ICES Journal of Marine Science

ICES International Council for the Exploration of the Sea
CIEM Conseil International pour l'Exploration de la Mer

ICES Journal of Marine Science (2013), 70(5), 955–967. doi:10.1093/icesjms/fss182

Fisheries management for regime-based ecosystems: a management strategy evaluation for the snow crab fishery in the eastern Bering Sea

Cody S. Szuwalski* and André E. Punt

School of Aquatic and Fishery Sciences, University of Washington, Box 355020, Seattle, WA 98195-5020, USA

**Corresponding Author: tel: +1 785 979 4453; fax: +1 206 685 7471; e-mail: szuwalsk@uw.edu*

Szuwalski, C., and Punt A. E. 2013. Fisheries management for regime-based ecosystems: a management strategy evaluation for the snow crab fishery in the eastern Bering Sea. – ICES Journal of Marine Science, 70: 955–967.

Received 13 August 2012; accepted 3 November 2012; advance access publication 4 December 2012.

Regime shifts are a prominent feature of the physical environment of some ecosystems and have the potential to influence stock productivity. However, few management strategies or harvest control rules (HCRs) consider the possibility of changes in stock productivity. A management strategy evaluation is conducted for the snow crab (*Chionoecetes opilio*) fishery in the eastern Bering Sea, an ecosystem influenced by regime shifts. Operating models that project recruitment as a single average (i.e. the current basis for management advice), regime-based with no relationship between recruitment and spawning biomass, and regime-based with control of recruitment oscillating between environmental conditions and spawning biomass are considered. An HCR that accounts for shifts in recruitment regime is compared with the *status quo* HCR for each operating model. The regime-based HCR increases yield and decreases variability in yield at the cost of a higher probability of overfishing in regime-based systems. However, the regime-based HCR slightly decreases yield (no change in variability) and increases the probability of overfishing in non-regime-based systems. Identifying changes in productivity that are definitely driven by environmental regime rather than fishing pressure is the largest difficulty in implementing these rules.

Keywords: eastern Bering Sea, management strategy evaluation, regime shifts, snow crab, stock assessment.

Introduction

Climate influences oceanic conditions which in turn influence the population dynamics of marine species and their fisheries (e.g. Hollowed *et al.*, 2001; Mantua and Hare, 2002). The impact of "regime shifts" (the rapid reorganization of an ecosystem driven by changes in large-scale climate forcing (Overland *et al.*, 2008) on marine fisheries) has received considerable attention in recent years (e.g. Litzow, 2006; Mueter *et al.*, 2007). Regime shifts appear to occur on a decadal time-scale and can influence the inferred productivity of stocks (e.g. Mantua and Hare, 2002; Rodionov and Overland, 2005). However, changes in productivity are rarely considered in stock assessments and when providing management advice.

Fishery managers often seek to maintain a population at or above a target biomass considered to provide the maximum sustainable yield (i.e. B_{MSY}). The value of B_{MSY} is strongly influenced by the productivity of a stock. Target biomasses for stocks managed by the North Pacific Fishery Management Council (NPFMC) are either set using an estimated stock–recruitment relationship or by specifying a proxy for B_{MSY} (NPFMC, 2007). The observations (or estimates) of spawning biomass and recruitment used to fit a stock–recruitment relationship or calculate the proxy for B_{MSY} are key to this process. Proxies for B_{MSY} are often calculated as the product of 35% of virgin spawning biomass per recruit (i.e. $SBPR_{35\%}$) and average recruitment. Average recruitment is usually based on the full time-series of spawning biomass and recruitment (e.g. Turnock and Rugolo, 2011). However, some estimates of recruitment may not be derived from the current "regime" if recruitment is a function of climate regime. Target biomasses calculated from the entire time-series will be higher than the "true" target biomass during "low" recruitment regimes and *vice versa*.

Management strategy evaluation (MSE) can assess the impact of assumptions regarding productivity on the ability of a management system to achieve its goals (Smith, 1994; Smith *et al.*, 1999). An MSE consists of three components: an operating model, an estimation model, and a harvest control rule (HCR). Operating models simulate populations that can be "observed" and "assessed" using an estimation model. An estimation model is a collection of equations that attempts to describe the dynamics of the population. Population parameters within the estimation model are estimated using non-linear optimization, and the estimates of these parameters are used to apply the HCRs, which are frameworks for deciding how catch limits for the fishery are to be calculated. Removals from the simulated populations are set to the catch limit from the HCR. A variety of operating models can be used to evaluate the impact of incorrect assumptions about the population dynamics in the estimation model (e.g. Punt, 2003; A'mar *et al.*, 2009a, b). The relative performance of combinations of estimation methods and HCRs (often referred to as management strategies) across operating models can also be compared using metrics important to management, such as long-term yield and the probability of being overfished (NPFMC, 2007).

MSE can also assess the impact of projected climate change on the ability of management strategies to achieve their goals. This involves identifying the population dynamics processes influenced by environmental conditions and linking them in the operating model to projections of the environmental covariates that best describe the region of study (Hollowed *et al.*, 2009). Ianelli *et al.* (2011) and A'mar et al. (2009b) performed MSEs for walleye pollock (*Theragra chalcogramma*) in which operating models were linked to Intergovernmental Panel on Climate Change (IPCC, 2007) climate projections for the North Pacific. They concluded that calculating target biomasses based on expectations generated from only recent recruitments performs similarly to using all observations of recruitment to set target biomass under stationary recruitment, but may offer advantages when environmental conditions change over time.

Management should consider the possibility that the productivity of a stock can change over time (and sometimes suddenly) in ecosystems with regime-based climate. We seek to understand the risk, relative performance, and trade-offs associated with HCRs that incorporate changes in expected recruitment induced by climate regime shifts compared with HCRs that ignore changes in average recruitment. These questions are explored in the context of the snow crab (*Chionoecetes opilio*) fishery in the eastern Bering Sea (EBS). The US domestic fishery for EBS snow crab only lands large male crab and is historically productive, with a maximum estimated biomass of over 680 000 t in the early 1990s (Turnock and Rugolo, 2011). However, both biomass and catch have been quite variable, and EBS snow crab was declared overfished in 1999 when it was assessed to have dropped below its minimum stock size threshold (MSST) (Turnock and Rugolo, 2011). A plan to rebuild the stock to its B_{MSY} proxy within 10 years (NPFMC/NMFS, 2000) was implemented in 1999, but declared a failure in 2009 (Turnock and Rugolo, 2011). The stock was declared rebuilt in 2011 when the stock was estimated to be above the B_{MSY} proxy.

"Regime shifts" have occurred in the Bering Sea most recently in 1977, 1989, and possibly 1999 (Overland *et al.*, 2008). These shifts influenced recruitment of species in the region (e.g. Adkison *et al.*, 1996; Mantua *et al.*, 1997; Wilderbuer *et al.*, 2002; Hunt *et al.*, 2011), and a recently suggested relationship between snow crab recruitment and the winter Pacific Decadal Oscillation (wPDO) proposes that snow crab recruitment is also influenced by regime shifts. Szuwalski and Punt (2012a) propose that drivers of recruitment oscillate between female spawning biomass (FSB) and the wPDO, with the change point linked to shifts in the average wPDO (see below for further discussion). The stock was declared overfished 10 years after the 1989 regime shift (seen strongly in the wPDO), at which time recruitment decreased markedly, and 10 years is the time a male crab takes to enter the mature population after fertilization. It is, therefore, possible that the overfished declaration and initial failure of the rebuilding plan was not solely the result of fishing pressure, but was also due to a change in productivity related to the 1989 shift in the wPDO.

The current HCR may not be appropriate if regime shifts influence recruitment of EBS snow crab. To evaluate the impact of regime-based dynamics on management performance, the trade-offs associated with two potential HCRs for the snow crab fishery (one of which considers shifts in productivity) are examined under three operating models that use different methods to simulate future recruitment (Figure 1).

Methods

Estimation method

The estimation method for all simulations is closely related to the currently used estimation method for EBS snow crab; it is size-based with considerations for sex, maturity state, and shell condition (Turnock and Rugolo, 2011; see Szuwalski and Punt 2012b, Appendix A for details). The estimation method involves fitting a population model to data from the directed fishery, bycatch from the trawl fishery, and data from the National Marine Fisheries Service (NMFS) summer survey. One major difference between this estimation method and that applied by Turnock and Rugolo (2011) is that the penalties on deviations in fishing mortality applied by Turnock and Rugolo (2011) are dropped, as suggested by Szuwalski and Punt (2012b). Removing these penalties results in poorer fits to the data, but considering the large bias introduced into estimates of the fishing mortality corresponding to MSY (F_{MSY}) and selectivity identified by Szuwalski and Punt (2012b), including these penalties in the estimation method would only demonstrate why penalties on fishing mortality should not be used. The most recent stock assessment included 2 years of data from an additional survey, but because this survey is unlikely to take place regularly in the future, it is ignored here. Simulated data representing the directed pot fishery, the NMFS summer trawl survey, and bycatch data from the groundfish trawl fishery are used during each year of the projection period to estimate trends in fishing mortality, numbers-at-length, and mature male biomass (MMB) using the estimation method. Production models and other simpler estimation methods were not considered because they estimate B_{MSY} and F_{MSY} poorly in this system (Punt and Szuwalski, 2012).

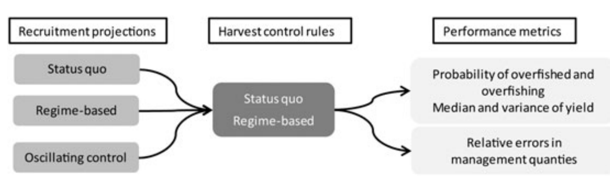

Figure 1. Schematic of the components and flow of the management strategy evaluation.

