PERSPECTIVE / PERSPECTIVE

Comparison of reference points estimated using a size-based method for two high-latitude crab species in the United States and Canada[1]

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Abstract: We briefly reviewed the decision rules currently used for managing two major high-latitude crab stocks, snow crab (*Chionoecetes opilio*) and Dungeness crab (*Cancer magister*), in the United States and Canada and compared them with model-based reference points, harvest rate, and biomass proportion relative to virgin biomass, developed using species- and area-specific parameters. The model followed a size-based approach, which incorporated Beverton–Holt and Ricker stock–recruitment models and estimated mean and median reference points. The recruitment was also perturbed to generate distributions of reference points. The Beverton–Holt stock–recruitment model provided a lower harvest rate than that of the Ricker model. Harvest rates were lower for combined sexes spawning biomass than for female-only spawning biomass. Increasing the minimum size at first capture and decreasing the handling mortality resulted in increased harvest rates. Changes in fishery duration and timing of fishery open date did not change the harvest rate appreciably. The harvest rates for the Canadian snow and Dungeness crabs were mostly higher than those estimated for the Bering Sea and Southeast Alaska stocks. Reliable estimates of a number of life history parameters are lacking for both species, and hence, the results of this exercise need to be treated in a precautionary manner.

Résumé : Nous examinons les règles de décision couramment utilisées dans la gestion de deux importants stocks de crabes des hautes latitudes, le crabe des neiges (*Chionoecetes opilio*), et le crabe dormeur (*Cancer magister*), aux États-Unis et au Canada. Nous les comparons aux points de référence basés sur des modèles, soit le taux de récolte et la biomasse en proportion de la biomasse vierge, qui utilisent des paramètres spécifiques à l'espèce et au lieu. Le modèle suit une approche basée sur la taille qui incorpore les modèles de stock–recrutement de Beverton–Holt et de Ricker et estime les points de référence moyens et médians. Le recrutement a aussi été modifié afin de produire des distributions de points de référence. Le modèle de stock–recrutement de Beverton–Holt génère un taux de récolte plus faible que le modèle de Ricker. Les taux de récolte sont plus faibles pour la biomasse des reproducteurs des deux sexes combinés que pour la biomasse des femelles reproductrices seulement. L'accroissement de la taille minimale à la première capture et la réduction de la mortalité due à la manipulation augmentent les taux de récolte. Des modifications de la durée de la pêche et de la date d'ouverture ne changent pas de façon appréciable le taux de capture. Les taux de capture du crabe des neiges et du crabe dormeur au Canada sont majoritairement plus élevés que ceux estimés pour les stocks de la mer de Béring et du sud-est de l'Alaska. Nous manquons d'estimations fiables de plusieurs des paramètres démographiques chez les deux espèces; il faut donc considérer les résultats de cet exercice avec circonspection.

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Introduction

Reference points (RPs) are used as benchmarks to assess the status of a stock or stock complex for management purposes. In the United States and Canada, they are defined often in terms of fishing mortality (F) and (or) stock biomass (B). The RPs can be derived by quantitative analysis or assigned an arbitrary value (Caddy and Mahon 1995). The RPs for data- and analysis-rich stocks are determined mostly by rigorous quantitative analysis, whereas RPs for data- and analysis-poor stocks are evaluated by limited quantitative analysis or assigned arbitrary values borrowed from fisheries for similar stocks from other jurisdictions.

Most fisheries are managed with the intention of attaining a stock level that produces maximum sustainable yield (MSY). The paucity of biological and fisheries information for many stocks has led to identifying surrogate RPs for the fishing mortality (F_{MSY}) and stock biomass level (B_{MSY}) that produce MSY. Although most of these surrogate RPs are derived for finfish stocks from an age-based analysis (Clark 1993), a number of them have been either directly applied or estimated for crab stocks. Some F_{MSY} proxies used in or estimated for crab stock management are natural mortality (M) for Bering Sea crab stocks (North Pacific Fishery Management Council (NPFMC) 1999) and $F_{0.1}$ used for Bering Sea crab stocks in the early 1990s (Reeves 1994) and proposed for Canadian Dungeness crab (*Cancer magister*) stocks (Zhang et al. 2002).

Traditional age-based population models, which mostly assume continuous growth, are not directly applicable to crab stocks because growth is discontinuous and routine ageing techniques are lacking even though lipofuscin age markers have recently been used to age blue crab (*Callinectes sapidus*) (Ju et al. 2003). Size-based population models (e.g., Zheng et al. 1995; Miller 2001) have been developed for crab stocks, but the suitability of F_{MSY}-based RPs for crab stocks has not been investigated fully using size-based analyses. High-latitude crab stocks, which are the focus of this paper, pose additional problems in assessment because most of them are managed by a males-only exploitation strategy, which is capable of drastically changing the sex ratio and possibly reducing the reproductive potential (Smith and Jamieson 1991; Rondeau and Sainte-Marie 2001); additionally, fishery information on the female component of these stocks is not available for comprehensive assessment.

In this paper, we briefly review decision rules currently used in the management of two major high-latitude crab fisheries in the United States and Canada and then contrast these present systems against the results of a size-based RP estimation procedure that incorporates crab life history parameters, including reproductive characteristics and recruitment variability. The analysis will also evaluate the RP decision rules against variation in the size, sex, and season rules that presently exist in these fisheries. The RP estimator is robust for data-poor and data-rich situations. The RPs can be used with or without actual survey biomass estimates for management purposes. Finally, we use the RP estimator to determine various RPs for relatively data-rich Bering Sea and eastern Canada snow crab (*Chionoecetes opilio*) stocks and data-poor Southeast Alaska and western Canada Dungeness crab stocks for referential system comparison.

Review of RPs in selected high-latitude crab fisheries in the United States and Canada

United States

Federally managed fisheries in the United States exclusive economic zone are directed by the Magnuson–Stevens Fishery Conservation and Management Act to manage in a precautionary fashion to attain near MSY-producing stock and exploitation levels on a long-term basis. The stock status determination criteria are definitions of overfishing (on F scale) and overfished conditions (on B scale) intended for use by the councils and US government to monitor the stock condition. If F exceeds the overfishing level, then the stock is declared to be subject to overfishing, and if the stock declines below the overfished biomass level, then the stock is declared overfished, and management actions in the form of reducing F or rebuilding plans must be implemented (Restrepo and Powers 1999).

The United States federal government through the NPFMC and the State of Alaska jointly manages the Bering Sea and Aleutian Islands crab stocks, whereas the State of Alaska solely manages the Gulf of Alaska and Southeast Alaska crab stocks. For the Bering Sea and Aleutian Islands crab stocks, the NPFMC (1999) defined the "overfishing" level by a constant fishing mortality MSY-Control Rule equating F_{MSY} to M. Because of the lack of plausible M estimates for each crab stock, an M of 0.3 for the *Chionoecetes* species group has been adopted. The M estimate was derived using Hoenig's (1983) formula relating M to longevity. The NPFMC defined the "overfished" status by the minimum stock size threshold, which is equal to half of the MSY stock size. The MSY stock size is estimated as the average total mature stock biomass observed over the 15-year period from 1983 to 1997, which is regarded as ecologically stable (NPFMC 1999).

In addition to federal management regulations, the Alaska Department of Fish and Game (ADFG) has developed harvest strategies for *Chionoecetes* species crab stocks in selected fisheries of the Bering Sea and Gulf of Alaska. The harvest strategies aim at keeping sufficient spawning biomass for stock productivity by controlling the removal of mature males. Guideline harvest level (GHL) is determined for the exploitable portion of a stock based on a stock abundance estimate and a target harvest rate, and minimum (threshold) stock size level (mainly of mature portion) and minimum GHL (for a few stocks) are also estimated for assessing stock viability and manageability under continued fishing. The Bering Sea and Aleutian Islands snow crab fishery is managed by sex (males only), size, and season restrictions with a GHL determined from mature male abundance. In addition, fishery performance within a season is monitored, and if the fishery is expected to exceed the GHL before the declared closure date, then the season is ended by an ADFG Commissioner's emergency order. Single-sex harvest has been in effect since the late 1940s to protect mature females for reproduction. Specific fishing seasons are set to avoid harvesting crabs during mating and molting (soft-shell) periods. To avoid overharvest of legal males within the GHL, a maximum harvest of 60% of the estimated abundance of exploitable legal males is enforced (Pengilly and

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Schmidt 1995). Incidental mortality of crabs in other fisheries (trawl, pot, and dredge) is reduced by enforcing maximum allowable crab bycatch thresholds, which are calculated as a percentage (of the crab abundance) in those fisheries, and closed areas (NPFMC 2001).

Because the stock assessment program for Southeast Alaska Dungeness crab stocks is in its infancy and population parameters are not well described, current management is primarily passive. The ADFG regulations for this fishery include a minimum size, males-only fishery, and a season closure during the late-summer female molting and mating period (16 August – 30 September) and for part of the male molting period (1 March – 14 June). However, the summer season significantly overlaps the late-spring and early-summer end of the primary male molting period (Koeneman 1985), and handling of soft-shelled crabs during the summer season can be extremely high in some years and areas (ADFG 2002). Southeast Alaska Dungeness crab management is based on the concept that if a single age-class of functionally mature prerecruit males are allowed to participate in mating prior to recruiting into the fishery, then virtually all legal males may be removed annually if crabs are protected during their mating and molting period. Harvest rates are roughly estimated to exceed 85% in some years. Nonetheless, when effort began increasing in the late 1980s, a complex system of limited entry, with four different pot number tier levels and a maximum number of entrants and pots, was implemented in 1997 (Shirley 1993). There are no GHLs set for this fishery and harvests are extremely variable between years, generally ranging from 900 to 2300 t depending on the strength of recruitment (ADFG 2002). Currently, year-class strength is assessed from the catch rate at the beginning of the fishery and there is allowance for curtailing fishing if a catastrophic year-class failure is detected. A stock assessment pot survey and tagging program is under development with goals of better describing life history parameters and providing a preseason index of crab abundance. Although only seven fishing districts are currently surveyed, approximately 70% of the annual harvest occurs in the surveyed districts.

Canada

Every Canadian snow crab stock is managed by sex (males only), size, season, effort (limited number of participants and traps by participant), and quota (total allowable catch and individual transferable quota). A consensus opinion has emerged that males have a terminal molt to maturity and this has important implications for management (Conan and Comeau 1986; Sainte-Marie et al. 1995). Discarding of legal-size males is in principle prohibited everywhere to prevent high-grading by shell condition or size, which can result in resource wastage and reduced yield per recruit. However, for some stocks, careful discarding of legal-size adolescent (preterminal molt) males and of soft-shelled adult males is encouraged as a measure to maximize yield per recruit and increase the probability of males mating at least once (Dufour et al. 1997; Bourassa and Dufour 2000). To limit handling mortality, partial or complete closures are imposed for some stocks when the proportion of soft-shelled crabs present in at-sea samples remains above 20% for a threshold number of consecutive days. Comprehensive, fishery-independent trawl or trap surveys exist for most stocks (e.g., Loch et al. 1995) and they provide information on both sexes (trawl) or mainly on males (trap). However, no analytically based RPs have been developed, and management of stocks currently depends on trends in survey biomass and age structure (from proxy shell condition), indices for prerecruits and recruits, fishery performance evaluation, and, in some places, monitoring of female reproductive condition.

The Dungeness crab fishery in Canada occurs in the waters off British Columbia. The coastal fisheries are divided into seven management areas. These areas vary from large physical regions such as the open-ocean fishery in Hecate Straits to small isolated inshore fisheries in the central coast fiords. The commercial fishery is managed by size and sex (males only) restrictions in all regions of the coast. The sport and First Nations fisheries are restricted by size alone. Additional management measures are implemented for the commercial fishery in specific regions of the coast depending on the biological, social, and economic objectives set for the specific area. These restrictions may include specific seasons to avoid handling mortality issues such as soft-shell periods. Exploitation rates in many areas of the coast are estimated to be well in excess of 0.9. The assessment of the fisheries to date has been to provide advice on ways to reduce mortality on sublegal male or female crabs. In general, there is a lack of biological information from most of the management regions, although there have been advisory documents suggesting the need to restrict the effort in certain fisheries. Recent directed studies of a fished and unfished population in close proximity have resulted in ongoing discussions and recommendations for adopting control rules based on $F_{0.1}$ on legal crabs and (or) fishery performance data indicating unacceptably high rates of discard crabs in the catch (Zhang et al. 2002).

RP estimation procedure

Siddeek (2003*a*) developed a size-based method to estimate RPs for Bristol Bay red king crab (*Paralithodes camtschaticus*) that incorporated size-invariant mortality and deterministic stock–recruitment (S–R) relationships. In this paper, that procedure was extended to incorporate size- and sex-specific mortality, complex mating behavior, and stochastic S–R relationships to determine the same set of RPs for the United States and Canada snow and Dungeness crab stocks. The RPs included threshold values of harvest rate, $U(F_{\mathrm{MSY}})$, effective spawning biomass ratio, $\mathrm{ESB}(F_{\mathrm{MSY}})/\mathrm{ESB}(0)$, and nominal mature biomass ratio, $\mathrm{SSB}(F_{\mathrm{MSY}})/\mathrm{SSB}(0)$. The $U(F_{\mathrm{MSY}})$ was considered as an F-based threshold (a limit RP), the $\mathrm{ESB}(F)$ was used in an S–R relationship to generate recruits, the $\mathrm{SSB}(F_{\mathrm{MSY}})/\mathrm{SSB}(0)$ was treated as a B-based threshold (a limit RP), and the $\mathrm{ESB}(F_{\mathrm{MSY}})/\mathrm{ESB}(0)$ was considered as another form of a B-based threshold (a limit RP).

Methods and materials

The notation used in the text, tables, and appendices are defined in the list of notations immediately after the list of references.

