Review of

Alaska Crab Overfishing Definitions

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Report to

University of Miami Independent System for Peer Reviews

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Executive summary

- This report is a review of proposed overfishing definitions (OFD) for Bering Sea and Aleutian Islands (BSAI) king and Tanner crab stocks. An OFD is required to meet National Standard 1 of the Magnuson-Stevens Fishery Conservation and Management Act. The proposal is for a five tier system, specifying an MSY control rule within each tier, and is intended to replace the existing three tier system.
- The existing OFD provides no effective cap on exploitation rates. As a framework, the proposed OFD represents a major improvement. If successfully implemented it will meet the National Standard 1 requirement for MSY control rules which, if implemented as a harvest strategy, would be expected to result in a long-term average yield approximating MSY. There are, however, a number of issues that need to be addressed before the proposed OFD could be implemented.
- The proposed framework is comprehensive and adaptable, allowing the definition of MSY control rules in a very flexible way. The disadvantage of this flexibility is that it also implies complexity – there are a number of parameters for which default values will need to be determined before implementation.
- The main difficulty in establishing default parameter values, and in finding proxy values for reference points in Tiers 3 and 4 of the proposed OFD, is in the definition of effective spawning biomass (ESB). ESB is used in the MSY control rules and in the stock-recruitment relationships that are used to find proxy values for F_{MSY} and to test the performance of the proposed OFD under various parameterisations. Any satisfactory definition of ESB must (a) be demonstrably proportional to total fertilised egg production (TFEP), and (b) be responsive to fishing mortality. The first criterion is met by none of the definitions of ESB considered thus far. The problem arises out of the complex mating systems of king and Tanner crabs coupled with fisheries directed only at males. Simple mating ratios appear inadequate to capture this complexity.
- Suggestions for simple interim definitions of ESB are made in this report, together with recommendations for further research to identify more satisfactory alternatives to be used in the future.
- Simulation modelling was used to compare the performance of OFDs and to provide insight into likely default values for parameters in the proposed OFD. This approach is sound in principle and correctly specified in practice (in terms of model structures), but given that the simulation outcomes depend on a correctly specified measure for ESB no default parameter values can yet be recommended.
- Simulations were undertaken by two modelling teams. This is a strength in terms of allowing critical analysis of assumptions and robust conclusions. However, there are differences between the teams in their interpretation of the available scientific evidence on some fundamental issues of crab life history. These differences will need to be resolved in order to progress the simulation modelling to a final outcome.
- Simulation outcomes were largely judged in terms of rebuilding times for depleted stocks. Other aspects of OFD performance will need to be tested, such as the trade-off

between rebuilding times and level and constancy of yield. It should also be recognised that maintaining sustainable exploitation of healthy stocks is as important a function of an OFD as allowing recovery of depleted stocks.

- An important problem with the simulations was that the MSY control rule was treated as if it was a harvest control rule. This fails to recognise the role of the State in defining a precautionary buffer between target and limit fishing mortality rates. It is also likely to lead to selection of default parameter values for the proposed OFD that will place undue constraints on the capacity of the State to manage the fisheries according to precautionary and other objectives. It is recommended that MSY control rules are always tested in conjunction with realistic State harvest strategies in the simulations.
- It is concluded that, although work remains to be done before the proposed OFD can be implemented, the obstacles to successful implementation are not insurmountable. Given the urgent need for the existing OFD to be replaced by a more satisfactory alternative, it is recommended that a simple interim definition of ESB be adopted in the immediate term and that new simulations aimed at identifying default parameter values are undertaken at the earliest opportunity. These simulations will involve harvest strategies as well as MSY control rules.

Recommendations

Recommendations arising from this review are listed under *ToR (b): Recommendations of improvements to proposed overfishing definitions* (p.21) and *ToR (e): Suggested research priorities* (p.24).

Background

The North Pacific Fishery Management Council (NPFMC) has determined that the current overfishing definitions (OFD) for Bering Sea and Aleutian Islands (BSAI) crab stocks are in need of revision. Proposals for revised OFDs have been developed by a four member Work Group reporting to the Crab Plan Team (CPT). A panel of three independent reviewers was invited by the Alaska Fisheries Science Center (AFSC) to review these proposals, along with simulation models used to test their performance and to determine default parameter values and proxies.

The review panel members were Patrick Cordue (independent consultant, New Zealand), Nick Caputi (Department of Fisheries, Western Australia) and the present author (Michael Bell, independent consultant, UK). The Terms of Reference for the review were:

(a) A statement of the strengths and weaknesses of the proposed overfishing definitions, simulation models and analytical approaches.

(b) Recommendations for improvements to proposed overfishing definitions or alternative definitions,

(c) A review of the model configurations, formulations and methods used to account for uncertainty.

(d) A review of input parameters (fishery, biological and life history parameters and spawner recruit relationships) used in simulation models.

(e) Suggested research priorities to improve our understanding of essential population and fishery dynamics necessary to formulate best management practices.

The summary of review findings given below is structured according to these Terms of Reference, although overlaps in the relevance of items means that most of the issues are covered under ToR (a). This report represents the individual opinion of the present author. No attempt was made to reach a consensus among the three reviewers, but it was apparent during the review meeting that differences among the reviewers are likely to be in emphasis rather than substance.

Description of review activities

Documents relating to overfishing definitions and management of Bering Sea and Aleutian Islands (BSAI) crab stocks were provided to reviewers on the web site www.afsc.noaa.gov/refm/stocks/CrabWs.htm. This web site was initially developed as part of an inter-agency workshop on crab overfishing definitions held in February 2006 in preparation for the CIE review and NPFMC action. Appendix 1 lists the key documents on this web site and other documents provided during and after the meeting. Prior to the meeting attention was drawn to a number of key documents which provide the necessary background for the review meeting:

(1) the Statement of Work for the Work Group responsible for developing proposals for the overfishing definition (Rugolo, 2004);

(2) a description of the proposed tier system for the overfishing definition (NPFMC, 2006; Siddeek & Zheng, 2006; Turnock & Rugolo, 2006a);

(3) stock assessments for Bristol Bay red king crab (Zheng, 2004) and eastern Bering Sea snow crab (Turnock & Rugolo, 2005);

(4) position papers discussing unresolved issues for the Work Group (Turnock & Rugolo, 2006b; Zheng, 2006)

(5) report and recommendations from the February workshop (NPFMC, 2006); and

(6) results of projections examining the performance of the proposed overfishing definition (Siddeek & Zheng, 2006; Turnock & Rugolo, 2006a).

A review meeting took place at the Alaska Fisheries Science Center, Seattle, 24-28 April 2006 (see Agenda at Appendix 2). The meeting was chaired by Anne Hollowed and Jim Ianelli of the NMFS. The meeting was introduced by Anne Hollowed, followed by a description of crab management and the need for a revised overfishing definition by Diana Stram, NPFMC. Over the course of three days, members of the interagency Work Group charged with developing proposals for a revised OFD (Shareef Siddeek and Jie Zheng of ADF&G, Jack Turnock and Lou Rugolo of NMFS) presented overviews of the proposed OFD and tier system, assessments for snow crab in the eastern Bering Sea and red king crab in Bristol Bay, approaches to estimating proxy values for biological reference points and simulations testing the performance of OFDs. Extensive discussions with CIE panel members took place alongside the presentations, so that this part of the programme extended to the end of the third day of the meeting. CIE panel members met on day 4 to discuss the main issues raised during the presentations, and sought some clarifications from NMFS staff involved in the review meeting. The remainder of the review meeting time was spent in preparing to write individual review reports.

Summary of findings

General

The existing OFD for BSAI crab stocks consists of three tiers, from Tier 1 for stocks with the least amount of information on stock status and exploitation to Tier 3 for stocks with the most amount of information (Turnock & Rugolo, 2006a). The maximum fishing mortality threshold (MFMT) is set to F_{MSY}, assumed to be equal to M (set to 0.2 for king crabs and 0.3 for snow and Tanner crabs). The minimum stock size threshold (MSST) is set to ½B_{MSY} for stocks in Tier 3, where B_{MSY} is assumed to take the value of the average of survey estimates of mature male and female biomass during 1983-97. MSST is undefined for stocks in Tiers 1 and 2. MSY is determined either as the product of F_{MSY} and B_{MSY} (Tier 3) or from a proxy of mature biomass and stock utilisation rate (Tiers 1 and 2).