Operating models

The operating models are based on the population dynamics model on which the estimation method is based and represent the "true" population dynamics. Six "scenarios" are considered where a "scenario" is the set of simulations resulting from the application of an HCR to a specific operating model. Sixty-five simulations were performed for each scenario (all projected 50 years). The parameters used to define the population dynamics model for each of these simulations were generated by sampling from the posterior distribution obtained by fitting the operating model to the actual data for EBS snow crab using a Markov-chain Monte Carlo (MCMC) algorithm. Parameter vectors were generated by implementing a 10% burn-in on 1 000 000 cycles of an MCMC algorithm and selecting a thinning ratio that returned the desired number of parameter vectors. Evidence of non-convergence of the MCMC algorithm was checked using several diagnostic statistics (e.g. lack of autocorrelation and the Geweke statistics; Gelman *et al.*, 2004). Only the manner in which recruitment is projected changes among operating models. These three methods of projecting recruitment are described below.

Status quo *recruitment*

The first operating model (*status quo*; Figure 2a) projects recruitment using a Beverton–Holt spawner–recruitment relationship with steepness set such that F_{MSY} is equal to $F_{35\%}$, because this is an implicit assumption of the current HCR. Recruitment is related to MMB (also an implicit assumption of the current HCR) with a 5-year lag. The projected recruitments are subject to bias-corrected lognormal error, with a standard deviation of the log similar to that estimated by fitting the population dynamics model to the actual data for EBS snow crab ($\sigma = 0.75$). The performance of the current HCR under this operating model serves as a reference for the other operating model/HCR combinations, because it is consistent with the assumptions of the current HCR.

Regime-based recruitment

A shift in average recruitment in 1995 divides the fishery's history into a period of relatively "high" recruitment (1984–1995) and one of lower recruitment (1996–2008). The second operating model ("regime-based"; Figure 2b) shifts between a "high" and a "low" recruitment regime every 10 years. The average recruitments during these regimes are similar to the observed averages (the high regime average recruitment is roughly double that of the low regime), and the overall average recruitment is equal to the average recruitment in the *status quo* operating model. The process error is again generated from a bias-corrected lognormal distribution with $\sigma = 0.75$. This operating model assumes no relationship between spawning biomass and recruitment, and represents an idealized regime-based system to evaluate the performance of regime-based HCRs. The true B_{MSY}, and hence the basis for evaluating whether the stock is really overfished, for this operating model is defined as $\mathrm{SBPRF}_{35\%}$ multiplied by the average recruitment within a regime.

Oscillating control recruitment

The third operating model ("Oscillating control"; Figure 2c) is also regime based, but incorporates the mechanism suggested by Szuwalski and Punt (2012a), in which regimes are demarcated by shifts in climate regime. Recruitment is "high", and related to FSB when the wPDO is "warm"; recruitment is "low" and related the environment when the wPDO is "cool" (see Figure 3a for fits of this recruitment model to actual data for

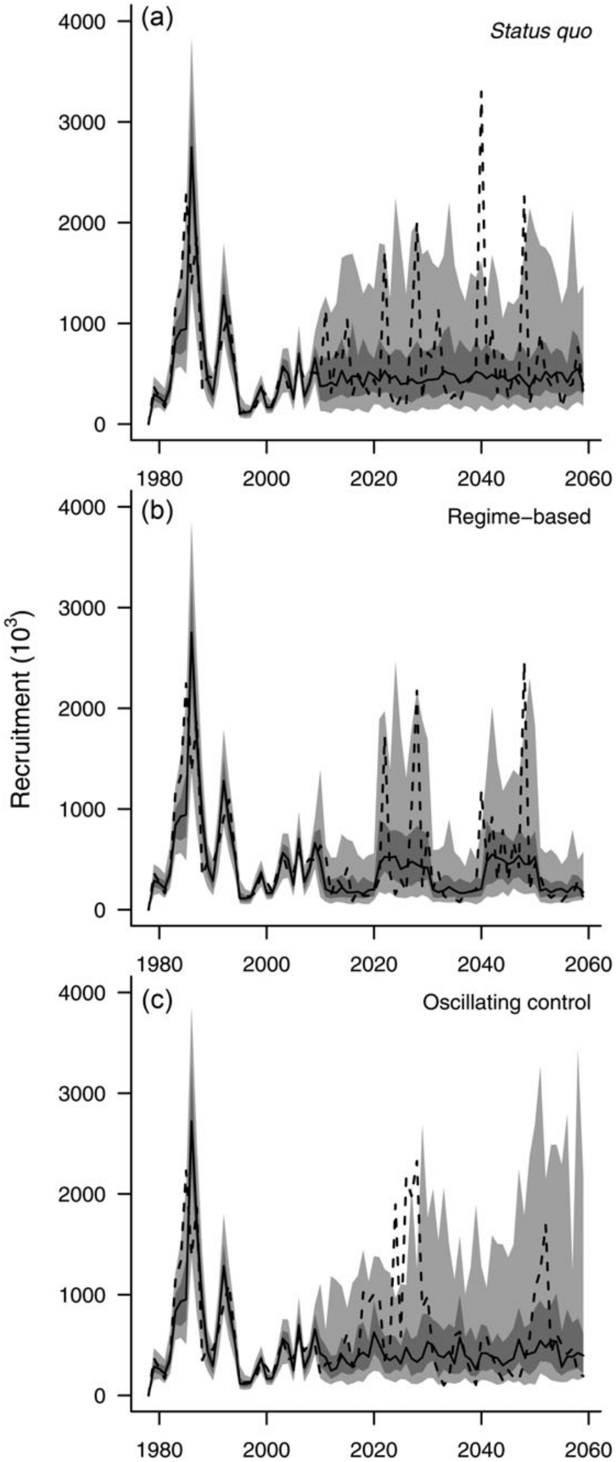

Figure 2. Projected recruitment for each operating model. The *status quo* operating model (a) represents a system in which there is a single relationship between MMB and recruitment over the projection period. Recruitment is not related to spawning biomass and alternates between "high" and "low" recruitment regimes in the "regime-based" operating model (b). Recruitment in the "oscillating control" operating model (c) shifts from a period of "high" recruitment related to female spawning biomass to periods of "low" recruitment related to projections of wPDO. Shifts between drivers occur with changes to the average value of the wPDO (Figure 3). Light grey represents the 5th and 95th intersimulation interval; dark grey is the 25th and 75th. The black line is the median, and the dashed line is one random realization of future recruitment.

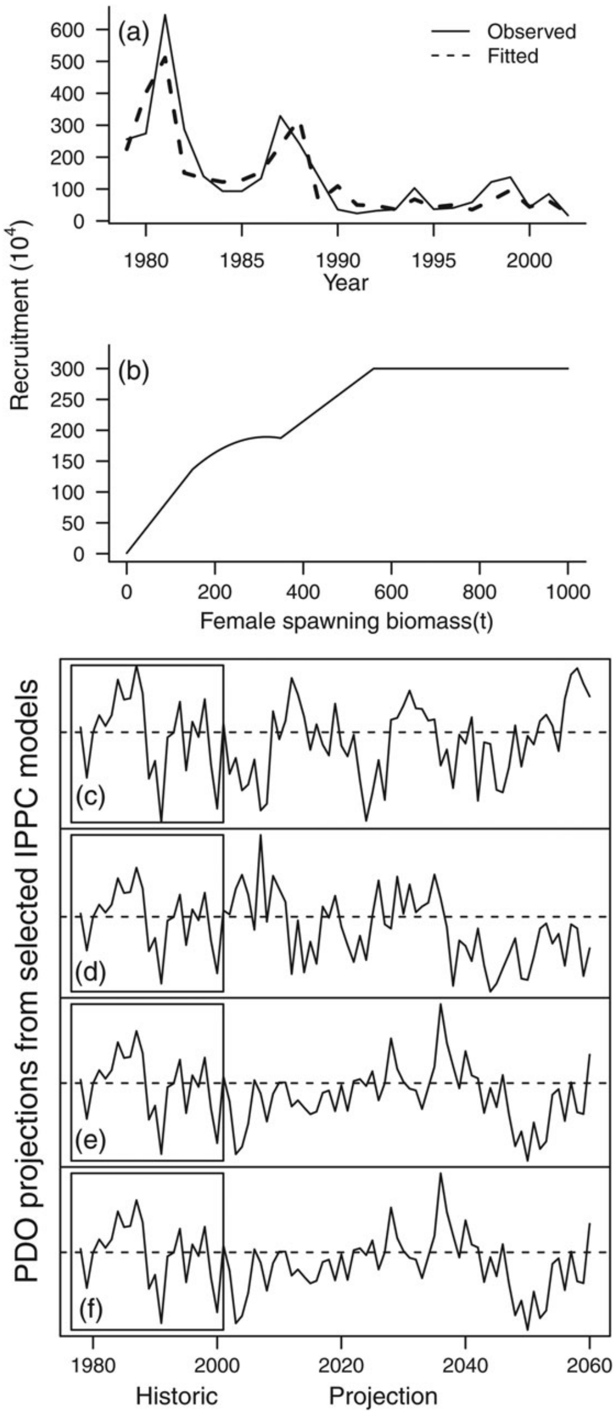

Figure 3. Fits of the oscillating control model from Szuwalski and Punt (2012a) (recruitment is in the year crabs recruit to the survey, i.e. 5 years after fertilization) (a). Realized stock recruitment relationship used in the "oscillating control" operating model (b). An arbitrary selection of four of the 10 projected time-trajectories of wPDO from Overland and Wang (2007) (c–f). The horizontal dashed line denotes the cut-off at which control of recruitment changes from FSB (above the line) to the wPDO. The "historical" period had a sustained period in which the wPDO was anomalously high, and this pattern is seen infrequently in the projections.

