Fishery Manuscript No. 20-03

Recommended Harvest Strategy for Bering Sea Tanner Crab

by

Benjamin Daly

Madison Heller-Shipley

Mark Stichert

William Stockhausen

André Punt

and

Scott Goodman

February 2020

Alaska Department of Fish and Game Divisions of Sport Fish and Commercial Fisheries

Symbols and Abbreviations

The following symbols and abbreviations, and others approved for the Système International d'Unités (SI), are used without definition in the following reports by the Divisions of Sport Fish and of Commercial Fisheries: Fishery Manuscripts, Fishery Data Series Reports, Fishery Management Reports, and Special Publications. All others, including deviations from definitions listed below, are noted in the text at first mention, as well as in the titles or footnotes of tables, and in figure or figure captions.

Weights and measures (metric)

centimeter	cm
deciliter	dL
gram	g
hectare	ha
kilogram	kg
kilometer	km
liter	L
meter	m
milliliter	mL
millimeter	mm

Weights and measures (English)

cubic feet per second	ft^3/s
foot	ft
gallon	gal
inch	in
mile	mi
nautical mile	nmi
ounce	oz
pound	lb
quart	qt
yard	yd

Time and temperature

day	d
degrees Celsius	°C
degrees Fahrenheit	°F
degrees kelvin	K
hour	h
minute	min
second	s

Physics and chemistry

all atomic symbols	
alternating current	AC
ampere	A
calorie	cal
direct current	DC
hertz	Hz
horsepower	hp
hydrogen ion activity (negative log of)	pH
parts per million	ppm
parts per thousand	ppt, ‰
volts	V
watts	W

General

Alaska Administrative Code	AAC
all commonly accepted abbreviations	e.g., Mr., Mrs., AM, PM, etc.
all commonly accepted professional titles	e.g., Dr., Ph.D., R.N., etc.
at	@
compass directions:	
east	E
north	N
south	S
west	W
copyright	©
corporate suffixes:	
Company	Co.
Corporation	Corp.
Incorporated	Inc.
Limited	Ltd.
District of Columbia	D.C.
et alii (and others)	et al.
et cetera (and so forth)	etc.
exempli gratia (for example)	e.g.
Federal Information Code	FIC
id est (that is)	i.e.
latitude or longitude	lat or long
monetary symbols (U.S.)	\$, ¢
months (tables and figures): first three letters	Jan,...,Dec
registered trademark	®
trademark	™
United States (adjective)	U.S.
United States of America (noun)	USA
U.S.C.	United States Code
U.S. state	use two-letter abbreviations (e.g., AK, WA)

Mathematics, statistics

all standard mathematical signs, symbols and abbreviations	
alternate hypothesis	H_A
base of natural logarithm	*e*
catch per unit effort	CPUE
coefficient of variation	CV
common test statistics	(F, t, χ^2, etc.)
confidence interval	CI
correlation coefficient (multiple)	R
correlation coefficient (simple)	r
covariance	cov
degree (angular)	°
degrees of freedom	df
expected value	*E*
greater than	>
greater than or equal to	≥
harvest per unit effort	HPUE
less than	<
less than or equal to	≤
logarithm (natural)	ln
logarithm (base 10)	log
logarithm (specify base)	log_2, etc.
minute (angular)	'
not significant	NS
null hypothesis	H_O
percent	%
probability	P
probability of a type I error (rejection of the null hypothesis when true)	α
probability of a type II error (acceptance of the null hypothesis when false)	β
second (angular)	"
standard deviation	SD
standard error	SE
variance	
population	Var
sample	var

FISHERY MANUSCRIPT SERIES NO. 20-03

RECOMMENDED HARVEST STRATEGY FOR BERING SEA TANNER CRAB

by

Benjamin Daly
Alaska Department of Fish and Game, Division of Commercial Fisheries, 351 Research Court, Kodiak, AK 99615

Madison Heller-Shipley
School of Aquatic and Fishery Sciences, University of Washington, Seattle, WA 98195-5020

Mark Stichert
Alaska Department of Fish and Game, Division of Commercial Fisheries, 351 Research Court, Kodiak, AK 99615

William Stockhausen
National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Alaska Fisheries Science Center, 600 Sand Point Way N.E., Building 4, Seattle, WA 98115

André E. Punt
School of Aquatic and Fishery Sciences, University of Washington, Seattle, WA 98195-5020

and

Scott Goodman
Natural Resources Consultants, Inc., 4039 21st Avenue West, Suite 404, Seattle, WA 98199

Alaska Department of Fish and Game
Division of Sport Fish, Research and Technical Services
333 Raspberry Road, Anchorage, Alaska, 99518-1565

February 2020

The Fishery Manuscript Series was established in 1987 by the Division of Sport Fish for the publication of technically-oriented results of several years' work undertaken on a project to address common objectives, provide an overview of work undertaken through multiple projects to address specific research or management goal(s), or new and/or highly technical methods, and became a joint divisional series in 2004 with the Division of Commercial Fisheries. Fishery Manuscripts are intended for fishery and other technical professionals. Fishery Manuscripts are available through the Alaska State Library and on the Internet: http://www.adfg.alaska.gov/sf/publications/ This publication has undergone editorial and peer review.