As pointed out in a presentation on the Statement of Work for the CPT Work Group (Rugolo, 2006), the existing OFD is unsatisfactory in a number of respects. Most importantly, the definition of sustainable yield involves all mature crabs, both sexes and all shell classes, irrespective of vulnerability to the directed fishery, and provides no effective cap on exploitation rates. Rugolo (2006) provides an example where catch levels for snow crabs could be set higher than the total exploitable biomass (legal males), without overfishing being declared. Projection models used by Turnock & Rugolo (2006a) demonstrate that fishery management under the current OFD cannot provide effective rebuilding to B_{MSY} from overfished stock levels for both red king and snow crab stocks (notwithstanding concerns about definitions of effective spawning biomass in these simulations – see below, p.15). The need for a revised OFD is very clearly established. The review findings presented below indicate that much work remains to be done before a revised OFD could be accepted, but retaining the *status quo* OFD is not a tenable option for the immediate future.

ToR (a): Strengths and weaknesses of the proposed overfishing definitions, simulation models and analytical approaches

Framework for overfishing definitions

Proposals for a revised OFD for BSAI crab stocks involve a system of five tiers, from Tier 1 for stocks with the most complete and reliable assessments to Tier 5 for stocks with data only on the catch history (Siddeek & Zheng, 2006; Turnock & Rugolo, 2006a). An MSY control rule for Tiers 1 to 4 involves defining F_{MSY} and B_{MSY} or proxies, and calculating the overfishing limit for fishing mortality F_{OFL} in terms of these values and parameters which define the slope of F_{OFL} in relation to stock biomass and the threshold stock level below which the fishery is closed. Figure 1 shows this proposed MSY control rule compared with the default MSY control rule advocated by Restrepo *et al.* (1998) in technical guidance on implementing National Standard 1 of the Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA). The proposed OFD is much more conservative than the default OFD in that for any positive value of the parameter α the value of F_{OFL} will always be lower for any given stock biomass level. The suggested default for MSST is $(1–M)*B_{MSY}$, which accords with the notion that under MSY harvest levels the scale of fluctuations in biomass around B_{MSY} is likely to be in the order of $M*B_{MSY}$. Although the proposed setting of MSST at $½B_{MSY}$ is lower than this default, this is scarcely relevant since reductions in fishing mortality at higher biomass levels provide for returning stock trajectories towards B_{MSY} even in the absence of special stock rebuilding plans. Indeed, it could be argued that MSST could be dispensed with altogether under the new proposals, although there is certainly merit in having a trigger point at which the effectiveness of F_{OFL} levels under the control rule are re-examined.

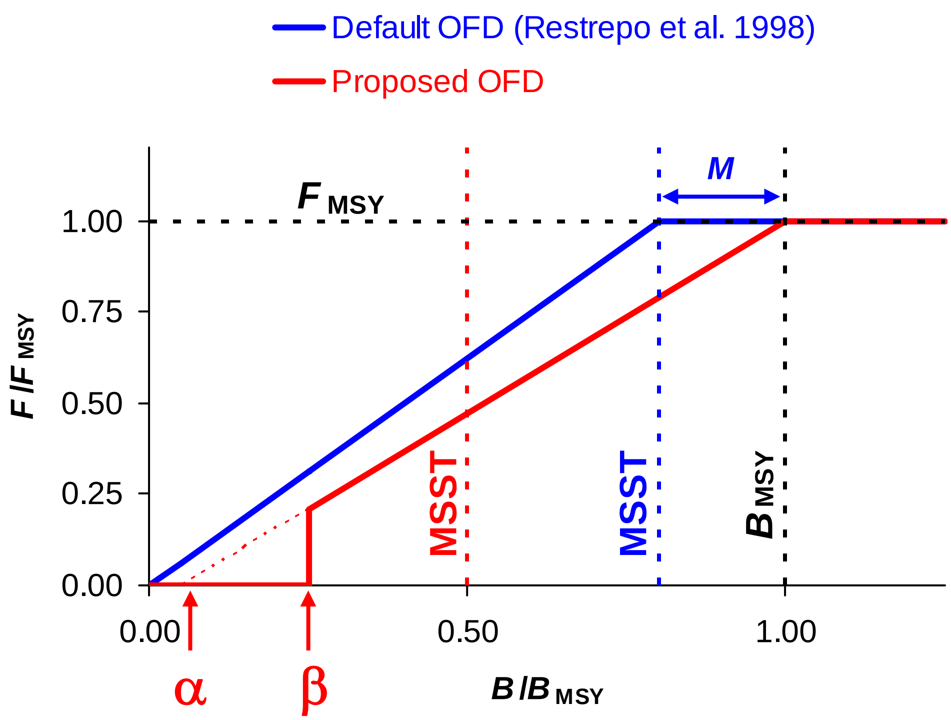

FIGURE 1. Proposed MSY control rule (red lines and captions) shown in relation to the default MSY control rule (blue lines and captions) put forward in technical guidance by Restrepo *et al.* (1998).

As a framework, the proposed OFD represents a major improvement over the existing OFD. National Standard 1 of the MSFCMA requires an MSY control rule which, if implemented as a harvest strategy, would be expected to result in a long-term average catch approximating MSY. If (and only if) successfully implemented, the proposed OFD would be expected to fulfil this requirement in the sense that the capacity of stocks to support harvests up to MSY should not be compromised by excessive fishing mortality. The same certainly could not be said of the existing OFD. As described below, there are a number of issues which need to be addressed before the proposed OFD could successfully be implemented. Given the inadequacy of the current OFD, it is vital that issues related to the implementation of the proposed OFD be resolved. Emphasis is given below to short-term actions that could be progressed on a time-scale to allow early implementation of the proposed OFD.

A second major strength of the proposed framework is that it is comprehensive. This is true in two senses. First, the use of a five tier system allows account to be taken of the state of knowledge of the stock and the reliability of assessments and monitoring data. Siddeek & Zheng (2006) and Turnock & Rugolo (2006a) allocate most of the 22 BSAI crab stocks to Tier 5, for which the overfishing limit depends only on an average of historical catches. No stock is expected to be allocated to Tiers 1 and 2, which require at least point estimates for F_{MSY} and $B_{MSY,}$ and only three stocks are allocated to Tier 3, requiring a reliable proxy for F_{MSY}. As surveys, assessments and monitoring systems improve, and as improved estimates of biological parameters become available, it would be expected that stocks could be promoted within the tier system. This perhaps applies mostly to Tier 3 and 4 stocks; information is perhaps likely to remain scanty for Tier 5 stocks taken mainly as a by-catch in groundfish-directed fisheries.

Second, the framework is comprehensive in the sense that it has several parameters which allow the dependence of F_{OFL} on stock biomass to be defined in a very flexible way. The α parameter acts as an *x*-intercept on the MSY control rule graph, determining how quickly F_{OFL} is reduced as biomass decreases, while the β parameter sets a biomass threshold for closure of the fishery (Figure 1). This allows great flexibility in defining the MSY control rule: *e.g.* $\alpha=-\infty$, $\beta=0$ defines a flat F_{MSY} control rule; $\alpha=\beta$ allows F_{OFL} to take any value between 0 and F_{MSY}, depending on biomass; *etc*. This flexibility allows the capacity for evolution, adaptation and refinement in the implementation of the OFD for individual stocks as more information becomes available.

There are also disadvantages to this flexibility. In the first place, freedom in defining the shape of the MSY control rule presents challenges for setting up starting defaults. Parameters α and β are arbitrary, in the sense that they have no objective definition – *e.g.* β is not defined as the threshold biomass at which there is an *x*% probability of event *y* occurring. This in itself is not necessarily a drawback, since it is the operational properties of the parameters that we are interested in, but it does mean that we can only determine the best combinations of parameters by examining the emergent properties of the systems in which they are defined. This requires extensive simulations (as by Siddeek & Zheng, 2006), in which we need to determine the criteria by which we judge one outcome better than another (see below).

A second disadvantage of the flexible formulation for the MSY control rule is that capacity for evolution also implies being subject to change. Given revision of assessments on an annual basis, there is the capacity to revise the parameters of the OFD on each occasion that it is applied. Revision of biomass and fishing mortality estimates as new data are added inevitably will change the perception of past stock status: biomass and fishing mortality levels previously considered as being within precautionary limits might, in the light of new data, be considered as representing overfished or overfishing states, and *vice versa*. This in itself is not a problem, as we can only act in the present, based on the best available information on current conditions. What is a problem, however, is that it is not just the estimates themselves that change, but also the reference points against which they are compared. This applies to F_{MSY}, B_{MSY} and their proxies (*i.e.* Tiers 1 to 3), which depend on the nature of the stock-recruitment relationship (SRR). Given poorly defined SRRs (*e.g.* Zheng, 2004), there is the capacity for new data points to be highly influential. Values α and β are less subject to annual change, given that they are selected rather than estimated, but it should be remembered that their influence on the performance of the OFD is inextricably linked with the particular values taken by F_{MSY} and B_{MSY}. For stocks close to overfished thresholds, even minor changes in the OFD could lead to instability in the management regime – *e.g.* opening and closing of the fishery. Radical changes in perception, if accepted as plausible, of course require radical management responses. Otherwise protocols are required for stabilising the OFD in the face of changing assessments. One approach would be to use moving averages (*e.g.* of F_{MSY} and B_{MSY} proxies in Tier 3) to reduce annual biases (as suggested by Nick Caputi during the review meeting). Another approach would be to set up a cycle of regular update assessments, where many assessment parameters would remain unchanged, and occasional full assessments with revision of F_{MSY} and B_{MSY} or proxies and testing whether current values of α and β remain appropriate. 'Update' assessments would be the sole responsibility of assessment authors, whereas 'full' assessments would have consequences for rigorous documentation and Council review. The latter approach is similar to that adopted by ICES in recent years.

