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Evaluating the impact of buffers to account for scientific uncertainty when setting TACs: application to red king crab in Bristol Bay, Alaska

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Increasingly, scientific uncertainty is being accounted for in fisheries management by implementing an uncertainty buffer, i.e. a difference between the limit catch level given perfect information and the set catch. An approach based on simulation is outlined, which can be used to evaluate the impact of different buffers on short- and long-term catches, discounted revenue, the probability of overfishing (i.e. the catch exceeding the true, but unknown, limit catch), and the stock becoming overfished (i.e. for crab, mature male biomass, MMB, dropping below one-half of the MMB corresponding to maximum sustainable yield). This approach can be applied when only a fraction of the uncertainty related to estimating the limit catch level is quantified through stock assessments. The approach is applied for illustrative purposes to the fishery for red king crab, *Paralithodes camtschaticus*, in Bristol Bay, AK.

Keywords: acceptable biological catch, buffer, harvest control rule, length-based stock assessment, management strategy evaluation, overfishing, uncertainty.

Introduction

There is an increasing trend worldwide for fisheries management decisions to be made using harvest control rules which aim to avoid fishing mortality rates exceeding limit values, to move stocks to a target level of biomass, and to avoid dropping stock sizes below limit reference points (e.g. Ministry of Fisheries, 2008; Smith *et al.*, 2008, 2009). A related trend is for the catch limits to be reduced in data-poor situations and, in particular, when the outcomes from harvest control rules are uncertain. For example, the potential biological removals method (Wade, 1998) used to identify the levels of removals of marine mammal populations consistent with the US Marine Mammal Act bases catch limits on the lower 20th percentile of the sampling distribution for the most recent estimate of abundance, whereas the harvest control rule developed by the International Whaling Commission reduces harvests when data are uncertain (Punt and Donovan, 2007). Within Australia, "discount factors" are applied when calculating recommended biological catches given the results from harvest control rules to account for scientific uncertainty (Smith *et al.*, 2009).

Within the United States, the 2006 reauthorization of the US Magnuson–Stevens Fishery Conservation and Management Act (MSA; US Public Law 104–297) impacted how fisheries management advice is provided and decisions made for US Federally managed fisheries. In particular, the overfishing level (OFL) for a stock is defined as the level of annual harvest which, if exceeded, would constitute overfishing under the MSA, generally interpreted as $F > F_{\mathrm{MSY}}$. The OFL includes landings, as well as all discards, and can be considered to be the maximum possible catch for a stock given perfect information. The acceptable biological catch (ABC) is an annual level of harvest that accounts for scientific uncertainty in the estimate of the OFL and is hence equal to or lower than the OFL given the need for risk averse management.

The requirement to set OFLs (or similar fishery controls) has been a standard component of fisheries management advice in the United States for several years. US Regional Fisheries Management Councils (RFMCs) have generally adopted Tier systems to which stocks are assigned. The Tiers depend on data availability and differ in terms of the OFL control rule [e.g. North Pacific Fishery Management Council (NPFMC), 2008]. However, the requirement to adjust OFLs to account for scientific uncertainty has proved challenging, and several approaches have been developed to implement this requirement. This paper outlines an approach developed for crab fisheries in the Bering Sea and Aleutian Islands (BSAI) region of the United States under the aegis of the NPFMC, but which has general applicability in the United States and more broadly.

The crab fishery in the BSAI consists of a number of species and stocks. Some stocks are managed solely by the State of Alaska, while ten other stocks are managed under a cooperative regime that defers the setting of certain management controls to the State of Alaska with Federal oversight. Under this framework, the setting of OFLs and ABCs is a Federal responsibility. State regulations are constrained by the provisions of a Fishery Management Plan, including its goals and objectives, the MSA national standards, and other applicable Federal laws (ADF&G, 2008). Therefore, for these ten stocks, the total allowable catch (TAC) is set by the State of Alaska subject to the constraint that the TAC cannot be higher than the ABC set by the NPFMC.

The ten stocks under cooperative management are of five species (four stocks of red king crab *Paralithodes camtschaticus*; one stock of snow crab *Chionoecetes opilio*, one stock of Tanner crab *C. bairdi*, two stocks of blue king crab *P. platypus*, and two stocks of golden (or brown) king crab *Lithodes aequispinus*). The fisheries for four of these stocks (Pribilof Islands red, blue, and golden king crab and Adak red king crab) are currently closed. The remaining stocks are currently fished, with the bulk of the revenue arising from Bristol Bay red king crab, from now on referred to as "red king crab", eastern Bering Sea snow crab, and Aleutian Islands golden king crab (Bowers *et al.*, 2010).

Red king crab is widely distributed throughout the BSAI, Gulf of Alaska, Sea of Okhotsk, and along the Kamchatka shelf. The fishery in Bristol Bay, AK, is by far the largest in US waters. This fishery was started by the Japanese in the 1930s using primarily tanglenets. The Japanese tanglenet fishery operated until 1974, with a hiatus from 1940 to 1952. A tanglenet fishery for red king crab was operated by USSR vessels from 1959 to 1971. Although US vessels first fished red king crab as early as 1947, it was only during the late 1960s that the domestic pot fishery expanded substantially (Bowers *et al.*, 2008).

The sets of specifications for how the results of stock assessments are used to compute ABCs are referred to as ABC control rules. Several approaches, including decision analysis [G. Thompson, National Marine Fisheries Service (NMFS), pers. comm.], were proposed as potential ABC control rules for BSAI crab. The approach selected by the NPFMC, and the one on which this paper is based, involved establishing an ABC (which is an estimated quantity and hence a random variable), using a function of the estimated uncertainty of the OFL and the probability that the ABC from the ABC control rule exceeds the true OFL, P^*, i.e.:

$$P(ABC(\hat{OFL}) > OFL) = P^* \qquad (1)$$

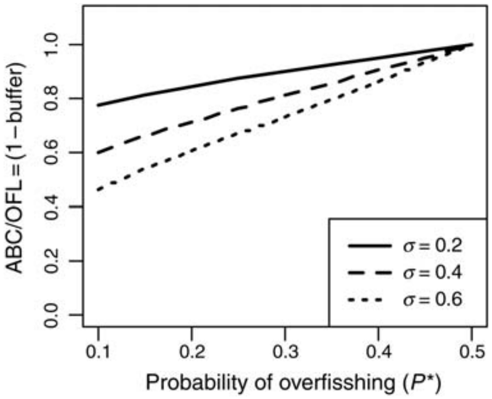

Figure 1. Relationship between the buffer (one less the ratio of the ABC to the OFL) and the probability of overfishing for different choices for σ when the OFL is assumed to be lognormally distributed.