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Determination of F_{MSY}, $U(F_{MSY})$, ESB(F_{MSY})/ESB(0), and SSB(F_{MSY})/SSB(0)

Determination of F_{MSY}-based RPs requires an S–R relationship, which is a difficult task for many stocks. Two well-known S–R models, Beverton–Holt (Beverton and Holt 1957) and Ricker (1954), with a plausible range of S–R shape parameter (τ) were used to explore the patterns and trends in RPs. To estimate RPs, first, initial cohort (prerecruit-1 and class-1) abundance was generated under a Beverton–Holt or Ricker S–R model using a set of formulas based on spawning biomass per recruit (Mace 1994). Second, a threshold fishing mortality was determined by maximizing the legal male yield for a given set of growth, fishery selectivity, and other mortality parameters (natural mortality, sublegal crab handling mortality, and bycatch mortality) for the deterministic S–R model. Third, the recruitment was randomly varied to generate a 100-generation fishery and the average legal male yield over 100 generations was maximized in a similar way to obtain another threshold fishing mortality. Although the latter threshold fishing mortality was closer to F_{MSY}, both estimates were treated as F_{MSY} because the central values of harvest rates under deterministic and stochastic recruit generations were the same (see the Results section). The F_{MSY} was determined by systematically searching for a maximum $Y(F)$ over the effective F (annual $F \times$ fishing period) within 0.0–5.0 by a small step of 0.1. The $U(F_{MSY})$ was estimated by dividing the MSY catch by the average MSY standing stock size of legal crabs. The effective spawning biomass based on plausible mating ratio and nominal mature biomass that ignored the mating ratio was also determined at F_{MSY}. The SSB(F_{MSY})/SSB(0) at F_{MSY} corresponds to the proportion of virgin biomass (so called "*B*-based RP"; Williams and Shertzer 2003) in the traditional $F_{\%SSB(0)}$ that maintains the mature biomass at the MSY-producing level. Mace (1994) followed a deterministic approach to generate the number of recruits. We incorporated recruitment variation in the S–R models to determine RP distributions. We considered separately female and combined sexes spawning biomass per recruit for recruit generation from S–R models. A flowchart showing the steps to estimate RPs is given in Fig. 1 and the spawning biomass per recruit derivation formulas are explained in Appendix A with underlying assumptions. Published and plausible biological and fisheries information on snow and Dungeness crab stocks that were used in the simulations are also provided (Appendix B).

Recruitment was modeled using the following two S–R models (Beverton and Holt (1957) and Ricker (1954), respectively) with lognormal random errors:

$$(1) \qquad R_t = \frac{\mathrm{ESB}}{\alpha + \beta \mathrm{ESB}} e^{\varepsilon_t - \sigma^2_{\varepsilon_t}/2}$$

and

$$(2) \qquad R_t = \gamma \mathrm{ESB} e^{-\theta \mathrm{ESB}} e^{\varepsilon_t - \sigma^2_{\varepsilon_t}/2}$$

where $\varepsilon_t = \rho\varepsilon_{t-1} + e_t$ and $e_t \sim N(0, \sigma^2_e)$ and ε_t is set to $Z\sigma_{\varepsilon_t}$ where $Z \sim N(0, 1)$ and

$$\sigma^2_{\varepsilon_t} = \frac{\sigma^2_e}{1-\rho^2}$$

From the deterministic form of the S–R relationship, the R_{max} for the Beverton–Holt S–R relationship is $1/\beta$ and that for the Ricker S–R relationship is $\gamma e^{-1}/\theta$.

Following Mace (1994), the S–R shape parameter (in Mace's terms, the extinction parameter), τ, can be written as

$$(3) \qquad \tau = \frac{(\mathrm{ESB}/R)_{\mathrm{ESB}=0}}{(\mathrm{ESB}/R)_{F=0}}$$

where $(\mathrm{ESB}/R)_{\mathrm{ESB}=0}$ equals α for the Beverton–Holt S–R model and $1/\gamma$ for the Ricker S–R model. Therefore

$$(4) \qquad \alpha = \tau(\mathrm{ESB}/R)_{F=0}$$

for the Beverton–Holt S–R model and

$$(5) \qquad \gamma = \frac{1}{\tau(\mathrm{ESB}/R)_{F=0}}$$

for the Ricker S–R model.

Thus, for a given τ and a fixed R_{max}, all parameters of the S–R relationships can be determined from an estimate of $(\mathrm{ESB}/R)_{F=0}$. Furthermore, by varying the τ value, different steepness (near the origin) and shape of the S–R curve can be obtained.

For RP estimation, $R(F)$, ESB(F), SSB(F), and $Y(F)$ estimates for the two S–R models are needed (Appendix A). The $R(F)$ was determined using the following formulas (Beverton and Holt (1957) and Ricker (1954), respectively) with either $(\mathrm{ESB}_{\mathrm{female}}/R)_F$ or $(\mathrm{ESB}_{\mathrm{combined\ sexes}}/R)_F$ determined from Appendix A formulas:

$$(6) \qquad R(F) = \frac{(\mathrm{ESB}/R)_F - \alpha}{\beta(\mathrm{ESB}/R)_F}$$

$$(7) \qquad R(F) = \frac{\ln(\gamma(\mathrm{ESB}/R)_F)}{\theta(\mathrm{ESB}/R)_F}$$

The M, h, BYM, and mating ratios involved in RP estimation were plausible fixed values selected from either literature or unpublished information (Appendix B). On the other hand, the τ value is largely unknown because of a lack of S–R relationship for many crab stocks (Zheng and Kruse 2003), and hence, a uniform distribution with a plausible continuous range was used to select the τ parameter.

Two types of simulations were performed to explore RPs. First, recruits were estimated from the deterministic form of the two S–R models for 500 randomly selected τ values from a uniform distribution in the 0.20–0.50 interval, and mean, median, and standard deviation of RPs were determined. Second, the estimated recruits were perturbed to simulate a 100-generation fishing history at different F levels, and mean yield at each F was determined from which the F_{MSY} and related RPs were calculated. Then the 2.5 and 97.5 percentiles, mean, median, and standard deviation of RPs were estimated. This simulation procedure can be explained by the following steps. (1) A set of 100 standard normal random numbers were used to perturb a set of 100 recruitments generated by spawning biomasses resulting from 100 generations of fishing (i.e., the simulation was dynamic with each perturbed recruitment producing different subsequent biomass), starting from a virgin stock, at a fixed F for fixed values of σ^2_e and ρ and a randomly selected value of τ, and an average (sustainable) yield at each F value was calculated. (2) The

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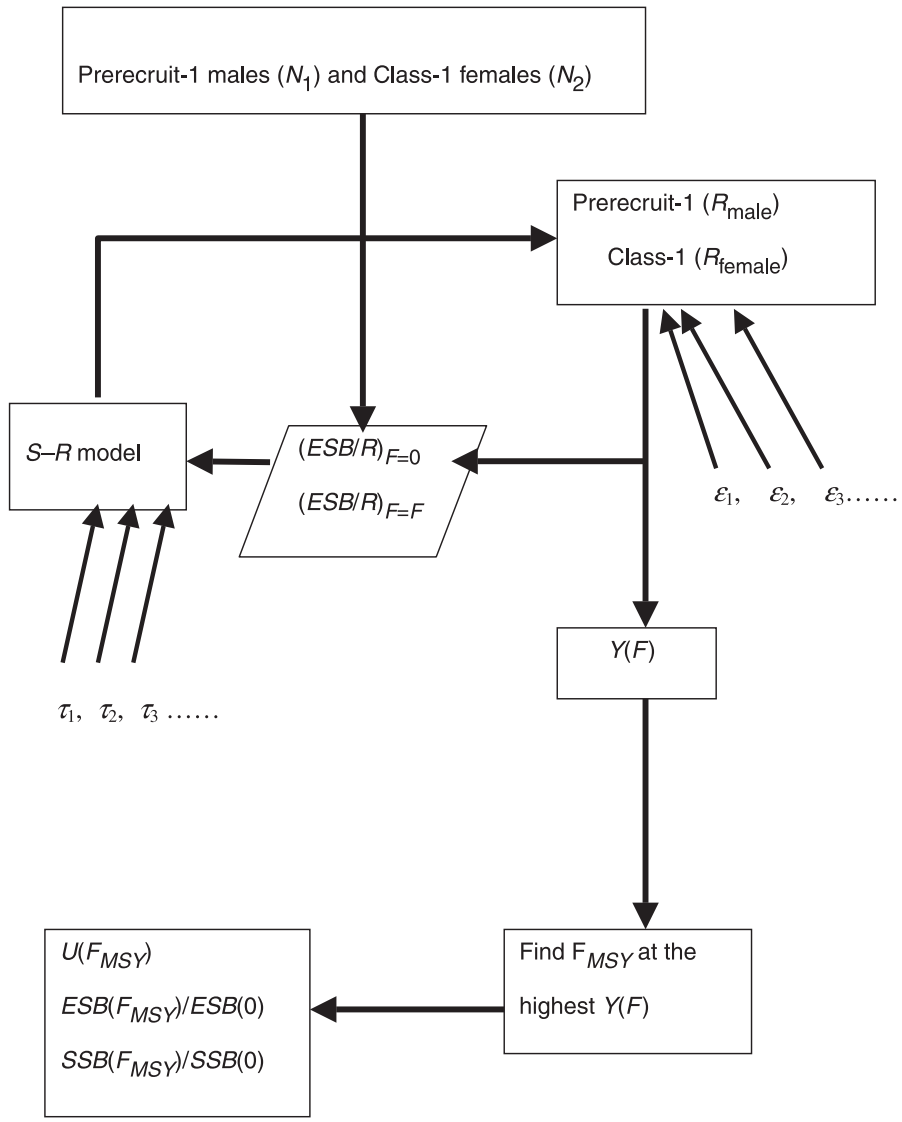
Fig. 1. Flow chart showing the approach to reference point estimation. $(ESB/R)_{F=F}$ and $(ESB/R)_{F=0}$, effective spawning stock biomass per recruit corresponding to a fishing mortality F and $F = 0$, respectively; $U(F_{MSY})$, exploitation rate corresponding to MSY-level fishing mortality F_{MSY}; ESB(F), ESB(F_{MSY}), and ESB(0), effective spawning stock biomass corresponding to a fishing mortality F, F_{MSY}, and $F = 0$, respectively; SSB(F), SSB(F_{MSY}), and SSB(0), nominal total mature stock biomass corresponding to a fishing mortality F, F_{MSY}, and $F = 0$, respectively; $Y(F)$, total yield for a fishing mortality F; τ, stock–recruitment shape parameter; ε, random error term.



F_{MSY} and related RPs were determined by searching for the F that produced the maximum average yield. (3) Steps 1 and 2 were then repeated for 500 τ values to obtain 500 RP values from which mean, median, and standard deviation of all RPs and a frequency distribution of one of the RPs, the harvest rate, were generated. In the first type of simulation, mean and median RPs were estimated for various scenarios of M, h, initial sex ratio, minimum legal size, fishing period, molting to fishing period, and type of spawner participant (female or combined sexes). The first simulation was a sensitivity analysis on RPs. In the second type of simulation, mean and median RPs were determined for low and high values of σ_e^2 and ρ with an arbitrarily selected single type of S–R model, spawner participant, and status quo values of other parameters. The purpose of the latter simulation was to explore the behavior of RPs under low and high recruitment perturbations and autocorrelation. Moreover, the latter simulation provides RPs related to long- term average yields, which correspond to the MSY yield defined in the US Magnuson–Stevens Fishery Conservation and Management Act. The autocorrelation scenario was considered only for the snow crab stocks because the Bering Sea and Canada snow crab recruitment dynamics appear to have this characteristic: low recruitment is followed by low recruitment and vice versa (Sainte-Marie et al. 1995; Comeau et al. 1998; Zheng and Kruse 2003). Information on the recruitment dynamics of Dungeness crab is lacking for both areas, and hence, the autocorrelation factor was ignored in the simulations. Simulations were performed with Fortran 90 with International Mathematical and Statistical Library (2000)

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routines for standard normal (RNNOA) and uniform (RNUN) random number generations using a fixed initial seed value.

Snow crab input values and RP estimation procedure

Bering Sea stock

The effective minimum size of retained crab, 102 mm carapace width (CW), is due to industry preference even though the ADFG prescribed a lower minimum legal size, 78 mm CW. Mature crabs of both sexes were assumed to have a terminal molt (Turnock 2003). We explored the effects on RPs of changes in the minimum capture size by ±10 mm CW. The purpose of this exercise was to investigate whether harvest rate could be increased (or decreased) with an increase (or decrease) in minimum size at first capture without jeopardizing the spawning potential. Small mature males may be capable of effectively inseminating fewer females than larger males during a breeding season owing to smaller gonads (Rondeau and Sainte-Marie 2001; B. Sainte-Marie, unpublished data). Therefore, plausible male to female mating ratios of 1:4 and 1:3 were selected for mature males <95 mm CW for primiparous and multiparous females, respectively (Appendix B, Table B2). For mature males ≥95 mm CW, the respective ratios were 1:9 and 1:6. Newly molted mature males are not expected to mate with mature females (Conan and Comeau 1986). So, new-shell, mature, male crab abundances were disregarded in calculating the effective spawning biomass. A conservative M value of 0.30 was used for both sexes (NPFMC 1999). The instantaneous handling mortality, $HM1_i$, was related to F through the selectivity function and handling mortality rate h. There was a 25% handling mortality rate ($h = 0.25$) on captured and subsequently released sublegal male and female crabs (Zheng et al. 2002). An h value of 0.25 was selected. Zero and 50% handling death rates were also considered in the RP simulations. The BYM was fixed at 0.01, which represents an estimate of maximum BYM based on 1994–1999 bycatch weighted (by stock size) average harvest rates from all nondirected fisheries (Siddeek 2002).

In general, the fishing season starts in mid-January and lasts until the GHL is achieved. The mean estimate of δ for the 1995–2002 fishing seasons was 0.1303 year (Siddeek 2003*b*). There is no precise identification of molting period for the Bering Sea snow crabs. The molting period may extend from February to July or early August with possible peaks in March, May, or June (R.S. Otto and B.G. Stevens, National Marine Fisheries Service, 301 Research Court, Kodiak, AK 99615, USA, personal communication). An arbitrary T value of 0.6667 (lapsed time between the midmolting period on 15 May and the fishery start date on 15 January) was used in the simulation for status quo RP determination. A zero T value was also considered to explore its effect on RPs.

The initial male to female ratio was set at 1:2 and the simulations were started with a maximum recruit number of 1000 for females and 500 for males. The number of males entering the prerecruit-1 size group (82–101 mm CW) was likely to be closer to half of the females entering the class-1 size group (50–59 mm CW) because of the possibility of male terminal molt occurring at sizes <82 mm CW (Sainte-Marie et al. 1995). The subsequent number of progenies produced by the spawners (i.e., total prerecruit-1 and class-1 crabs) was divided into 1:2 between new-shell prerecruit-1 males and new-shell class-1 females and distributed within each 5-mm interval in the respective stage using a normal distribution with mean equal to the midvalue of the size range and standard deviation approximately equal to the stage size range divided by 6. The initial male to female ratio was also changed to 3:4 to explore its effect on RPs. The subsequent growth increment at each molt was assumed to be normally distributed with size-specific means and standard deviations to determine proportion ($P_{l',l}$) of crabs falling into each size bin as a result of growth. Plausible prerecruit-1 age of 6 years for males, class-1 age of 4 years for females (Somerton 1981; Reeves 1994), and a maximum age of 16 years (based on 1% survival at the maximum age for an M of 0.30) were used to track the cohort for RP estimation.