Benjamin Daly, Mark Stichert
Alaska Department of Fish and Game, Division of Commercial Fisheries,
351 Research Ct., Kodiak, Alaska, 99615, USA

Madison Heller-Shipley, Andre Punt
School of Aquatic and Fishery Sciences, University of Washington, Seattle, WA 98195-5020
92 NE Boat St., Seattle, Washington 98105

William Stockhausen
National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Alaska Fisheries Science Center, 600 Sand Point Way N.E., Building 4, Seattle, Washington, 98115

and

Scott Goodman
Natural Resources Consultants, Inc., 4039 21st Avenue West, Suite 404
Seattle, Washington, 98199

This document should be cited as follows:
Daly, B., M. Heller-Shipley, M. Stichert, W. Stockhausen, A. E. Punt, and S. Goodman. 2019. Recommended harvest strategy for Bering Sea Tanner crab. Alaska Department of Fish and Game, Fishery Manuscript Series No. 20-03, Anchorage.

TABLE OF CONTENTS

Page

LIST OF TABLES

Table **Page**

LIST OF FIGURES

ABSTRACT

The Alaska Department of Fish and Game (ADF&G) harvest strategy for Bering Sea Tanner crab has evolved over the past 40 years in response to fluctuations in biomass, advancements in understanding of Tanner crab biology, and continued improvements in assessment modelling approaches. Although the intent of all harvest strategy changes was to improve the stability of this fishery and minimize closures, this fishery has been closed 5 out of the last 10 seasons and currently has the most complicated strategy of all the Bering Sea Aleutian Islands (BSAI) crab stocks. In collaboration among ADF&G, the University of Washington, the National Oceanic and Atmospheric Administration (NOAA), and the commercial crab industry, we take a holistic approach using the most current scientific methods to evaluate and advance a new harvest strategy that explicitly incorporates conservation and economic goals. Specifically, we used a Management Strategy Evaluation (MSE) via 100-year forecast simulations to examine the ability of 15 harvest strategies to provide sustainable harvest. Additionally, we recomputed historical total allowable catches (TACs) to further understand harvest strategy performance using “real” data (i.e., not simulated data in the MSE forecast simulations). Of the 15 strategies, 7 were discarded due to conservation concerns (e.g., high probability of total fishery mortality exceeding federal overfishing limits), and two were discarded due to economic concerns (e.g., low projected catch). Because male-only policies ignore the contribution of females to the reproductive potential of the population, we focused our recommendation on polices that include consideration of mature female biomass. Of those 4 remaining policies, we recommend a harvest policy that includes a threshold for opening the fishery of 25% of the long-term (1982-2018) average of mature male biomass, a minimum (5% or 10%) and 20% maximum exploitation rate on mature male biomass adjusted for relative mature female biomass, and a 50% maximum exploitation rate on exploitable, industry-preferred size legal male abundance. Our analysis suggests these policies balance the tradeoff between conservation and economic considerations.

Key words: Eastern Bering Sea, Tanner crab, harvest strategy, total allowable catch

INTRODUCTION

BACKGROUND

Tanner crab (*Chionoecetes bairdi*) are broadly distributed in the eastern Bering Sea (EBS), with commercial concentrations in Bristol Bay and around the Pribilof Islands. Larvae hatch during mid to late spring, develop through two planktonic larval stages over several months, and molt to the post-larval megalopal stage, which settles to the ocean bottom on the continental shelf presumably based on environmental cues that signal suitable benthic habitat (Incze et al. 1982; Incze et al. 1987). Larvae mostly occur in the upper 40 m of the water column with no evidence of diel vertical migration (Incze et al. 1987). After settlement, megalopae molt into the first juvenile instar (C1), at which point they take an adult-like benthic form.