Figure 1 summarizes the relationship between the OFL and the ABC for the case in which the OFL is lognormally distributed with the standard error of the log given by σ. The "buffer" (denoted Ω in this paper) is the difference between the ABC and the OFL and is larger for lower values of P^* (reflecting additional precaution) and higher values for σ (reflecting additional uncertainty).

The selected approach therefore conceptually follows several methods suggested previously to address scientific uncertainty regarding reference points and the outputs from control rules (Caddy and McGarvey, 1996; Prager *et al.*, 2003; Shertzer *et al.*, 2008; Prager and Shertzer, 2010), i.e. that to prevent the OFL being exceeded, the catch limit should be less than the OFL, with the size of the buffer depending on the extent of uncertainty. The key scientific question associated with the application of Equation (1) is how to quantify scientific uncertainty (i.e. the size of σ in Figure 1), and the key policy variable is the value for P^* which is required by MSA to be <0.5. Quantifying scientific uncertainty (and hence how to define the probability distribution for the OFL) is a technical consideration, and under the MSA must be based on the "best available science". However, the choice of a value for P^* is a policy decision involving the trade-off between short-term fishery benefits, and the probability of undesirable impacts to the managed stock, among other things.

This paper uses Equation (1) to compute an ABC for red king crab based on data up to 2008 (i.e. the 2009 ABC), then evaluates alternative choices for P^* (uncertainty buffers) in terms of expected biological outcomes, including the probability of overfishing occurring (the catch exceeding the true, but unknown, OFL) and the stock becoming overfished (the MMB dropping below the minimum stock size threshold) and the impact on revenue from fishing. The biological performance measures are equivalent to fishing mortality exceeding F_{LIM} and biomass dropping below B_{LIM} in the ICES management environment. The uncertainty associated with the estimate of the OFL can be divided into sources which can be quantified (such as sampling error) and those which cannot (such as the validity of proxy estimates of F_{MSY}). This paper therefore defines the uncertainty accounted for by the buffer as the sum of the uncertainty which can be quantified using the stock assessment and the unquantifiable uncertainty which is specified based largely on expert opinion and comparisons with other stocks.

Material and methods

Stock assessment and OFL determination for red king crab

The population dynamics model on which management advice is based (Supplementary material) is a sex-, length-, and shell condition-structured model [Equation (S1)]. It considers 20 length classes for males and 16 for females, each of 5 mm carapace length (CL) from 65 mm CL. The model distinguishes three major fisheries (the directed fishery, primarily using pots; the fishery for groundfish which takes red king crab as bycatch; and the pot fishery for Tanner crab which also takes red king crab as bycatch). It includes the years from 1968 onwards, primarily because the surveys conducted by the US NMFS started in that year. The 238 free parameters of this model are the annual recruitments by sex, the fully selected annual fishing mortality rates by sex, the parameters which determine fishery and survey selectivity as a function of length, survey catchability, the parameters that determine the probability of moulting for males (all females are assumed to moult each year), and the parameters that determine the length classes to which recruits are assigned. The data used to fit the model include fishery catch mass data (discarded and retained for the pot fishery, discarded for the Tanner and groundfish trawl fisheries), the length compositions for the fishery catches, estimates of biomass from the NMFS trawl survey (1968—present) and from the Bering Sea Fisheries Research Foundation surveys in 2007 and 2008, and the length-composition data from the NMFS trawl survey. A number of penalties are placed on the parameters of the model (e.g. that the numbers of recruits by sex each year are approximately equal, Zheng and Siddeek, 2009).

The OFL for red king crab is based on the Tier 3 harvest control rule (NPFMC, 2008). The Tier 3 harvest control rule is used to calculate the fishing mortality on which the OFL is based, F_{OFL}, for stocks for which reliable estimates of the stock–recruitment relationship are not available, but proxies for fishing mortality and biomass corresponding to maximum sustainable yield (F_{MSY} and B_{MSY}) can be estimated. The default proxy for F_{MSY} is $F_{35\%}$, the fishing mortality rate for the directed (pot) fishery, F^{dir}, which reduces MMB-per-recruit (MMB/R) to 35% of its unfished value. When calculating MMB/R, the full-selection fishing mortality for the trawl fishery and that for the Tanner crab fishery are set to averages over the most recent 5 years, while the full-selection fishing mortality for the bycatch of males and females in the directed pot fishery [Equation (S5)] is set to $F^{\mathrm{dir}}\sum_{t=2004}^{2008}F_t^{\mathrm{disc},s}/\sum_{2004}^{2008}F_t^{\mathrm{dir}}$. These assumptions are all reasonable in particular, because (relative to the catch of males in the directed fishery) the catches in the trawl and Tanner fisheries and of females are small. The proxy for B_{MSY} is the MMB/R corresponding to $F_{35\%}$ multiplied by the average recruitment from 1995 to 2008, a period of years selected by the NPFMC Crab Plan Team and the NPFMC Scientific and Statistical Committee as being when recruitment was higher compared with 1985–1994 and because there was a potential regime shift in 1989 (Overland *et al.*, 1999). The resulting Tier 3 control rule is:

$$F_{\mathrm{OFL}} = \max\left\{0, F_{35\%}\min\left[1, \frac{(B_{\mathrm{current}} - \alpha B_{35\%})}{(1-\alpha)B_{35\%}}\right]\right\}, \qquad (2)$$

where B_{current} is the MMB at the time of mating after the OFL is removed, and α is the proportion of $B_{35\%}$ at which the OFL is zero. As B_{current} is a function of F_{OFL}, Equation (2) has to be solved numerically.

The catch numbers by length and sex on which the OFL is based are calculated using Equations (S4), (S6), and (S7), where the full-selection directed pot fishing mortality equals F_{OFL}, and the full-selection fishing mortalities for the trawl fishery, for the Tanner crab, and for the bycatch of males and females in the directed pot fishery are set as when calculating MMB/R. The OFL in mass is calculated by multiplying the catch numbers by sex and length by weight by sex and length.