Eastern Canada stock

The estimation procedures were the same as that for the Bering Sea stock with a few exceptions, but the input parameter values differed and were derived when available from stocks in the estuary and northern Gulf of St. Lawrence. All mature females and males were considered to be terminally molted individuals. The total catch was estimated only for the mature postmolt 2- to 4-year age groups. The minimum legal size is 95 mm CW. So, we explored the effects on RPs for changes in the minimum capture size by ±10 mm CW. The selection of mating ratio was the same as before, but different M values were used for different postmolt ages and sexes (Appendix B, Table B2). An h value of 0.12 and a BYM value of 0.01 were considered in RP simulations. Zero and 25% handling mortality rates were also considered.

The spring fishery in the estuary and northern Gulf of St. Lawrence starts in April and the catch quotas are usually met within about 10 weeks. Thus, the estimate of δ was 0.1923 year. The peak molting period is May; therefore, a T value of 0.875 (lapsed time between the midmolting period on 15 May and the fishery start date on 1 April) was used in the simulation for status quo RP determination. A zero T value was also considered for RP calculation.

The number of individuals entering the cohort, the initial male to female ratio, and the initial size frequency distribution were set the same as for the Bering Sea stock. However, the size-classes used in the model were different from those used for the Bering Sea stock. Plausible prerecruit-1 and class-1 ages (approximately 7.5 years for males and 5.5 years for females) and maximum ages (approximately 18.0 years for males and 13.0 years for females) (Sainte-Marie et al. 1995; Alunno-Bruscia and Sainte-Marie 1998) were used to track the cohort for RP estimation.

Dungeness crab input values and RP estimation procedure

Southeast Alaska stock

The same estimation procedures used for snow crab analyses were applied to Dungeness crab stocks, but the input parameter values differed. The minimum legal size is 165 mm CW. We explored the effects on RPs for changes in the minimum capture size by ±10 mm CW. Because infor-

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mation on mating ratio is lacking for the Dungeness crab stocks, an arbitrary mating ratio of 1:3 borrowed from other families of crabs (Siddeek 2002, 2003*a*, 2003*b*) was used for the entire mature size groups. An M value of 0.47 (G. Bishop, unpublished data), an h value of 0.15, and a BYM value of 0.01 were chosen for RP estimation (Appendix B, Table B3). Zero and 30% handling mortality rates were also considered in the analyses.

The Southeast Alaska summer fishery starts on 15 June and ends on 15 August and the fall and winter season fishery starts on 1 October, ending 30 November or 28 February, depending on location. The fishery is 4 or 5 months in duration depending on the major fishing area. Based on the 4-month duration, the estimate of δ was 0.3333 year. The molting period extends from spring to summer and an arbitrary peak molting date of 15 April was considered for estimating T, which was 0.4583 year. A zero T value was also considered for RP determination.

The initial male to female ratio was set at 1:1, and the simulations were started with a maximum recruit number of 1000 for each sex. The subsequent number of progenies produced by the spawners was divided into 1:1 between new-shell prerecruit-1 males and new-shell class-1 females and distributed within each 5-mm interval following the same procedure used for snow crab. Plausible prerecruit-1 age of 3 years for males, class-1 age of 1 year for females (based on Butler's (1961) age-specific size data), and a maximum age of 10 years (based on 1% survival at the maximum age for an M of 0.47) were used to follow the cohort life span for RP determination.

Western Canada stock

The estimation procedures were the same as those for the Southeast Alaska stock with a few changes in the input parameter values (Butler 1961; Smith and Jamieson 1989). The minimum legal size is 155 mm CW (note: CW in this case refers to notch-to-notch measurement that is equivalent to the legal size limit of 165 mm as measured point-to-point). We explored the effects on RPs for changes in the minimum capture size by ±10 mm CW. The selection of mating ratio was the same as that for the Southeast Alaska stock. However, the M values were much higher; an M value of 0.91 for the prerecruit-1 males and class-1 females and another M value of 0.75 for the recruits and postrecruit males and class-2 females (Z. Zhang and J. Boutillier, unpublished data). The selection of h and BYM was the same as that for the Southeast Alaska stock.

The Fraser River Delta fishery on the western coast of Canada is from 1 July to 30 November, which provided a δ value of 0.4167 year. Considering an approximate peak molting time of 1 May, the T value was estimated at 0.1667 year. A zero T value was also considered for RP estimation.

The initial number of individuals entering the cohort and the initial male to female ratio were set the same as for the Alaska stock. Plausible prerecruit-1 age of 2 years for males, class-1 age of 1 year for females (based on Butler's (1961) age-specific size data), and a maximum age of 6 years (based on 1% survival at the maximum age for an M of 0.83 (mean of 0.91 and 0.75)) were used to follow the cohort life span for RP determination.

Results

Comparison of snow crab RPs

We compared the RP estimates for each stock for different input parameter values, between stocks of the same species for respective status quo input parameter values, and for each stock for variability of RPs under recruitment variation for the status quo input parameter values. The effects on RPs for changes in input parameter values were similar for the deterministic Beverton–Holt and Ricker S–R models. For brevity, we provided most results for the Beverton–Holt S–R relationship, which produced a lower harvest rate than the Ricker S–R model.

Bering Sea stock

The mean harvest rate under a deterministic Beverton–Holt S–R relationship increased from 0.31 to 0.36 as the minimum legal size was increased from 92 to 112 mm CW for the combined sexes spawners. At the current minimum marketable size of 102 mm CW, the mean harvest rate (±SD) was 0.37 (±0.04) and the mean SSB(F_{MSY})/SSB(0) ratio was 0.48 (±0.02). When only females were considered as spawners, the mean harvest rate at the current minimum marketable size increased to 0.49 (±0.05). As the handling mortality was increased, the mean harvest rate decreased slightly, but when it was reduced to zero, the mean harvest rate increased dramatically to 0.50 and the mean SSB(F_{MSY})/SSB(0) ratio also increased to 0.54. There were very small changes in the mean SSB(F_{MSY})/SSB(0) ratio for these scenarios (0.43–0.48) except for the zero handling mortality rate. Changing the current fishery opening date in relation to the peak molting time did not affect any of the RPs. Halving or doubling the current fishing period also did not affect the mean RP values. On the other hand, the change in the initial male to female ratio from 1:2 to 3:4 increased the mean harvest rate from 0.37 to 0.43 and reduced the mean ESB(F_{MSY})/ESB(0) ratio from 0.55 to 0.53 and the mean SSB(F_{MSY})/SSB(0) ratio from 0.48 to 0.43. There were very small differences among the mean and median values of all RPs (Table 1).

Eastern Canada stock

The eastern Canada stock exhibited RP trends similar to those of the Bering Sea stock but with slightly higher harvest rates. The mean harvest rate under a deterministic Beverton–Holt S–R relationship increased from 0.32 to 0.40 as the minimum capture size was increased from 85 to 105 mm CW for the combined sexes spawners. At the current minimum legal size of 95 mm CW, the mean harvest rate was 0.40 (±0.08) and the mean SSB(F_{MSY})/SSB(0) ratio was 0.49 (±0.02). When only females were considered as spawners, the mean harvest rate at the current minimum legal size increased to 0.44 (±0.05). There were very small changes in the mean SSB(F_{MSY})/SSB(0) ratio for these scenarios (0.49–0.50). The RPs behaved similarly to those of the Bering Sea stock for similar changes in start date of fishing from the molting period, fishing period, handling mortality, and initial male to female ratio. There were very little differences among the mean and median values of all RPs (Table 2).

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Table 1. Comparison of reference point estimates (mean, median) for Bering Sea snow crab for various scenarios for 500 randomly selected S–R shape parameter (τ) values within 0.20–0.50, a BYM of 0.01, an *M* of 0.30, under terminal molt of mature components of both sexes assumption, and recruits deterministically generated from the Beverton–Holt S–R model.

Spawners	Total	Total	Total	**Female**	Total	Total	Total	Total	Total	Total
Initial male:female ratio	1:2	1:2	1:2	1:2	1:2	1:2	1:2	**3:4**	1:2	1:2
L_c (mm CW)	**92**	102	**112**	102	102	102	102	102	102	102
T	0.6667	0.6667	0.6667	0.6667	**0.0000**	0.6667	0.6667	0.6667	0.6667	0.6667
δ	0.1303	0.1303	0.1303	0.1303	0.1303	0.1303	0.1303	0.1303	**0.2606**	**0.0652**
h	0.25	0.25	0.25	0.25	0.25	**0.00**	**50.00**	25.00	0.25	0.25
$U(F_{MSY})$	0.31, 0.29	0.37, 0.34	0.36, 0.34	0.40, 0.39	0.37, 0.34	0.50, 0.50	0.32, 0.32	0.43, 0.42	0.36, 0.34	0.37, 0.35
	(0.04)	(0.04)	(0.05)	(0.05)	(0.04)	(0.07)	(0.03)	(0.05)	(0.04)	(0.04)
$ESB(F_{MSY})/ESB(0)$	0.51, 0.52	0.55, 0.55	0.57, 0.57	0.54, 0.54	0.55, 0.55	0.62, 0.62	0.48, 0.48	0.53, 0.52	0.55, 0.55	0.55, 0.55
	(0.02)	(0.02)	(0.02)	(0.01)	(0.02)	(0.01)	(0.03)	(0.02)	(0.02)	(0.02)
$SSB(F_{MSY})/SSB(0)$	0.45, 0.46	0.48, 0.48	0.49, 0.49	0.48, 0.47	0.48, 0.48	0.54, 0.54	0.43, 0.43	0.43, 43	0.48, 0.48	0.48, 0.48
	(0.02)	(0.02)	(0.01)	(0.01)	(0.02)	(0.01)	(0.03)	(0.01)	(0.02)	(0.02)

Note: Total is combined sexes, and other parameters are defined in the notation section. Values and text in bold refer to changes in input values, and values in parentheses are standard deviations.

Table 2. Comparison of reference point estimates (mean, median) for eastern Canada snow crab for various scenarios for 500 randomly selected S–R shape parameter (τ) values within 0.20–0.50, a BYM of 0.01, variable *M* values, terminal molt of mature components of both sexes, and recruits deterministically generated from the Beverton–Holt S–R model.

Spawners	Total	Total	Total	**Female**	Total	Total	Total	Total	Total	Total
Initial male:female ratio	1:2	1:2	1:2	1:2	1:2	1:2	1:2	**3:4**	1:2	1:2
L_c (mm CW)	**85**	95	**105**	95	95	95	95	95	95	95
T	0.875	0.875	0.875	0.875	**0.000**	0.875	0.875	0.875	0.875	0.6667
δ	0.1923	0.1923	0.1923	0.1923	0.1923	0.1923	0.1923	0.1923	**0.3846**	**0.0962**
h	0.12	0.12	0.12	0.12	0.12	**0.00**	**0.25**	0.12	0.12	0.12
$U(F_{MSY})$	0.32, 0.31	0.40, 0.40	0.40, 0.40	0.44, 0.45	0.40, 0.40	0.45, 0.45	0.33, 0.35	0.51, 0.53	0.35, 0.34	0.36, 0.35
	(0.04)	(0.08)	(0.06)	(0.05)	(0.08)	(0.07)	(0.06)	(0.02)	(0.05)	(0.05)
$ESB(F_{MSY})/ESB(0)$	0.49, 0.49	0.49, 0.48	0.48, 0.48	0.48, 0.48	0.49, 0.48	0.48, 0.47	0.50, 0.49	0.72, 0.72	0.50, 0.50	0.50, 0.50
	(0.03)	(0.04)	(0.03)	(0.02)	(0.04)	(0.03)	(0.05)	(0.01)	(0.03)	(0.03)
$SSB(F_{MSY})/SSB(0)$	0.50, 0.50	0.49, 0.49	0.49, 0.49	0.50, 0.50	0.50, 0.49	0.48, 0.47	0.51, 0.50	0.51, 0.51	0.50, 0.50	0.50, 0.50
	(0.02)	(0.02)	(0.02)	(0.01)	(0.02)	(0.02)	(0.03)	(0.01)	(0.02)	(0.02)

Note: Total is combined sexes, and other parameters are defined in the notation section. Values and text in bold refer to changes in input values, and values in parentheses are standard deviations.

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Comparison of RPs between Bering Sea and eastern Canada stocks

The mean harvest rates for the Bering Sea stock were slightly lower than those for the eastern Canada stock under deterministic Beverton–Holt (0.37 versus 0.40) and Ricker S–R relationships (0.43 versus 0.48) and the mean nominal mature biomass ratios were also slightly lower under the respective S–R relationships (0.48 versus 0.49 and 0.53 versus 0.56, respectively). But the mean effective spawning biomass ratio behaved oppositely. The effects on threshold median RPs were similar (Tables 1–3).

We report only the 100-generation fishery simulations with the stochastic recruitment to the Beverton–Holt S–R model for brevity. The trends were the same for the Ricker model, but the harvest rates were higher. For the Bering Sea stock, the 2.5–97.5 percentile interval of harvest rate was 0.32–0.45 with a mean of 0.37 (±0.04) and a median of 0.34 for both low (0.7 and 0.6) and high (0.9 and 0.9) sets of σ_e and ρ values and combined sexes spawners. The corresponding values for the eastern Canada stock were 0.29–0.53 with a mean of 0.40 (±0.08) and a median of 0.40. Thus, the amount of recruitment variability did not affect the central values of harvest rate within each stock, but the estimates for the eastern Canada stock were slightly higher because of different mortality and growth parameter values. The percentile limits for the nominal mature biomass ratios were similar for both stocks, 0.53–0.56 and 0.55–0.58 for the low- and 0.52–0.53 and 0.53–0.54 for the high-recruitment variability for the Bering Sea and eastern Canada stocks, respectively. The mean and median values for both stocks ranged 0.53–0.56 for the two levels of variability (Table 4). Thus, the MSY-level mature biomasses were slightly higher than half of the mature virgin biomass under the variable recruitment hypothesis. The distributions of harvest rate were skewed to the right for both stocks (Fig. 2). The distribution was truncated because the τ values were (randomly) selected from a fixed interval of 0.20–0.50. Individual results showed that the harvest rate was inversely related to τ. The mode toward the lowest harvest rate bin of the distribution indicated that at higher τ values, the RP estimator yielded closer harvest rate estimates. To estimate a realistic harvest rate value for a stock, a true τ value is needed, which can be calculated only if an S–R relationship is available for the stock.