The two most important components of the OFD are stock biomass and fishing mortality, *i.e.* the *x*- and *y*-axes for the MSY control rule (Figure 1). The way these two parameters are defined is critical to the successful operation of the OFD. In the existing OFD there are logical inconsistencies between the way these are defined in the threshold values and the way they are applied in determining harvest levels. The proposed OFD potentially resolves these inconsistencies, but successful implementation of the proposed framework depends critically on the correct definitions of biomass and fishing mortality. The definition of fishing mortality appears not to be a concern. As defined in the framework, *F* applies to all vulnerable portions of the population, including discards of females and undersized/unmarketable males. Mortality of trawl by-catch is a separate issue (see below), but provided that this is adequately accounted for in the assessment and simulation models, this is not a problem in terms of the framework. Within the framework, '*F*' refers to δF for fully selected crabs, where δ is the time interval over which the fishery occurs. Provided that F_{MSY} and F_{OFL} are expressed in this same currency, then the way that fishing mortality is defined in the OFD framework is satisfactory. The same cannot be said of stock biomass. 'Biomass' here refers to spawning potential, and in fact need not be expressed in biomass units at all. As emphasised by Patrick Cordue on numerous occasions during the review meeting, the biomass measure would be expected to be proportional to total fertilized egg production (TFEP). Discussion of this critical issue in relation to MSY control rules and SRRs is deferred to a later section (see p.15). It is enough to note here that the various options for defining effective spawning biomass (ESB) considered in the simulation studies (Siddeek & Zheng, 2006; Turnock & Rugolo, 2006a) appear unlikely to meet this criterion of proportionality with TFEP. Successful implementation of the proposed OFD will not be possible until a satisfactory definition of ESB is determined. This issue affects the definition of SRRs on which estimation of F_{MSY} or proxies and testing of the OFD depends.

Estimating proxy values for biological reference points

In 'data-rich' situations (stocks in Tiers 1 and 2), F_{MSY}, B_{MSY} and associated quantities can be estimated directly, but for all other cases we need proxies for these values. Restrepo *et al.* (1998) offer extensive guidance on selecting among the various candidates for proxies in 'data-moderate' and 'data-poor' situations. Siddeek & Zheng (2006) and Turnock & Rugolo (2006a) opted to consider $F_{x\%}$ values as proxies for F_{MSY} for Tier 3 stocks, where x is the percentage of virgin spawning potential per recruit (SPR) at equilibrium. Given that the OFD requires a working definition of spawning potential (*i.e.* ESB) irrespective of the approach to deriving proxies, selection of proxy values on the basis of SPR is a sensible approach despite the difficulty in defining ESB. Restrepo *et al.* (1998) advocate the use of $F_{x\%}$ in preference to yield per recruit reference points ($F_{0.1}$ and F_{max}) and SRR-based reference points (F_{med}). NPFMC (2006) recommended the range $F_{50\%}$ to $F_{60\%}$ based on previous work by the CPT Work Group. According to the method of Clark (1991), whereby the most likely value of F_{MSY} is selected at the intersection of yield curves from the most and least productive of a plausible range of SRRs, this range of $F_{x\%}$ appears reasonable. At present, the use of $F_{x\%}$ and the approach to selecting the appropriate x% can both be endorsed as satisfactory approaches to deriving F_{MSY} proxies for Tier 3 stocks, but the issue cannot reasonably be progressed further towards selection of actual values without first resolving issues relating to the definition of ESB and hence SRRs (see p.15). Two further points can be made in this context. First, SPR-based reference points are likely to be highly sensitive to assumptions about growth. Estimation of growth patterns was not discussed in detail during the review meeting, but it seems safe to suppose that moult frequencies and increments are fairly poorly resolved for BSAI crab stocks. New information on growth potentially could be very influential in identifying reference points. It is recommended that the sensitivity of reference points and the performance of the OFD be explored in relation to uncertainty about growth. Second, the question of the likely form of the SRR should be addressed. For example, are there *a priori* reasons for selecting a Ricker rather than a Beverton-Holt SRR, *e.g.* likely cannibalism of pre-recruits by the adult stock? It is recommended that the plausible range of SRR types be examined carefully in the light of what is known about recruitment biology, with a view to constraining the range of SRRs that are considered in selecting biological reference points.

For Tier 4 stocks the proxy for F_{MSY} is defined as γM. The use of M as the basis for a proxy is consistent with the guidelines given by Restrepo *et al.* (1998) for 'data-poor' situations, and appears sensible given the available options. However, determining default values for γ presents difficulties. Presumably, values would be selected at the group- rather than stock-level, where one group was king crabs (*Lithodes* and *Paralithodes* spp.) and the other was snow and Tanner crabs (*Chionoecetes* spp.). Additional information on individual stocks seems likely to result in promotion to Tier 3 rather than modification of γ. The precise role of γ in the proxy needs to be clarified. It appears that it is not involved in a 'currency' change in the OFD, given that fishing mortality is already expressed in terms that account for the timing and selectivity of the fishery (see above). Instead, γ appears genuinely to scale M towards the appropriate F_{MSY}. In the absence of further information, it seems reasonable to suppose that γ=1 would be an appropriate default, but analyses and simulations of the type applied to Tier 3 stocks may be informative about the most likely values.

Simulation modelling

Simulation models were separately developed by ADF&G staff (Siddeek & Zheng, 2006) and NMFS staff (Turnock & Rugolo, 2006). Differences of approach potentially shed light on the sensitivity of simulation outcomes to particular modelling choices, and final conclusions about the performance and parameterization of the OFD could be more robust as a result. There is a need for critical analyses comparing the results of the two simulation approaches, but this will first need agreements on some critical biological issues and some common grounds for comparison (see below).

Simulation models for BSAI crabs are likely to have much in common with the length-based assessment (LBA) models: the first are used for forward projections, the second to estimate parameters. If assessment parameters (both estimated parameters and those fixed *a priori*) are to be used in simulation models, it is vital that the model structures be identical, since they are likely to be valid only in the context in which they are estimated or applied. Modelling of uncertainty in the population dynamic and survey processes should preserve the covariance structure of parameters estimated in the assessments.

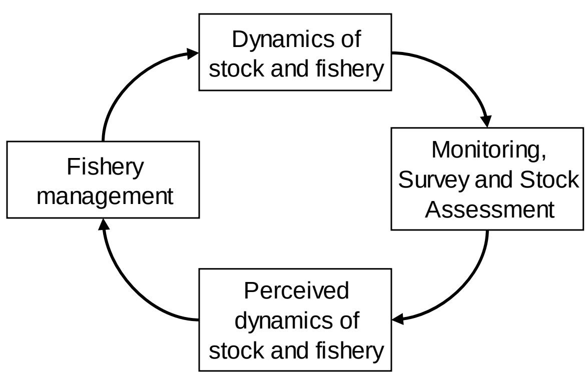

FIGURE 2. Processes involved in simulating fishery management.

As noted by Restrepo *et al.* (1998), various sources of uncertainty are involved in modelling fishery management. These include uncertainty owing to the accuracy and precision of estimates, choice of model structure, natural variability of stock dynamics and errors in the implementation of management measures. Figure 2 shows schematically the major processes involved in simulating a fishery management system – each box and each arrow comes with its own component of uncertainty which should be incorporated within the simulation. The distinction between the 'perceived' and 'true' dynamics is particularly important. Turnock & Rugolo (2006a) incorporate observation errors by applying autocorrelated lognormal errors to abundance within the simulations. This approach is probably adequate for the purposes of comparing the performance of alternative OFDs, but it is recommended that in the long-term the model be extended to include the full assessment-management processes.