Developing an OFL distribution

The uncertainty of the OFL due to the estimation error can be computed using a variety of methods. However, for the purposes of this paper, this source of uncertainty was quantified using Bayesian methods. This involved specifying prior distributions for all parameters of the model (all uniform) and applying the Metropolis–Hastings version of the Markov chain Monte Carlo (MCMC) algorithm (Hastings, 1970), as implemented in the AD Model Builder package (http://admb-foundation.org/) to sample 800 equally likely sets of parameter vectors from the posterior distribution. The application of the MCMC algorithm was based on 10 000 000 cycles, of which the first 5 000 000 were ignored as a "burn-in" and remaining chain thinned so that the final posterior sample was based on 800 points. A variety of diagnostic statistics and plots were examined to assess lack of convergence to the posterior distribution.

The samples from the posterior distribution for the OFL reflect the uncertainty associated with fitting the model to the data assuming that the model is correct and that $F_{\mathrm{MSY}} = F_{35\%}$. However, several potentially important sources of uncertainty are ignored in the MCMC sampling procedure and this is reflected *inter alia* by the very narrow (unrealistically narrow) posterior intervals for the model outputs, including the OFL (see below). Specifically, some of the key parameters of the population dynamics model (including the relationship between the growth increment and length, and the value for survey catchability) are prespecified rather than being estimated, and the extent to which $F_{35\%}$ and $B_{35\%}$ (even if they could be estimated accurately and precisely) are actually equal to F_{MSY} and B_{MSY} is unknown (and unquantifiable at present). The unquantifiable uncertainty associated with the OFL can be considered to be "additional" uncertainty (*sensu* Ralston *et al.*, 2011). Therefore, a Monte Carlo distribution for the OFL is generated by sampling values for the model parameters from their joint posterior distribution and accounting for an extra level of uncertainty by adding a lognormal deviation to the numbers-at-length, i.e.:

$$\tilde{N}_{l,t}^{s} = N_{l,t}^{s}e^{\varepsilon-\sigma_b^2/2} \quad \text{and} \quad \tilde{O}_{l,t}^{s} = O_{l,t}^{s}e^{\varepsilon-\sigma_b^2/2}, \quad \varepsilon \sim N(0;\sigma_b^2), \qquad (3)$$

where $N_{l,t}^{s}$ is the estimate of the number of new shell crab of sex s in length class l at the start of year t, $O_{l,t}^{s}$ the estimate of the number of old shell crab of sex s in length class l at the start of year t, $\tilde{N}_{l,t}^{s}$ and $\tilde{O}_{l,t}^{s}$ the estimates of numbers-at-length after accounting for additional uncertainty, and σ_b the extent of additional uncertainty. Therefore, the uncertainty associated with the OFL is that based on estimation uncertainty conditioned on the assumed model and the Tier system and that associated with other (essentially unquantifiable) sources of uncertainty. Note that ε is perfectly correlated among sexes, time, and length classes.

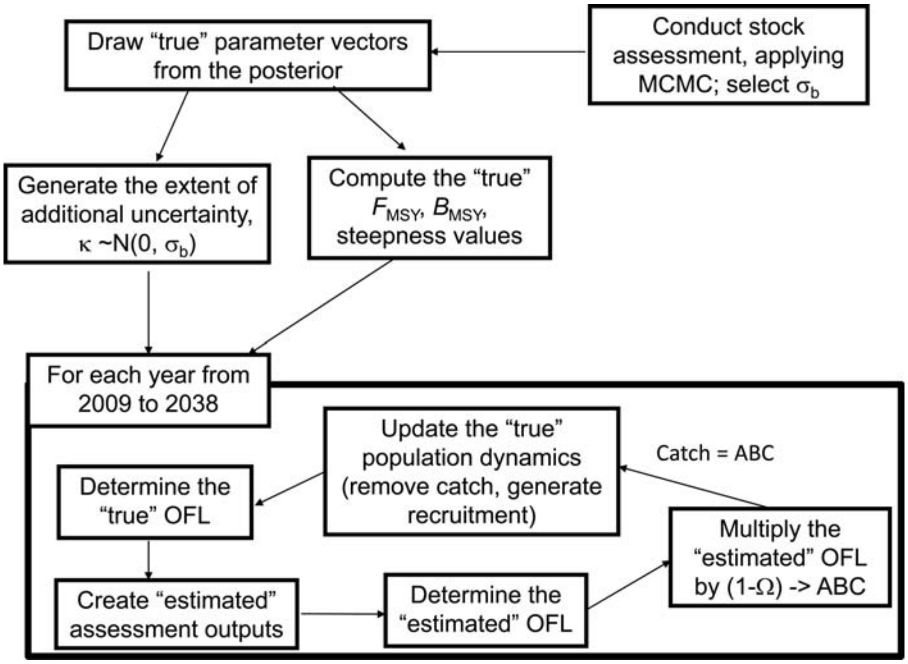

Figure 2. Flowchart of the algorithm used to evaluate the medium- and long-term implications of the alternative choices for the buffer.

Evaluating buffer levels and choices for *P**

For the purposes of this paper, the annual process of determining a TAC for red king crab involves (a) conducting a stock assessment based on the length-, sex-, and shell condition-structured model, (b) computing an OFL based on Equation (2), and (c) applying an ABC control rule to calculate an ABC and setting the TAC to the landed portion of ABC. This process is conceptually similar to the application of a "management procedure" (Butterworth, 2007; Punt, 2006), although the exact specifications for the assessment are not fixed, but can change annually depending on availability of new data and analyses. Nevertheless, it should be possible to use management strategy evaluation (Butterworth and Punt, 1999; Punt, 2006; Rademeyer *et al.*, 2007; Smith *et al.*, 2008) to evaluate the performance of the process of setting annual TACs for red king crab using the scheme outlined above.

Equation (1) is equivalent to a constant buffer between the ABC and the OFL, i.e. $ABC = (1-\Omega)OFL$ under the assumption that the level of uncertainty for the OFL does not change over time. Under this assumption, therefore, there is a 1:1 relationship between Ω (the uncertainty buffer) and P^*. The medium- and long-term implications of different choices for Ω or P^* are evaluated by projecting the population dynamics model for red king crab ahead 30 years (30–year period is sufficiently long that the resource equilibrates close to the proxy for B_{MSY} underdeterministic conditions) given catches based on steps (a)–(c) above.