Eastern Bering Sea Tanner crab have highly variable and episodic recruitment, which resulted in a “boom or bust” style fishery. The stock was targeted by Japanese and Russian fleets starting in 1965, which continued under quotas negotiated through a U.S.–Japan bilateral agreement until 1978 when foreign fisheries for snow crab (*Chionoecetes opilio*) and Tanner crab were prohibited under the Magnuson–Stevens Fisheries Conservation and Management Act (Otto, 1989). The U.S. Tanner fishery developed in the mid-1970s with peak landings in 1977 (67 million lb) and 1990 (40 million lb), but low abundance resulted in fishery closures in 1985, 1986, 1997-2004, 2010-2012, 2016, and 2019 (a 40% closure rate since 1982; Figure 1). The eastern Bering Sea Tanner crab fishery has been prosecuted under the Crab Rationalization Program since 2005/06, which resulted in dramatic changes in fishing practices: most notably, reduced fleet size (from 146 to 50 vessels) and increased average pot soak time (from 38 h to 64 h).

Bering Sea Tanner crab is considered a single stock but is managed in two areas east and west of 166° W long due to uncertainty about stock structure and to protect against local depletion. Tanner crab are widely distributed over the NOAA bottom-trawl survey area without discontinuity between Bristol Bay and around the Pribilof Islands concentrations, but differences in size-at-maturity are well documented between the areas east and west of 166° W long (Somerton 1981; Zheng 2008; Zheng and Pengilly 2011) and have important implications for management of the stock, including different legal sizes (Zheng and Pengilly 2011). Simulated larval trajectories suggest that the EBS Tanner crab stock consists of a metapopulation composed of multiple subunits that are connected via variable dispersal rates, and that the Bristol Bay component is quasi-isolated, relying heavily on local retention for the supply of recruits (Richar et al. 2015). Genetic research has failed to detect evidence of two distinct, non-intermixing, non-interbreeding stocks (Johnson 2019), supporting the concept of a metapopulation composed of two sub-units. As such, the current practice of managing Bering Sea Tanner crab as one stock with separate total allowable catches (TACs) set for each sub-stock east and west of 166° W long reflects the current state of the science for Tanner crab biology.

PURPOSE

The purpose of this report is to provide the basis for a recommended update to the Bering Sea Tanner crab harvest strategy 5 AAC 35.508. We provide a brief history of the fishery, an overview of the fishery management goals and objectives, and the need for an updated harvest strategy. We describe the harvest strategies evaluated and the forecast simulation methods and results, and provide our recommended harvest strategy.

FEDERAL–STATE CO-MANAGEMENT

The North Pacific Fishery Management Council (NPFMC) Fishery Management Plan (FMP) for Bering Sea/Aleutian Islands (BSAI) king and Tanner crabs establishes a State/Federal cooperative management regime that defers crab management to the State of Alaska with Federal oversight (NPFMC 2011). The FMP applies to 10 king and Tanner crab stocks in the BSAI: four red king crab *Paralithodes camtschaticus* stocks (Bristol Bay, Pribilof Islands, Norton Sound, and Adak); two blue king crab *P. platypus* stocks (St. Matthew Island and Pribilof Islands); two golden king crab stocks (Aleutian Islands and Pribilof Islands); the EBS Tanner crab *Chionoecetes bairdi* stock; and the EBS snow crab *C. opilio* stock. Status determination criteria for crab stocks are annually calculated using a five-tier system that accommodates varying levels of uncertainty of information. Under the five-tier system, overfishing levels (OFL) and acceptable biological catch (ABC) levels are annually formulated (NPFMC 2007). The OFL is calculated using a maximum sustainable yield (MSY) control rule and is derived through the annual assessment process, under the framework of the tier system. The ABC is typically set well below the OFL to account for "the scientific uncertainty in the estimate of OFL and any other specified scientific uncertainty" (NPFMC 2011). Prior to the 2012 stock assessment, Tanner crab was managed as a Tier 4 stock using a survey-based assessment approach. Based on recommendations from its Crab Plan Team (CPT) and Scientific and Statistical Committee (SSC), the NPFMC adopted a size-structured stock assessment model in 2012 to estimate status determination criteria and overfishing levels using the Tier 3 control rule.

Under the FMP's cooperative management regime, annual harvest levels and other management actions for the FMP crab stocks are determined by the Alaska Department of Fish and Game (ADF&G) according to State commercial fishery regulations established by the Alaska Board of Fisheries (BOF) and the guidance provided by the BOF Policy on King and Tanner Crab Resource Management Goal and Benefits, subject to the constraint that such harvest levels and management actions are consistent with provisions of the FMP, the national standards of the Magnuson–Stevens Fishery Conservation and Management Act (MSA), and other applicable federal laws. FMP Amendment 38 established the optimum yield (OY) for each crab stock as a range from 0 pounds to less than the OFL. That definition of the OY range enables the State to determine appropriate harvest levels—either as a total allowable catch (TAC) for the fisheries included in the federal Crab Rationalization Program or as a guideline harvest level (GHL) for the non-rationalized fisheries—below the ABC to prevent overfishing or to address other possible impacts to the reproductive potential of a stock that are not accounted for in the federal determination of the OFL. Hence, ADF&G has the responsibility under Amendment 38 not only to establish the annual harvest level for each of the FMP stocks sufficiently below the ABC so that the sum of all sources of fishing mortality (including retained catch, cost-recovery fisheries, bycatch mortality in the directed fishery, and bycatch mortality in all non-directed fisheries) does not exceed the ABC but also to account for numerous other factors and OY considerations, including scientific uncertainty not already accounted for in the ABC itself.