EBS snow crab). Hence, control of recruitment "oscillates" from spawning biomass to environmental effects depending on the current climate regime. Model 1 from Szuwalski and Punt (2012a) was selected to project recruitment because it uses only the wPDO as a predictor during "cool" regimes. Incorporating the wPDO in the projection model is important because it defines the point at which recruitment dynamics shift.

Recent recruitments during a warm period not used when developing the original wPDO/recruitment model indicate an increase in recruitment (Turnock and Rugolo, 2011) larger than that would be predicted by parameter estimates in Szuwalski and Punt (2012a), given the recent low level of FSB. This suggests a density-related effect on recruitment not originally observed, and higher productivity at lower spawning biomasses. Consequently, the relationship between recruitment and FSB is modelled using the function in Figure 3b. Productivity is higher for low spawning biomasses, but recruitment generation reverts to the model from Szuwalski and Punt (2012a) when FSB is >350 000 t. A cap of 3 million recruits is imposed before error is added. Ten IPCC climate models (all under the A1B emission scenario) were used to project the wPDO. Overland and Wang (2007) selected these ten models given their ability to simulate large-scale aspects of the climate in the EBS (e.g. sea ice area). Control of recruitment oscillates from FSB to the wPDO at the midpoint between the average wPDO of the "cool" and "warm" regimes in the oscillating control model (horizontal dotted line in Figure 3c–f). FSB determines recruitment when the average projected wPDO is above the horizontal line in Figure 3c–f; the wPDO determines recruitment when the wPDO is less than the cutoff. The standard deviation of log-recruitment for this operating model is based on the fit of the model of Szuwalski and Punt (2012a) to the actual estimates of recruitment ($\sigma = 0.41$).

The true B_{MSY} during cool regimes is calculated as the average recruitment for the recruitment regime multiplied by $\mathrm{SBPRF}_{35\%}$. Determining the "true" B_{MSY} for warm phases is not straightforward because recruitment is related to FSB, but only males are fished. The number of males necessary to inseminate the females present is an appropriate way to define the true B_{MSY} under these conditions. However, this number is unknown. Males expend <2.5% of their sperm reserves with each ejaculation and can copulate with more than one female during a mating season. Additionally, males and females have asynchronous maturity schedules and can store sperm from year to year (Rondeau and Sainte-Marie, 2001). Considering this, and the flexibility of male mating strategies as seen through time spent guarding a receptive female (Rondeau and Sainte-Marie, 2001), the required male-to-female sex ratio is likely <1. In laboratory studies, Rondeau and Sainte-Marie used effective sex ratios from 0.06 to 0.39 to examine the influence of sex ratio on sperm allocation and guarding time. Spermathecal load (the amount of sperm a female stored) declined with the sex ratio. The definition of B_{MSY} for this operating model for cold regimes (and also the current management strategy) leads to a sex ratio of roughly 0.33 on average (three females for each male), which is at the high end of the range tested by Rondeau and Sainte-Marie and is relatively conservative. Therefore, the true B_{MSY} during warm regimes is calculated in the same manner as during cool regimes for this operating model.

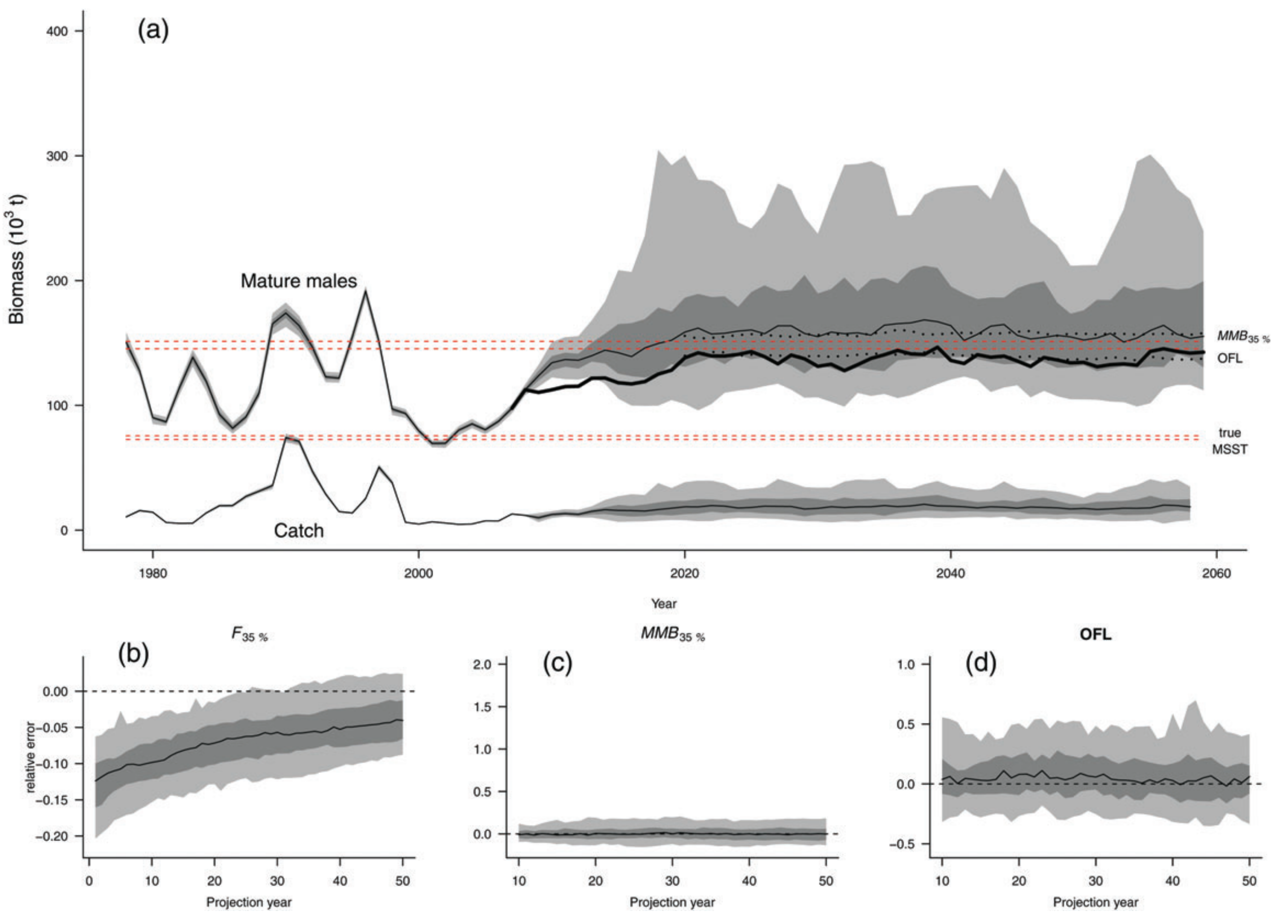

Figure 4. Results for the scenario in which the operating model is *status quo* and the estimation method is also *status quo*. MMB and catch in thousands of tonnes (a). Thick solid line is the median (over simulations) from applying only the OFL HCR. Dashed lines are ranges for true $MMB_{35\%}$ (top) and minimum stock size threshold, MSST (bottom); each simulation had a slightly different "true" $MMB_{35\%}$, hence the "range". Dotted lines are the range for the estimated $MMB_{35\%}$. Distributions of relative error for $F_{35\%}$ (b), $MMB_{35\%}$ (c), and the OFL (d). The scale for $MMB_{35\%}$ and the OFL will remain the same across all scenarios for ease of comparability. For all graphs, light grey outlines 5th and 95th quantiles; dark grey outlines 25th and 75th quantiles. Thin solid lines are the medians.

Harvest control rules

HCRs determine removals using estimates of biomass and calculated target biomasses. This study considers two HCRs that differ in the assumptions made regarding the productivity of the stock as seen through recruitment.

Status quo *HCR*

The North Pacific Fishery Management Council (NPFMC) and the Alaska Department of Fish and Game (ADFG) jointly manage EBS snow crab. The NPFMC primarily sets the overfishing level (OFL), the Acceptable Biological Catch (ABC), and the MSST, and the ADFG sets the total allowable catch (TAC). The TAC must be lower than the ABC (which for Alaska crab is essentially the same as the OFL) so that catches removed from the stock for these simulations are the lower of the OFL and the TAC from the ADFG HCR.

The OFL is determined using the estimates of MMB from the NPFMC assessment and a HCR (Equations 1–3) (NPMFC, 2007).

Stock status level:

$$\frac{MMB_{\mathrm{current}}}{MMM_{35\%}} > 1 \tag{1a}$$

$$\beta < \frac{MMB_{\mathrm{current}}}{MMM_{35\%}} \le 1 \tag{2a}$$

$$\frac{MMB_{\mathrm{current}}}{MMM_{35\%}} \le \beta \tag{3a}$$

F_{OFL}:

$$F_{\mathrm{OFL}} = F_{35\%} \tag{1b}$$

$$F_{\mathrm{OFL}} = \frac{F_{35\%}((MMB_{\mathrm{current}}/MMB_{35\%}) - \alpha)}{1-\alpha} \tag{2b}$$

$$\text{Directed fishery } F = 0 \tag{3b}$$

where α determines the fishing mortality rate used to compute F_{OFL}, as MMB decreases to $\beta^* MMB_{35\%}$, and β determines the threshold level of biomass at or below which directed fishing is prohibited. $MMB_{35\%}$ is a proxy for B_{MSY}, equal to average recruitment multiplied by $SPPR_{35\%}$.