An important issue for the simulations undertaken by both Siddeek & Zheng (2006) and Turnock & Rugolo (2006a) is that they treat the MSY control rule as if it were both a harvest strategy and a rebuilding plan. Fishing mortality in the simulations always takes the value of F_{OFL}. In one sense this could be seen as fair enough, since this is a worst case scenario and the OFD is already very precautionary as a framework and could conceivably be viewed as constituting a default rebuilding plan for depleted stocks. Restrepo *et al.* (1998) note that an MSY control rule that incorporated 'built-in' rebuilding might be used "if a Council wished to minimize the range of stock sizes within which special rebuilding plans would be required". However, if it really is the case that the MSY control rule is seen as sufficiently precautionary to be used as a harvest strategy, then either it implies that the OFD is likely to be unduly restrictive in that it allows very little room for manoeuvre by the State fishery managers, or else it appears to by-pass the requirement for the State to act in a precautionary manner in maintaining a buffer between F_{OFL} and the target F used in setting TACs. At the State level, harvest strategies may well incorporate multiple management objectives, going beyond mere stock conservation. Indeed, for fisheries that are economically as well as biologically healthy, it is desirable that management objectives incorporating socio-economic aims should explicitly be stated. An MSY control rule that seeks to take the role of a default harvest strategy is unlikely to be conducive to such enlightened management. This is relevant to the current simulations, because it implies that they are modelling scenarios that will never (or at least should never) happen in practice. The role of the OFD is not to replace the requirement for precautionary management by the State, but to provide the context in which this can occur. State management could either use the OFD as a Federal check on the admissibility of their preferred harvest strategy, or as a fixed point of reference to determine their harvest strategy (*e.g.* setting TACs consistent with 0.75 F_{OFL}). In either case, it is the harvest strategy, not the MSY control rule, that is applied to the stock. It is therefore recommended that a credible State harvest strategy is *always* included in simulations of the performance of an OFD for BSAI crab stocks. If, on the other hand, it *is* intended that the OFD should take on the role of a precautionary harvest strategy, this should be explicitly stated and the performance of the OFD should be considered in terms beyond average stock size and rebuilding times.

It is in any case desirable to examine multiple aspects of the performance of a proposed OFD. It is relatively easy to define management measures that are just precautionary, less easy to define ones that balance precaution against other objectives for a fishery. For depleted stocks, there is an obvious trade-off between short-term pain and long-term gain. In other words, shorter rebuild times to higher stock levels come at the expense of immediate losses of yield. More generally, management responses to changing stock sizes have consequences for the level and, particularly, the variability of yield. Different

OFDs with similar properties in terms of rebuild time and probability, may differ strongly in their properties with respect to short-term losses and long-term constancy of yield. It is recommended that trade-offs involving yield (or any other fishery management objectives) be included in simulation studies of the performance of OFDs for BSAI crabs. Again, it should be emphasised that simulations should not consider OFDs in isolation from harvest strategies.

Even if we set aside management objectives other than stock conservation, an OFD can be viewed as serving two roles: (i) it is intended to allow depleted stocks to grow towards biomass levels capable, on average, of supporting MSY; and (ii) it is intended to prevent the fishery from causing stock biomass to decline below these levels. The simulations for BSAI crabs have focussed on the first role to the exclusion of the second. In part this is natural, since the α and particularly β parameters are most relevant to recovery from low stock sizes. However, recognising the role of the OFD in allowing fisheries to operate at sustainable levels over the long-term, it is recommended that the simulations use a variety of different starting biomass levels up to B_{MSY}, rather than just considering depleted stocks. Note that, for the purposes of comparing between the Siddeek & Zheng (2006) and the Turnock & Rugolo (2006) modelling approaches, the same selection of starting biomass levels (in terms of fractions of B_{MSY}) should be used by both modelling teams.

The biggest differences between the two modelling teams were in their interpretation of certain biological issues critical to the definition of the spawning stocks. Many issues that divide the two groups are highlighted in the ADF&G and NMFS position documents (Turnock & Rugolo, 2006b; Zheng, 2006). The February Workshop Report (NPFMC, 2006) makes what are intended to be definitive statements on some of these issues, but it is apparent that it is possible to interpret these statements in more than one way. For example, at the review meeting it was particularly apparent that different views had been taken about the minimum interval between moulting and mating for new shell male snow crabs, with strong implications for their participation in primiparous and multiparous matings and hence for the definition of the male spawning stock. It is beyond the remit of the present review to arbitrate on such issues, but there is a strong need either for the two modelling teams to agree on the interpretation of the best available scientific information, or for this interpretation to be determined by a third party. In cases of genuine uncertainty about the biological processes, this should be included in the simulations as sensitivity analyses.

Effective spawning biomass and the stock-recruitment relationship

If there is one crucial issue on which the proposed OFD succeeds or fails, it is in the definition of effective spawning biomass (ESB). ESB plays two roles in the OFD: first, it is the *x*-axis of the MSY control rule, determining the value of F_{OFL} and being the scale on which MSST and B_{MSY} are measured; second, it is the controlling variable for the stock-recruitment relationship (SRR), used in determining F_{MSY} or its proxy and in testing the performance of the OFD. The two roles are linked, since the outcome of applying the MSY control rule is intended to be a long-term average catch approximating

MSY (Restrepo *et al.*, 1998), and this outcome is achieved through translation of ESB into future recruits. To clarify: the MSY control rule does not simply avoid the recruitment failure that ultimately leads to stock extinction, although successful operation of the rule should in fact achieve this aim; rather, it has the more positive aim of encouraging stock size to reach a level that maximizes the delivery of biomass to the directed fishery. The first is more characteristic of the ICES paradigm of precautionary fishery management, and requires knowledge or assumptions about the left-hand portion of the SRR, *i.e.* what happens to recruitment at low stock sizes. The second, which applies under the National Standard Guidelines, requires knowledge or assumptions about the full form of the SRR, *i.e.* what happens at all stock sizes.

As noted above, it was agreed at the review meeting that the first essential property of any measure of ESB is that it should be proportional to total fertilised egg production (TFEP). A secondary property, needed for successful definition of an OFD, is that ESB should be sensitive to fishing mortality. Indeed, if ESB was not responsive to changes in fishing mortality, there would be no point in having an OFD! These two requirements have led to some widely varying definitions of ESB by the two Work Group teams (Siddeek & Zheng, 2006; Turnock & Rugolo, 2006a). The most obvious definition for ESB is the total biomass of mature females. This falls at both hurdles – the first because TFEP depends also on the availability of males as mating partners, the second because fishing mortality is directed at males, females being sensitive only to by-catch and discard mortality. The next step is to suppose that each male present in the population can mate with a certain number of females (the 'mating ratio') and that ESB is best defined by the minimum of total biomass of mature females and the biomass of mature females that is capable of being mated by the mature males present in the population. Setting aside the issue of determining which males participate in mating (see above), this is an improvement in that it recognises that TFEP is limited by the availability of males. However, the use of a mating ratio is a gross simplification of the complex mating system of snow, Tanner and king crabs, and this definition of ESB is still only weakly sensitive to fishing mortality. Turnock & Rugolo (2006a) attempted to deal with the latter issue by adding in the total biomass of mature males. This, however, is logical only as an *ad hoc* measure, and takes a step further away from a definition of ESB that is acceptable on biological grounds. Siddeek & Zheng (2006) used the mating ratio to calculate a male component to ESB in complement to the female component. Although an improvement, this still falls a long way short of a biologically realistic definition that could be used with confidence to test, parameterise and apply a working OFD. Estimation of F_{MSY} and proxies and other outcomes of simulations were found to be very sensitive to mating ratio and other facets of the definition of ESB.

The central problem is that a simple, robust and biologically meaningful index of TFEP is required, whereas the complexities of BSAI crab mating systems allow no simple answers. Sperm storage by females, sperm rationing by males, size-assortative mating, non-participation in mating by new shell males, lower clutch fullness in primiparous females, the existence of 'graveyard' females – these and, no doubt, many other factors make it extremely difficult *a priori* to write down a suitable expression for ESB based on simple, easily measurable quantities. Given size-fecundity relationships that appear to be linear rather than cubic functions of carapace width in snow crabs (within clutch fullness categories), it is even questionable whether spawning potential is best measured as a biomass. Patrick Cordue suggested during the review meeting that it would be enlightening to construct an individual-based model (IBM), incorporating and simulating the various features of crab mating and egg production systems. Hypotheses about the causes and consequences of size-assortative mating may profitably be explored in this context – changes in the rate of successful mating as population density changes are likely to differ strongly according to whether male-male competition (ousting of small males by large males) or loading constraints (limits to the size of female that can be handled by a male of a given size) are the primary cause of size-assortation. Spatial factors, in relation to migration patterns and the location of primiparous and multiparous matings, could also be explored using an IBM. Imperfect knowledge of some or even many aspects of these systems may make it difficult to parameterise an IBM with any certainty. However, given plausible assumptions it may be possible to draw deductions about at least the functional form of any satisfactory definition of ESB. Furthermore, an IBM may provide insights into the conditions under which the effective sex ratio may be genuinely limiting for egg production. Although the primary aim of the OFD is to allow optimum recruitment rather than to prevent recruitment failure, it is nevertheless useful to know the circumstances under which this might be expected to occur.