We explored the RPs with the assumption of annual spawning. However, snow crabs may exhibit a 2-year reproductive cycle depending on environmental factors (Sainte-Marie 1993), especially temperature (Moriyasu and Lanteigne 1998). We examined the effect of this possibility on estimates of RP by halving the mating ratio of multiparous females. The mean harvest rate estimates for the deterministic Beverton–Holt S–R model were 0.37 versus 0.30 for the Bering Sea stock and 0.40 versus 0.33 for the eastern Canada stock under annual and biennial reproductive cycles, respectively. The corresponding median harvest rates were 0.34 versus 0.28 and 0.40 versus 0.29, respectively. The mean total mature biomass ratios were 0.48 versus 0.44 for the Bering Sea stock and 0.49 versus 0.44 for the eastern Canada stock under annual and biennial reproductive cycles, respectively. The corresponding median total mature biomass ratios were 0.48 versus 0.44 and 0.49 versus 0.45, respectively.

Table 3. Comparison of reference point estimates (mean, median) for Bering Sea and eastern Canada snow crab for 500 randomly selected S–R shape parameter (τ) values within 0.20–0.50, a BYM of 0.01, an initial male:female ratio of 1:2, and terminal molt of mature components of both sexes.

Stock	Bering Sea	Eastern Canada
L_c (mm CW)	102	95
T	0.6667	0.875
δ	0.1303	0.1923
h	0.25	0.12
M	0.30	Variable
$U(F_{MSY})$	0.43, 0.42 (0.08)	0.48, 0.45 (0.12)
$ESB(F_{MSY})/ESB(0)$	0.60, 0.60 (0.01)	0.52, 0.52 (0.02)
$SSB(F_{MSY})/SSB(0)$	0.53, 0.53 (0.01)	0.56, 0.56 (0.03)

Note: The recruits were simulated deterministically by the Ricker S–R model using combined sexes as spawners. Other parameters are defined in the notation section. Values in parentheses are standard deviations.

Comparison of Dungeness crab RPs

Southeast Alaska stock

The mean harvest rate under a deterministic Beverton–Holt S–R relationship increased from 0.79 to 0.93 as the minimum legal size was increased from 155 to 175 mm CW for the combined sexes spawners. At the current minimum legal size of 165 mm CW, the mean harvest rate was 0.79 (±0.09), the threshold median harvest rate was 0.79, and the mean nominal mature biomass ratio was 1.00 (±0.0001). When only females were considered as spawners, the mean and median harvest rates at the current minimum legal size increased to 0.96 (±0.0004). As the handling mortality was increased from 0.0 to 0.30, the mean and median harvest rates dropped from 0.93 to 0.64 and 0.63, respectively. Changes in T and fishing period had very little effect on any of the RP estimates. The mean and median nominal mature biomass ratios approached 1.00 for all scenarios except for zero handling mortality for which it was 0.41 (±0.01) (Table 5).

Western Canada stock

The western Canada stock exhibited RP trends similar to those of the Southeast Alaska stock under both S–R models but with slightly higher harvest rates and lower total biomass ratios owing to high M values and different growth parameter values. The mean harvest rate increased slightly from 0.85 to 0.88 as the minimum legal size was increased from 145 to 165 mm CW for the combined sexes spawners. The threshold median harvest rate increased from 0.83 to 0.87 for the same increase in legal size. At the current minimum legal size of 155 mm CW, the mean harvest rate was 0.85 (±0.03), the median harvest rate was 0.82, and the mean and median nominal mature biomass ratios were 0.92 (±0.01) and 0.91, respectively. When only females were considered as spawners, the mean and median harvest rates at the current minimum legal size increased to 0.88 (±0.04) and 0.87, respectively. The biomass ratios were over 0.90 and there were very little changes in the two biomass ratios except when handling mortality was zero. When handling mortality was zero, the mean and median harvest rates increased to

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Table 4. Comparison of 2.5–97.5 percentiles, mean, median, and standard deviation of reference point estimates for Bering Sea and eastern Canada snow crab for 500 randomly selected S–R shape parameter (τ) values within 0.20–0.50 and 100 perturbed recruits for 100-generation fishing at each *F* level.

Stock	Bering Sea	Bering Sea	Eastern Canada	Eastern Canada
L_c (mm CW)	102	102	95	95
T	0.6667	0.6667	0.875	0.875
ρ	0.60	0.90	0.60	0.90
σ_e	0.70	0.90	0.70	0.90
δ	0.1303	0.1303	0.1923	0.1923
h	0.25	0.25	0.12	0.12
M	0.30	0.30	Variable	Variable
U(F_{MSY})				
2.5%–97.5%	0.32–0.45	0.32–0.45	0.29–0.53	0.29–0.53
Mean, median	0.37, 0.34	0.37, 0.34	0.40, 0.40	0.40, 0.40
SD	0.04	0.04	0.08	0.08
ESB(F_{MSY})/ESB(0)				
2.5%–97.5%	0.56–0.59	0.53–0.55	0.53–0.59	0.52–0.54
Mean, median	0.58, 0.59	0.54, 0.54	0.55, 0.55	0.53, 0.53
SD	0.01	0.003	0.02	0.01
SSB(F_{MSY})/SSB(0)				
2.5%–97.5%	0.53 – 0.56	0.52 – 0.53	0.55 – 0.58	0.53 – 0.54
Mean, median	0.55, 0.56	0.53, 0.53	0.56, 0.56	0.53, 0.53
SD	0.01	0.003	0.01	0.004

Note: The recruits were generated from the Beverton–Holt S–R model with combined sexes as spawners and an initial male:female ratio of 1:2. The reference points were determined by maximizing the average yield at each *F* level and mean and median reference point values were estimated for 500 S–R curves. The BYM was set at 0.01 and terminal molt of mature components of both sexes was assumed for both stocks. Other parameters are defined in the notation section.

Fig. 2. Distributions of harvest rate under 100-generation fishing for 500 randomly selected S–R shape parameter values under a stochastic Beverton–Holt S–R model. Histograms for (*a*) σ_e = 0.7 and ρ = 0.6 and (*b*) σ_e = ρ = 0.9 for the Bering Sea snow crab stock; histograms for (*c*) σ_e = 0.7 and ρ = 0.6 and (*d*) σ_e = ρ = 0.9 for the eastern Canada snow crab stock.

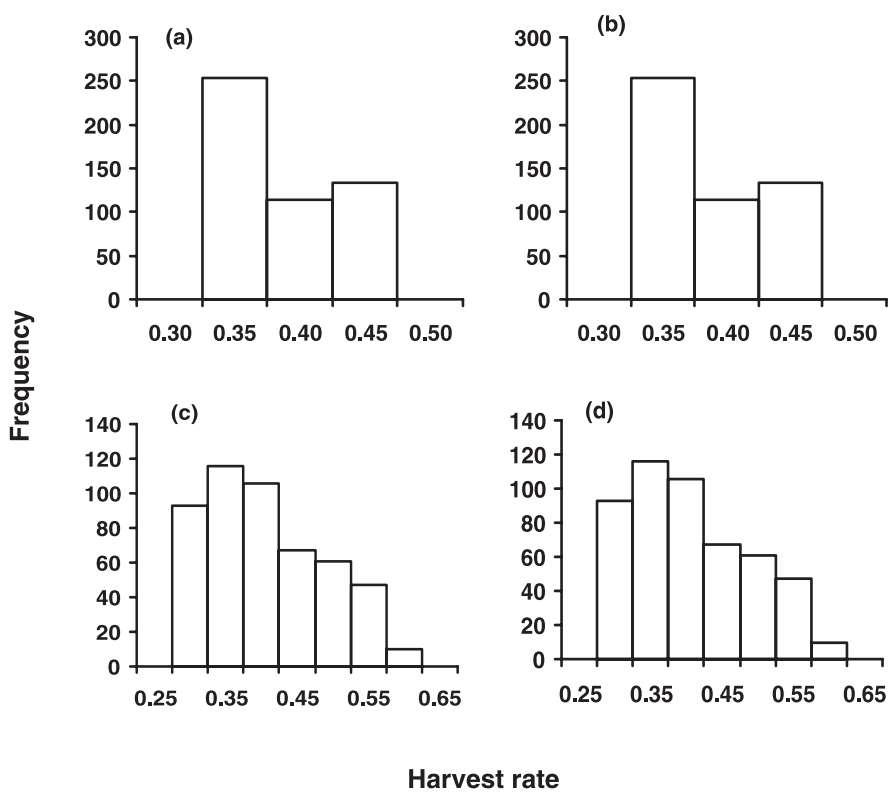

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Table 5. Comparison of reference point estimates (mean, median) for Southeast Alaska Dungeness crab for various scenarios for 500 randomly selected S–R shape parameter (τ) values within 0.20–0.50, a fixed BYM of 0.01, an *M* of 0.47 for both sexes, an initial male:female ratio of 1:1, and recruits deterministically generated from the Beverton–Holt S–R model.

Spawners	Total	Total	Total	**Female**	Total	Total	Total	Total
L_c (mm CW)	**155**	165	**175**	165	165	165	165	165
T	0.4583	0.4583	0.4583	0.4583	**0.0000**	0.4583	0.4583	0.4583
δ	0.3333	0.3333	0.3333	0.3333	0.3333	0.3333	**0.6666**	**0.1667**
h	0.15	0.15	0.15	0.15	0.15	**0.00**	0.15	0.15
$U(F_{MSY})$	0.79, 0.79	0.79, 0.79	0.93, 0.96	0.96, 0.96	0.79, 0.79	0.93, 0.93	0.64, 0.63	0.81, 0.80	0.79, 0.79
	(0.07)	(0.09)	(0.06)	(0.0004)	(0.09)	(0.002)	(0.06)	(0.11)	(0.08)
$ESB(F_{MSY})/ESB(0)$	1.00, 1.00	1.00, 1.00	1.00, 1.00	1.00, 1.00	1.00, 1.00	0.79, 0.79	1.00, 1.00	0.98, 1.00	1.00, 1.00
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.03)	(0.0001)	(0.03)	(0.0001)
$SSB(F_{MSY})/SSB(0)$	1.00, 1.00	1.00, 1.00	1.00, 1.00	1.00, 1.00	1.00, 1.00	0.41, 0.41	1.00, 1.00	1.00, 1.00	1.00, 1.00
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.01)	(0.0001)	(0.0001)	(0.0001)

Note: Total is combined sexes, and other parameters are defined in the notation section. Values and text in bold refer to changes in input values, and values in parentheses are standard deviations.

0.94, while the mean and median total mature biomass ratios decreased to 0.51 and 0.52, respectively. The RPs behaved similarly to those of the Southeast Alaska stock for similar changes in δ, *T*, and *h* (Table 6).

Comparison of RPs between Southeast Alaska and Western Canada stocks

The mean and median harvest rates under deterministic Beverton–Holt S–R relationship with combined sexes as spawners and status quo input parameter values were slightly higher for the western Canada stock (0.85 and 0.82, respectively) than those for the Southeast Alaska stock (0.79). The mean and median effective and total spawning biomass ratios were above 0.90 for both stocks (Tables 5 and 6). The central values of harvest rate under the deterministic Ricker S–R model behaved oppositely with Southeast Alaska stock estimates slightly higher than those for the western Canada stock (0.95–0.96 versus 0.93–0.94, respectively) (Table 7).

We restricted the 100-generation fishery simulations with the stochastic recruitment to the Beverton–Holt model for brevity. The trends were the same for the Ricker model, but the harvest rates were higher. For the Southeast Alaska stock, the 2.5–97.5 percentile interval of harvest rate was 0.66–0.92 with a mean of 0.79 (±0.09) and a median of 0.79 for both low (0.7) and high (0.9) σ_e values, combined sexes spawners, and status quo other parameter values. The corresponding values for the western Canada stock were 0.82–0.90 with a mean of 0.85 (±0.03) and a median of 0.82 (Table 8). Thus, the amount of recruitment variability did not appreciably affect the harvest rate for this species either. The big difference in *M* between the two stocks did not have a dramatic effect on the harvest rate estimates, owing perhaps to different growth patterns dampening the effect of *M* on RP estimates for these stocks. The distribution of harvest rate was flat for the Southeast Alaska stock, while it was skewed to the right for the western Canada stock (Fig. 3). The reason for the truncated figures was previously explained. The flat distribution for the Southeast Alaska stock indicated that any harvest rate within that range was equally likely and the harvest rate estimate was strongly influenced by the τ value. This distribution pattern was unique to the Southeast Alaska stock. Other input parameters being similar, one possible reason for this pattern was different growth parameter values for this stock; the male growth increment was independent of the size, and the molt probability parameters were also quite different from those of the other stocks (see Appendix B).

Discussion

The threshold harvest rate was inversely related to the S–R shape parameter (τ) of the S–R curves. Since S–R relationships were lacking for the two crab species, τ values within a plausible range of 0.20–0.50 were used to explore the patterns and trends in RPs. The present τ range was wider on the lower side of τ values than that set for the Bristol Bay red king crab (Siddeek 2003*a*) to accommodate highly productive Dungeness crab. The Bristol Bay red king crab τ estimate of 0.24 (Siddeek 2003*c*) from an established S–R relationship (Zheng et al. 1995) justified this extension. Temporal and density variations in growth and maturity

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Table 6. Comparison of reference point estimates (mean, median) for western Canada Dungeness crab for various scenarios for 500 randomly selected S–R shape parameter (τ) values within 0.20–0.50, a fixed BYM of 0.01, a prerecruit-1 and class-1 M of 0.91, a recruit, postrecruit, and class-2 M of 0.75, an initial male:female ratio of 1:1, and recruits deterministically generated from the Beverton–Holt S–R model.

Spawners	Total	Total	Total	**Female**	Total	Total	Total	Total	Total
L_c (mm CW)	**145**	155	**165**	155	155	155	155	155	155
T	0.1667	0.1667	0.1667	0.1667	**0.0000**	0.1667	0.1667	0.1667	0.1667
δ	0.4167	0.4167	0.4167	0.4167	0.4167	0.4167	0.4167	**0.8334**	**0.2083**
h	0.15	0.15	0.15	0.15	0.15	**0.00**	**0.30**	0.15	0.15
$U(F_{MSY})$	0.85, 0.83	0.85, 0.82	0.88, 0.87	0.88, 0.87	0.84, 0.82	0.94, 0.94	0.75, 0.75	0.84, 0.88 (0.05)	0.87, 0.87 (0.01)
	(0.02)	(0.03)	(0.04)	(0.04)	(0.03)	(0.01)	(0.01)		
$ESB(F_{MSY})/ESB(0)$	1.00, 1.00	1.00, 1.00	1.00, 1.00	1.00, 1.00	1.00, 1.00	0.81, 0.81	1.00, 1.00	1.00, 1.00 (0.0001)	1.00, 1.00 (0.0001)
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.03)	(0.0001)		
$SSB(F_{MSY})/SSB(0)$	0.93, 0.92	0.92, 0.91	0.97, 0.98	0.99, 1.00	0.92, 0.91	0.51, 0.52	0.91, 0.90	0.98, 1.00 (0.03)	0.88, 0.88 (0.03)
	(0.03)	(0.04)	(0.03)	(0.02)	(0.04)	(0.02)	(0.04)		

Note: Total is combined sexes, and other parameters are defined in the notation section. Values and text in bold refer to changes in input parameter values, and values in parentheses are standard deviations.