The FMP authorizes the State to set preseason TACs under State regulations. Currently, the Bering Sea Tanner crab annual TAC is set by state regulation (5 AAC 35.508), as approved by the BOF in March 2011:

(a) In the Bering Sea District, the commercial C. bairdi Tanner crab fishery may open only if an analysis of preseason survey data indicates that the population at the time of the survey is at or above 40 percent of the long-term average (1975-2010) of mature female crab biomass in the Eastern Subdistrict.

(b) If preseason survey data indicates that the population at the time of the survey is at or above 40 percent of the long-term average of mature female biomass in the eastern Subdistrict for the second consecutive year, the department shall establish a separate total allowable catch level for that portion of the Bering Sea District that is east of 166° W. long. and for that portion of that is west of 166° W. long. Under the provisions of (c) and (d) of this section. If the commercial C. bairdi Tanner crab fishery in the Bering Sea District did not open in the previous season because the threshold requirements specified in (a) of this section were not met, the total allowable catch level for that portion of the Bering Sea District that is east of 166° W. long. and for that portion of that is west of 166° W. long., as computed under (c) and (d) of this section, shall be reduced by one-half.

(c) In that portion of the Bering Sea District that is east of 166° W. long., and under the restrictions of (e) and (f) of this section, the total allowable catch level shall be established as follows:

(1) if B_E is less than 25 percent of $B_{E,(1975\text{-}2010)}$, the fishery will not open;

(2) if B_E is at least 25 percent but not greater than 100 percent of $B_{E,(1975\text{-}2010)}$, the total allowable catch will be computed as $(0.9)x(B_E/ B_{E,(1975\text{-}2010)})xC_{E,MSY}$; and

(3) if B_E is greater than 100 percent of $B_{E,(1975\text{-}2010)}$, the total allowable catch will be computed as $(0.9)xC_{E,MSY}$.

(d) In that portion of the Bering Sea District that is west of 166° W. long., and under the restrictions of (e) and (f) of this section, the total allowable catch level shall be established as follows:

(1) if B_W is less than 25 percent of $B_{W,(1975\text{-}2010)}$, the fishery will not open;

(2) if B_W is at least 25 percent but not greater than 100 percent of $B_{W,(1975\text{-}2010)}$, the total allowable catch will be computed as $(0.9)x(B_W/ B_{W,(1975\text{-}2010)})xC_{W,MSY}$; and

(3) if B_W is greater than 100 percent of $B_{W,(1975\text{-}2010)}$, the total allowable catch will be computed as $(0.9)xC_{W,MSY}$.

(e) Notwithstanding (b) – (d) of this section, the total allowable catch for

(1) that portion of the Bering Sea District that is east of 166° W. long. may not exceed 50 percent of the estimated biomass of male C. bairdi Tanner crab, that are 127 millimeters (five inches) or greater in carapace width, including the lateral spines, discounted by fishery selectivity, that would survive in the absence of fishing mortality until the estimated mean time of mating; and

(2) that portion of the Bering Sea District that is west of 166° W. long. may not exceed 50 percent of the estimated biomass of male C. bairdi Tanner crab, that are 127 millimeters (five inches) or greater in carapace width, including the lateral spines, discounted by fishery selectivity, that would survive in the absence of fishing mortality until the estimated mean time of mating.

(f) Notwithstanding (b) – (e) of this section, in implementing this harvest strategy, the department shall consider the reliability of the estimates of C. bairdi Tanner crab, the manageability of the fishery, and other factors the department determines necessary to be consistent with sustained yield principles and to use the best scientific information available and consider all sources of uncertainty as necessary to avoid overfishing.