The TAC is determined by the State of Alaska using the following HCR to determine fishing mortality on mature males.

Stock status level:

$$TMB < \gamma \tag{4a}$$

$$\gamma \leq TMB \leq \rho \tag{5a}$$

$$TMB \geq \rho \tag{6a}$$

Fishing mortality:

$$\text{Fishing mortality} = 0 \tag{4b}$$

$$\text{Fishing mortality} = \frac{0.75 * F_{\mathrm{MSY}}((TMB/Avg\ TMB) - \delta)}{1 - \delta} \tag{5b}$$

$$\text{Fishing mortality} = 0.75 * F_{\mathrm{MSY}} \tag{6b}$$

where TMB is total mature (male and female) biomass at the time of the survey (note that the OFL control rule uses only MMB), γ is the minimum TMB threshold for opening the fishery, F_{MSY} is assumed to equal to the assumed natural mortality rate (0.3 year^{-1} according to ADFG), $AvgTMB$ is the average estimate of TMB at the time of the survey from the stock assessment over the years 1983–1997 (Turnock and Rugolo, 2011), ρ is the TMB at which the full exploitation rate is applied (currently 921.6 million pounds), and δ is a constant (0.35) that determines the slope of the relationship between fishing mortality and TMB. The fishing mortality is zero if TMB is $< \gamma$. The TAC computed according to the ADFG harvest strategy is the lesser of the outcome from the above HCR and 58% of exploitable legal male abundance.

The federal and ADFG HCRs depend on target biomasses. The federal HCR is based on a proxy for B_{MSY}, which is $SPPR_{35\%}$ multiplied by average estimated recruitment for 1979–present. The ADFG HCR depends on the TMB during the years 1983–1997, which corresponds to a period of relatively good recruitment. Assumptions about incoming recruitment can affect the validity of these target biomasses.

The federal HCR is applied without the ADFG HCR for the *status quo* operating models to demonstrate the conservative nature of the ADFG HCR compared with the federal HCR. All other scenarios are based on the combination of the two HCRs.

Regime-based HCR

HCRs that limit the observations of recruitment used to calculate expected recruitment can be formulated. Averages calculated in sliding windows might be used to calculate expected recruitment (e.g. A'mar *et al.*, 2009a), but shifts in productivity can be sudden in regime-based systems. A sliding window approach would identify gradual changes in productivity, but sudden shifts would not be well-captured until many years after the regime shift. Consequently, estimated target biomasses may be higher than the productivity of the stock would imply if average recruitment dropped, which would increase the likelihood of falsely declaring a stock overfished, and *vice versa*.

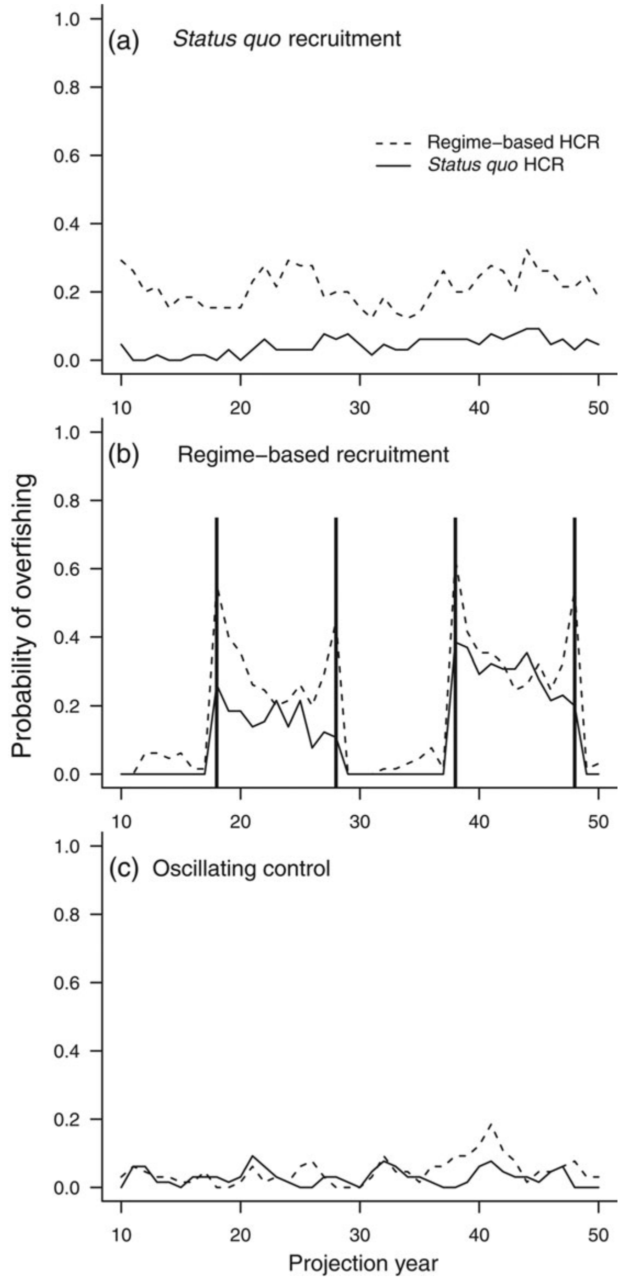

Figure 5. Probability of overfishing as the percentage of simulations in a given year in which the removed catch exceeded the overfishing limit (OFL) for a regime-based HCR and the *status quo* HCR under three future recruitment models. Vertical lines in (b) indicate the years in which the regime switched.

Sudden shifts in productivity are addressed here by incorporating an algorithm, such as Rodionov's sequential t-test analysis for regime shifts (STARS; Rodionov, 2004) into the HCR. STARS assumes a length of regime and defines a "previous regime" based on the assumed regime length and available data. Next, the deviations of each new year's data from the previous regime's average are compared with a t-distribution defined by the mean and variance of the observed data for the previous regime. A new regime is considered to have possibly begun when the deviation for the new year is significantly different ($p < 0.1$) from the mean of the previous regime. A shift in regime is "confirmed" when the

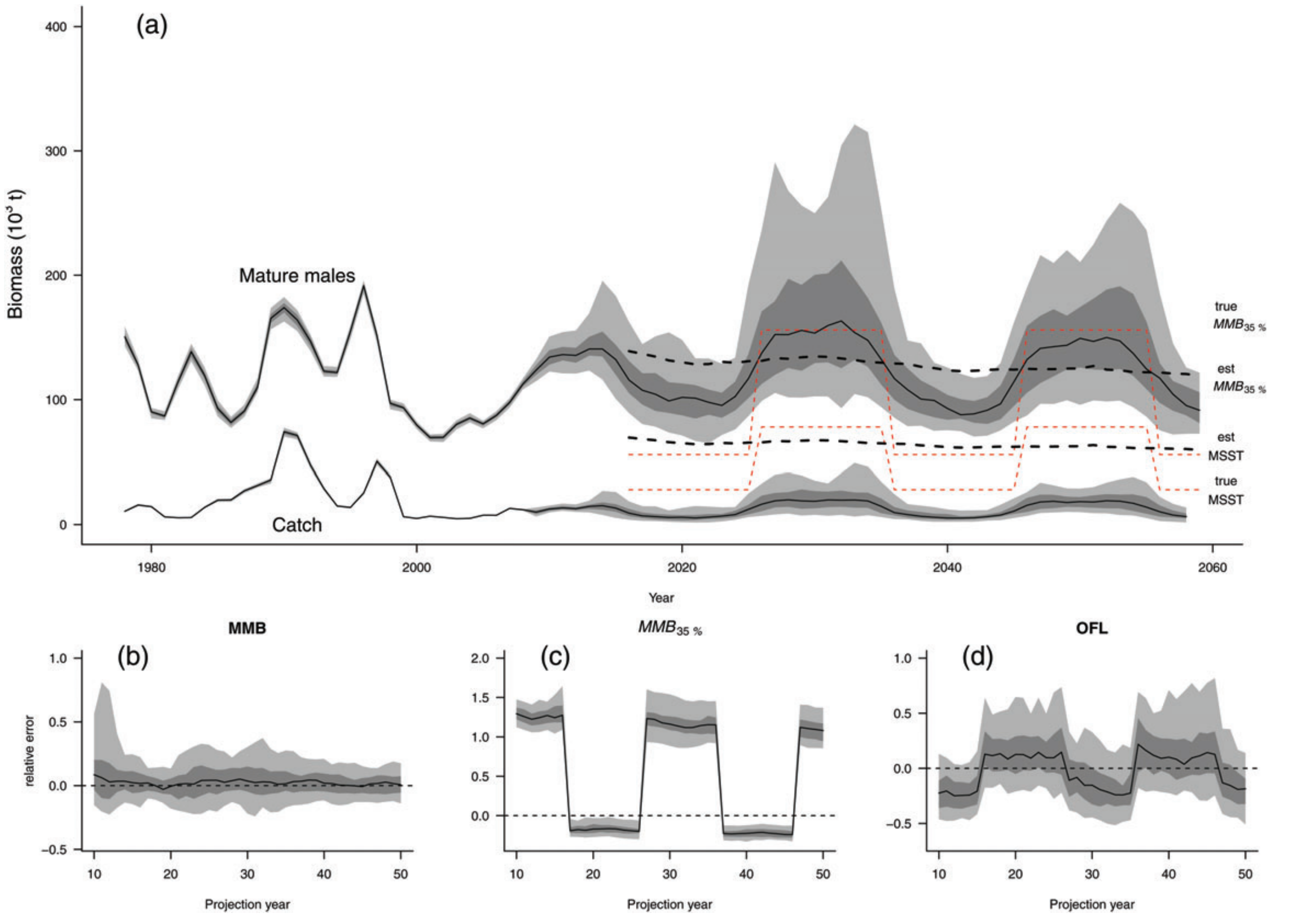

Figure 6. Results for a scenario in which the operating model is "regime-based" and the estimation method is *status quo*. MMB and catch in thousands of tonnes (a). Thick dashed line is the median estimated $MMB_{35\%}$. Thin dashed lines are ranges for the true $MMB_{35\%}$ (top) and MSST (bottom). Distributions of relative error in MMB (b), $MMB_{35\%}$ (c), and the OFL (d). For all graphs, light grey outlines 5th and 95th quantiles; dark grey outlines 25th and 75th quantiles. Thin solid lines are the medians.

algorithm has progressed the number of years into the "new" regime that is the assumed length of the regime, without encountering observations that are inconsistent with a shift.