Table 7. Comparison of reference point estimates (mean, median) for Southeast Alaska and western Canada Dungeness crab for 500 randomly selected S–R shape parameter (τ) values within 0.20–0.50, a BYM of 0.01, an h of 0.15, and an initial male:female ratio of 1:1.

Stock	Southeast Alaska	Western Canada
Spawners	Total	Total
L_c (mm CW)	165	155
T	0.4583	0.1667
M	0.47	0.91, 0.75
$U(F_{MSY})$	0.95, 0.96 (0.02)	0.93, 0.94 (0.002)
$ESB(F_{MSY})/ESB(0)$	0.97, 0.96 (0.02)	1.00, 1.00 (0.0001)
$SSB(F_{MSY})/SSB(0)$	1.00, 1.00 (0.0001)	1.00, 1.00 (0.0001)

Note: The recruits were simulated deterministically by the Ricker S–R model. Total is combined sexes, and other parameters are defined in the notation section. Values in parentheses are standard deviations.

probability were ignored for simplicity in modeling. The simulations considered various random slope parameter values within this range and included both deterministic as well as stochastic recruitment to obtain central RP values. This assumes that there are many trajectories underlying a given S–R curve, perhaps owing to a given set of data covering different environmental regimes, and a central (mean and median) RP value within those trajectories was chosen as being representative. However, uncertainty in input parameter values compelled us to take a precautionary approach and suggest low harvest rate values from a harvest rate distribution. Since the distributions of harvest rate were mostly skewed, or flat in one case, median estimates were given with means. Random variation in recruitment was introduced into the model using overall low and high recruitment noises of 0.7 and 0.9 and, in the case of snow crab, an additional low and high autocorrelation parameter of 0.6 and 0.9. Similar low values of recruitment errors have been observed in some crab S–R model fittings (e.g., Bristol Bay red king crab; Zheng et al. 1995). The increase in S–R noise, however, did not affect the harvest rate estimates but changed the biomass ratio values.

The lower limits of size groups considered for RP determination were roughly 50% maturity size of males and females or above the 50% maturity size and approximately one molt increment below the legal size. We used these lower cutoff points with the expectation of using a constant M value among mature crabs in the simulations. However, a variable set of M values was used for the eastern Canada snow crab and western Canada Dungeness crab stocks because estimates of M were available for these stocks. By excluding mature males and females that are smaller than the lower size limit of prerecruit-1 or class-1 size groups, respectively, we have disregarded a portion of mature biomass in the S–R relationship. We assumed this to be minor in comparison with considering variable unknown M values at lower size groups. We also ignored the spatial distribution of different components of stocks in the model for simplicity. For example, only a portion of the total male breeding population may be available to mate either primiparous or multiparous snow crab females owing to depth segregation by age or size (Lovrich et al. 1995).

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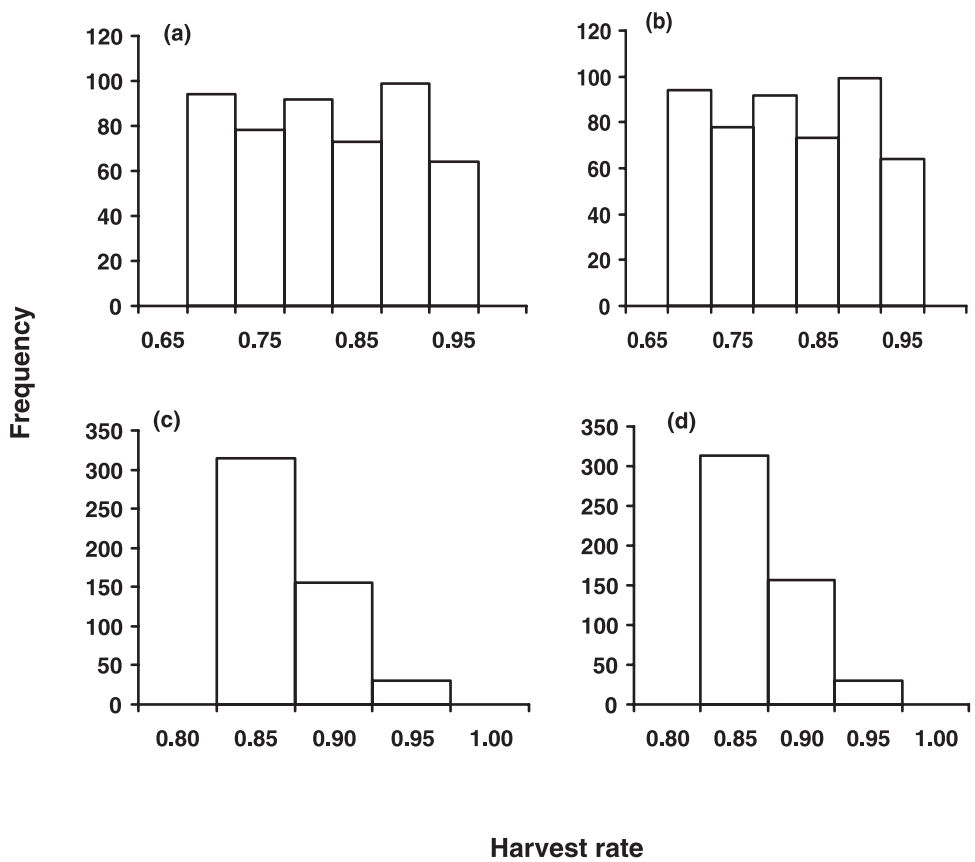
Table 8. Comparison of 2.5–97.5 percentiles, mean, median, and standard deviation of reference point estimates for Southeast Alaska and western Canada Dungeness crab for 500 randomly selected S–R shape parameter (τ) values within 0.20–0.50 and 100 perturbed recruits for 100-generation fishing at each F level.

Stock	Southeast Alaska	Southeast Alaska	Western Canada	Western Canada
L_c (mm CW)	165	165	155	155
T	0.4583	0.4583	0.1667	0.1667
σ_e	0.70	0.90	0.70	0.90
M	0.47	0.47	0.91, 0.75	0.91, 0.75
U(F_{MSY})				
2.5%–97.5%	0.66–0.92	0.66–0.92	0.82–0.90	0.82–0.90
Mean, median	0.79, 0.79	0.79, 0.79	0.85, 0.82	0.85, 0.82
SD	0.09	0.09	0.03	0.03
ESB(F_{MSY})/ESB(0)				
2.5%–97.5%	0.75–0.83	0.71–0.79	0.80–0.85	0.76–0.81
Mean, median	0.79, 0.79	0.75, 0.75	0.83, 0.84	0.79, 0.79
SD	0.03	0.03	0.02	0.01
SSB(F_{MSY})/SSB(0)				
2.5%–97.5%	0.82–1.00	0.78–1.00	0.71–0.78	0.68–0.74
Mean, median	0.93, 0.95	0.91, 0.92	0.73, 0.72	0.70, 0.69
SD	0.06	0.08	0.02	0.02

Note: The recruits were generated from the Beverton–Holt S–R model with combined sexes as spawners and an initial male:female ratio of 1:1. The reference points were determined by maximizing the average yield at each F level and mean and median reference point values were estimated for 500 S–R curves. A BYM of 0.01 and an h of 0.15 were used. Other parameters are defined in the notation section.

Fig. 3. Distributions of harvest rate under 100-generation fishing for 500 randomly selected S–R shape parameter values under a stochastic Beverton–Holt S–R model. Histograms for (*a*) σ_e = 0.7 and (*b*) σ_e = 0.9 for the Southeast Alaska Dungeness crab stock; histograms for (*c*) σ_e = 0.7 and (*d*) σ_e = 0.9 for the western Canada Dungeness crab stock.



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Simulation results provided the following general conclusions:

First, when M was increased, $U(F_{MSY})$ increased for both species for the status quo input parameter values. For snow crab, the $U(F_{MSY})$ estimate for the eastern Canada stock was slightly higher than that for the Bering Sea stock. This was due to three reasons. (*i*) The M was lower for the Bering Sea stock than that for the eastern Canada stock. We used an M value of 0.3 for both sexes considering the longevity of snow crab (NPFMC 1999; Turnock 2003), even though Zheng (2003) estimated higher M values (0.46–0.97) for different size groups under terminal molt assumption. Zheng (2003) observed that higher M values did not improve the fit to survey abundance data over lower M values under nonterminal molt assumption. (*ii*) The handling mortality rate for the eastern Canada stock was nearly half of that for the Bering Sea stock. Our results showed that the harvest rate was inversely related to the handling mortality rate. (*iii*) The 2- to 4-year postmolt age groups were considered for yield estimation for the eastern Canada stock, whereas all groups were considered for the Bering Sea stock. When only 2- to 4-year postmolt groups were considered for the Bering Sea stock, the $U(F_{MSY})$ increased slightly.

Uncertainty in stock parameter values and a possibility of biennial spawning under certain environmental conditions dictate a precautionary approach to managing the two snow crab stocks. As a preliminary management measure, a harvest rate of 0.30 on legal males, which is closer to the 2.5 percentile values under stochastic Beverton–Holt recruitment as well as to the estimates under biennial spawning assumption, could be used as a threshold level for both stocks.

For Dungeness crab, the $U(F_{MSY})$ for the Southeast Alaska stock was lower (0.79) than that for the western Canada stock (0.85) at the current legal size exploitation because the M estimate for the Alaskan stock was lower (0.47) than that for the western Canadian stock. High M values for the western Canadian stock (0.91 and 0.75) are reasonable considering its shorter life expectancy (6 years) compared with that for the Southeast Alaska stock (10 years) and prevalence of molt-induced, short-term high mortality (Zhang et al. 2002). The comparison of modeling results for the Southeast Alaska and Fraser River Delta Dungeness crab stocks indicated that the model results were almost exclusively driven by the M and growth parameter values for the area. For example, when the model was run with a high M of 0.8 for the Southeast Alaska stock, the mean and median harvest rates reached 0.94 (±0.002). The M is known to vary considerably both temporally and spatially along the coast (Butler and Hankin 1992; Zhang et al. 2002). Therefore, using the results from this exercise for extrapolation to all the different regions of the coast should be treated with extreme caution. The mean and median harvest rates (0.85 and 0.82, respectively) from the model using Fraser River Delta information are higher than $F_{0.1}$ calculations for northern areas of British Columbia, which indicated harvest rates of 0.65–0.75 (Zhang et al. 2002). Even with uncertainty in various input parameters to the model, the Fraser River Delta crab fisheries would presently be described as being overfished. Although no reliable estimate of harvest rate is available for Dungeness crab in Southeast Alaska, recruit composition of the stock suggests that harvest rates in some years are over 0.85, which would be overexploited, as it exceeds the threshold estimate of 0.79. Similar to snow crab harvest rate recommendations, 2.5 percentile harvest rate values under stochastic Beverton–Holt recruitment, 0.66 for the Southeast Alaska stock and 0.82 for the western Canada stock, could be used as preliminary threshold RP values.

Second, when the initial ratio of prerecruit-1 males and class-1 females was changed, the RP estimates also changed. Therefore, a plausible initial male to female ratio value is needed for reliable estimation of RPs.

Third, the mean harvest rate for female-only spawners was higher than that for the combined sexes spawners. In the absence of established S–R relationships, the results from the combined sexes S–R model offer a precautionary lower $U(F_{MSY})$.

Fourth, the mean harvest rate for the Beverton–Holt S–R relationship was lower than that for the Ricker S–R model. This appeared to be a model-based result and was observed for the other king and Tanner crab (*Chionoecetes bairdi*) stocks in the Bering Sea as well (Siddeek 2002).

Fifth, for the snow crab, the mean and median nominal mature biomass ratios varied within the range 43–49% and 49–51% of the virgin biomass for varying parameter values (except the unlikely event of zero handling mortality) for the deterministic Beverton–Holt S–R relationship and 53–56% and 53–56% for the stochastic Beverton–Holt S–R model for the Bering Sea and the eastern Canada stocks, respectively. When good estimates of virgin biomass and current biomass are available, this percentage can be used to estimate $SSB(F_{MSY})$, minimum stock size threshold, and total allowable catch (Siddeek 2002). On the other hand, the stochastic S–R modeling suggested that in the absence of an F_{MSY} estimate, mainly because of lack of an S–R relationship and unavailability of biomass estimates, a suitable $F_{\%SSB(0)}$ value within the range of 53–56% could be used as a threshold level for management. For a start, a threshold fishing mortality equivalent to $F_{55\%SSB(0)}$ may be considered as a benchmark for management of less investigated snow crab stocks. A similar approach can be followed for the Dungeness crab stocks and the results suggest a threshold fishing mortality equivalent to $F_{70\%SSB(0)}$ for the western Canada stock and $F_{93\%SSB(0)}$ for the Southeast Alaska stock. However, one should be cautious when using $F_{\%SSB(0)}$ alone as a management tool because a poor estimate of M could influence its outcome (Clark 2002).

Under precautionary management, the target harvest rates should be set at lower levels to provide a buffer against overshooting $U(F_{MSY})$, perhaps at 75% of the $U(F_{MSY})$ when the stocks are near or above the MSY-producing levels, and reduced further by a proportion of current stock biomass over MSY-producing stock biomass when they are below MSY-producing levels (Restrepo and Powers 1999). The Bering Sea snow crab stock has been declared overfished and this procedure was followed in the rebuilding strategy. Based on an M value of 0.3, the harvest rate on mature male abundance of the stock at the time of the survey was set at 0.225 (= 0.75 × 0.3), and a stairstep function of harvest rate based on current $SSB(F)$ and $SSB(F_{MSY})$ with a 58% maximum harvest rate cap on marketable-size male abundance was prescribed to obtain the harvestable number of marketable-size crabs from mature male abundance for rebuilding this stock

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(Zheng et al. 2002). However, the harvest rates estimated in this paper are based on marketable-size crabs at the time of fishing and the estimated median value under the Beverton–Holt S–R model is 0.34. Seventy-five percent of this estimate is 0.26. If the harvest rate on mature males recommended in the rebuilding plan is followed, then the harvest rate that is effective on marketable-size males at the time of fishing, which takes place approximately 6 months after the survey, to obtain the GHL will be much higher than 0.26, which may lead to overfishing.