(g) In this section,

(1) "B_E" mean the biomass of male C. bairdi Tanner crab in the portion of the Bering Sea District that is east of 166° W. long. that are more than 112 millimeters in carapace width estimated for the time of the preseason survey;

(2) "$B_{E,(1975\text{-}2010)}$" means the mean value of the biomass of male C. bairdi Tanner crab in the portion of the Bering Sea District that is east of 166° W. long. that are more than 112 millimeters in carapace width estimated for the time of the preseason survey for the period 1975-2010;

(3) "B_W" mean the biomass of male C. bairdi Tanner crab in the portion of the Bering Sea District that is west of 166° W. long. that are more than 102 millimeters in carapace width estimated for the time of the preseason survey;

(4) "$B_{w,(1975\text{-}2010)}$" means the mean value of the biomass of male C. bairdi Tanner crab in the portion of the Bering Sea District that is west of 166° W. long. that are more than 102 millimeters in carapace width estimated for the time of the preseason survey for the period 1975-2010;

(5) "$C_{E,MSY}$" means the catch biomass of male C. bairdi Tanner crab in the portion of the Bering Sea District that is east of 166° W. long. that are more than 127 millimeters (five inches) or greater in carapace width, including lateral spines, resulting from fishing on the estimated mature male biomass at the estimated mean time of mating at the full-selection F_{MSY} rate or a proxy for the F_{MSY} rate;

(6) "$C_{W,MSY}$" means the catch biomass of male C. bairdi Tanner crab in the portion of the Bering Sea District that is west of 166° W. long. that are more than 127 millimeters (five inches) or greater in carapace width, including lateral spines, resulting from fishing on the estimated mature male biomass at the estimated mean time of mating at the full-selection F_{MSY} rate or a proxy for the F_{MSY} rate;

(7) "mature female crab" means for

(A) that portion of the Bering Sea District that is east of 166° W. long., a female C. bairdi Tanner crab that is more than 84 millimeters in carapace width; and

(B) that portion of the Bering Sea District that is west of 166° W. long., a female C. bairdi Tanner crab that is more than 79 millimeters in carapace width.

The above language was modified during the May 2017 BOF meeting to 1) change how female maturity is defined (i.e., based on abdominal flap morphology rather than a carapace width [CW] size cut-off), 2) modify the years used to define the mature male and female biomass threshold to 1982-2016, 3) expand the spatial range that is considered for the mature female biomass threshold calculation to include the entire NOAA EBS summer bottom trawl survey area, and 4) include a "female error band" control rule that reduces the exploitation on industry-preferred size (>127 mm CW including spines) male crabs when the mature female threshold falls within the 95 percent confidence interval of the current year point estimate of mature female biomass (ADF&G 2017b).

Current regulations (5 AAC 39.645 (d)(4)(D)) stipulate that onboard observers are required on catcher vessels during harvest of 30 percent of the total *C. bairdi* Tanner crab weight harvested on each catcher vessel while operating fishing gear during each registration year or during the period when the department randomly selects between 30 percent and 100 percent of the catcher vessels engaged in directed harvest of *C. bairdi* Tanner crab to carry onboard observers for 100 percent of the fishing time of each selected catcher vessel. These requirements apply unless a catcher vessel harvests *C. bairdi* Tanner crab as incidental catch during directed fishing for either Bristol Bay red king crab or Bering Sea snow crab, where observer coverage requirements for those directed fisheries would apply to the Tanner crab incidental harvest.

The Bering Sea District of Tanner crab Registration Area J includes all Bering Sea waters north of 54° 36′ N lat and east of the Maritime Boundary Agreement Line that is described in the text of and depicted in the annex to the Maritime Boundary Agreement between the United States and the Union of Soviet Socialist Republics signed in Washington, June 1, 1990, and as that Maritime Boundary Agreement Line is depicted on NOAA *Chart #513* (7th Edition, June 2004) and NOAA *Chart #514* (7th Edition, January 2004), adopted by reference. This district is divided into the Eastern and Western Subdistricts at 173° W long. ADF&G manages the stock in two areas east and west of 166° W long (ADF&G 2017a; Figure 2).

MANAGEMENT GOALS AND OBJECTIVES

An optimal harvest strategy for any fishery resource depends on fishery management goals and objectives. The management goal in the FMP is to "*maximize the overall long-term benefit to the nation of BSAI king and Tanner crab stocks by coordinated federal and state management, consistent with responsible stewardship for conservation of the crab resources and their habitats*". Within the scope of the management goal, the FMP identifies seven management objectives, which conforms to the Magnuson–Stevens Act national standards (NPFMC 2011).

- Biological Conservation Objective: Ensure the long-term reproductive viability of king and Tanner crab populations.
- Economic and Social Objective: Maximize economic and social benefits to the nation over time.
- Gear Conflict Objective: Minimize gear conflict among fisheries.
- Habitat Objective: Preserve the quality and extent of suitable habitat.
- Vessel Safety Objective: Provide public access to the regulatory process for vessel safety considerations.

- Due Process Objective: Ensure that access to the regulatory process and opportunity for redress are available to interested parties.
- Research and Management Objective: Provide fisheries research, data collection, and analysis to ensure a sound information base for management decisions.