STARS was incorporated into an HCR in this analysis to detect changes in recruitment "regime". HCRs with target biomasses based on expected recruitment for the current recruitment regime (with "recruitment regime" defined by STARS) are used here to capture sudden changes in productivity and will be referred to as "regime-based". An increase in overfishing due to poor identification of regime shifts can occur when HCRs incorporate STARS (A'mar *et al.*, 2009a). However, snow crab are observed as "recruits" to the survey several years before recruiting to the exploitable population, so perhaps changes in recruitment regimes will be identified more easily. The regime-based HCR presented only changes the way expected recruitment to the smallest size class in the model is calculated and hence the average recruitment term when computing the B_{MSY} proxy. Spawning biomass-per-recruit calculations used to calculate B_{MSY}, therefore, do not depend on regime, i.e. regime shifts are assumed only to influence recruitment to the smallest size class in the population dynamics model, not natural mortality, growth, or any other biological processes. This is reasonable because environmental conditions are thought to impact early life stages most heavily (Kruse *et al.*, 2007).

A regime-based alternative for the application of the ADFG HCR is difficult to formulate because the target biomass is based on TMB during 1983–1997. However, the relevant laws (Alaska Statutes, 2012) state that the target biomass is meant to be analogous to B_{MSY}. Regime-based versions of the ADFG HCR were developed in a similar manner to the federal HCR by estimating a proxy for both F_{MSY} and B_{MSY}, except that B_{MSY} is based on total mature biomass instead of MMB. F_{MSY} is set as $F_{35\%}$ in the same manner as the federal HCR (i.e. the spawning biomass referenced is MMB, not TMB) because only males are fished. These proxies for B_{MSY} and F_{MSY} are used in place of the ADFG reference points.

Performance metrics

Management strategies applied by the NPFMC seek to achieve maximum sustainable yield while avoiding overfishing and overfished stocks. Consequently, the most important metrics for measuring performance of an HCR are long-term yield, the probability of a stock becoming overfished, and the probability of overfishing. The probability of correctly identifying overfishing and overfished statuses can be evaluated because both the "true" and "estimated" states of the fishery are known in the operating model. Performance metrics are calculated over the last 40 years of the simulation period

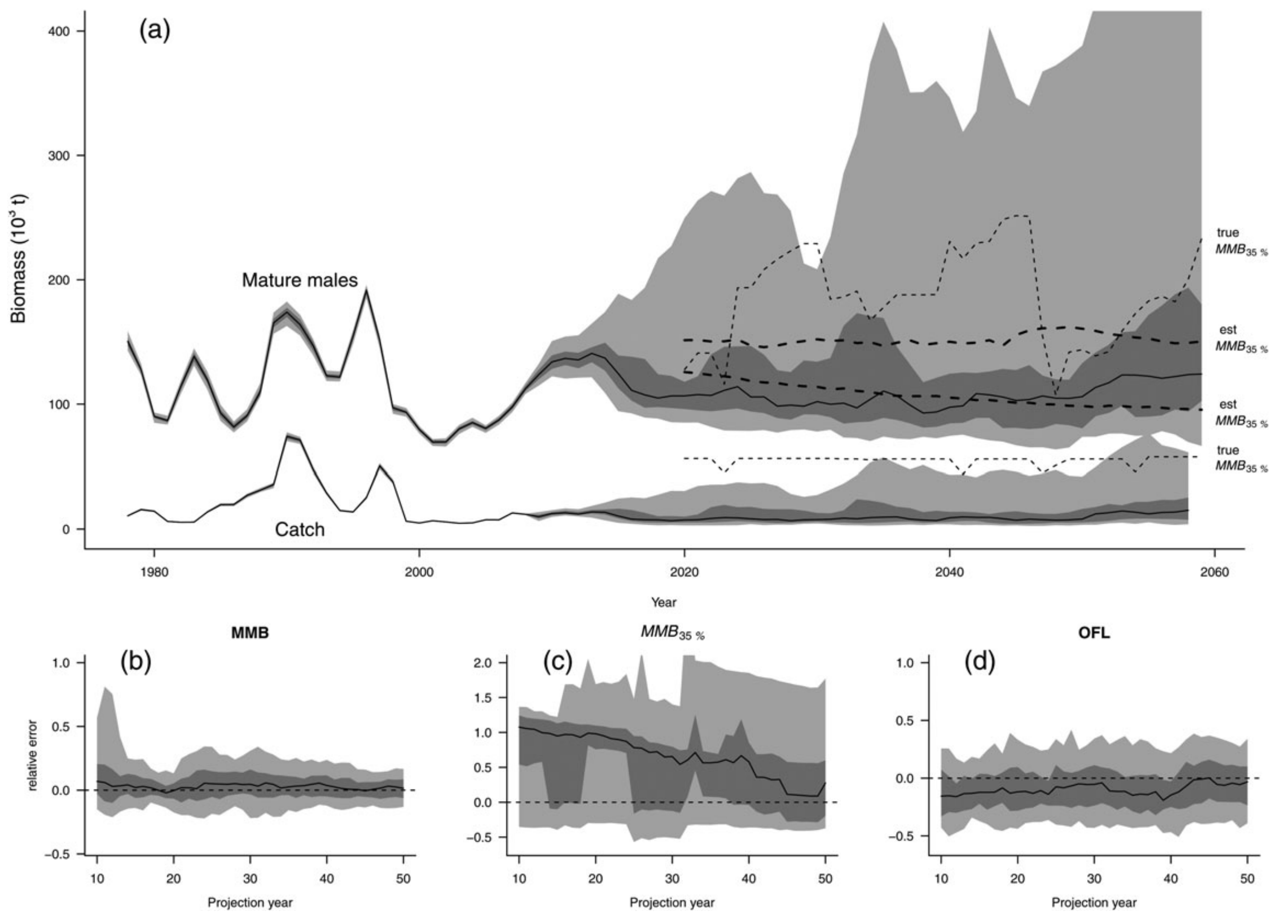

Figure 7. Results for the scenario in which the operating model is "oscillating control" and the management strategy is *status quo*. MMB and catch in thousands of tonnes (a). Thick dashed line is the range of estimated $MMB_{35\%}$. Thin dashed lines are ranges for the true $MMB_{35\%}$ (top). Distributions of relative error in MMB (b), $MMB_{35\%}$ (c), and the OFL (d). For all graphs, light grey outlines 5th and 95th quantiles; dark grey outlines 25th and 75th quantiles. Thin solid lines are the medians.

to allow two full cycles of 10-year alternating regimes. Finally, relative error in the estimates of B_{MSY}, MMB, and the OFL are examined to determine whether the nature of biases in these quantities noted by Szuwalski and Punt (2012b) are compounding, self-correcting or persistent. Relative error is formulated as:

$$E_t^{i,j} = \frac{\bar{Q}_t^{i,j} - Q_t^{i,j}}{Q_t^{i,j}}, \tag{7}$$

where $E_t^{i,j}$ is the relative error for quantity i during year t for simulation j, $Q_t^{i,j}$ is the true (i.e. based on the operating model) value for quantity i during year t for simulation j, and $\bar{Q}_t^{i,j}$ is the estimate of quantity i during year t for simulation j from the estimation method. The median absolute relative error (MARE, a measure of error and bias) and the mean-median [mean (over simulations) median (over years)] relative error over the last 40 years of the projections (MMRE, a measure of bias) for selected management quantities summarize the results and follow the format: B_{MSY} [0.02; 0.03], where 0.02 is the MARE and 0.03 is the MMRE. An MMRE and MARE of 0.0 represent perfectly accurate (MMRE and MARE) and precise (only for MARE) estimates; MARE is always positive, but MMRE can be negative.

Results

Performance of the *status quo* HCR

The *status quo* HCR returned the mean–median MMB during the years 2020–2059 to 108% of $MMB_{35\%}$ (Figure 4a). The true population was not overfished in any of the scenarios because (i) the ADFG HCR combined with the federal HCR is conservative compared with the federal HCR on its own (Figure 4a) and (ii) the estimation method underestimates $F_{35\%}$ (Figure 4b). The negative bias in $F_{35\%}$ gradually lessens over the course of the projections to −5% and is accompanied by a decreasing estimated B_{MSY} proxy ($MMB_{35\%}$) [0.07; 0.0] (Figure 4c). This pattern in $F_{35\%}$ is nearly identical in all simulations. The median estimated $MMB_{35\%}$ over the projection period was essentially unbiased by the end of the projection period. The OFL had an overall bias of 4% (MARE = 0.18, Figure 4d). The "true" OFL is the catch that would result from applying the "true" $F_{35\%}$ as calculated from the operating model. Overfishing (based on a comparison of the true OFL and the actual removals) occurred only in 4% of the simulations (Figure 5a). The mean–median catch over the projection period was 40 600 t, with a standard deviation of 2200 t.