The medium-term implications are evaluated using the results of projections for the first 6 years of the projection period, while the long-term implications consider the entire 30-year projection period. The projections account for uncertainty related to: (i) the values for the parameters of the model used to represent the stock dynamics, (ii) the recruitment to the modelled population for each future year, (iii) the form of the stock–recruitment relationship (Ricker or Beverton–Holt for the application of this paper), and (iv) other (unquantified) sources of uncertainty. These sources of uncertainty reflect much of the scientific uncertainty intended to be accounted for by the buffer between the OFL and the ABC.

The algorithm used is as follows (see also Figure 2).

(i) Fit the stock assessment model to the actual data to obtain the "best estimates" of parameters of the model.

(ii) Apply the MCMC method to obtain a set of 800 equally likely sets of parameter vectors from the posterior distribution for these parameters. This step quantifies the uncertainty related to source (i) outlined above.

(iii) For each draw from the posterior distribution:

  (a) Calculate $F_{35\%}$, and set F_{MSY} to $F_{35\%}$.

  (b) Find the value for the steepness of the stock–recruitment relationship (the fraction of unfished recruitment at 20% of the unfished MMB) so that MSY occurs at F_{MSY}.

  (c) Set R_0 (the virgin recruitment) so that B_{MSY} occurs at $B_{35\%}$ when full-selection fishing mortality in the directed fishery equals F_{MSY}.

  (d) Calculate the extent of variability (quantified using a standard deviation, i.e. σ_R) between the actual recruitment estimates and the values predicted by the stock–recruitment relationship for the years corresponding to B_{MSY}.

(iv) Set the value for F_{OFL} used when setting the OFL to the median of the values for $F_{35\%}$ across the draws from the posterior (i.e. the projections are undertaken under the assumption that the proxy for F_{MSY} is correct on average when setting OFLs).

(v) Set the value for σ_R used when generating future recruitment to the median of the values for σ_R across the draws from the posterior [source (ii) above].

- (vi) For each draw from the posterior distribution and choice of a buffer:
    - (a) Generate an assessment bias, κ, from $N(0;\ \sigma_b^2)$ which is constant over time—this bias represents the "additional" uncertainty, which would not be captured by sampling from a posterior distribution [source (iv) above].
    - (b) For each year of the 30-year projection period:
        1. Compute the true OFL (the OFL based on the parameters generated from the posterior distribution).
        2. Generate the data on which the TAC will be based by generating a random variable ε_y from $N(0;\ \sigma_w^2)$ which represents the annual deviation in the assessment result from the true value then multiplying all the population-related information needed to set the ABC (MMB at mating, numbers-at-length) by $e^{\kappa+\varepsilon_y-\sigma_b^2/2-\sigma_w^2/2}$ to generate the information used when setting the ABC. The value for σ_w is set to the standard deviation of the logarithm of the estimate of MMB at mating in the last year of the assessment (0.05 for red king crab) across the draws from the posterior. The numbers by length used to calculate the OFL relate to the true numbers at length are therefore generated according to the equation:

$$N_{l,y}^{s,\mathrm{GEN}} = N_{l,y}^{s,\mathrm{TRUE}} e^{\kappa+\varepsilon_y-\sigma_b^2/2-\sigma_w^2/2.} \tag{4}$$

        3. Compute the OFL based on the data generated at the previous step and multiply it by the $(1-\Omega)$ to compute the ABC.
        4. Set the TAC to the landed component of the ABC.
        5. Project the population ahead one year and generate the recruitment for the next year based on the stock–recruitment relationship, with the level of variation in recruitment set to the value for σ_R.

The calculations of this paper are based on the assumption that the F_{MSY} and B_{MSY} proxies are correct (i.e. $F_{\mathrm{MSY}} = F_{35\%}$, $B_{\mathrm{MSY}} = B_{35\%}$). Equation (4) includes two sources of uncertainty: one that is random from one year to the next and one that is the same for all years in a projection. The latter allows for sources of uncertainty which are likely to persist over time such as incorrect specifications for model parameters such as natural mortality and survey catchability, and the impact of assumptions such as that the assessed area is homogeneous with respect to population length and sex structure. The assumption of perfect correlation over 30 years is an extreme assumption, which could be relaxed to reflect that future research would reduce these sources of uncertainty. However, this latter complication has been ignored in the absence of what the major sources of error are, and the rate at which they would be mitigated by future research.

The projections are not based on simulating the application of the actual stock assessment as is common when applying management strategy evaluation (e.g. A'mar *et al.*, 2008). This is primarily because the impacts of many of the sources of "additional" uncertainty cannot be easily simulated. Equation (4) is therefore a pragmatic yet realistic way to represent assessment uncertainty.

Performance metrics

The medium- and long-term implications of the different buffers (and choices for P^*) are quantified in terms of their impact on stock status (measured in terms of MMB at the time of mating relative to $B_{35\%}$), the probability of overfishing (i.e. total catch $>$ true OFL), and the probability of the stock becoming overfished ($B_{\mathrm{current}} < 0.5\,B_{35\%}$), as well as on projected catches and total present value (*TPV*) of discounted first-wholesale revenues (i.e. "discounted revenues"). The results of the medium- and long-term projections are also shown in the form of (pointwise) distributions for time-trajectories of each performance metric.

The economic impacts of the choices for Ω are evaluated in terms of the impact on projected *TPV* over the 30-year projection period:

$$TPV = \sum_y \frac{V_y}{(1+r)^{y+1}} \tag{5}$$

where r is the economic discount rate, and V_y is the revenue for year y. These revenues are defined by:

$$V_y = C_y[\bar{K} + x_1 S_K]\,[\bar{P}_y + x_2 S_{\bar{P}_y}] \tag{6}$$

where C_y is the landings of male crab (in weight) in the directed (pot) fishery during year y, $\bar{K}$ and S_K the mean and standard error of the product recovery rate, $\bar{P}_y$ and $S_{\bar{P}_y}$ the mean and standard deviation of the price forecast for the first wholesale price during year y (see NPFMC, 2010, for the details on how the price forecasts were made), and x_1 and x_2 are randomly distributed $\sim N[0,1]$. To estimate economic metrics that reflect the uncertainty in price and catch projections, distributions for V_y and *TPV* are generated using independent random draws from the x_1 and x_2 distributions for each of the 800 C_y trajectories for each buffer, and median and 90% intervals calculated. Discount rates of 0.027 and 0.070 were employed following US Office and Management and Budget Guidance (OMB, 2009) and reflect the economic effect of time preference on the evaluation of catch projections over the medium and long term. Product recovery rates are used to convert the landings into estimated finished product to calculate gross first wholesale revenue (which captures total direct revenue in the harvesting and processing sectors of the fishery). Since finished crab products from the BSAI crab fisheries are sold into the international market and represent a relatively small fraction of total supply (Greenberg *et al.*, 1995), price-taking behaviour by Alaskan red king crab producers is assumed (such that P_y is independent of the amount of landings). All price and revenue values are presented as real 2008 US dollars, the final year in the time-series used to develop the price forecasting model. Historical monetary time-series were converted to real 2008 dollars using the US Bureau of Labor Statistics producer price index for processed and unprocessed fish commodities (PPI code 0223; BLS, 2010).

Results

OFL distributions for red king crab

The MMB at the time of mating is estimated to have recovered to above the proxy for B_{MSY} ($B_{35\%}$) in the 2000s following good

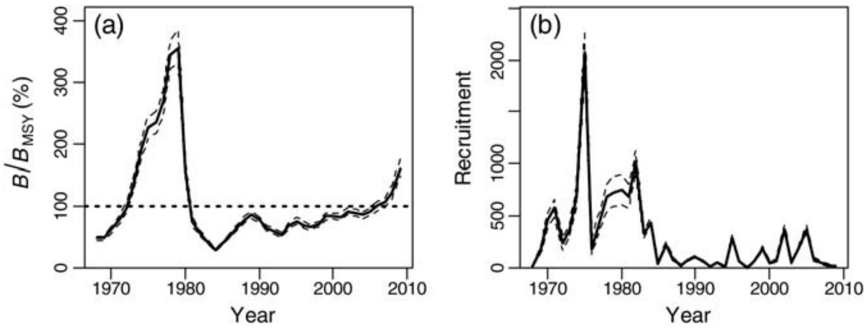

Figure 3. Posterior distributions (medians and 90% posterior intervals) for MMB at mating relative to the proxy for B_{MSY} (a) and annual recruitment to the model (b).

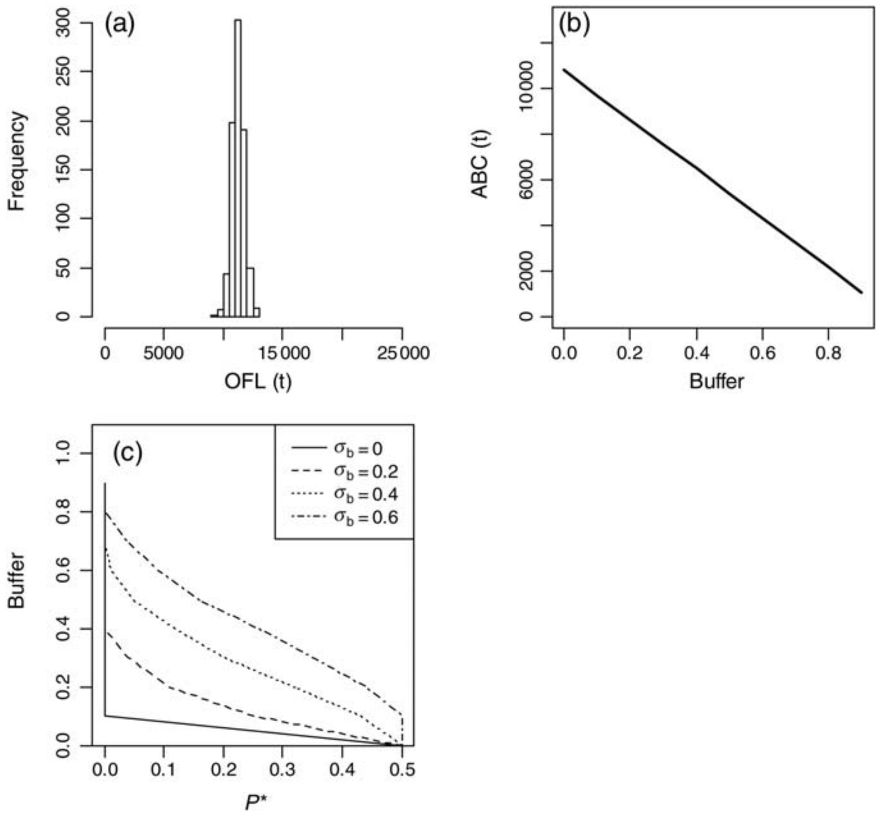

Figure 4. Posterior distribution for the OFL when no allowance is made for "additional uncertainty" (a), the relationship between the buffer (Ω) and the resulting ABC (b), and the relationship between the buffer and P^* for different values for the extent of "additional uncertainty" (c).

recruitment in the late 1990s and lower catches in the recent past (Figure 3a). However, recruitment since 2007 is estimated to have been weak (Figure 3b). Given that the stock is estimated to be above $B_{35\%}$, the fishing mortality for the directed fishery used to compute the OFL is $F_{35\%}$ (the proxy for F_{MSY}). The posterior median estimate for the OFL for 2009 is 10 774 t of which 9559 t pertains to landings and the remainder to discards in the directed fishery and bycatch in other fisheries. The extent of uncertainty associated with the current biomass is, however, unrealistically low (Figure 3a), which leads to a very tight posterior distribution for the OFL if additional uncertainty is ignored (Figure 4a).

There is a linear relationship between the ABC and the buffer (Figure 4b), with the ABC set equal to the OFL when there is no buffer ($\Omega = 0$) and the ABC being 10% of the OFL when the buffer is set to 90% ($\Omega = 0.9$). The relationship between the buffer and P^* is, however, not simple linear proportionality (Figure 4c). Moreover, the impact of the (assumed) extent of additional uncertainty is substantial given that the uncertainty of the OFL estimated from the assessment is low. Specifically, the buffer gets larger (and hence the ABC decreases) for the same value for P^* as the value for σ_b is increased. For example, the buffer for a P^* of 0.4 is 1% if there is no uncertainty that is not captured by the stock assessment, but is 6, 16, and 28% if σ_b is 0.2, 0.4, and 0.6 (Figure 4c).