A second approach to finding an appropriate functional form for ESB would be to examine data that are already available from the annual surveys. In some years at least, when environmental temperatures favour the presence of ovigerous females in the population at the time of the survey, it may be possible to measure egg production directly. Data on female size and clutch fullness are routinely collected, which would allow calculation of total egg production. Calculation of TFEP would depend on whether or not it is possible to draw deductions about fertilisation rates from egg colour (blue coloration means a developing and hence definitely fertilised egg, orange coloration could mean either unfertilised or simply early stage). Is it perhaps possible to make deductions about relative fertilisation rates, even if there is no confidence that these can absolutely be estimated? If so, then both sides of the equation relating TFEP to crab population structure are known in at least relative terms – it merely (!) remains to estimate the functional form.

The IBM and the survey data approaches to estimating ESB, or at least a functional form for ESB, are both medium- to long-term projects, and are thus unlikely to yield results that are useful for the timely implementation of the proposed OFD. A short-term, probably interim, solution is required. Replacement of the existing OFD is an urgent priority, even if this requires a less than perfect solution to the definition of ESB. Given fisheries that preferentially remove males from their target populations, we know that male availability is the most likely limiting factor for successful reproduction in BSAI crabs. Accordingly, any meaningful definition of ESB must include mature males. Perhaps the most likely candidate for an interim definition of ESB is the total mature male biomass. This definition was proposed at the review meeting by Nick Caputi. It has the virtues of being simple (given agreement as to what constitutes the mature male population) and being responsive to fishing mortality. This definition will certainly be *wrong*, particularly at higher stock sizes where it is more likely that recruitment will be egg-limited than sperm-limited[1], but it has the highly desirable property that it may be a very good measure of the degree to which spawning potential is impaired at low stock sizes, at which the MSY control rule will cause fishing mortality to be reduced or the fishery to be closed. As noted above, this does not accord entirely with the philosophy of the OFD, but it is nevertheless an extremely important function for it to fulfil. Moreover, if at higher biomass levels stock size assumes a relatively minor role compared with environmental factors (see below), *i.e.* 'noise' makes a greater contribution to recruitment variation than the underlying SRR, then an incorrectly specified ESB is much less of a problem.

The following course of action is recommended for incorporating a stock biomass measure into the OFD and in modelling SRRs for BSAI crab stocks:

(1) Agree a simple short-term interim measure for ESB and prescribe that this is the definition that will be used in implementing the proposed OFD. Total mature male biomass is a strong candidate for this measure.

(2) Again in the short-term, use estimates from the stock assessments to explore the relationship between recruitment and the two axes of mature male biomass and mature female biomass. It is unlikely that data will be available over much of this surface, but it is worth establishing the extent to which variability in recruitment can be accounted for by the joint effects of these two variables.

(3) In the medium-term, examine the suitability of survey data for estimating TFEP, and explore the possibility of using these data to determine the appropriate functional form for ESB. If necessary, this should be supplemented with direct field measurements of clutch fertilisation rates.

(4) In the medium- to long-term, construct an IBM of BSAI crab mating and egg production systems, aiming to determine the appropriate functional form for ESB. It is important that the IBM be spatially structured, to examine the spatial co-incidence of different population components at mating time and to consider the delivery of larvae to suitable settlement areas.

Before leaving the topic of SRRs it is worth considering sources of variation in recruitment other than ESB. This is relevant in two respects. First, if ESB plays a relatively minor role in determining recruitment, this is important both for simulating the performance of the OFD and for approaches to management. For recruitment-driven fisheries, conservation of spawning stock biomass becomes less important compared with managing the mortality of recruits that are delivered to the fishery (subject, of course, to precautionary minimum stock biomass levels). This is particularly so if natural mortality is high and recruitment is very variable between years. This is perhaps more typical of

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[1] In fact the application of a mating ratio to mature female biomass could be seen as dealing with the transition from sperm-limitation to egg-limitation as stock size increases, but the sensitivity of F_{MSY} to choice of mating ratio together with other uncertainties make it preferable to adopt a more simple approach. The use of mature male biomass will introduce its own problems for selection of an F_{MSY} proxy, but choice of a value between $F_{50\%}$ and $F_{60\%}$ could be made based on operational properties even if it could not be defended as an unbiased proxy.

shorter-lived species than snow, Tanner or king crabs, such as estuarine bivalves or blue crabs, but it might be worth considering the effects of such recruitment patterns in the simulation models (some simulations of random recruitment were shown by Shareef Siddeek during the review meeting). This also highlights the importance of ensuring that the error components of the SRRs in the simulations are adequately characterised.

The second point of relevance is the issue of regime shift and stock productivity. Changes in abundance and distribution of some BSAI crab stocks have been attributed to changes in the climatic and oceanographic regime in the Bering Sea, although a lack of coherence of change between different stocks may cast some doubt on this hypothesis (Zheng & Kruse, 2006). Dew & McConnaughey (2005) emphasise the role of fishing mortality rather than regime shift in causing the decline of Bristol Bay red king crab after 1980, suggesting *inter alia* that intensive trawling in an area important to spawning females may have affected delivery of larvae to the most suitable grounds for settlement. Deciding whether or not regime shift is responsible for recent recruitment levels is extremely important, given that management priorities for a depleted stock will be very different to those for a stock which has simply become less productive. Restrepo *et al.* (1998) note that "for a period of declining abundance, the 'burden of proof' should initially rest on demonstrating that the environment (as opposed to fishing) caused the decline, and that, therefore, the target control rule should be modified". It is beyond the scope of the current review to offer a view on which are the most likely causes of changes in abundance of BSAI crab stocks, but it is recommended that a consensus be sought among the relevant experts about whether regime shift or fishing mortality are the most likely causes of change, and that this consensus be used to inform development of the most appropriate OFD.

Stock assessments

Stock assessments for Bristol Bay red king crab (Zheng, 2004) and eastern Bering Sea snow crab (Turnock & Rugolo, 2005) were briefly presented at the meeting. In both cases a length-based assessment (LBA) model was constructed, accounting for the complex, discontinuous growth patterns of the two species. Given the emphasis on other issues, it was not possible to examine the assessments in detail during the meeting. However, the assessments are essential to the OFDs because: (i) they yield values which will eventually be compared with the criteria of the MSY control rules; and (ii) they yield values which allow the OFD to be parameterised and tested. Brief comments on some of the main features of the assessments are given below, but this should not be treated as a full assessment of the assessment methodologies and outcomes. A review of the eastern Bering Sea snow crab assessment has recently been undertaken on behalf of CIE by Maunder (2003).

LBA models are used for both red king crab and snow crab assessments. The two approaches differ principally in the number of free parameters (more for snow crabs) and method of estimation (sum-of-squares based on lognormal errors for red king crabs, maximum likelihood for snow crabs). The method of dealing with size transitions in each model appears satisfactory, if based on rather slender data resources. Lack of opportunity to examine this in detail prevents further comment on this potentially important issue, but the dependence on and sensitivity to poorly known biological parameters in the assessments warrants further study in the future. Given the complexity of these models – in terms of both structure and number of parameters – it would be reassuring to see corroboration of the broad patterns of assessment results drawn from comparisons with the outcomes of simpler assessment approaches (*e.g.* Collie-Sissenwine Analyses) which make fewer demands on knowledge of biological parameters such as growth.

In general, biological realism is a strength in these LBA models (to the extent that this realism can be supported by available information), but within the biologically realistic model structures it is desirable to seek the most parsimonious descriptions (fewest parameters) of the data and processes. In the case of the snow crab model almost 300 parameters are estimated and it is appropriate to ask whether every one of these is necessary, or indeed supported by the data. In particular, selectivity parameters proliferate, with variation according to years, sexes and shell conditions; it seems likely that this complexity could be drastically reduced by applying a few well chosen *a priori* assumptions about selectivity patterns, with advantages for the precision of estimates. Some parameter sharing may also be possible within models. For example, in the red king crab model is it reasonable to suppose that patterns of annual recruitment are likely to be similar between males and females? If so, there is no need to estimate the two patterns separately; any departures from 1:1 sex ratio at recruitment can be dealt with by including an additive parameter rather than treating the patterns as completely independent. In general, it is recommended that maximum use be made of external information, whether as potential explanatory variables (*e.g.* environmental signals) for recruitment patterns or to determine the likely values of parameters to be estimated.