Mean–median MMB fluctuated widely around the estimated $MMB_{35\%}$ when applying the *status quo* HCR to data generated from the "regime-based" operating model (Figure 6a). MMB

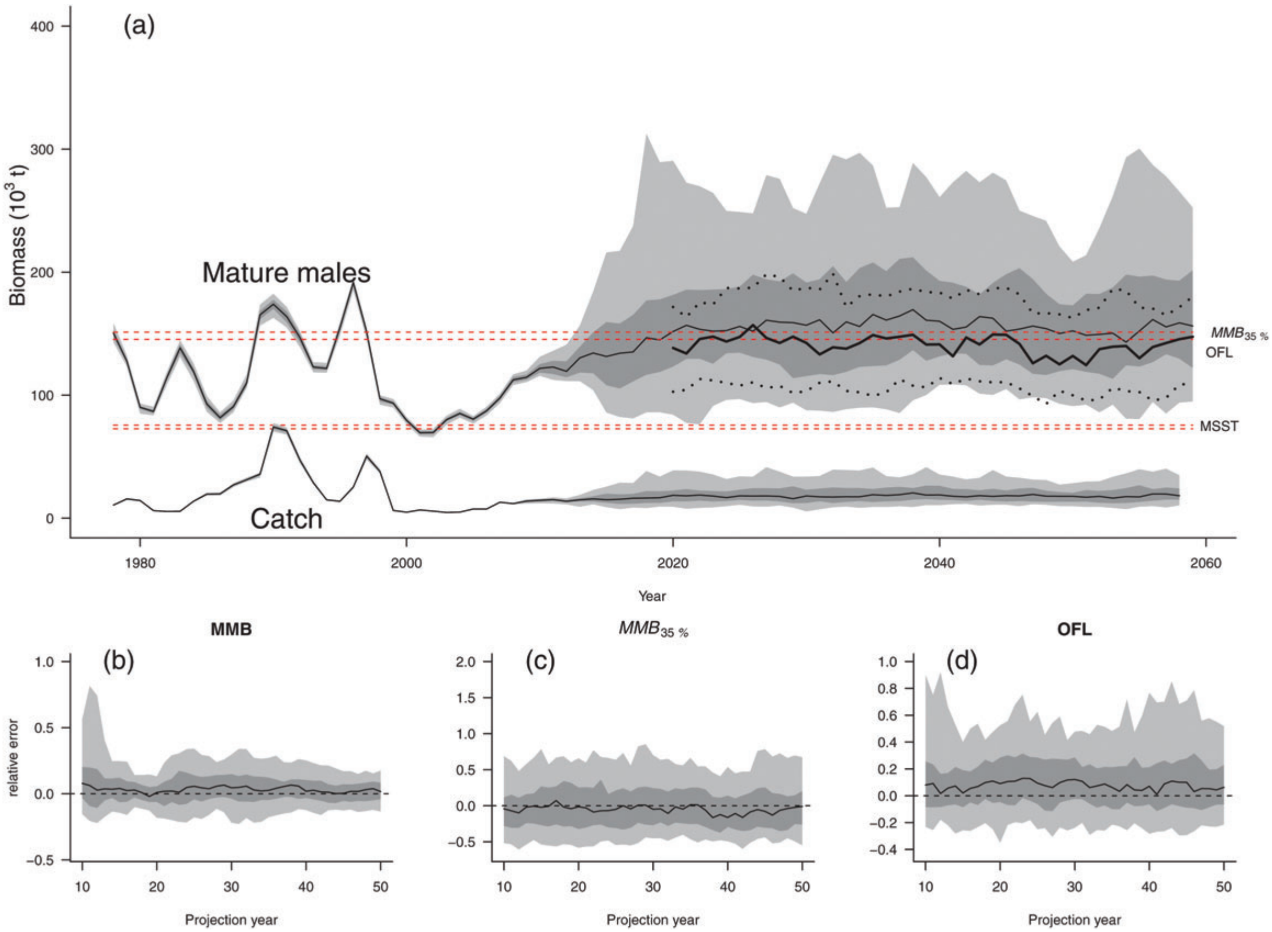

Figure 8. Results for a scenario in which the operating model is *status quo* and the management strategy is "regime-based". MMB and catch in thousands of tones (a). Thick solid line is the median from applying only the OFL HCR. Dashed lines are ranges for $MMB_{35\%}$ (top) and MSST (bottom). Dotted lines are the range for estimated B_{MSY}. Distributions of relative error in MMB (b), $MMB_{35\%}$ (c), and the OFL (d). For all graphs, light grey outlines 5th and 95th quantiles; dark grey outlines 25th and 75th quantiles. Thin solid lines in all plots are the medians.

was well below the estimated $MMB_{35\%}$, but above the true $MMB_{35\%}$ in low recruitment regimes; MMB was nearly at the true $MMB_{35\%}$ on average and well above the estimated $MMB_{35\%}$ in high regimes. This is intuitive because the estimation method uses all available recruitment observations (rather than those that pertain to the current regime) to calculate the B_{MSY} proxy. Estimates of $MMB_{35\%}$ [0.70; 0.87] were highly biased because the *status quo* HCR could not track the true target biomass (Figure 6a,c). This bias, coupled with positive bias in MMB [0.10; 0.03] (Figure 6b), resulted in a slightly negatively biased and relatively imprecise estimate of the OFL [0.23; −0.03] (Figure 6d). The mean–median catch over the projection was 27 600 t (s.d. = 12 800 t). Overfishing never occurred within high regimes, but occurred 19% of the time during low regimes (Figure 5b).

Projected MMB and catch under the *status quo* HCR in the oscillating control operating model are uncertain because of the variation among IPCC models used for projection (Figure 7a). Recruitment during periods in which recruitment is related to FSB can be much higher than when it is driven by the wPDO (see Figure 3c–f, for example). A large variability in recruitment translated into a huge loss of precision and positive bias in the estimated $MMB_{35\%}$ [0.73; 0.67] (Figure 7c). The positive bias in $MMB_{35\%}$ resulted in a negative bias in the OFL and relatively low precision [0.19, −0.10] (Figure 7d). The median catch over the projection for this scenario was 20 200 t (s.d. = 5200 t) and overfishing occurred with an average probability of 3% (Figure 5c).

Performance of the "regime-based" HCR

The utility of regime-based HCRs in non-regime-based systems is determined by the magnitude of bias and imprecision caused by using a selection of observations to calculate average recruitment. The bias in $MMB_{35\%}$ did not increase markedly under the *status quo* operating model, but the precision deteriorated [0.29; 0.05] (Figure 8c). This translated into a loss of precision and additional bias in the estimate of the OFL [0.21; 0.08], and also to an increased probability of overfishing (to 23%; Figure 5a). The median catch over the projection period was 39 700 t (s.d. = 2130 t), 3% lower than under the *status quo* HCR.

The value of a regime-based HCR is most easily seen when they are applied to the regime-based operating model. Compared with the *status quo* HCR, estimation of $MMB_{35\%}$ was nearly unbiased (−0.02 for regime-based vs. 0.87 for *status quo*) and much more precise (MARE = 0.35 vs. 0.70) under the regime-based HCR because it is able to track the true $MMB_{35\%}$ (Figure 9a,c). The precision of the OFL did not change, but the bias changed