A 0.32 exploitation rate on legal males was set empirically for the southern Gulf of St. Lawrence snow crab stock for a few years in the past. Loch et al. (1995, p. 262) explained the genesis of this RP as being "70% of the lower confidence limit of the exploitable biomass estimate for 1990". This RP was increased to 0.38 in 1992 and then decreased, and for the 2002 fishing season, it was suddenly hiked to over 0.50 (Hébert et al. 2003), which may have led to overfishing. Indeed, the 75% level of the mean and median harvest rate (= 0.40) at the current legal size under the Beverton–Holt S–R model is 0.30, which is close to the initial empirically set value.

Long-term success of RPs will depend on whether or not fishing is a neutral force in phenotypic and genotypic selection. If there is selection against large size-at-maturity, then yield may gradually be lost and the optimal exploitation rate for the long term might be less than predicted by the model. Some evidence of long-term declining size trends in males in heavily fished populations exists for the blue crab *C. sapidus* (Abbe 2002). Environmental and ecosystem changes may also affect the threshold values but were not considered in this modeling exercise.

There are a number of criticisms for using model-based RPs as a management procedure (Hilborn 2002). Hilborn discussed the dark side of RPs stating that virgin biomasses as well as RPs were difficult to determine and advocated use of data-based management procedures (e.g., catch rate). Indeed, quota recommendations based on purely biomass-based policy will be sensitive to changes in virgin and current biomass estimates (Clark 2002). However, in this paper, we derived F_{MSY}-based mean and median harvest rates and spawning and mature biomass ratios feasible under a broad range of S–R relationships, which are independent of the actual biomass estimate but dependent on life history parameters, as possible management procedures, especially for data- and analysis-poor crab stocks. But precise estimates of RPs by this method depend on good estimates of natural mortality, mating ratio, specific S–R relationship, and initial sex ratio. In the application of this method to snow crab and Dungeness crab stocks, some of these parameters were borrowed from similar stocks, were simply educated guesses, or considered a range of values. Greater effort should be devoted to determine reliable estimates of these parameters. Finally, because of uncertainty in input parameters and models in any stock assessment, we recommend a combination of model- and data-based approaches to set harvest rate and allowable catch and monitor the success of management decisions on crab stocks. The data-based approach should not be restricted to catch rate alone but should also include other indices, especially those related to reproduction and strength of incoming recruitment.

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Notation used in the text, tables, and appendices

t_r relative age at recruitment in years

λ relative maximum age of a cohort in years

$R(F)$ total number of prerecruit-1 and class-1 progenies produced by effective spawning stock biomass corresponding to fishing mortality F, ESB(F)

R_{max} maximum R

$(ESB/R)_F$ and $(ESB/R)_{F=0}$ effective spawning stock biomass per recruit corresponding to a fishing mortality F and $F = 0$, respectively

$(ESB/R)_{ESB=0}$ effective spawning stock biomass per recruit determined as the reciprocal of the slope at the origin of the stock–recruitment (S–R) curve

h mortality rate resulting from handling of sublegal male and all female crabs

$HM1_{l'}$ instantaneous handling mortality of male at size l'

$HM2_{l'}$ instantaneous handling mortality of female at size l'

BYM constant annual instantaneous bycatch mortality in nondirected fisheries

$s_{l'}$ fishery selectivity probability at size l'

δ duration of average fishing period as a fraction of a year (handling and fishing mortality occur during this time period; hence, handling mortality and annual fishing mortality values are scaled to this period)

$U(F_{MSY})$ exploitation rate corresponding to F_{MSY}, equivalent to threshold harvest rate

τ a parameter estimated from a spawning biomass per recruit ratio that influences the steepness near the origin and overall shape of the S–R curve

$P_{l',l}$ probability of crabs in a size group l' growing into a size group l

$N(F)_{l',t}$ and $N(0)_{l',t}$ abundances in numbers in a size-class l' of a cohort of new-shell crabs corresponding to a fishing mortality F (for legal males) and $F = 0$ (for females or sublegal males), respectively, in year t

$O(F)_{l',t}$ and $O(0)_{l',t}$ abundances in numbers in a size-class l' of a cohort of old-shell crabs corresponding to a fishing mortality F (for legal males) and $F = 0$ (for females or sublegal males), respectively, in year t

$S(F)_{l',t} = N(F)_{l',t} + O(F)_{l',t}$,

$\overline{N}(F)_t$ and $\overline{N}(0)_t$) average abundances in numbers in a cohort corresponding to a fishing mortality F (for legal males) and $F = 0$ (for females or sublegal males), respectively, in year t

subscripts subscripts attached to abundance notations are as follows: ipre, immature prerecruit male; ipost, immature postrecruit male; mpre, mature prerecruit male; mpost, mature postrecruit male; icl1, immature class-1 female; icl2, immature class-2 female; mcl1, mature class-1 female; mcl2, mature class-2 female; p, number of prerecruit-1 size intervals; q, number of recruit and postrecruit size intervals; r, number of class-1 female size intervals; s, number of class-2 female size intervals

$mm_{l'}$ mature male molting probability in a size-class l' ($mf_{l'}$ for females)

$im_{l'}$ immature male molting probability in a size-class l' ($if_{l'}$ for females)

$a_{l'}$ immature male (or female) maturity probability in a size-class l'

MSSN(F) sum of average mature legal and sublegal male crab abundances in number over an average fishable life span (i.e., mature male stock abundance) corresponding to a fishing mortality F on legal males

FSSN(0) sum of average mature female crab abundances in number over an average fishable life span (i.e., mature female stock abundance) corresponding to a zero fishing mortality

CW carapace width

L_c minimum capture size

$\overline{B}(F)_t$ and $\overline{B}(0)_t$ average effective spawning biomasses (adjusted for male to female mating ratio) in a cohort corresponding to a fishing mortality F (for legal males) and $F = 0$ (for females or sublegal males), respectively, in year t

MSSB(F) sum of average effective spawning biomass of mature legal and sublegal male crabs over an average fishable life span (i.e., effective spawning stock biomass of males) corresponding to a fishing mortality F on legal males

FSSB(0) sum of average effective spawning biomass of mature female crabs over an average fishable life span (i.e., effective spawning stock biomass of females) corresponding to a zero (direct) fishing mortality on females

ESB(F), ESB(F_{MSY}), and ESB(0) effective spawning stock biomass corresponding to a fishing mortality F, F_{MSY}, and $F = 0$, respectively, on legal males

SSB(F), SSB(F_{MSY}), and SSB(0) nominal (unadjusted for male to female mating ratio) total mature stock biomass corresponding to a fishing mortality F, F_{MSY}, and $F = 0$, respectively, on legal males

T time elapsed between the midmolting period (i.e., start of a biological year) and start date of a fishing period as a fraction of a year

$c(F)_t$ sum of catches in all size groups of legal males in a cohort in number corresponding to a fishing mortality F in year t

$y(F)_t$ sum of catches in all size groups of legal males in a cohort in weight corresponding to a fishing mortality F in year t

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$C(F)$	sum of $c(F)_t$ through the fishable life span (i.e., stock catch in number) from t_r to λ
$Y(F)$	sum of $y(F)_t$ through the fishable life span (i.e., stock catch in weight) from t_r to λ
α, β, γ, and θ	parameters in the S–R models
ρ	recruitment autocorrelation parameter
σ_e	standard deviation of recruitment noise in the S–R models
j, l', and t	summation indices
e	base of natural logarithms

Appendix A. Calculation steps to determine effective spawning stock biomass per recruit of female $(ESB_{female}/R)_F$ and combined sexes $(ESB_{combined\ sexes}/R)_F$.

The following assumptions were made to simplify the derivation: (*i*) growth is constant for each time step; (*ii*) mortality takes place immediately after growth; (*iii*) maturity probability is constant for each time step; (*iv*) instantaneous bycatch mortality, BYM, is constant and independent of size, sex, and shell condition; (*v*) instantaneous natural mortality, *M*, is independent of shell condition; (*vi*) instantaneous fishing mortality, *F*, and handling mortality, HM, are size dependent; (*vii*) Recruits generated from S–R models have a constant sex ratio.

Male cohort dynamics

Male prerecruit-1 group consists of p size classes and recruits and postrecruits consist of q size classes. The following models are applicable to the size intervals.

Prerecruit-1 (l = 1 to p)

When $t + 1 = 0$,

$$\text{(A1)}\quad \text{Prerecruit} - 1 = S_{\text{ipre}}(0)_l + S_{\text{mpre}}(0)_l$$

where S is the sum of new- and old-shell crab abundances. When $t + 1 \geq 1$,

$$\text{(A2)}\quad N_{\text{mpre}}(0)_{l,t+1} = \sum_{l'=1}^{l}[S_{\text{mpre}}(0)_{l',t}\text{mm}_{l'}P_{l',l} + S_{\text{ipre}}(0)_{l',t}\text{im}_{l'}a_{l'}P_{l',l}]\text{e}^{-(M+\text{HM1}_{l'}\delta+\text{BYM})}$$

$$\text{(A3)}\quad O_{\text{mpre}}(0)_{l,t+1} = [S_{\text{mpre}}(0)_{l,t}(1-\text{mm}_l)]\text{e}^{-(M+\text{HM1}_l\delta+\text{BYM})}$$

$$\text{(A4)}\quad N_{\text{ipre}}(0)_{l,t+1} = \sum_{l'=1}^{l}[S_{\text{ipre}}(0)_{l',t}\text{im}_{l'}(1-a_{l'})P_{l',l}]\text{e}^{-(M+\text{HM1}_{l'}\delta+\text{BYM})}$$

$$\text{(A5)}\quad O_{\text{ipre}}(0)_{l,t+1} = [S_{\text{ipre}}(0)_{l,t}(1-\text{im}_l)]\text{e}^{-(M+\text{HM1}_l\delta+\text{BYM})}$$

Recruits and postrecruits ($l = p + 1$ to $p + q$)

When $t + 1 = 0$,

$$\text{(A6)}\quad N_{\text{ipost}}(0)_l = N_{\text{mpost}}(0)_l = 0$$

When $t + 1 = 1$,

$$\text{(A7)}\quad N_{\text{mpost}}(0)_{l,t+1} = \sum_{l'=1}^{p}[N_{\text{mpre}}(0)_{l',t}\text{mm}_{l'}P_{l',l} + N_{\text{ipre}}(0)_{l',t}\text{im}_{l'}a_{l'}P_{l',l}]\text{e}^{-(M+\text{HM1}_{l'}\delta+\text{BYM})}$$

$$\text{(A8)}\quad N_{\text{ipost}}(0)_{l,t+1} = \sum_{l'=1}^{p}[N_{\text{ipre}}(0)_{l',t}\text{im}_{l'}(1-a_{l'})P_{l',l}]\text{e}^{-(M+\text{HM1}_{l'}\delta+\text{BYM})}$$

When $t + 1 \geq 2$,

$$\text{(A9)}\quad N_{\text{mpost}}(F)_{l,t+1} = \sum_{l'=1}^{p}[S_{\text{mpre}}(0)_{l',t}\text{mm}_{l'}P_{l',l} + S_{\text{ipre}}(0)_{l',t}\text{im}_l, a_{l'}P_{l',l}]\text{e}^{-(M+\text{HM1}_{l'}\delta+\text{BYM})}$$
$$+ \sum_{l'=p+1}^{l}[S_{\text{mpost}}(F)_{l',t}\text{mm}_{l'}P_{l',l} + S_{\text{ipost}}(F)_{l',t}\text{im}_l, a_{l'}P_{l',l}]\text{e}^{-(Fs_{l'}\delta+M+\text{BYM})}$$

$$\text{(A10)}\quad O_{\text{mpost}}(F)_{l,t+1} = [S_{\text{mpost}}(F)_{l,t}(1-\text{mm}_l)]\text{e}^{-(Fs_l\delta+M+\text{BYM})}$$

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$$\text{(A11)}\quad N_{\text{ipost}}(F)_{l,t+1} = \sum_{l'=1}^{p}[S_{\text{ipre}}(0)_{l',t}\text{im}_{l'}(1-a_{l'})P_{l',l}]\text{e}^{-(M+\text{HM1}_{l'}\delta+\text{BYM})} + \sum_{l'=p+1}^{l}[S_{\text{ipost}}(F)_{l',t}\text{im}_{l'}(1-a_{l'})P_{l',l}]\text{e}^{-(Fs_{l'}\delta+M+\text{BYM})}$$

$$\text{(A12)}\quad O_{\text{ipost}}(F)_{l,t+1} = [S_{\text{ipost}}(F)_{l,t}(1-\text{im}_l)]\text{e}^{-(Fs_l\delta+M+\text{BYM})}$$

Female cohort dynamics

The same set of formulas is used for female cohort abundance estimation by setting F to 0 and using female molt probability, growth increment, and maturity probability models and female instantaneous handling mortality. Note: terminal molt at maturity on male and female snow crabs can be evoked by setting the molt probability (male molt probability mm_l or female molt probability mf_l) to 0.