Medium- and long-term implications of buffer choices

The values for the proxies for F_{MSY} and B_{MSY} are independent of the choice of the stock–recruitment relationship. The fits of the two stock–recruitment relationships are relatively poor, as indicated by high (generally >1) values for σ_R, the extent of unexplained variation about the stock–recruitment relationship. The results for a Ricker stock–recruitment relationship are qualitatively (and quantitatively) identical to those for the Beverton–Holt stock–recruitment relationship (results not shown). Consequently, the remaining analyses of this paper are based on the Beverton–Holt form of this relationship.

Figure 5 contrasts time-trajectories of MMB relative to the proxy for B_{MSY} and the landings in the directed fishery for no buffer (i.e. ABC = OFL), a buffer of 0.3 (i.e. ABC = 0.7 OFL), and a buffer of 0.6 (i.e. ABC = 0.4 OFL) for the case in which $\sigma_b = 0.2$ (the value selected by the NPFMC Crab Plan Team as being appropriate to red king crab; NPFMC, 2010). The MMB is currently estimated to be well above B_{MSY} (Figure 5a). Consequently, the OFL (and ABC) are larger than long-term average catches for the first 5 years of the projection period. However, owing to the sequence of below-average recruitments (Figure 3b), the stock drops to B_{MSY} (or lower) before recovering in response to lower catches. The Tier 3 harvest control rule is based on MMB only, so it does not react proactively to the sequence of poor incoming recruitments.

There are differences in long-term MMB/B_{MSY} among the no buffer, buffer = 0.3, and buffer = 0.6 alternatives, with larger buffers leading to larger stock sizes (Figure 5a). The long-term catches under a buffer of 0.3 are very similar to those for no buffer in the long term, although there are marked differences in catches during the early years of the projection period. This arises because no buffer and a buffer of 0.3 correspond to equilibrium points of the yield curve with similar yields, but different biomass levels (i.e. no buffer and a buffer of 0.3 both lead to "pretty good yield"—Hilborn, 2010). The extent of interannual variation in biomass is lowest for the no buffer alternative. However, no buffer corresponds to the greatest variation in catches.

The time-trajectories of discounted revenue depend on the size of the buffer and assumed discount rate (r; Figure 6). A higher discount rate places greater weight on revenues in the early years of the forecast, with the result that higher catches in the out years of the forecast contribute less to relative present value when discounted at $r = 0.07$ than at $r = 0.027$ (Figure 6). Therefore, although the long-term catches under smaller buffers may be similar to those under larger buffers, the higher catches in the earliest years mean that the discounted revenue is greater for smaller buffers.

Implications of "additional" uncertainty

BSAI crab stocks managed under the MSA are declared to be "overfished" if they decline below the overfished threshold of 0.5 B_{MSY}. Figure 7, which generalizes Figure 6 by considering a

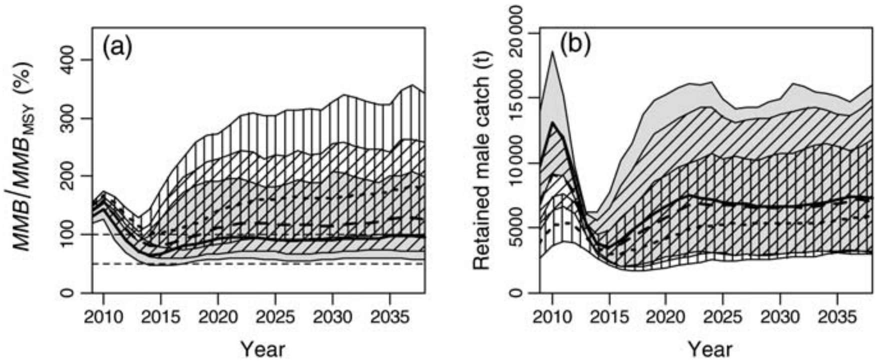

Figure 5. Time-trajectories of MMB at mating relative to $B_{35\%}$ (the proxy for B_{MSY}) and catch (median and 90% intervals), for three choices for the buffer between the OFL and the ABC (no buffer: solid line and filled shading; buffer = 0.3: dashed lines and diagonal shading; buffer = 0.6: dotted lines and vertical shading) for $\sigma_b = 0.2$ and a Beverton–Holt stock–recruitment relationship. The lower horizontal dashed line in the left panel indicates the overfished threshold (0.5 $B_{35\%}$).

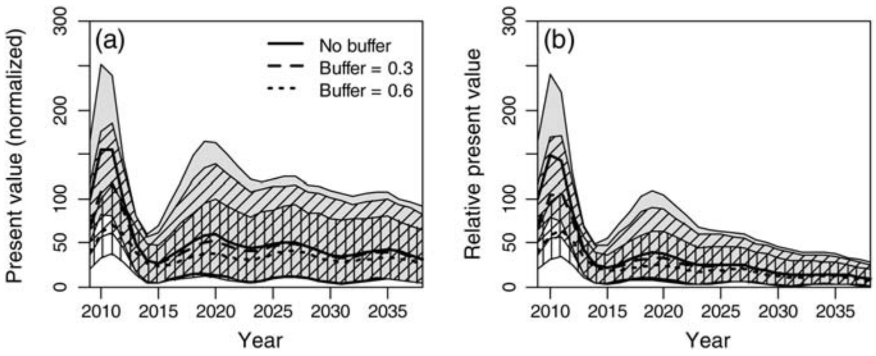

Figure 6. Time-trajectories (medians and 90% intervals) of the present value of the estimated revenue normalized relative to the median estimated revenue for the no buffer case in the first year of the projection period for three choices for the buffer between the OFL and the ABC (no buffer: solid line and filled shading; buffer = 0.3: dashed lines and diagonal shading; buffer = 0.6: dotted lines and vertical shading) for $\sigma_b = 0.2$, and a Beverton–Holt stock–recruitment relationship. Results are shown for a discount rate r of 0.027 (a) and 0.07 (b).