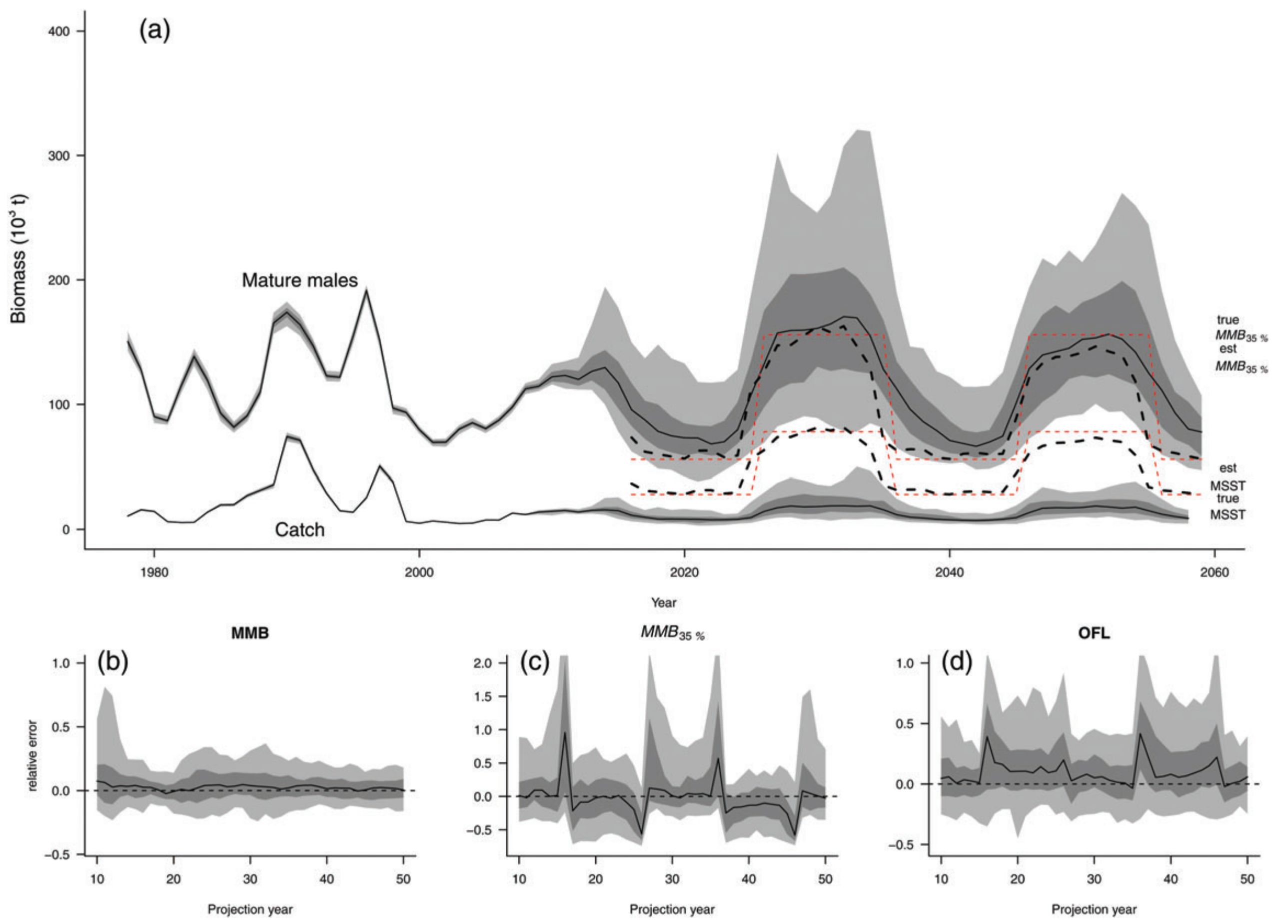

Figure 9. Results for a scenario in which the operating model is "regime-based" and the management strategy is "regime-based". MMB and catch in thousands of tones (a). Thick dashed line is the median estimated $MMB_{35\%}$ and MSST. Thin dashed lines are the median for the true $MMB_{35\%}$ (top) and MSST (bottom). Distributions of relative error in MMB (b), $MMB_{35\%}$ (c), and the OFL (d). For all graphs, light grey outlines 5th and 95th quantiles; dark grey outlines 25th and 75th quantiles. Thin solid lines are the medians.

sign and increased to 0.09 (Figure 9d). This was reflected in an increased probability of overfishing (19; 33% in high regimes, 3% in low regimes; Figure 5b), with particularly high probability around the years when the regime switches from high to low. There was an increase in mean–median catch (28 500 t) and a decrease in variability (s.d. = 10 100 t) when compared with the *status quo* HCR.

Projected MMB, B_{MSY}, and catch were highly variable in the scenarios in which recruitment followed the oscillating control model and the regime-based HCR was applied (Figure 10a). Estimates of $MMB_{35\%}$ [0.27; 0.03] improved compared with the *status quo* HCR (Figure 10c), while the bias in the OFL did not change magnitude, but changed signs [0.16; 0.05] (Figure 10d). There was a slight increase in the probability of overfishing compared with the *status quo* HCR (from 3 to 6%, respectively; Figure 5c), but the mean–median catch increased to 22 600 t (s.d. = 3600 t).

Discussion

Incorporating changes in inferred productivity in management strategies can reduce bias in calculated target biomasses, increase catches, and reduce variability in catches in regime-based systems. However, imprecision in target biomasses increases, the probability of overfishing increases, and yield is lost when applied to non-regime-based systems. Although observing recruits several years before entering the fishery was a potential opportunity to better identify shifts in regime, overfishing still increased under regime-based HCRs, mirroring the results of A'mar *et al.* (2009a) for walleye pollock in the Gulf of Alaska. There are two reasons for this: (i) shifts in regime were not captured in exactly the year they occurred because within-regime variability in recruitment was high and (ii) estimates of the B_{MSY} proxy were noisy because average recruitment was calculated using relatively few data points.

Regime-based target biomasses are most useful when the underlying dynamics of a system are truly regime-like and shifting from a "high" regime to a "low" regime. A stock may be falsely declared overfished under these circumstances if the *status quo* HCR is applied, which could result in potentially costly rebuilding plans. This did not happen in this study because (i) the fishing mortality from the ADFG HCR is conservative and (ii) the differences in average recruitment among regimes were not large enough for this to occur without higher fishing mortality. However, high fishing mortalities coincided with the overfished declaration for the actual fishery. Shifting from a "low" to a "high" regime under regime-based management strategies usually

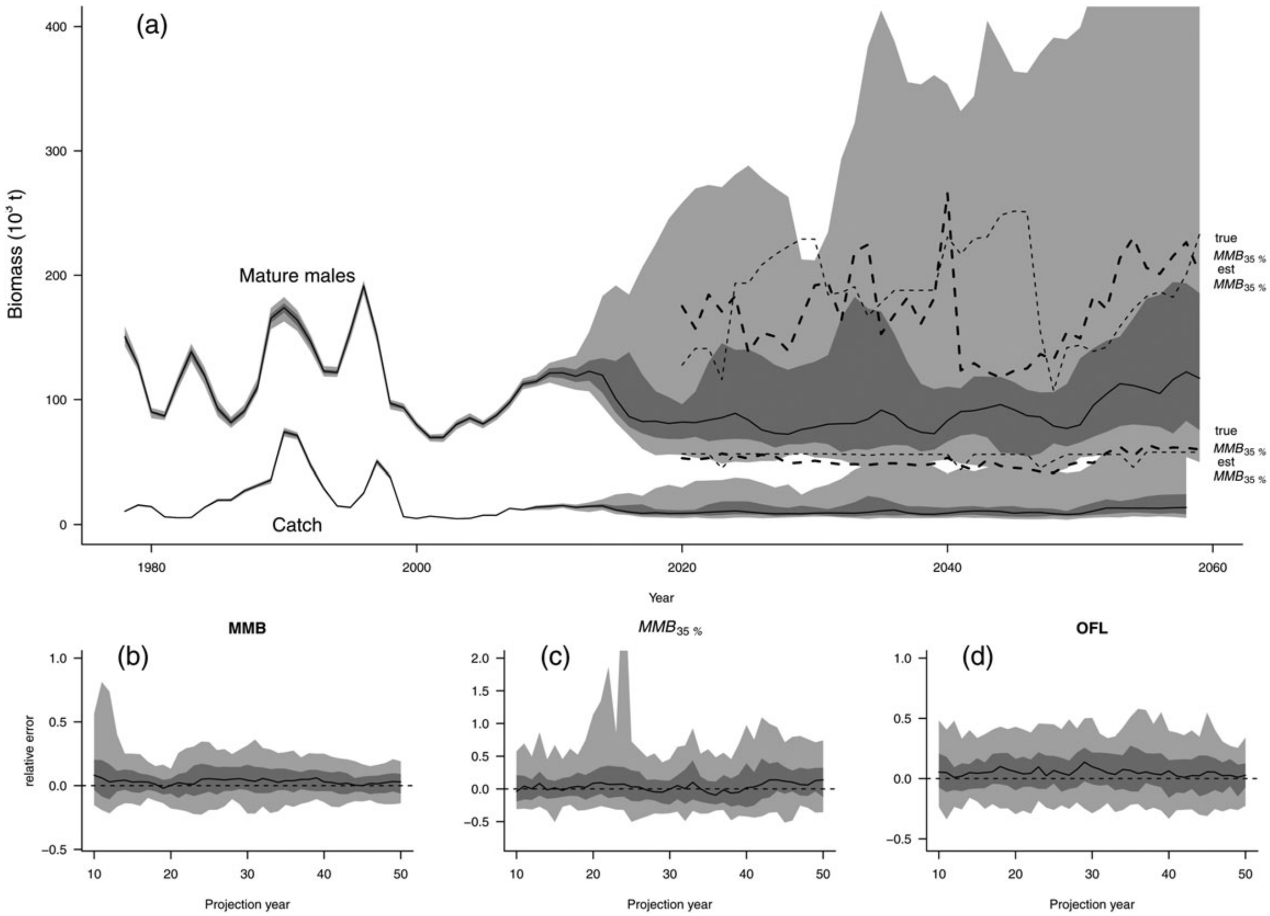

Figure 10. Results for a scenario in which the operating model is "oscillating control" and the management strategy is "regime-based". MMB and catch in thousands of tones (a). Thick dashed line is the range of estimated $MMB_{35\%}$. Thin dashed lines are range for the true $MMB_{35\%}$ (top). Distributions of relative error in MMB (b), B_{MSY} (c), and the OFL (d). For all graphs, light grey outlines 5th and 95th quantiles; dark grey outlines 25th and 75th quantiles. Thin solid lines are the medians.

leads to a reduction in fishing pressure because the estimate of the B_{MSY} proxy increases. This potentially reduces the OFL, which is counter to the actions taken by a non-regime-based management strategy. Consequently, regime-based HCRs have some utility, but only when the dynamics are truly regime-based. The deeper (and more complicated) issue that needs to be addressed before implementation of regime-based HCRs is determining when population dynamics are truly regime-like.