In March 1990, the BOF adopted a fishery management policy for king and Tanner crabs (ADF&G 1990; also listed in ADF&G 2017a). The goal of the policy is to maintain and improve crab resources for the greater overall benefit to Alaska and the nation. Achievement of this goal is constrained by the need to minimize: (1) risk of irreversible adverse effects on reproductive potential; (2) harvest during biologically sensitive periods; (3) adverse effects on non-targeted portions of the stock; and (4) adverse interactions with other stocks and fisheries. The policy endeavors to maintain a healthy stock, provide for a sustained and reliable supply of high-quality product that leads to substantial and stable employment, and provide for subsistence and personal use of the resource. The BOF specified a series of policies to protect the crab stock and provide optimum utilization:

1. Maintain crab stocks composed of various sizes and age classes of mature animals in order to maintain the long-term reproductive viability of the stock and reduce industrial dependency on annual recruitment, which is extremely variable. Benefits of this policy are most apparent when weak recruitment occurs. As population abundance and structure change with declining recruitment, harvests should be reduced.
2. Routinely monitor crab resources to provide information on abundance of females as well as prerecruit, recruit, and postrecruit males. This is necessary to detect changes in the population that may require adjustments in management to prevent irreversible damage to the reproductive potential of each stock and to better achieve the benefits listed above. Harvests must be conducted in a conservative manner in the absence of adequate information on stocks.
3. Protect king and Tanner crab stocks during biologically sensitive periods of their life cycle. Closure of the fishing season is necessary at times surrounding the annual mating, molting, and egg hatching periods in order to reduce unnecessary mortality of soft animals, disturbance during mating, and damage to egg clutches.
4. Minimize handling and unnecessary mortality of non-legal crabs and other non-target animals. Capture and handling of females, sublegal males, and animals of other species results in a loss of reproductive ability and biomass that may be detrimental to a stock.
5. Maintain an adequate brood stock to rebuild king or Tanner crab populations when they are depressed. Maintenance of an adequate broodstock takes precedence over short-term economic considerations. When populations are at or below threshold (the minimum stock size that allows sufficient recruitment so that the stock can rebuild itself), fisheries must be closed and must remain closed until there is adequate broodstock.
6. Establish management measures in each fishing area based on the best available information. Stock and fishery characteristics, as well as available data, vary from area to area within Alaska. Actual management practices in each area will vary accordingly.
7. Establish regulations that will help improve the socioeconomic aspects of management by harvesting crab when their meat yield is highest, providing for fair starts and closures to seasons, ensuring enforceability or regulations, and taking other measures to provide for an orderly fishery.

Current size-sex-season measures (i.e., 3-S: harvest of only large males and no fishing during spring molting and mating periods) are generally consistent with these policies and are based on economic consideration of market value, protection of females, and allowance of at least one mating season for males. Our analysis evaluated criteria that parallel goals outlined in the Federal FMP and BOF fishery management policy for king and Tanner crabs. The BOF policy on king and Tanner crab management provides specific criteria under which alternative harvest strategies can be evaluated. The Magnuson–Stevens Fishery Conservation and Management Act provides additional criteria (NMFS 1996). In particular, National Standard 1 states that "conservation and management measures shall prevent overfishing while achieving, on a continuing basis, the optimal yield from each fishery."

HARVEST STRATEGY REVISION NEED

The ADF&G harvest strategy for Bering Sea Tanner crab has evolved in parallel with advancements in understanding of Tanner crab biology and assessment modeling approaches. 3-S management was implemented in the 1970s based on economic considerations of market value and meat yield, fishing opportunity, protection of females for reproduction, and the intent to allow at least one mating season for mature males prior to harvest. With population declines in the 1990s, the stock fell below the minimum stock size threshold established in the FMP and was declared overfished in 1998, which resulted in the development of a federal rebuilding plan. As part of a comprehensive rebuilding plan, the BOF adopted a revised harvest strategy informed by computer simulations based on a size-structured population model that 1) included a minimum threshold of mature female biomass, 2) applied harvest rates on mature male biomass based on the mature female biomass status, and 3) employed a maximum exploitation rate on legal male abundance (Zheng and Kruse 1999).

The female threshold was implemented as a conservation measure to maintain adequate broodstock to allow sufficient recruitment (per BOF Policy 5; ADF&G 1990). The female threshold was based on a poorly fitting S-R relationship for Bristol Bay Tanner crab and estimates of effective spawning biomass (ESB) informed by estimates of mature male and female abundance, mature female shell condition proportions, and assumptions about mating behavior during low and high population densities (Zheng and Kruse 1998). Because ESB equaled mature female biomass for a majority of the years analyzed and the analysis was c omplex, mature female biomass was used as a substitute for ESB (Zheng and Kruse 1998; Zheng and Kruse, 1999). The threshold was set at 21 million lb of mature female biomass in the eastern Subdistrict (i.e., east of 173° W long), which represented a level of ESB slightly above the smallest ESB with an above average recruitment level (Zheng and Kruse 1999).