Both assessments are tied in to survey data, with the assumption that the survey represents the complete population. This assumption is precautionary, since it will tend to give an upwards bias to estimates of *F* and a downwards bias to estimates of population abundance. However, the assumption is unnecessary since the survey catchability could be estimated within the assessment: it is recommended that estimation of survey *q* be included within the assessments. It is further recommended that depletion experiments be undertaken using the survey gear and vessel to assess gear efficiency and selectivity. This approach is preferable to the 'underbag' experiments which have so far been used.

The red king crab assessment model includes estimation of *M* values for four different periods in females and for three different periods in males. This is done primarily to account for differences in population dynamics during the early 1980s. It is not clear that there is an objective basis for selection of the periods (which differ between males and females) beyond achieving a closer fit to the survey data. Without data on changes in specific mortality factors, it is not defensible to use *ad hoc* model adjustments to infer changes in *M* on the basis of model fit. Lack-of-fit could be due to factors other than natural mortality, such as catchability changes or changes in the relative spatial distributions of the stock and the fishery. Furthermore, '*M*' as estimated in the red king crab assessments is actually a compound of natural mortality and indirect (by-catch) fishing mortality. It is highly desirable to separate these components, perhaps using effort data from the by-catch fleets.

More use of fishing effort data could be made in both snow crab and red king crab assessments. There may well be problems in defining meaningful effort and CPUE indices, particularly for the by-catch fleets, but there are potentially great benefits in doing so. Firstly, it may be important to understand spatial processes in the stocks and the fisheries. It is probably unrealistic to expect that spatial processes could be incorporated in the LBA models in the near future, but statistical analyses of CPUE and effort data may well be informative about shifts in the location of the stock or the fishery, which in turn may be informative about selectivity and mortality processes that are addressed within the models. Secondly, it is important to gain a better insight into the contribution of by-catch mortality to overall mortality in BSAI crab stocks. In this case direct use of effort data in the LBA may be possible. According to Dew & McConnaughey (2005), by-catch mortality of females could have been an important factor in the decline of Bristol Bay red king crab stocks after 1980. Whilst this is not the only view of causes of decline, it does highlight the importance of understanding by-catch mortality. Dew & McConnaughey (2005) also question the representation of 'red bag' catches in estimates of the by-catch component of red king crab removals. Again, whether or not this proves to be a real source of bias in the data, it highlights the importance of understanding and quantifying the contribution of by-catch to overall fishing mortality. This is important for both assessments and OFDs.

ToR (b): Recommendations of improvements to proposed overfishing definitions

Recommendations about how the proposed OFD could be developed or improved are scattered through the preceding sections. The main points are highlighted again below, together with some additional recommendations on the simulations and OFD framework.

- The proposed OFD can be accepted as a framework, but it is urgently necessary to make progress on defining values for the reference points (F_{MSY} or proxies) and defaults for parameters α, β and γ. This will only be possible when a satisfactory interim definition for ESB is derived and the proposed OFD is tested in conjunction with realistic harvest strategies. Retention of the existing OFD is not an option.
- Protocols are needed for dealing with the addition of new annual assessment estimates to existing OFDs. This might involve use of running averages or a cycle of update assessments and full revisions to the OFD.
- In the short-term, there needs to be a prescriptive interim definition of how ESB is to be calculated and used in the OFD and simulations. Mature male biomass is a strong candidate for this definition. Subsequent improvements to the definition of ESB, *e.g.* based on the analysis of survey data or the outcome of an IBM, should be extensively reviewed and documented before being adopted in a revised OFD.

- In the immediate term, simulations to test the performance of the proposed OFD and to determine appropriate values for α, β and γ in the MSY control rule must include realistic harvest strategies. To do otherwise is either to take the view that no precautionary buffer is needed between F_{OFL} and the target F or to determine OFDs that allow the State very little room for manoeuvre in setting harvest strategies to meet precautionary and other objectives.
- There needs to be agreement on the criteria used to test OFDs in the simulations. Rebuilding time for a depleted stock would be an important criterion, but trade-off statistics involving the level and variability of yield in the short- and long-term are also needed.
- The default OFD of Restrepo *et al.* (1998) should be included in comparisons of the performance of different OFDs. This is less precautionary than the proposed OFD framework, but specifies a higher value of MSST given M<0.5 (see Figure 1). It will need to be established that the increased complexity involved in the proposed OFD (*i.e.* the α and β parameters) offers significant improvements over the default OFD in terms of the agreed test criteria.
- The simulations should include a range of starting values for stock biomass, in terms of fractions of B_{MSY}. This is because rebuilding is not the only function of an effective OFD – it is also intended to define sustainable exploitation of a healthy stock.
- There needs to be agreement between ADF&G and NMFS teams on the interpretation of the available evidence on biological processes (*e.g.* moulting/mating cycles) in BSAI crab stocks. In cases of genuine uncertainty, this should be included in sensitivity analyses. Comparisons between the ADF&G and NMFS simulation modelling approaches would be facilitated by the use of common starting points for the simulations (fractions of B_{MSY}).
- Simulation testing of the performance of proposed OFDs must take appropriate account of observation error, *i.e.* the difference between the simulated 'reality' and the 'observations' used in applying the OFD. Ideally, this would involve simulating the survey and assessment processes (see Figure 2), but simulating the errors directly would probably be adequate given knowledge of their likely magnitude and autocorrelations.
- For Tier 5 stocks, it is not appropriate to use the average catch for a single fixed period of years to define the OFL. The period should be defined separately for each stock based, where possible, on four criteria: (i) stability of catches; (ii) lack of trend in CPUE; (iii) lack of trend in fishing effort; and (iv) a stable spatial distribution of the fishery, showing no expansion or shift in the distribution of fishing effort. If possible, the use of these criteria should be supported by simulation studies.
- In the medium-term, consideration should be given to including uncertainty measures within the Tiers of the OFD. This might involve estimating probabilities for the current location of a stock in relation to status determination criteria rather than just using point estimates.
- In the medium-term, consideration should be given to reducing the complexity of the OFD. For example, would a flat F_{MSY} control rule (in conjunction with a

precautionary harvest strategy) perform as well as the proposed MSY control rule, thus removing the need to define α and β?

- In the medium-term, further attention should be paid to the role of by-catch mortality in determining the effectiveness of the OFD. At present, by-catch mortality is seen as a context for the OFD, but it is a context that readily changes in response to the fortunes of other fisheries. Ideally, by-catch mortality should be included in the F that is compared with F_{OFL} (with implications for defining F_{OFL}). This has the disadvantage that the by-catch F will need to be projected before the TAC can be calculated, but it does allow an OFD that does not require revision each time the by-catch mortality regime changes.
- In the long-term, it is recommended that OFDs include multi-species considerations. This is necessary because: (i) by-catch of BSAI crabs in trawl fisheries, whether or not removed in the form of commercial landings, is potentially an important contribution to overall fishing mortality; and (ii) the catches of even directed fisheries are often mixed in species composition. Construction of robust single species OFDs is a necessary precursor to more complex management systems, but management of trade-offs between competing objectives for mixed or interacting fisheries potentially offers the capacity to maximize overall conservation (and revenue) benefits.
- Another long-term objective should be to include spatial considerations within the OFD. For spatially structured stocks, the consequences of fishing mortality for future recruitment depend heavily on when and where the mortality occurs. As an example, the hypothesis of Dew & McConnaughey (2005) that trawling in the south-eastern Bering Sea has disrupted the 'endless belt' reproductive strategy of red king crabs holds strong implications for spatial management. In this case the implications apply to the by-catch fleets, but it is easy to envisage cases where spatial management considerations would apply to the directed fishery. The inclusion of spatial management criteria in an OFD implies that the current type of MSY control rule would no longer be appropriate. Equilibrium recruitment at a given level of fishing mortality is the determinant of F_{MSY}, but in the case of spatial management there is no single F_{MSY}, and recruitment is determined by considerations beyond a 'global' SRR.

ToR (c): Review of model configurations, formulations and methods used to account for uncertainty

The model configurations, formulations and methods used to account for uncertainty have already been reviewed under ToR (a) alongside the OFDs and simulation models. Model structures (LBAs and projection models) appear to be sufficient and appropriate to the life-histories of BSAI crab stocks, although there remain some disagreements about the details of some biological processes. Likewise, model fitting procedures for the LBAs appear satisfactory, although this was not an aspect that could be examined in detail during the review. The review team did not take up the offer of access to AD Model Builder and Fortran code for the models. This was partly because there would have been insufficient time to read and thoroughly understand the code, but also because the presentations and documentation for the review made it clear that the technical expertise of the modelling teams was not in question.