Legal male harvest

When $t + 1 = 0$, catch = 0. When $t + 1 \geq 1$, mature crab catch in number of crabs is

$$\text{(A13)}\quad c_{\text{mpost}}(F)_t = \sum_{j=p+1}^{p+q}\frac{Fs_j}{(Fs_j+M+\text{BYM})}N_{\text{mpost}}(F)_{j,t}\,\text{e}^{-MT}(1-\text{e}^{-(Fs_j+M+\text{BYM})\delta}) + \sum_{j=p+1}^{p+q}\frac{Fs_j}{(Fs_j+M+\text{BYM})}O_{\text{mpost}}(F)_{j,t}\text{e}^{-MT}(1-\text{e}^{-(Fs_j+M+\text{BYM})\delta})$$

and the corresponding catch in weight is

$$y_{\text{mpost}}(F)_t = \sum_{j=p+1}^{p+q}\frac{Fs_j}{(Fs_j+M+\text{BYM})}N_{\text{mpost}}(F)_{j,t}W_j\,\text{e}^{-MT}(1-\text{e}^{-(Fs_j+M+\text{BYM})\delta}) + \sum_{j=p+1}^{p+q}\frac{Fs_j}{(Fs_j+M+\text{BYM})}O_{\text{mpost}}(F)_{j,t}W_j\,\text{e}^{-MT}(1-\text{e}^{-(Fs_j+M+\text{BYM})\delta})$$

Immature crab catch in number of crabs is

$$\text{(A14)}\quad c_{\text{ipost}}(F)_t = \sum_{j=p+1}^{p+q}\frac{Fs_j}{(Fs_j+M+\text{BYM})}N_{\text{ipost}}(F)_{j,t}\text{e}^{-MT}(1-\text{e}^{-(Fs_j+M+\text{BYM})\delta}) + \sum_{j=p+1}^{p+q}\frac{Fs_j}{(Fs_j+M+\text{BYM})}O_{\text{ipost}}(F)_{j,t}\,\text{e}^{-MT}(1-\text{e}^{-(Fs_j+M+\text{BYM})\delta})$$

and the corresponding catch in weight is

$$y_{\text{ipost}}(F)_t = \sum_{j=p+1}^{p+q}\frac{Fs_j}{(Fs_j+M+\text{BYM})}N_{\text{ipost}}(F)_{j,t}W_j\,\text{e}^{-MT}(1-\text{e}^{-(Fs_j+M+\text{BYM})\delta}) + \sum_{j=p+1}^{p+q}\frac{Fs_j}{(Fs_j+M+\text{BYM})}O_{\text{ipost}}(F)_{j,t}W_j\,\text{e}^{-MT}(1-\text{e}^{-(Fs_j+M+\text{BYM})\delta})$$

Then, the total legal male catch ($C(F)$ in number and $Y(F)$ in weight) for an average fishery life span (λ) of the cohort (i.e., the stock catch) is

$$\text{(A15)}\quad C(F) = \sum_{t=t_r}^{\lambda}(c_{\text{mpost}}(F)_t + c_{\text{ipost}}(F)_t)$$

$$\text{(A16)}\quad Y(F) = \sum_{t=t_r}^{\lambda}(y_{\text{mpost}}(F)_t + y_{\text{ipost}}(F)_t)$$

MSY-level fishing mortality and harvest rate of legal males

$Y(F)$ is maximized to obtain F_{MSY} by systematically varying the F value from 0 to 5 by a step of 0.1 for a given set of fixed M (universal constant or constant specific for sex, stage, or postmolt age), h, BYM, T, and δ values. The corresponding reference point harvest rate is estimated as follows:

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$$\text{(A17)}\quad U(F_{\mathrm{MSY}}) = \frac{C(F_{\mathrm{MSY}})}{\sum_{t=t_r}^{\lambda}\sum_{j=p+1}^{p+q}[(N_{\mathrm{mpost}}(F)_{j,t} + N_{\mathrm{ipost}}(F)_{j,t})\,\mathrm{e}^{-MT} + (O_{\mathrm{mpost}}(F)_{j,t} + O_{\mathrm{ipost}}(F)_{j,t})\,\mathrm{e}^{-MT}]}$$

Average male spawner numbers

When $t + 1 \geq 0$,

$$\text{(A18)}\quad \overline{N}_{\mathrm{mpre}}(0)_{t+1} = \sum_{l'=1}^{p} N_{\mathrm{mpre}}(0)_{l',t+1}(1 - \mathrm{e}^{-(M+\mathrm{HM1}_{l'}\delta+\mathrm{BYM})})/(M + \mathrm{HM1}_{l'}\,\delta + \mathrm{BYM})$$

$$\text{(A19)}\quad \overline{O}_{\mathrm{mpre}}(0)_{t+1} = \sum_{l'=1}^{p} O_{\mathrm{mpre}}(0)_{l',t+1}(1 - \mathrm{e}^{-(M+\mathrm{HM1}_{l'}\delta+\mathrm{BYM})})/(M + \mathrm{HM1}_{l'}\,\delta + \mathrm{BYM})$$

When $t + 1 \geq 1$,

$$\text{(A20)}\quad \overline{N}_{\mathrm{mpost}}(F)_{t+1} = \sum_{l'=1}^{p} N_{\mathrm{mpre}}(0)_{l',t+1}(1 - \mathrm{e}^{-(M+\mathrm{HM1}_{l'}\delta+\mathrm{BYM})})/(M + \mathrm{HM1}_{l'}\,\delta + \mathrm{BYM}) + \sum_{l'=p+1}^{p+q} N_{\mathrm{mpost}}(F)_{l',t+1}(1 - \mathrm{e}^{-(M+\mathrm{Fs}_{l'}\delta+\mathrm{BYM})})/(M + Fs_{l'}\,\delta + \mathrm{BYM})$$

$$\text{(A21)}\quad \overline{O}_{\mathrm{mpost}}(F)_{t+1} = \sum_{l'=1}^{p} O_{\mathrm{mpre}}(0)_{l',t+1}(1 - \mathrm{e}^{-(M+\mathrm{HM1}_{l'}\delta+\mathrm{BYM})})/(M + \mathrm{HM1}_{l'}\,\delta + \mathrm{BYM}) + \sum_{l'=p+1}^{p+q} O_{\mathrm{mpost}}(F)_{l',t+1}(1 - \mathrm{e}^{-(M+\mathrm{Fs}_{l'}\delta+\mathrm{BYM})})/(M + Fs_{l'}\,\delta + \mathrm{BYM})$$

The sum of average mature abundances in number over the reproductive ages of male is estimated by

$$\text{(A22)}\quad \mathrm{MSSN}(F) = \sum_{t=t_r-1}^{\lambda}(\overline{N}_{\mathrm{mpre}}(0)_t + \overline{O}_{\mathrm{mpre}}(0)_t) + \sum_{t=t_r}^{\lambda}(\overline{N}_{\mathrm{mpost}}(F)_t + \overline{O}_{\mathrm{mpost}}(F)_t)$$

No F occurs in the female average mature abundance equations; instead, $\mathrm{HM2}_{l'}$ occurs. The relevant equations are as follows. When $t + 1 \geq 0$,

$$\text{(A23)}\quad \overline{N}_{\mathrm{mcl1}}(0)_{t+1} = \sum_{l'=1}^{r} N_{\mathrm{mcl1}}(0)_{l',t+1}(1 - \mathrm{e}^{-(M+\mathrm{HM2}_{l'}\delta+\mathrm{BYM})})/(M + \mathrm{HM2}_{l'}\,\delta + \mathrm{BYM})$$

$$\text{(A24)}\quad \overline{O}_{\mathrm{mcl1}}(0)_{t+1} = \sum_{l'=1}^{r} O_{\mathrm{mcl1}}(0)_{l',t+1}(1 - \mathrm{e}^{-(M+\mathrm{HM2}_{l'}\delta+\mathrm{BYM})})/(M + \mathrm{HM2}_{l'}\,\delta + \mathrm{BYM})$$

When $t + 1 \geq 1$,

$$\text{(A25)}\quad \overline{N}_{\mathrm{mcl2}}(0)_{t+1} = \sum_{l'=1}^{r} N_{\mathrm{mcl1}}(0)_{l',t+1}(1 - \mathrm{e}^{-(M+\mathrm{HM2}_{l'}\delta+\mathrm{BYM})})/(M + \mathrm{HM2}_{l'}\,\delta + \mathrm{BYM}) + \sum_{l'=r+1}^{r+s} N_{\mathrm{mcl2}}(0)_{l',t+1}(1 - \mathrm{e}^{-(M+\mathrm{HM2}_{l'}\delta+\mathrm{BYM})})/(M + \mathrm{HM2}_{l'}\,\delta + \mathrm{BYM})$$

$$\text{(A26)}\quad \overline{O}_{\mathrm{mcl2}}(0)_{t+1} = \sum_{l'=1}^{r} O_{\mathrm{mcl1}}(0)_{l',t+1}(1 - \mathrm{e}^{-(M+\mathrm{HM2}_{l'}\delta+\mathrm{BYM})}) \,/\, (M + \mathrm{HM2}_{l'}\delta + \mathrm{BYM}) + \sum_{l'=r+1}^{r+s} O_{\mathrm{mcl2}}(0)_{l',t+1}(1 - \mathrm{e}^{-(M+\mathrm{HM2}_{l'}\delta+\mathrm{BYM})}) \,/\, (M + \mathrm{HM2}_{l'}\delta + \mathrm{BYM})$$

The sum of average mature abundances in number over the reproductive ages of female is estimated by

$$\text{(A27)}\quad \mathrm{FSSN}(0) = \sum_{t=t_r-1}^{\lambda}(\overline{N}_{\mathrm{mcl1}}(0)_t + \overline{O}_{\mathrm{mcl1}}(0)_t) + \sum_{t=t_r}^{\lambda}(\overline{N}_{\mathrm{mcl2}}(0)_t + \overline{O}_{\mathrm{mcl2}}(0)_t)$$

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Effective spawning biomass

The mating ratio (the number of females that a male can mate during a spawning period) is applied to adjust the average spawning stock abundances to determine effective female (FSSB(F)), male (MSSB(F)), and total (ESB(F)) spawning stock biomass corresponding to a fishing mortality F. For example, if one male mates with three females during the breeding period, the effective spawning abundance for each sex is estimated as follows: (*i*) if FSSN(0) ≤ MSSN(F), then male effective spawning abundance is set at FSSN(0)/3 and the corresponding female value is set at FSSN(0), (*ii*) if FSSN(0) > MSSN(F) but 3 × MSSN(F) ≥ FSSN(0), then male effective spawning abundance is set at FSSN(0)/3 and the corresponding female estimate is set at FSSN(0), and (*iii*) if FSSN(0) > MSSN(F) but 3 × MSSN(F) < FSSN(0), then male effective spawning abundance is set at MSSN(F) and the corresponding female value is set at 3 × MSSN(F).

Male effective spawning biomass

The effective spawning biomass for males, MSSB(F), is estimated by the following formulas. When $t + 1 \geq 0$,

$$\text{(A28)}\quad \overline{B}_{\text{mpre}}(0)_{t+1} = \left[\sum_{l'=1}^{p} N_{\text{mpre}}(0)_{l',t+1} W_{l'}(1 - \mathrm{e}^{-(M+\text{HM1}_{l'}\delta+\text{BYM})})/(M + \text{HM1}_{l'}\,\delta + \text{BYM}) + \sum_{l'=1}^{p} O_{\text{mpre}}(0)_{l',t+1} W_{l'}(1 - \mathrm{e}^{-(M+\text{HM1}_{l'}\delta+\text{BYM})})/(M + \text{HM1}_{l'}\,\delta + \text{BYM})\right] \frac{\text{effective MSSN}(F)}{\text{MSSF}(F)}$$

When $t + 1 \geq 1$,

$$\text{(A29)}\quad \overline{B}_{\text{mpost}}(F)_{t+1} = \left[\sum_{l'=1}^{p} N_{\text{mpre}}(0)_{l',t+1} W_{l'}(1 - \mathrm{e}^{-(M+\text{HM1}_{l'}\delta+\text{BYM})})/(M + \text{HM1}_{l'}\,\delta + \text{BYM}) + \sum_{l'=p+1}^{p+q} N_{\text{mpost}}(F)_{l',t+1} W_{l'}(1 - \mathrm{e}^{-(M+\text{Fs}_{l'}\delta+\text{BYM})})/(M + Fs_{l'}\,\delta + \text{BYM}) + \sum_{l'=1}^{p} O_{\text{mpre}}(0)_{l',t+1} W_{l'}(1 - \mathrm{e}^{-(M+\text{HM1}_{l'}\delta+\text{BYM})})/(M + \text{HM1}_{l'}\,\delta + \text{BYM}) + \sum_{l'=p+1}^{p+q} O_{\text{mpost}}(F)_{l',t+1} W_{l'}(1 - \mathrm{e}^{-(M+\text{Fs}_{l'}\delta+\text{BYM})})/(M + Fs_{l'}\,\delta + \text{BYM}\right] \frac{\text{effective MSSN}(F)}{\text{MSSN}(F)}$$

Therefore,

$$\text{(A30)}\quad \text{MSSB}(F) = \sum_{t=t_r-1}^{\lambda} \overline{B}_{\text{mpre}}(0)_t + \sum_{t=t_r}^{\lambda} \overline{B}_{\text{mpost}}(F)_t$$

Female effective spawning biomass

Corresponding equations for female effective spawning biomass, FSSB(0), are as follows. When $t + 1 \geq 0$,

$$\text{(A31)}\quad \overline{B}_{\text{mcl1}}(0)_{t+1} = \left[\sum_{l'=1}^{r} N_{\text{mcl1}}(0)_{l',t+1} W_{l'}(1 - \mathrm{e}^{-(M+\text{HM2}_{l'}\delta+\text{BYM})})/(M + \text{HM2}_{l'}\,\delta + \text{BYM}) + \sum_{l'=1}^{r} O_{\text{mcl1}}(0)_{l',t+1} W_{l'}(1 - \mathrm{e}^{-(M+\text{HM2}_{l'}\delta+\text{BYM})})/(M + \text{HM2}_{l'}\,\delta + \text{BYM})\right] \frac{\text{effective FSSN(0)}}{\text{FSSN(0)}}$$

When $t + 1 \geq 1$,

$$\text{(A32)}\quad \overline{B}_{\text{mcl2}}(0)_{t+1} = \left[\sum_{l'=1}^{r} N_{\text{mcl1}}(0)_{\text{mcl1}\,l',t+1} W_{l'}(1 - \mathrm{e}^{-(M+\text{HM2}_{l'}\delta+\text{BYM})})/(M + \text{HM2}_{l'}\,\delta + \text{BYM}) + \sum_{l'=1}^{r} O_{\text{mcl1}}(0)_{l',t+1} W_{l'}(1 - \mathrm{e}^{-(M+\text{HM2}_{l'}\delta+\text{BYM})})/(M + \text{HM2}_{l'}\,\delta + \text{BYM})\right] \frac{\text{effective FSSN(0)}}{\text{FSSN(0)}}$$

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$$+\left[\sum_{l'=r+1}^{r+s} N_{\mathrm{mcl2}}(0)_{l',t+1} W_{l'}(1-\mathrm{e}^{-(M+\mathrm{HM2}_{l'}\delta+\mathrm{BYM})})/(M+\mathrm{HM2}_{l'}\delta+\mathrm{BYM})\right.$$
$$\left.+\sum_{l'=r+1}^{r+s} O_{\mathrm{mcl2}}(0)_{l',t+1} W_{l'}(1-\mathrm{e}^{-(M+\mathrm{HM2}_{l'}\delta+\mathrm{BYM})})/(M+\mathrm{HM2}_{l'}\delta+\mathrm{BYM}\right]\frac{\text{effective FSSN}(0)}{\mathrm{FSSN}(0)}$$

Therefore,

$$\text{(A33)}\quad \mathrm{FSSB}(0)=\sum_{t=t_r-1}^{\lambda}\overline{B}_{\mathrm{mcl1}}(0)_t+\sum_{t=t_r}^{\lambda}\overline{B}_{\mathrm{mcl2}}(0)_t$$

The effective spawning stock biomasses per recruit of female and combined sexes are determined by

$$\text{(A34)}\quad (\mathrm{ESB}_{\mathrm{female}}/R)_F=\mathrm{FSSB}(0)/R_{\mathrm{female}}(F)$$

$$\text{(A35)}\quad (\mathrm{ESB}_{\text{combined sexes}}/R)_F=(\mathrm{MSSB}(F)+\mathrm{FSSB}(0))/R_{\text{combined sexes}}(F)$$

The effective total spawning stock biomass, ESB(F), is

$$\text{(A36)}\quad \mathrm{ESB}(F)=\mathrm{FSSB}(0)+\mathrm{MSSB}(F)$$

The nominal total mature stock biomass, SSB(F), is calculated using eq. A36 ignoring mating ratio.