The ADF&G harvest strategy for Bering Sea Tanner crab was updated in 2011 to address the concept of a male terminal molt, and temporal and spatial changes in size at maturity, with the aim to increase fishery yield, reduce on-deck sorting time and discarded bycatch of male Tanner crab, and avoid excessively targeting on fast-growing, large crab (Zheng and Pengilly 2011). It has been long recognized that the female Tanner crab molt to maturity is a terminal molt (i.e., that crab will never molt and grow after the molt to maturity), but the concept of a male terminal molt was controversial (Donaldson and Johnson 1988; Zheng et al. 1998; Zheng and Kruse 1999; Zheng and Pengilly 2011) until 2005 when it became more widely accepted (Tamone et al. 2005; Tamone et al. 2007; Zheng et al. 2011). The 2011 update changed the female threshold to 40% of the long-term (1975-2010) average of mature female biomass, which approximated 21 million lb established in the 1999 harvest strategy revision. The 2011 update is largely intact in the current harvest strategy and includes the following: 1) a minimum size limit, 2) a mature female biomass threshold, 3) a harvest control rule that varies with an index of mature male biomass, and 4) a buffer on the harvest level to avoid overfishing. The 2011 update incorporated elements of the stock assessment model including model-based estimates of fishery selectivity, natural mortality, and F_{MSY} (i.e., the instantaneous fishing mortality that will produce maximum sustainable yield) to better align the state harvest strategy with the federal ABC approach and to reflect the current state of the science (Zheng and Pengilly 2011).

Since the 2011/12 season, the Bering Sea Tanner crab fishery has been closed for 4 out of 9 seasons (44% closure rate) as a result of failing to meet mature female threshold requirements. Following the fishery closure in 2016, the calculation and utility of the female-based threshold was questioned. As a result, the ADF&G harvest strategy for Bering Sea Tanner crab was updated in 2017 to address 1) uncertainty in mature female biomass estimates, 2) the definition of female maturity, 3) years for the mature female threshold calculation, and 4) the spatial area to include when calculating the mature female threshold. The 2017 update included 1) changes to the years used to calculate the long-term average to better reflect the contemporary environmental conditions and to better align with the federal stock assessment model, 2) female maturity definition based on abdominal flap morphology rather than a carapace width (CW) size cut-off, 3) the inclusion of female crabs in both the Eastern and Western Subdistricts (i.e., the full NOAA EBS bottom trawl survey area), and 4) a reduced exploitation rate on males when the female threshold falls with the 95% confidence interval of the estimate of mature female biomass (the "female error band rule").

The current harvest strategy is improved relative to past versions, but it is the most complicated of the harvest strategies for all of the BSAI crab stocks, with elements that can lead to abrupt changes in annual TACs that are economically suboptimal. Our goal is to develop a new harvest strategy that uses the most up-to-date biological information available to simplify the harvest strategy control rules, address the utility of considering females when setting TACs, and address the abrupt interannual changes in TAC levels. Although the "female error band rule" adopted in 2017 achieves these goals in part, it was meant as a temporary measure until a more comprehensive update could be formally conducted using a robust forecasting analysis that could evaluate conservation and economic considerations for a suite of harvest strategy scenarios.

In a collaborative effort to increase transparency for the review of historical, updated, and new biological information with comanagers and stakeholders, the Bering Sea Fisheries Research Foundation (BSFRF) hosted a two-day workshop in December 2017. Organizers invited researchers with an established history with, and depth of understanding of, Bering Sea Tanner crab biology as well as fishery stakeholders and managers (Goodman 2018). The specific focus and primary question of the BSFRF Bairdi Tanner Crab Workshop was how the treatment of mature female Tanner crab should be best considered within the ADF&G harvest strategy. The goal of the workshop was to consider further refinement to the current ADF&G Bering Sea Tanner crab harvest strategy, consider the most appropriate measure of reproductive capacity for Bering Sea Tanner crab, and determine a research work plan toward a broader management strategy evaluation (MSE) for Bering Sea Tanner crab. The workshop reached a consensus regarding further consideration of how females and reproductive capacity should be considered in Bering Sea Tanner crab management. Three key summary statements in this consensus were as follows: "1) uncertainty about the idea of a cut-off in the harvest strategy based on females, absent other indicators that quantify spawning/mating threats, 2) consideration of an approach that brings the female threshold down in its level of impact within the harvest strategy to function more as a baseline indicator along with other indicators to be identified, and 3) that improved tracking of females from a research perspective could help managers, but that in general, it doesn't appear that arguments for a strict female control rule are as reliable as currently applied" (Goodman 2018). Final workshop recommendations included "an approach to revise the bairdi harvest strategy that improves the economic outlook to the industry and acknowledges the importance of the bairdi reproductive capacity to conserve the stock" (Goodman 2018). The workshop recognized inconsistencies with how Tanner females are included in fisheries management relative to other BSAI crab stocks but also highlighted the uncertainty involved with the consideration of mature females in the management of a male-only fishery.