ToR (d): Review of input parameters used in simulation models

Input parameters used in the simulation models included biological and fishery parameters and SRRs. Again, these have largely been discussed already under ToR (a). It is worth re-iterating that there remain several important points of difference between ADF&G and NMFS teams in interpretation of the scientific evidence on biological processes in BSAI crab stocks, and it is important that these differences are resolved. For progress in parameterising the OFDs it is necessary to draw up a clear and unequivocal agreed framework of crab life-history processes. Irresolvable points of genuine uncertainty should (a) be accounted for in sensitivity analyses, and (b) serve as a focus for future research efforts.

Opportunity to examine important fundamental biological parameters was limited during the review. In common with many if not most exploited species, M is poorly known for BSAI crab stocks, and there is a slender basis for drawing inferences about likely values. Values of 0.2 or 0.3 used as proxies for F_{MSY} for Tier 4 stocks and alternative values for M used in the simulation models appear to have been derived from considerations of longevity. The estimates are satisfactory to the extent that they are at least plausible. There is no obvious basis for their revision, although it should be noted that there should be consistency of selected best values across assessment models, simulation models and OFDs, unless precautionary considerations dictate otherwise.

Growth parameters are also poorly known, which could have important implications for assessments, simulation models and estimation of $F_{x\%}$ values in the selection of F_{MSY} proxies. The sensitivity of the models to assumptions about growth are certainly worth exploring, although it is also possible that internal consistency in the assessment-simulation-OFD model complex may be more important than absolute lack of bias when determining the most effective OFD.

ToR (e): Suggested research priorities

Some priorities for research have already been identified in the preceding sections. These are collected together below, together with some further suggestions aimed at improving the understanding of essential population and fishery dynamics necessary to formulate best management practices.

- The first and most urgent research priority is to determine the appropriate functional form for calculating a measure of ESB that is proportional to TFEP. This is required for the MSY control rules and for the SRRs that are used to derive F_{MSY} values and proxies, to find likely default values to parameterise the OFDs and to test the performance of OFDs. As described under ToR (a), mature male biomass may be an appropriate candidate for an interim definition of ESB, but cross-correlations between the various options (*e.g.* B_0 mating ratio applied to mature female biomass) should be examined to determine the extent to which they are measuring the same dimension of variability (*i.e.* measures that go up and down in rough concert with various alternative formulations of spawning potential, even if the correspondences are non-linear). In the medium- to long-term, construction of an IBM and analysis of survey data are the most likely routes to improving the formulation of ESB (see under ToR (a) above).

- Field estimation of clutch fertilisation rates during annual surveys is important for improving the understanding of the determinants for TFEP. This would need to be carried out over a number of years (preferably contrasting) for meaningful conclusions to be drawn. The study may shed light on whether it is possible to use records of egg colour to drawn conclusions about variations in fertilisation rates over a longer series of years.
- Depletion experiments using the survey vessel and gear should be used to obtain estimates of survey efficiency and selectivity. This information could be incorporated into the assessments for snow crab and red king crab, allowing more robust and parsimonious models. As pointed out by Nick Caputi during the review meeting, catch rate data from intensively fished areas may also allow estimation of selectivity and catchability parameters for commercial fishing operations.
- It is recommended that spatial management considerations be included in the future development of OFDs (see recommendation under ToR (b)).
- It is recommended that multi-species considerations be included in the future development of OFDs (see recommendation under ToR (b)).
- Further use of CPUE and fishing effort data could be made in the assessments. It is recommended that effort and CPUE data be collated for both directed fisheries and by-catch fleets and that trends in these data be examined in a spatial context. Generalised linear modelling or other appropriate statistical techniques could be used to extract annual and spatial signals. Use of these signals in the assessments should be investigated, *e.g.* to improve understanding of the contribution of by-catch mortality to overall levels of fishing mortality.
- It is recommended that there be an investigation of the sensitivity of biological reference points and the performance of the OFD to uncertainty about biological parameters, especially growth.
- If lack of information about growth is determined to be an important source of uncertainty about the effectiveness of assessment and precautionary fishery management, it is recommended that field tagging studies be used to estimate growth increments and moulting frequency in BSAI crab stocks. Properly designed tagging studies, *e.g.* involving sufficiently large samples of crabs tagged in relatively shallow waters, could also shed light on rates of natural mortality. Lipofuscin measurements could also be used to investigate the relationship of size with age, although this may depend on the development of routine methods of lipofuscin determination that can be applied to large samples.
- Under ToRs (a) and (b) it was recommended that that the ADF&G and NMFS teams need to reach agreement on the interpretation of the available information on some key

biological processes in BSAI crabs, *e.g.* the interval between moulting and participation in mating by new shell male snow crabs. Where genuine uncertainty remains about key biological processes, this should be used as a focus for new research on crab life-histories, particularly if simulations reveal that the OFD is sensitive to this uncertainty.

- Further research is needed into the relative roles played by fishing operations and changes in the climatic and oceanographic regime in determining past trends in BSAI crab stocks. A consensus on this contentious issue is needed before progress can be made in determining agreed protocols for detecting the effects of regime shifts on crab productivity and in determining the appropriate management response to such shifts.

Conclusions

A great deal of effective research and analytical work has been undertaken to put forward proposals for an OFD that is a vast improvement on the current flawed OFD. In my view this effort has been largely successful in that the proposed OFD is one that can now be accepted as a framework. The challenge now is to progress the parameterisation of the framework to the point where it can be implemented. This means finding default values for the parameters within each tier, *e.g.* stock-specific values for α and β in Tier 3 and group-specific values of α, β and γ in Tier 4, and proxy values for F_{MSY} in Tier 3. At present it is not yet possible to recommend particular values for these parameters, because certain issues need to be resolved before the performance of the OFD under any given parameterisation can effectively be tested. The approach to finding appropriate defaults using simulation models can nevertheless be endorsed as sound in principle and correctly specified in practice (in terms of model structures).

There are two main obstacles to finding default values for the OFD parameters. The first is that there is not yet a satisfactory measure of ESB to used in the MSY control rules and in the SRRs within the simulations. Ideally, ESB should be a measure that is proportional to TFEP; none of the candidate measures considered so far meet this criterion. Recommendations are made in this report for a simple interim measure that could be used immediately and for research aimed at finding more satisfactory long-term solutions.

The second main obstacle is that the role of the harvest strategy in determining the performance of the OFD has not yet been considered. Simulations have so far treated MSY control rules as if they were harvest strategies. On the one hand, this does not recognise the requirement for the State to maintain a precautionary buffer between F_{OFL} and the target F. On the other hand, choice of an MSY control rule on this basis is likely to result in an OFD that places undue constraints on the capacity of the State to manage BSAI crab fisheries according to precautionary and other objectives. What is needed is for MSY control rules to be tested in conjunction with realistic State harvest strategies. Only then can an OFD be selected that serves its proper role of providing limits rather than targets for safe management.

From this I conclude that there remains some work to be done before the OFD can be accepted for implementation. However, the obstacles are not insurmountable, even in the short-term. Given the urgent need for the current OFD to be replaced by a more satisfactory alternative, the Crab Plan Team and its Work Group should be encouraged to select an interim measure for ESB and to use simulations of MSY control rules in conjunction with harvest strategies to select appropriate parameters for an OFD that can be implemented in the short-term. This report also contains recommendations for improvements and developments to the OFD in the medium- to long-term and for supporting research, but these should not be seen as reasons to delay implementation.

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Restrepo, V.R., Thompson, G.G., Mace, P.M., Gabriel, W.L., Low, L.L., MacCall, A.D., Methot, R.D., Powers, J.E., Taylor, B.L., Wade, P.R. & Witzig, J.F., 1998. *Technical guidance on the use of precautionary approaches to implementing National Standard 1 of the Magnuson-Stevens Fishery Conservation and Management Act.* NOAA Technical Memorandum NMFS-F/SPO-##.

Rugolo, L., 2004. *North Pacific Fisheries Management Council Bering Sea/Aleutian Islands King and Tanner Crab Working Group: Draft Statement of Work.* NMFS/ADF&G, Kodiak/Seattle/Juneau.

Rugolo, L. 2006. *Statement of Work: NPFMC BSAI King and Tanner Crab Working Group*. www.afsc.noaa.gov/refm/docs/2006/crab/Statement%20of%20Work.ppt

Siddeek, M.S.M. & Zheng, J., 2006. *Reference point estimation analysis for the Bering Sea and Aleutian Islands (king and Tanner) crab revised fisheries management plan.* ADF&G, Juneau.

Turnock, B.J. & Rugolo, L.J., 2005. *Stock assessment of eastern Bering Sea snow crab.* NMFS, Seattle/Kodiak.

Turnock, B.J. & Rugolo, L.J., 2006a. *Analysis of proposed overfishing tier system for BSAI king and Tanner crab stocks.* NMFS, Seattle/Kodiak.

