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An evaluation of stock–recruitment proxies and environmental change points for implementing the US Sustainable Fisheries Act

André E. Punt[a,*], Cody S. Szuwalski[a], William Stockhausen[b]

[a] School of Aquatic and Fishery Sciences, University of Washington, Box 355020, Seattle, WA 98195, USA
[b] Alaska Fisheries Science Center, 7600 Sand Way Point Way NE, Seattle, WA 98115, USA

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ABSTRACT

The US Sustainable Fisheries Act requires overfishing limits for all managed stocks and evaluations of whether stocks are in overfished status or subject to overfishing. Overfishing is defined relative to the exploitation rate corresponding to MSY, F_{MSY}, while being in an overfished state relates to stock biomass relative to the biomass corresponding to MSY, B_{MSY}. F_{MSY} and B_{MSY} are impossible to estimate for most US fish and invertebrate stocks. Consequently, management advice for Bering Sea and Aleutian Islands (BSAI) crab stocks is based on "proxies", such as that F_{MSY} is approximated by $F_{35\%}$. Furthermore, B_{MSY} should be defined under prevailing environmental conditions, which implies using only past data under current environmental conditions to estimate B_{MSY}. Assessments for five BSAI crab stocks are used to evaluate the estimates of B_{MSY} from a variety of methods for calculating B_{MSY} proxies. Analyses based on fitting stock–recruitment relationships to the estimates of recruitment and mature male biomass from these assessments suggest that the assumption $F_{MSY} = F_{35\%}$ is generally reasonable, but that the stock and recruitment data do not generally support the current B_{MSY} values. Changes over time in average recruitment and in the form of the stock–recruitment relationship were found for most stocks. Of the methods considered, fitting stock–recruitment relationships and exploring whether they have changed over time appears the most promising approach. The dynamic B_0 method also appears promising, but there is considerable uncertainty in B_{MSY} values between harvest control rules, and assumptions regarding how recruitment is adjusted given changes in mature male biomass.

1. Introduction

The 2006 reauthorization of the US Magnuson–Stevens Fishery Conservation and Management Act (MSA; US Public Law 104–297) impacted how fisheries management advice is provided and decisions made for US federally managed fisheries. In particular, the overfishing limit (OFL) for a stock is defined as the level of annual harvest which, if exceeded, would constitute overfishing under the MSA. 'Status determination' for fish and invertebrate stocks managed by the US federal government is therefore based on assessing stock status relative to B_{MSY} (the biomass corresponding to maximum sustainable yield, MSY) and exploitation rate relative to F_{MSY}, while the OFL is defined as the catch corresponding to an exploitation rate of F_{MSY}. Evaluation of stock status and the setting of OFLs therefore require that B_{MSY} and F_{MSY} can be estimated, and control rules which relate these quantities to the OFL developed. However, the values for B_{MSY} and F_{MSY} are not estimated for most US fish and invertebrate stocks. For example, estimates of B_{MSY} are available for only three fish stocks in the Alaskan waters: eastern Bering Sea (EBS) walleye pollock, (*Theragra chalcogramma*), Bering Sea and Aleutian Islands (BSAI) yellowfin sole (*Limanda aspera*), and BSAI northern rock sole (*Lepidopsetta polyxystra*) (NPFMC, 2012a). Such estimates are not available for crab stocks in this region because stock–recruitment relationships are often poorly defined or very uncertain. Consequently, it is necessary to set F_{MSY} and B_{MSY} to "proxy" values to provide management advice. For example, the overfishing definitions and OFL control rule definitions for the crab stocks in the BSAI region of the US are based on a tier system, where the tier level relates to the amount of information available for a given stock and defines the proxies used for F_{MSY} and B_{MSY} (Table 1; NPFMC 2008).

The crab fishery in the BSAI consists of several species and stocks. Some stocks are managed solely by the State of Alaska, while other stocks are managed under a cooperative regime that defers the setting of certain management controls to the State of Alaska with federal oversight. Under this framework, the setting of OFLs

* Corresponding author. Tel.: +1 206 221 6319; fax: +1 206 685 7471.
E-mail addresses: aepunt@uw.edu, aepunt@u.washington.edu (A.E. Punt).

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Table 1
Five-tier system for setting overfishing limits for crab stocks. The tiers are listed in descending order of information availability (NPFMC, 2008).

Information available	Tier	Stock status level	F_{OFL}/OFL
B, B_{MSY}, F_{MSY}, and pdf of F_{MSY}	1	a. $B/B_{MSY} > 1$ b. $\beta < B/B_{MSY} \le 1$ c. $B/B_{MSY} \le \beta$	$F_{OFL} = \mu_A$ = arithmetic mean of the pdf $F_{OFL} = \mu_A(B/B_{MSY} - \alpha)/(1 - \alpha)$ Directed fishery $F = 0$ $F_{OFL} \le \mu_A$
B, B_{MSY}, F_{MSY}	2	a. $B/B_{MSY} > 1$ b. $\beta < B/B_{MSY} \le 1$ c. $B/B_{MSY} \le \beta$	$F_{OFL} = F_{MSY}$ $F_{OFL} = F_{MSY}(B/B_{MSY} - \alpha)/(1 - \alpha)$ Directed fishery $F = 0$ $F_{OFL} \le F_{MSY}$
B, $F_{35\%}$, $B_{35\%}$[a]	3	a. $B/B_{35\%} > 1$ b. $\beta < B/B_{35\%} \le 1$ c. $B/B_{35\%} \le \beta$	$F_{OFL} = F_{35\%}$ $F_{OFL} = F_{35\%}(B/B_{35\%} - \alpha)/(1 - \alpha)$ Directed fishery $F = 0$ $F_{OFL} \le F_{35\%}$
B, M, B_{ref}	4	a. $B/B_{ref} > 1$ b. $\beta < B/B_{ref} \le 1$ c. $B/B_{ref} \le \beta$	$F_{OFL} = \gamma M$ $F_{OFL} = \gamma M(B/B_{ref} - \alpha)/(1 - \alpha)$ Directed fishery $F = 0$ $F_{OFL} \le \gamma M$
Stocks with no reliable estimates of biomass or *M*.	5		Average catch from a time period to be determined, unless the SSC recommends an alternative value based on the best available scientific information.