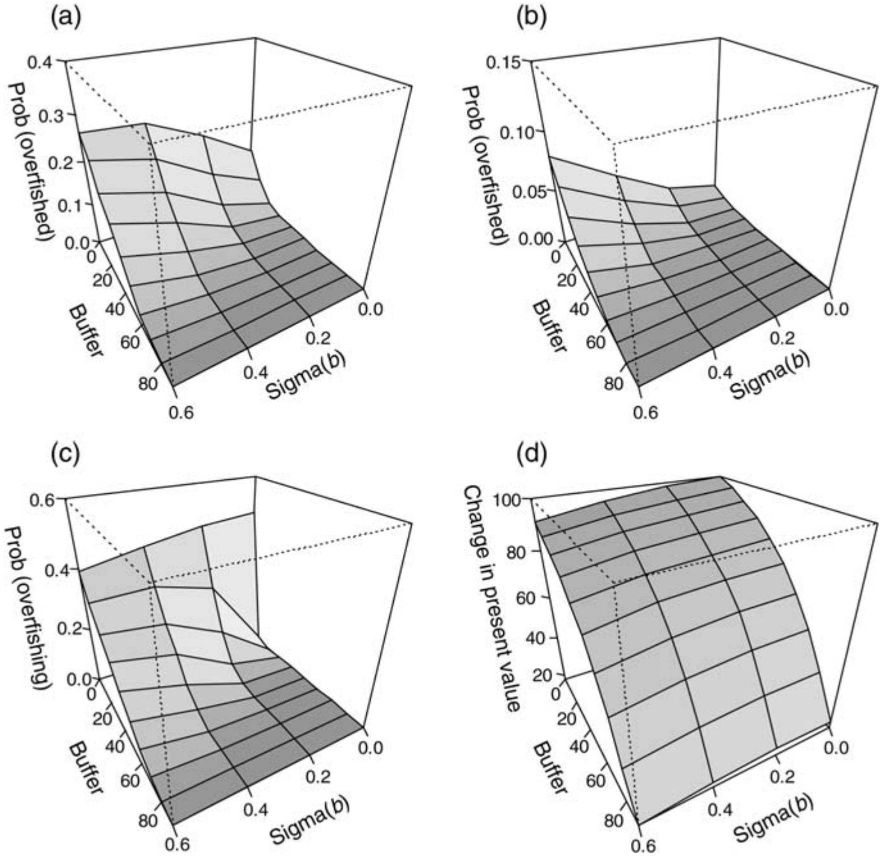

Figure 7. Relationships between the probability of being overfished (once in the 30-year projection period) (a) and on annual basis (b), the probability of overfishing occurring on annual basis (c), and percentage change in *TPV* of revenue ($r = 0.027$) (d) as a function of the extent of additional uncertainty and the buffer between the ABC and the OFL (in %).

range of values for σ_b, explores the relationship between the size of the buffer, the probability of the stock being overfished (once during the 30-year projection period and yearly), the probability of overfishing (catch > true OFL), and the economic value of catch levels, for different choices for σ_b. As expected, the annual probability of being overfished (Figure 7b) is lower than the probability of being overfished at least once during the 30-year projection period (Figure 7a). The probabilities of being overfished are lower for lower values for the extent of additional uncertainty, whereas the probability of overfishing is high when there is no buffer for all values of σ_b (Figure 7c). The probability of overfishing is 0.466 (slightly less than the nominal 0.5 value) when there is no buffer. This occurs because the Tier 3 OFL control rule has a breakpoint at B_{MSY} [Equation (2)] so an underestimate of $\mathrm{MMB}/B_{\mathrm{MSY}}$ can lead to a greater underestimate of the OFL than the extent to which the OFL is overestimated when $\mathrm{MMB}/B_{\mathrm{MSY}}$ is overestimated, at least for MMB values of B_{MSY} or lower.

The probability of overfishing decreases as the size of the buffer is increased. However, this reduction results in substantially lower annual catches and economic value. For example, the landings in the directed fishery in 2009/2010 drop from 8300 to 3900 t as the buffer is increased from 0 to 60%. The estimated long-term economic effect ($r = 0.027$) of a buffer of 60% relative to no buffer is estimated to be a 35% reduction in *TPV* (no additional uncertainty) and a 37% reduction in *TPV* ($\sigma_b = 0.6$; Figure 7d).

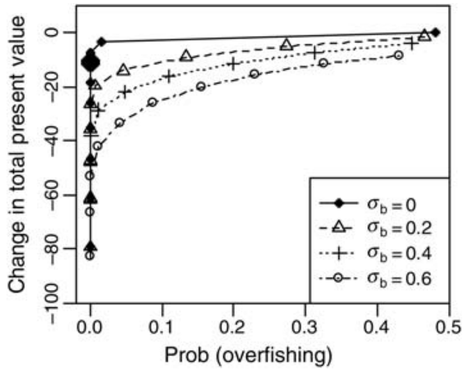

Figure 8. Relationship between the percentage change in *TPV* from the case of no buffer and no "additional" uncertainty (and for $r = 0.027$) and the probability of overfishing yearly. The symbols denote specific choices for the buffer (0, 0.1, etc. reading from the right of each line).

There is, as expected, a trade-off between *TPV* and the probability that the catch exceeds the OFL yearly (Figure 8), with the trade-off most evident if there is considerable additional uncertainty (e.g. $\sigma_b = 0.6$). The trade-off curves in Figure 8 also indicate that, depending on the value for σ_b, there are choices for the buffer for which an incremental increase in the buffer leads to additional losses in revenue, but no benefits in terms of stock conservation. Specifically, for $\sigma_b = 0$, values for a buffer of <0.7 lead to lower *TPV*, but to essentially no reduction in the probability of overfishing compared with a buffer of 0.3 (Figure 8, large dot). In contrast, compared with no buffer, a relatively small increase in the buffer leads to a large reduction in the probability of overfishing, but a relatively small reduction in *TPV*. Moreover, and as expected, lower values for σ_b lead to "better" outcomes as indicated by higher *TPV* for the same probability of overfishing.

Discussion

Buffers and trade-offs

Imposition of a buffer between the OFL and ABC achieves the goal of reducing the probability of overfishing. However, there is a trade-off between reducing the probability of overfishing (and being driven into an overfished state) and the consequential reduction in catches and hence fishery revenues. The impact of a large buffer is partially mitigated if reduced catches in the short-term lead to higher catches over the longer term. However, the economic benefits of these longer term catches do not fully offset the costs of short-term reductions in revenue because of discounting.

