	0.15
	rho_107.5	0.32	0.5	0.49	0.63
	rho_112.5	0	0.02	0.05	0.21
	rho_117.5	0	0.03	0.06	0.24
	rho_122.5	0.18	0.39	0.38	0.53
	init_N_127.5	14492.17	49130.05	61816.75	181006.72
	init_N_132.5	27614.42	81164.3	89686.37	197785.77
	init_N_137.5	46118.19	112465	118088.74	220945.08
	init_N_142.5	43062.85	104335.5	107859.83	194900.97
	init_N_147.5	47026.48	97305.3	100320.13	171295.12
	init_N_152.5	25048.16	59809.6	64756.25	129361.27
	init_N_157.5	7967	22956.05	25640.76	56741.1
	init_N_162.5	9251.85	28065.85	29963.89	59563.29
	init_N_167.5	8827.52	26713.5	28525.42	58233.39
	init_N_172.5	2869.16	12308.55	15162.13	45298.39
	init_N_177.5	630.63	2826.59	3822.28	12864.49
	init_N_182.5	96.53	5260.84	9106.96	38808.24
	init_N_187.5	114.4	7292.94	11971.33	49487.04

Note: The units for average crab recruitment (avgR and Rec_YEAR) are millions.

Table 5 Posterior Distribution Summary Statistics for Model Parameters in Sub-area 29-7

Area	Parameter	2.50%	Median	Mean	97.50%
Area 29-7	avgR	0.21	0.27	0.3	0.5
	M1	0.58	0.6	0.6	0.62
	M2	0.58	0.6	0.6	0.62
	beta1	17.75	22.38	22.23	26
	beta2	0.93	0.95	0.95	0.98
	sigG	1.38	2.07	2.12	3.08
	P95_1991	135.11	136.96	136.98	138.86
	P50_1991	163.72	168.61	168.79	174.76
	Fishery_S50_1991	138.49	146.46	147.15	159.28
	Fishery_S95_1991	152	165.59	167.1	190.73
	DFO_S50_1991	140.98	143.35	143.34	146.13
	DFO_S95_1991	157.95	161.09	161.1	164.53
	Rec_1991	0.13792755	0.2049845	0.27318937	0.68400472
	Rec_1992	0.17992348	0.3131215	0.44987045	1.0872985
	Rec_1993	0.45891105	0.698062	0.69912644	0.9586087
	Rec_1994	0.2338616	0.3829845	0.49129126	1.228722
	Rec_1995	0.66395947	0.906867	1.00089272	1.67874175
	Rec_1996	0.78726933	0.9643705	0.97590777	1.23448125
	Rec_1997	0.25226985	0.393632	0.39075689	0.52080525
	Rec_1998	0.22497152	0.3064955	0.31025476	0.42280123
	Rec_1999	0.14639462	0.207054	0.2215118	0.37650353
	Rec_2000	0.06476594	0.127455	0.16652175	0.39843677
	Rec_2001	0.28227862	0.3632735	0.39844972	0.70619437
	Rec_2002	0.1079439	0.164876	0.18766243	0.3906287
	Rec_2003	0.13117077	0.2334655	0.28490198	0.6444179
	Rec_2004	0.16380552	0.237237	0.24838557	0.4014706
	Rec_2005	0.11446685	0.1815715	0.19539184	0.3388176
	Rec_2006	0.1005148	0.1557295	0.16940155	0.30164488

Area	Parameter	2.50%	Median	Mean	97.50%
Area 29-7	Rec_2007	0.06436311	0.1044755	0.11434692	0.2354915
	Rec_2008	0.05391024	0.1121945	0.13486763	0.3278222
	Rec_2009	0.07198831	0.1533845	0.18847625	0.46064707
	Rec_2010	0.1653951	0.304646	0.33465682	0.645504
	Rec_2011	0.14241445	0.2877565	0.33024512	0.75182577
	Rec_2012	0.30374888	0.634843	0.70084995	1.48727425
	rho_102.5	0.17	0.27	0.28	0.44
	rho_107.5	0.18	0.26	0.26	0.35
	rho_112.5	0.16	0.22	0.22	0.3
	rho_117.5	0.06	0.15	0.15	0.21
	rho_122.5	0.03	0.09	0.09	0.15
	init_N_127.5	9346.25	23412.45	27246.26	66490.7
	init_N_132.5	9024.53	22443.2	24243.94	53091.56
	init_N_137.5	9660.58	26021.25	27379.53	53112.33
	init_N_142.5	6247.89	17817.05	19659.88	43351.37
	init_N_147.5	3995.36	10899.95	12805.54	31086.14
	init_N_152.5	2313.92	6679.07	7874.05	19922.56
	init_N_157.5	1039.9	3440.74	3984.46	10044.36
	init_N_162.5	501.66	1564.98	1921.79	5199.39
	init_N_167.5	380.62	1268.83	1486.72	3887.39
	init_N_172.5	330.17	1103.31	1286.81	3395.14
	init_N_177.5	136.6	475.46	603.92	2039.48
	init_N_182.5	498.87	6164.59	6655.52	16460.21
	init_N_187.5	138.93	4878.15	6624.3	24044.83

Note: The units for average crab recruitment (avgR and Rec_YEAR) are millions.