The accuracy of estimates (or proxies) of F_{MSY} is potentially more important than designation of a target biomass. The target biomass determines what proportion of F_{MSY} is applied: the full F_{MSY} is applied when the current mature biomass is above B_{MSY}; some fraction of F_{MSY} is applied when the current mature biomass is below B_{MSY}. This analysis assumed that the population processes that determine the proxy for F_{MSY} (e.g. natural mortality, growth, and selectivity for crabs large enough to have recruited to the survey gear) do not change from one regime to another. This may be a poor assumption if a stock has documented changes in one of these processes in response to environmental changes. However, studies (tagging or otherwise) required to identify these changes every time a regime shift is suspected for EBS snow crab are not currently feasible. Similarly, applying the estimation method over a much shorter period to generate "regime-specific" estimates of F_{MSY} is not likely to lead to reliable estimates because of the lack of contrast over short time-series. Many years of data that span high and low stock sizes that have undergone high and low fishing pressure are necessary to truly understand the response of a stock to fishing (Magnusson and Hilborn, 2007).

As for the future of the snow crab fishery, levels of catch will likely never reach those experienced in the 1980s due to the well-defined harvest strategy. Future recruitment may be typified by increasingly frequent periods of good recruitment, which will be seen as higher levels of MMB. However, some IPCC models suggested that MMB may never reach historical highs. In general, these projections should not be interpreted too strongly—their main utility here is for identifying HCRs which are robust to uncertainty and not for making predictions. Environmental–recruitment relationships often collapse with the addition of new data (Myers, 1998), and a spatial component not accounted for in this analysis may influence recruitment (e.g. Parada *et al.*, 2010). Additional years of recruitment estimates (particularly after the recent juxtaposition of very cold and very warm years in the Bering Sea) should be informative as to the veracity of the oscillating control model.

Regime-based HCRs are risky when applied to non-regime-based systems and there is a positive bias in F_{MSY}; this may result in an unchecked downward trajectory in the mature biomass (i.e. recruitment overfishing—this did not occur in any of the scenarios presented here because F_{MSY} was underestimated). Regime-based dynamics cause population dynamics to be non-stationary, but most management strategies are based on stationary population dynamics. Incomplete understanding of non-stationary dynamics in a system requires a precautionary approach if stationary dynamics are assumed in the management strategy. Future research on methods to definitively declare regime shifts and identify stocks within those systems influenced by these shifts are likely required before regime-based HCRs will be implemented by management agencies.

Acknowledgements

We thank the North Pacific Research Board for funding this work, James Overland and Muyin Wang for providing projections of the PDO, and Jack Turnock for providing his assessment code. We thank two anonymous reviewers for their comments on an earlier draft of the paper. This is NPRB publication #374.

References

Adkison, M. D., Peterman, R. M., Lapointe, M. F., Gillis, D. M., and Korman, J. 1996. Alternative models of climatic effects on sockeye salmon (*Oncorhynchus nerka*) productivity in Bristol Bay, Alaska and Fraser River, British Columbia. Fisheries Oceanography, 5: 137–152.

Alaska Statutes. 16.05.251. 2012. 5 AAC 35.517. Bering Sea *C. opilio* Tanner crab harvest strategy.

A'mar, Z. T., Punt, A. E., and Dorn, M. W. 2009a. The impact of regime shifts on the performance of management strategies for the Gulf of Alaska walleye pollock (*Theragra chalcogramma*) fishery. Canadian Journal of Fisheries and Aquatic Science, 66: 2222–2242.

A'mar, Z. T., Punt, A. E., and Dorn, M. W. 2009b. The evaluation of two management strategies for the Gulf of Alaska walleye pollock fishery under climate change. ICES Journal of Marine Science, 66: 1614–1632.

Gelman, A., Carlin, J. B., Stern, H. S., and Rubin, D. B. 2004. Bayesian Data Analysis, 2nd edn. Chapman and Hall, London. 668 pp.

Hollowed, A. B., Bond, N. A., Wilderbuer, T. K., Stockhausen, W. T., A'mar, Z. T., Beamish, R. J., Overland, J. E., *et al.* 2009. A framework for modeling fish and shellfish responses to future climate change. ICES Journal of Marine Science, 66: 1584–1594.

Hollowed, A. B., Hare, S. R., and Wooster, W. S. 2001. Pacific Basin climate variability and patterns of Northeastern pacific marine fish production. Progress in Oceanography, 49: 257–282.

Hunt, G. L., Coyle, K. O., Eisner, L. B., Farley, E. V., Heintz, R. A., Mueter, F., Napp, J. M., *et al.* 2011. Climate impacts on eastern Bering Sea foodwebs: a synthesis of new data and an assessment of the Oscillating Control Hypothesis. ICES Journal of Marine Science, 68: 1284–1296.

Ianelli, J. N., Hollowed, A. B., Haynie, A. C., Mueter, F. J., and Bond, N. A. 2011. Evaluating management strategies for eastern Bering Sea walleye pollock (*Theragra chalcogramma*) in a changing environment. ICES Journal of Marine Science, 68: 1297–1304.

IPCC. 2007. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Ed. by R. K. Pachauri, and A. Reisinger. IPCC, Geneva. 104 pp.

Kruse, G. H., Tyler, A. V., Sainte-Marie, B., and Pengilly, D. 2007. A workshop on mechanisms affecting year-class strength formation in snow crabs, *Chionoecetes opilio*, in the eastern Bering Sea. Alaska Fishery Research Bulletin, 12: 278–291.

Litzow, M. A. 2006. Climate regimes shifts and community reorganization in the Gulf of Alaska: how do recent shifts compare with 1976-1977? ICES Journal of Marine Science, 63: 1386–1396.

Magnusson, A., and Hilborn, R. 2007. What makes fisheries data informative? Fish and Fisheries, 8: 337–358.

Mantua, N. J., and Hare, S. R. 2002. The Pacific decadal oscillation. Journal of Oceanography, 58: 35–44.

Mantua, N. J., Hare, S. R., Zhang, Y., Wallace, J. M., and Francis, R. C. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bulletin of American Meteorological Society, 78: 1069–1079.

Mueter, F. J., Boldt, J. L., Megrey, B. A., and Peterman, R. M. 2007. Recruitment and survival of northeast Pacific Ocean fish stocks; temporal trends, covariation and regime shifts. Canadian Journal of Fisheries and Aquatic Science, 64: 911–927.

Myers, R. A. 1998. When do environment-recruitment correlations work? Reviews in Fish Biology and Fisheries, 8: 285–305.

NPFMC (North Pacific Fishery Management Council)/NMFS (National Marine Fisheries Service). 2000. Environmental assessment for the Bering Sea snow crab rebuilding plan. Amendment 14. North Pacific Fishery Management Council, Anchorage, AK, USA. www.dakr.noaa.gov.

NPFMC (North Pacific Fishery Management Council)/NMFS (National Marine Fisheries Service). 2007. Environmental Assessment for Amendment 24. Overfishing definitions for Bering Sea and Aleutian Islands King and Tanner crab stocks. North Pacific Fishery Management Council, Anchorage, AK, USA. www.dakr.noaa.gov.

Overland, J., Rodionov, S., Minobe, S., and Bond, N. 2008. North Pacific regime shifts: definitions, issues, and recent transitions. Progress in Oceanography, 77: 92–102.

Overland, J. E., and Wang, M. 2007. Future climate of the North Pacific Ocean. EOS Transactions of the American Geophysical Union, 88: 178–182.

Parada, C., Armstrong, D. A., Ernst, B., Hinckley, S., and Orensanz, J. M. 2010. Spatial dynamics of snow crab (*Chionoecetes opilio*) in the eastern Bering Sea—Putting together the pieces of the puzzle. Bulletin of Marine Science, 86: 413–437.

Punt, A. E. 2003. Evaluating the efficacy of managing West Coast groundfish resources through simulations. Fish Bulletin US, 101: 860–873.

Punt, A. E., and Szuwalski, C. S. 2012. How well can F_{MSY} and B_{MSY} be estimated using empirical measures of surplus production? Fisheries Research, 134–136: 113–124.

Punt, A. E., Szuwalski, C. S., and Turnock, J. 2012a. Determining implications of uncertainty in snow crab (Chionoecetes opilio) recruitment using Management Strategy Evaluation. North Pacific Research Board Final Report 813, 118 p.

Rodionov, S. 2004. A sequential algorithm for testing climate regime shifts. Geophysical Research Letters, 31: L09204.

Rodionov, S., and Overland, J. E. 2005. Application of a sequential regime shift detection method to the Bering Sea ecosystem. ICES Journal of Marine Science, 6: 328–332.

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

Smith, A. D. M. 1994. Management strategy evaluation: the light on the hill. *In* Population Dynamics for Fisheries Management, pp. 249–253. Ed. by D. A. Hancock. Australian Society for Fish Biology, Perth, WA.

Smith, A. D. M., Sainsbury, K. J., and Stevens, R. A. 1999. Implementing effective fisheries management systems – management strategy evaluation and the Australian partnership approach. ICES Journal of Marine Science, 56: 967–979.

Szuwalski, C. S., and Punt, A. E. 2012b. Identifying research priorities for management under uncertainty: The estimation ability of the stock assessment method used for eastern Bering Sea snow crab (*Chionoecetes opilio*). Fisheries Research, 134–136: 82–94.

Turnock, B. J., and Rugolo, L. J. 2011. Stock Assessment of eastern Bering Sea snow crab. *In* NPFMC (North Pacific Fishery Management Council). Stock Assessment and Fishery Evaluation Report for the King and Tanner Crab Fisheries of the Bering Sea and Aleutian Islands Region: 2011 Crab SAFE. September 2011. North Pacific Fishery Management Council, Anchorage, AK, USA.

Wilderbuer, T. K., Hollowed, A. B., Ingraham, W. J., Jr, Spencer, P. D., Connors, M. E., Bond, N. A., and Walters, G. E. 2002. Flatfish recruitment response to decadal climatic variability and ocean conditions in the eastern Bering Sea. Progress in Oceanography, 55: 235–247.

Handling editor: Emory Anderson