A further result of the evaluation is the diminishing cost-effectiveness for incremental increases in buffer sizes (Figure 8). Unfortunately, the threshold buffer level associated with this result depends on σ_b, implying that the decision-makers would need to be advised regarding the most appropriate value for σ_b to make rational decisions. While it is not possible to estimate σ_b (otherwise it would not be additional uncertainty), the NPFMC Crab Plan Team evaluated the factors likely to lead to additional uncertainty for all 10 BSAI crab stock qualitatively, such as whether key model parameters were prespecified. The stocks were then ranked according to how many of the unquantified uncertainties applied to each, and each stock was assigned to a "class" of unquantified uncertainty (represented by values for σ_b of 0.2, 0.4, and 0.6). Red king crab in Bristol Bay is one of the best studied (and assessed) of these stocks, which led the NPFMC Crab Plan Team to recommend that management be based on a value for σ_b of 0.2.

Advantages and disadvantages of the approach for evaluating buffers

Management strategy evaluation has become the standard way to evaluate the performance of monitoring strategies and harvest control rules (Butterworth, 2007; Kell *et al.*, 2007). The approach of this paper is similar in many ways to management strategy evaluation, but with some key differences. In particular, although account is taken of estimation error, the annual stock assessment is not simulated, but is rather approximated as draws of numbers-by-length and—sex [Equation (3)]. Although it would be relatively straightforward to apply the actual stock assessment method to simulated monitoring data, this would require that the operating model capture the "additional" uncertainty explicitly. However, although the primary sources of "additional" uncertainty can be listed, the magnitude of their effects cannot easily be determined at present (and if they could be, this would be included in the distributions for the OFL).

Within the United States, each RFMC has a different way to account for uncertainty in the ABC control rule, with some endorsing a P^* (or P^* modified by Tiers) approach, including the Western Pacific Fishery Management Council (WPFMC), the Pacific Management Council (PFMC), Gulf of Mexico Fishery Management Council (GMFMC), the South Atlantic Fishery Management Council (SAFMC) and the Mid-Atlantic Fishery Management Council (MAFAC). Some, such as WPFMC and MAFMC, endorse an approach in which P^* is based on various criteria such as life-history characteristics, stock status, overfishing status and assessment type. Others have pursued approaches more similar to the NPFMC's in treating uncertainty and risk as distinct entities, calculating values for total uncertainty, and demonstrating analytically how uncertainty impacts the perception of risk. The PFMC selected a P^* ranging across stocks from 0.45–0.40. However, they estimated a total uncertainty parameter (which for this BSAI crab analysis was split into σ_w and σ_b) which varies by Tier level (Ralston *et al.*, 2011).

Unlike the other RFMCs, the NPFMC formally compared different buffers in terms of the trade-off between the risk of overfishing or of the stock becoming overfished and expected revenue. Compared with the other RFMCs, the approach of this paper has the advantages of formally distinguishing between quantified and unquantified uncertainty and taking account of both when selecting a buffer between the OFL and ABC. The PFMC approach is based on the assumption that unquantified uncertainty can be captured by between-assessment variation due to changes in assumptions regarding prespecified parameters and choices for data types. However, there is very little between-assessment variation for most BSAI crab stocks because the same scientists conduct the assessments for each stock over time, making this approach inappropriate for BSAI crab (the inferred σ_b would be close to zero for most stocks). Moreover, the PFMC approach will not capture uncertainties which are not represented by between-assessment variation in assessment results such as the appropriateness of proxy estimates for F_{MSY}. The major disadvantage of the approach of the present paper is that without careful consideration, the values assumed for the extent of additional variation may be arbitrary. For BSAI crab, this concern was reduced by ranking multiple stocks using consistent criteria. Nevertheless, while the concern that the values of σ_b are incorrect cannot be ignored, assuming $\sigma_b = 0$, which is common when evaluating control rules, is clearly invalid generally.

Extensions and applications beyond North Pacific crab

The analyses of this paper are based on several assumptions which can be varied as appropriate in other applications. Some key examples include:

(i) The analyses were based on the assumption that the estimated OFL is correct "on average", and that it is primarily the imprecision of the estimate of the OFL that means that the estimated OFL differs from the true OFL. It would be relatively straightforward to extend the analysis to allow for bias (e.g. that $F_{\text{MSY}} \neq F_{35\%}$), for example, by postulating (e.g. using a meta-analysis) a distribution for the ratio $F_{\text{MSY}}/F_{35\%}$.

(ii) The analyses were based on the assumption that there is no implementation error (e.g. catches actually equal TACs and discarding of legal crab does not take place). This is generally the case for the major BSAI crab stocks. However, the approach of this paper could be extended to account for such error were it relevant in an actual case.

(iii) There is some evidence for serial correlation in recruitment (in particular the sequence of poor recruitments from 2007 for red king crab). The possibility of such correlation could be included when generating future recruitment and would likely lead to higher probabilities of the stock being driven below the overfished level.

The method of this paper can be applied straightforwardly to alternative methods for estimating the OFL. For example, NPFMC (2010) applied it to data-rich stocks (red king crab and EBS snow crab) for which proxies for F_{MSY} and B_{MSY} exist, and to stocks for which data on abundance from surveys are available, but it is currently not possible to estimate $F_{35\%}$. The method could be applied to the types of control rules used in Australia to provide recommended biological catches (Smith *et al.*, 2008). These control rules use assessment output along with target exploitation rates for data-rich stocks and use catch curve analysis and trends in fishery cpue for data-poor stocks.

The performance metrics considered were those presented to the NPFMC. However, other performance metrics could have been used to summarize performance. In particular, many management strategy evaluations have reported the extent of interannual variation in catch limits.

Finally, the simulations reflect the current situation for BSAI crab stocks that stock assessments are conducted annually and OFLs and ABCs updated yearly. This is not, however, a common feature of how fish and invertebrate stocks in other countries (e.g. Australia and New Zealand) as well as other regions of the United States are managed. Rather OFLs and ABCs are set for several years and updated irregularly. The impact of irregular updates to OFLs and ABCs could be explored using the approach of this paper by modifying the frequency of changes to the ABC. Furthermore, account could be taken of "learning" and hence reducing the bias between the true and estimated biomass, effects such as regime shifts, changes over time in growth rates, and large-scale mortality events such as those which have been postulated for red king crab (Zheng and Siddeek, 2009).

Supplementary material

Supplementary data are available at *ICESJMS* online.

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