Auxiliary models

Weight – carapace width (CW) relationship

For estimating a mean weight W_l of a CW interval l (Beyer 1987),

$$\text{(A37)}\quad W_l=\left(\frac{1}{\mathrm{CW}_{\mathrm{up}}-\mathrm{CW}_{\mathrm{low}}}\right)\left(\frac{a}{b+1}\right)\left(\mathrm{CW}_{\mathrm{up}}^{b+1}-CW_{\mathrm{low}}^{b+1}\right)$$

where

$$\text{(A38)}\quad W=a\mathrm{CW}^b$$

and $\mathrm{CW}_{\mathrm{up}}$ and $\mathrm{CW}_{\mathrm{low}}$ are the upper and lower size limits, respectively, of a CW interval, and a and b are model parameters.

Handling mortality on sublegals

The $\mathrm{HM}i_{l'}$ (i = 1 for males and i = 2 for females) at CW interval l' is defined as a function of $Fs_{l'}$, h, and δ, ignoring M and BYM as follows:

$$1-\mathrm{e}^{-\mathrm{HM}i_{l'}\delta}=h(1-\mathrm{e}^{-Fs_{l'}\delta})$$

Therefore,

$$\text{(A39)}\quad \mathrm{HM}i_{l'}=-\frac{1}{\delta}\ln[1-h(1-\mathrm{e}^{-Fs_{l'}\delta})]$$

Note that F accounts for legal and sublegal catches, but only an h proportion of sublegal male and female eventually dies as a result of handling and throwing them back to sea. The selectivity $s_{l'}$ applies to a range of sizes covering legal and sublegal crabs.

$\mathbf{P}_{l',l}$ *determination*

Annual growth increment (x) of crabs is assumed to have a normal distribution with a mean growth increment G_l and a standard deviation σ_l. Then:

$$\text{(A40)}\quad P_{l',l}=\frac{\displaystyle\int_{l_1-\tau_{l'}}^{l_2-\tau_{l'}}\mathrm{e}^{\frac{-(x-G_l)^2}{2\sigma_l^2}}\mathrm{d}x}{\displaystyle\sum_{l=1}^{n}\int_{l_1-\tau_{l'}}^{l_2-\tau_{l'}}\mathrm{e}^{\frac{-(x-G_l)^2}{\sigma_l^2}}\mathrm{d}x}$$

where

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(A41) $G_l = a1 + b1\bar{l}$

and n is the total number of CW intervals available in a cohort for $P_{l',l}$ estimation, σ_l is estimated from G_l assuming a 10% coefficient of variation, l_2 and l_1 are the lower and upper limits, respectively, of a receiving CW interval l for $P_{l',l}$ estimation, $\tau_{l'}$ is the midwidth of a providing CW interval l' for $P_{l',l}$ estimation, $\bar{l}$ is the midwidth of a width interval l, and $a1$ and $b1$ are linear model parameters.

Pot selectivity

A double logistic function is used to get a dome-shaped pot selectivity (s_l) curve for snow crab:

(A42) $$s_l = \left(\frac{1}{1 + e^{-a5(l-b5)}}\right)\left(\frac{1}{1 + e^{c(1-d)}}\right)$$

where $a5$, $b5$, c, and d are model parameters and l is the size. A linear function is used for pot selectivity of Dungeness crab:

(A43) $s_l = a4 - b4\,(157.5 - l)$

where $a4$ and $b4$ are linear model parameters and l is the size.

Molt probability

Molt probability is given by

(A44) $$f(l) = 1 - \frac{1}{1 + e^{-a3(l-b3)}}$$

where $f(l)$ can be mm_l, im_l, mf_l, or if_l; $a3$ and $b3$ are model parameters; and l is the size.

Maturity probability

Maturity probability (a_l) for snow crab males or females is

(A45) $$a_l = \frac{1}{1 + e^{-a2(l-b2)}}$$

where $a2$ and $b2$ are model parameters and l is the size.

References

Beyer, J.E. 1987. On length–weight relationships: Part 1: computing the mean weight of the fish in a given length class. ICLARM Fishbyte, **5**: 11–13.

Appendix B

Appendix appears on the following page.

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Table B1. Input parameters of Bering Sea snow crab for reference point estimation.

	Male		Female		
Parameter	Prerecruit-1	Recruit and postrecruit	Class-1	Class-2	Remarks
Size range (mm CW)	82–101	102–131	50–59	60–69	
Natural mortality rate (*M*)	0.30	0.30	0.30	0.30	NPFMC 1999
Handling mortality rate (*h*)	0.25	0.25	0.25	0.25	Zheng et al. 2002
Bycatch mortality (BYM)	0.01	0.01	0.01	0.01	Siddeek 2002
Growth increment model: *a*1, *b*1	8.8706, 0.1742	8.8706, 0.1742	11.68, 0.0	11.68, 0.0	Turnock 2003
Maturity probability: *a*2, *b*2	0.12, 88.00	0.12, 88.00	0.1628, 48.7665	0.1628, 48.7665	Siddeek 2003*b*
Molt probability: *a*3, *b*3					
Immature	0.0498,140.2407	0.0498,140.2407	100% molt	100% molt	Turnock 2003
Mature	0% molt	0% molt	0% molt	0% molt	Turnock 2003
Weight–length model: *a*, *b*	0.00023, 3.12948	0.00023, 3.12948	0.00253, 2.56427	0.00253, 2.56427	Somerton 1981
Pot selectivity probability: *a*5, *b*5, *c*, *d*					
Mature new shell	0.2379, 102.2655, 0.3458, 129.23	0.2379, 102.2655, 0.3458, 129.23			B.J. Turnock (National Marine Fisheries Service, 7600 Sand Point Way NE, Seattle, WA 98115, USA, unpublished data)
Mature old shell	0.189, 104.2308, 0.1498, 109.578	0.189, 104.2308, 0.1498, 109.578	0.2573, 67.282, –1.0, 0.0	0.2573, 67.282, –1.0, 0.0	B.J. Turnock (unpublished data)
Immature new/old shell	0.1 × mature selectivity	0.1 × mature selectivity	0.1 × mature selectivity	0.1 × mature selectivity	Appendix B (Table B2)
Male:female mating ratio					
Primiparous	1:4	1:9			Appendix B (Table B2)
Multiparous	1:3	1:6			

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Table B2. Input parameters of eastern Canada snow crab for reference point estimation.

	Male		Female		
Parameter	Prerecruit-1	Recruit and postrecruit	Class-1	Class-2	Remarks
Size range (mm CW)	75–94	95–134	45–54	55–69	
Natural mortality rate (M)	0.2 (postmolt 1–3 years) 0.5 (postmolt 4 years) 3.0 (postmolt 5 years)	0.1 (postmolt 1–3 years) 0.2 (postmolt 4 years) 0.5 (postmolt 5–6 years) 3.0 (postmolt 7–9 years)	0.15 (postmolt 1–3 years) 0.35 (postmolt 4 years) 0.7 (postmolt 5–6 years) 3.0 (postmolt 7 years)	0.15 (postmolt 1–3 years) 0.35 (postmolt 4 years) 0.7 (postmolt 5–6 years) 3.0 (postmolt 7 years)	B. Sainte-Marie (preliminary estimates from unpublished tag–recapture data)
Handling mortality rate (h)	0.12	0.12	0.12	0.12	Dufour et al. 1997
Bycatch mortality (BYM)	0.01	0.01	0.01	0.01	Appendix B (Table B1)
Growth increment model: $a1$, $b1$	8.573, 0.11	8.573, 0.11	3.503, 0.104	3.503, 0.104	Sainte-Marie et al. 1995; Alunno-Bruscia and Sainte-Marie 1998
Maturity probability: $a2$, $b2$	0.25, 75.00	0.25, 75.00	0.45, 48.00	0.45, 48.00	B. Sainte-Marie (unpublished data)
Weight–length model: a, b	0.000313, 3.062	0.000313, 3.062	0.00097, 2.745	0.00097, 2.745	B. Sainte-Marie (unpublished data for intact mature males and females of shell condition 2)
Pot selectivity probability: $a5$, $b5$, c, d					
Mature new shell	0.2039, 78.8002, 0.1064, 31.5604	0.2039, 78.8002, 0.1064, 31.5604	Zero selectivity	Zero selectivity	Estimates for males from data in Hoenig and Dawe (1991) and B. Sainte-Marie (unpublished data)
Mature old shell	0.2039, 78.8002, 0.1064, 31.5604	0.2039, 78.8002, 0.1064, 31.5604	Zero selectivity	Zero selectivity	
Immature new/old shell	0.1 × mature selectivity	0.1 × mature selectivity	0.1 × mature selectivity	0.1 × mature selectivity	
Molt probability					Terminal molt: Conan and Comeau 1986; Sainte-Marie et al. 1995. Mean incidence of skip-molting from Comeau et al. (1998)
Immature	70% molt	70% molt	70% molt	70% molt	
Mature	0% molt	0% molt	0% molt	0% molt	
Male:female mating ratio					Rondeau and Sainte-Marie 2001; B. Sainte-Marie (unpublished data)
Primiparous	1:4	1:9			
Multiparous	1:3	1:6			

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Table B3. Input parameters of Southeast Alaska Dungeness crab for reference point estimation.

	Male		Female		
Parameter	Prerecruit-1	Recruit and postrecruit	Class-1	Class-2	Remarks
Size range (mm CW)	135–164	165–224	70–84	85–169	
Natural mortality rate (M)	0.47	0.47	0.47	0.47	Preliminary estimate from tag–recapture data (G. Bishop, unpublished data)
Handling mortality rate (h)	0.15	0.15	0.15	0.15	Appendix B (Table B4)
Bycatch mortality (BYM)	0.01	0.01	0.01	0.01	Appendix B (Table B1)
Growth increment model: $a1$, $b1$	29.91, 0.0	29.91, 0.0	28.5364, –0.1027	28.5364, –0.1027	Tag–recapture data (G. Bishop, unpublished data); Koeneman 1985
Maturity probability	100% mature	100% mature	100% mature	100% mature	Appendix B (Table B4)
Molt probability: $a3$, $b3$					
Immature	100% molt	100% molt	100% molt	100% molt	Appendix B (Table B4)
Mature	1.974, 164.6285	1.974, 164.6285	100% molt	100% molt	Tag–recapture data (G. Bishop, unpublished data)
Weight–length model: a, b	0.0002, 2.9348	0.0002, 2.9348	0.00037, 2.8339	0.00037, 2.8339	Appendix B (Table B4)
Pot selectivity probability: $a4$, $b4$					
Mature new/old shell	$a4 = 1.0$, $b4 = 0.037$ when $130 \leq CW < 155$; $b4 = 0.0$ when $CW > 155$	$a4 = 1.0$, $b4 = 0.037$ when $30 \leq CW < 155$; $b4 = 0.0$ when $CW > 155$	$a4 = 1.0$, $b4 = 0.037$ when $130 \leq CW < 155$; $b4 = 0.0$ when $CW > 155$	$a4 = 1.0$, $b4 = 0.037$ when $130 \leq CW < 155$; $b4 = 0.0$ when $CW > 155$	Appendix B (Table B4)
Immature new/old shell	0.1 × mature selectivity	0.1 × mature selectivity	0.1 × mature selectivity	0.1 × mature selectivity	Appendix B (Table B2)
Male:female mating ratio					
Primiparous and multiparous	1:3	1:3			Preliminary value

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Table B4. Input parameters of western Canada Dungeness crab for reference point estimation.

	Male		Female		
Parameter	Prerecruit-1	Recruit and postrecruit	Class-1	Class-2	Remarks
Size range (mm CW)	130–154	155–194	105–119	120–149	
Natural mortality rate (M)	0.91	0.75	0.91	0.75	Z. Zhang and J. Boutillier (unpublished data)
Handling mortality rate (h)	0.15	0.15	0.15	0.15	Zhang et al. 2002
Bycatch mortality (BYM)	0.01	0.01	0.01	0.01	Appendix B (Table B1)
Growth increment model: $a1$, $b1$	18.07, 0.069	18.07, 0.069	32.35, –0.136	32.35, –0.136	Smith and Jamieson 1989
Maturity probability	100% mature	100% mature	100% mature	100% mature	Male mature >115.9 mm CW and female mature >90.8 mm CW (Butler 1961)
Molt probability: $a3$, $b3$					
Immature	100% molt	100% molt	100% molt	100% molt	Smith and Jamieson 1989; Zhang et al. 2002
Mature	0.08774, 172.4828	0.08774, 172.4828	100% molt	100% molt	
Weight–length model: a, b	0.0002, 2.9348	0.0002, 2.9348	0.00037, 2.8339	0.00037, 2.8339	Zhang et al. 2002
Pot selectivity probability: $a4$, $b4$					
Mature new/old shell	$a4 = 1.0$, $b4 = 0.037$ when $130 \leq CW < 155$; $b4 = 0.0$ when $CW > 155$	$a4 = 1.0$, $b4 = 0.037$ when $130 \leq CW < 155$; $b4 = 0.0$ when $CW > 155$	$a4 = 1.0$, $b4 = 0.037$ when $130 \leq CW < 155$; $b4 = 0.0$ when $CW > 155$	$a4 = 1.0$, $b4 = 0.037$ when $130 \leq CW < 155$; $b4 = 0.0$ when $CW > 155$	Zhang et al. 2002
Immature new/old shell	0.1 × mature selectivity	0.1 × mature selectivity	0.1 × mature selectivity	0.1 × mature selectivity	Appendix B (Table B2)
Male:female mating ratio					
Primiparous and multiparous	1:3	1:3			Preliminary value

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