[a] 35% is the default value unless the SSC recommends a different value based on the best available science.

is a federal responsibility. State regulations are constrained by the provisions of a Fishery Management Plan, including its goals and objectives, MSA national standards, and other applicable federal laws (ADF, 2008). There are ten stocks under cooperative management (four stocks of red king crab *Paralithodes camtschaticus*; one stock of snow crab *Chionoecetes opilio*, one stock of Tanner crab *C. bairdi*, two stocks of blue king crab *P. platypus*, and two stocks of golden (or brown) king crab *Lithodes aequispinus*). The fisheries for four of these stocks (Pribilof Islands red, blue, and golden king crab and Adak red king crab) are closed at present. The remaining stocks are fished, with the bulk of the revenue arising from Bristol Bay red king crab, EBS snow crab, and Aleutian Islands golden king crab (Bowers et al., 2008).

None of the BSAI crab stocks are currently (as of 2010) placed in tiers 1 and 2 of Table 1 (the levels requiring the highest amount of information), but two stocks (EBS snow crab, and Bristol Bay red king crab) are in tier 3 (stocks with quantitative stock assessments and for which estimates of $F_{35\%}$, the exploitation rate which would reduce the mature male biomass-per-recruit at mating to 35% of its unfished level, can be calculated, but for which a well-defined stock–recruitment relationship is not available). Five stocks are in tier 4 (stocks for which measures of biomass are available, there is an estimate of natural mortality, M, but an estimate of $F_{35\%}$ is not available) and three stocks are in tier 5 (stocks for which reliable estimates of biomass are not currently available). $F_{35\%}$ was selected as the proxy for F_{MSY} based on projections for a range of harvest rates, followed by application of the minimax method of Clark (1991) (NPFMC, 2008).

The proxy for B_{MSY} for tier 3 stocks is the average recruitment over a period recommended by the Scientific and Statistical Committee (SSC) of the North Pacific Fishery Management Council multiplied by mature male biomass-per-recruit corresponding to $F_{35\%}$. In contrast, the proxy for B_{MSY} for tier 4 stocks is simply the average mature male biomass (MMB) over a recommended period (see Table 2 for the most recent recommendations for the five stocks considered in this paper). The ranges of values for B_{MSY} in Table 2 are, however, based on expert judgment (except for that for Bristol Bay red king crab which is based on changes on mean recruitment; Zheng and Siddeek, 2010). Therefore, it is not clear whether the estimates of B_{MSY} for tier 3 stocks are consistent with a F_{MSY} proxy of $F_{35\%}$ nor whether the assumed values for B_{MSY} (tier 4 stocks) and the average recruitment at which MSY is assumed to occur (tier 3 stocks) are consistent with the data from the stock assessments on which they are nominally based. Furthermore, the assumption that F_{MSY} is approximately $F_{35\%}$ may be in error.

Average recruitment calculated for use in proxies for management targets represents a manager's expectation about the future productivity of a stock. Using average recruitment from an extended period from the past implicitly assumes that the future will be similar to the past. However, the physical environment of the Bering Sea exhibits large, persistent shifts on a decadal scale that can be seen through variables such as sea surface temperature and the Aleutian Low Pressure Index. These changes in the environment can result in 'regime shifts' (Hare and Mantua, 2000) that can be detected in many biological and physical indices (Overland et al., 2008) and sometimes influence the productivity of fish and invertebrate stocks. Consequently, some estimates of recruitment from the past may not be informative about the current productivity of a stock.

Shifts in climate regime in the North Pacific have been observed most recently during 1977, 1989, and 1999 (Overland et al., 2008) and there are many examples of recruitment responding to these shifts. Conners et al. (2002) reported increases in recruitment for Pacific cod (*Gadus macrocephalus*), rock sole (*Lepidopsetta bilineatea*), flathead sole (*Hippoglossoides elassodon*) and walleye pollock (*Theragra chalcogramma*) in the Bering Sea after the 1977 regime shift, and Bristol Bay sockeye salmon was also observed to increase after the 1977 shift (Adkison et al., 1996). Control of walleye pollock recruitment in the Gulf of Alaska appeared to shift from environmental effects on larvae to top-down predation on juveniles after the 1977 regime shift (Bailey, 2000). Similarly, control of Pacific cod abundance in the North Pacific changed from top-down effects to

Table 2
BSAI crab stocks, and the years used to compute mean recruitment (tier 3) and reference biomass (tier 4). The B_{MSY} proxies implied by the way management advice was given in 2010 are listed along with $F_{35\%}$. "Current" for this table, and the analyses of this paper is 2010.

Stock	Tier	Years	B_{MSY} proxy	$F_{35\%}$
Bristol Bay red king crab	3	1994–current	37,000 t	0.208
EBS snow crab	3	1979–current	124,000 t	0.466
EBS Tanner crab	4	1974–1980	58,000 t	0.519
St. Matthew Island blue king crab	4	1989–current	6600 t	0.375
Pribilof Islands red king crab	4	1980–1997	2400 t	0.138