Turnock, B.J. & Rugolo, L.J., 2006b. *Unresolved issues concerning proposed overfishing definitions for Bering Sea and Aleutian Islands king and Tanner crab stocks: National Marine Fisheries Service.* NMFS, Seattle/Kodiak.

Zheng, J., 2004. *Bristol Bay red king crab stock assessment in 2004.* ADF&G, Juneau.

Zheng, J., 2006. *Issues dividing the Crab Work Group.* ADF&G, Juneau.

Zheng, J. & Kruse, G.H., 2006. Recruitment variation of eastern Bering Sea crabs: Climate-forcing or top-down effects? *Progress in Oceanography*, **68**, 184-204.

APPENDIX 1: Bibliography of materials provided during the review meeting

The key documents referred to during the review are listed below:

Dew, C.B. & McConnaughey, R.A., 2005. Did trawling on the brood stock contribute to the collapse of Alaska's king crab? *Ecological Applications*, **15**, 919-941.

Maunder, M.N., 2003. *Review of the stock assessment and harvest strategy for eastern Bering Sea snow crab.* CIE, University of Miami.

NPMFC, 2006. *Workshop Report: Crab Overfishing Definitions Inter-agency Workshop. February 28-March 1, 2006, Alaska Fisheries Science Center, Seattle, WA.* NPMFC, Anchorage.

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Rugolo, L., 2004. *North Pacific Fisheries Management Council Bering Sea/Aleutian Islands King and Tanner Crab Working Group: Draft Statement of Work.* NMFS/ADF&G, Kodiak/Seattle/Juneau.

Rugolo, L. 2006. *Statement of Work: NPFMC BSAI King and Tanner Crab Working Group*. www.afsc.noaa.gov/refm/docs/2006/crab/Statement%20of%20Work.ppt

Siddeek, M.S.M. & Zheng, J., 2006. *Reference point estimation analysis for the Bering Sea and Aleutian Islands (king and Tanner) crab revised fisheries management plan.* ADF&G, Juneau.

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Turnock, B.J. & Rugolo, L.J., 2006a. *Analysis of proposed overfishing tier system for BSAI king and Tanner crab stocks.* NMFS, Seattle/Kodiak.

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Zheng, J. & Kruse, G.H., 2006. Recruitment variation of eastern Bering Sea crabs: Climate-forcing or top-down effects? *Progress in Oceanography*, **68**, 184-204.

Further documentation available to the reviewers, including presentations given to the crab overfishing workshop is given at:

http://www.afsc.noaa.gov/refm/stocks/CrabWs.htm

APPENDIX 2: Agenda for the review meeting

Center of Independent Experts
Alaska Crab Overfishing Definitions

April 24 - 29, 2006

Alaska Fisheries Science Center, Seattle, WA

Apr 14th 2006 Draft Agenda

Purpose: To solicit expert advice on proposed overfishing definitions for Bering Sea and Aleutian Islands crab stocks. We are requesting a review of issues critical to formulating new overfishing definitions, biological reference points, input parameters, modeling approaches and methods to deal with uncertainty.

DAY 1 (Center Director's Conference Room)

8:00 Coffee and informal discussions

8:30 Introductions - Charge for the CIE –Hollowed

8:50 History of crab management - current overfishing definitions and need for revision - Stram or Designee

9:10 Overview of proposed revisions - Working group

- Working group Statement of Work (20 min) - Rugolo
- Tier System review (20 min) - Zheng
- Brief Description of Snow Crab Assessment (40 min) -Turnock

10:30 Break

10:30 – 12:00 Overview continued – working group

- Brief Description of Red King Crab Assessment (40 min) -Zheng
- Projection Model structure (Siddeek and / or Turnock)

12:00 – 1:00 Break for lunch

1:00-1:30 Overview continued – working group

- Approaches to estimate proxy values for biological reference points – Turnock
- Approaches to estimate proxy values for biological reference points - Siddeek

1:30 – 2:00 Review Workshop Report and Recommendations on crab biology – Stram or designee

2:00 – 2:30 Review of Workshop Report and Recommendations on crab modeling - Ianelli

2:30 Break

2:45-3:45 Review of information available for managed crab stocks - Rugolo

3:45 – 5:00 Performance of Tier System Preliminary results

- Red King Crab – Siddeek
- Red King Crab – Turnock

DAY 2 (CD Conference Room)

8:30 Coffee and informal discussions

8:30 – 10:00 Performance of Tier System Preliminary results continued

- Snow Crab – Turnock
- Snow Crab – Siddeek
- Blue King Crab/Golden Crab - Siddeek

10:00 Break

10:30 – 12:00 Questions and Answers for panel.

12:00 Lunch

1:00 – 5:00 Open question and answer session – or independent work sessions with CIE reviewers.

DAY 3 (CD Conference Room)

8:30 Coffee and informal discussions

9:00 Open question and answer session – or independent work sessions with CIE reviewers.

DAY 4 (CD Conference Room)

8:30 Panel discussions and writing team – NMFS and ADF&G biologists return to offices but remain on cal questionsl

DAY 5 (CD Conference Room)

8:30 Panel discussions and writing team – NMFS and ADF&G biologists return to offices but remain on call to answer questions

APPENDIX 3: Statement of Work

STATEMENT OF WORK

April 19, 2006

General

The Alaska Fisheries Science Center (AFSC) requests review of proposed overfishing definitions and simulation models used to evaluate biological reference points for Bering Sea and Aleutian Islands King and Tanner crab stocks. The North Pacific Fishery Management Council (NPFMC) has determined that the existing overfishing definitions for Bering Sea and Aleutian Islands King and Tanner crab stocks need revision. The AFSC is seeking review of the population dynamics models developed for revising the overfishing definitions.

There are currently 22 Bering Sea and Aleutian Islands crab stocks under the Federal Bering Sea Aleutian Island Crab Fishery Management Plan (FMP) of which 7 are considered major stocks. Four of the seven major crab stocks have been declared overfished and rebuilding plans developed within the last 7 years. Of the remaining three stocks, only one has been relatively stable at a low level, another has maintained stable catch for several years, however, even for this stock it appears recruitment may be declining. While the remaining stock has increased, survey abundance estimates have low precision and the fishery is closed due to bycatch concerns. There is no consensus on the principal cause of declines in Bering Sea crab stocks.

A panel of 3 consultants is requested for this review. The panel will need to be thoroughly familiar with various subject areas involved in analytical stock assessment, including population dynamics theory, length based stock assessment models, rebuilding analyses, estimation of biological reference points and harvest strategy modeling for invertebrates, as well as invertebrate biology. The CIE consultants will travel to Seattle, Washington to meet with the four member Interagency Work Group charged with developing the new overfishing definitions. We request that one member of the Panel should be present at the May meeting of the NPFMC Crab Plan Team in Anchorage, Alaska. The report generated by the consultants should include:

a. A statement of the strengths and weaknesses of the proposed overfishing definitions, simulation models and analytical approaches.
b. Recommendations for improvements to proposed overfishing definitions or alternative definitions,
c. A review of the model configurations, formulations and methods used to account for uncertainty.
d. A review of input parameters (fishery, biological and life history parameters and spawner recruit relationships) used in simulation models.

e. Suggested research priorities to improve our understanding of essential population and fishery dynamics necessary to formulate best management practices.

AFSC will provide copies of the NPFMC Work Group statement of work, proposed overfishing definitions, preliminary results of simulations, discussion of input parameters, a copy of the code for the snow crab stock assessment, and the AD Model Builder and Fortran code used for reference point estimation. The panel will meet with scientists from the Alaska Fisheries Science Center and the Alaska Department of Fish and Game from April 24 to April 28, 2006, in Seattle, Washington.

Expected Products:

- One member of the panel will attend the May meeting of the Crab Plan Team to discuss the panels findings regarding the strengths and weaknesses of proposed definitions and modeling approaches.
- No later than June 1, 2006, panelists will submit a written report of findings, analysis, and conclusions. The report should be addressed to the "UM Independent System for Peer Reviews", and sent to David Die, UM/RSMAS, 4600 Rickenbacker Causeway, Miami, FL 33149 (or via email to ddie@rsmas.miami.edu).

Signed________________________

Date____________

ANNEX I: REPORT GENERATION AND PROCEDURAL ITEMS

1. The report should be prefaced with an executive summary of findings and/or recommendations.

2. The main body of the report should consist of a background, description of review activities, summary of findings, and conclusions/recommendations.

3. The report should also include as separate appendices the bibliography of materials provided by the Center for Independent Experts and the center and a copy of the statement of work.

4. Individuals shall be provided with an electronic version of a bibliography of background materials sent to all reviewers. Other material provided directly by the center must be added to the bibliography that can be returned as an appendix to the final report.

Please refer to the following website for additional information on report generation: http://www.rsmas.miami.edu/groups/cimas/Report_Standard_Format.html