CONSIDERATION OF MATURE FEMALES

A stock-recruit or spawner-recruit (S-R) relationship predicts likely recruitment of progeny from a given spawning stock size: commonly used S-R models are those developed by Ricker (1954; dome-shaped) and Beverton and Holt (1957; asymptotic). For crabs, significant stock-recruit relationships are rare due to difficulty in defining underlying physical processes that influence larval supply and survival to the juvenile stages (Wahle 2003). A weak S-R relationship exists for Bristol Bay red king crab (BBRKC) based on historical (1975-2001) survey data, but no such relationship exists for Tanner crab, because both weak and strong recruitment occurs for both low and high effective spawning biomass (Zheng and Kruse 2003). The causes for crab recruitment cycles are unknown, but the lack of a S-R relationship implies that environmental factors largely dictate year class strength. Accordingly, the lack of a S-R relationship does not suggest that mature female crabs are irrelevant for population reproductive output, but rather that crab recruitment cycles are highly sensitive to environmental conditions such as food availability, predator abundance, ocean current strength and direction, thermal stress, and ocean pH levels. Specific mechanisms for recruitment fluctuations are largely unknown for BSAI crab stocks but are probably influenced by complex interactions of biotic and abiotic forcing and are subject to ongoing research efforts (e.g., Daly et al. *In prep*).

BSAI crab stock assessments use mature male biomass (MMB) as a proxy for egg production, largely due to uncertainties related to identifying the component of mature males that participate in mating and defining optimal sex ratios (NPFMC 2008). This is further complicated by the fact that mature female *Chionoecetes* crabs can mate with multiple males in a single season and can store sperm via spermathecae, which could subsequently be used to fertilize embryos in the absence of males. Additionally, molt timing of males may impact their likelihood of participating in mating, which confounds estimates of sex ratios. The Center for Independent Experts (CIE) review of federal overfishing definitions recommended that "research be conducted toward estimating an egg production index that should replace the use of MMB in future reference point estimation", and further recommended research to better understand "basic reproductive dynamic relationships" in that endeavor (NPFMC 2008) signaling that some consideration of female reproductive potential is warranted for managing BSAI crab stocks. The federal Bering Sea Tanner crab stock assessment uses mature male biomass as the "currency" of crab spawning biomass but acknowledges that stock-level egg production is a better measure of stock-level reproduction capacity (Stockhausen 2019). As such, mature male biomass is likely not ideal as an indicator for reproductive potential or stock health.

Female reproductive output (egg production) is the starting point for generating subsequent recruitment in a population. Although mature male or female abundance or biomass can be used as proxies, a more refined index of reproductive output that accounts for variability in the size-fecundity relationship may be a more robust indicator of stock reproductive health. Temporal trends in mature female abundance and egg production track closely for Bering Sea snow and Tanner crab (Webb 2014; Slater et al. *In prep*), suggesting that mature female abundance is a reasonable proxy for an egg production index. A clutch fullness index is part of the standard data collection on the NOAA annual EBS summer bottom trawl survey and serves as a useful index for snow crab reproductive potential (Webb et al. 2016). Sperm limitation (as evidenced by unfertilized embryos) has not been detected for Bering Sea snow (L. Slater, Commercial Fisheries Biologist, ADF&G, Kodiak, personal communication) or Tanner crab (Knutson 2020) in the Bering Sea, suggesting adequate mating opportunities among mature male and female crabs.

Negative impacts of a male-only fishery on the reproductive potential of a population, however, are not unprecedented for Alaska crab stocks. For example, in southeast Alaska, Tanner crab stored sperm cell counts are negatively correlated with fishery exploitation rates and high levels of sperm reserves were associated with a high ratio of large old-shell males to multiparous females (Webb and Bednarski 2010), signaling that male-only harvest may decrease levels of stored sperm available for fertilization of subsequent clutches. Variation in operational sex ratios affects sperm reserves in Canadian snow crab stocks (Sainte-Marie et al. 2008), suggesting the potential for instability of reproductive potential with shifting population mating dynamics.

Given the complexity of mating dynamics for Bering Sea crab stocks and broad acceptance by the scientific community of the importance of mature females for crab reproductive potential, all state BSAI crab harvest strategies include some consideration of mature females for stocks for which there is reliable mature female abundance data. Bristol Bay red king crab is largely considered to be the most studied BSAI crab stock and employs a stair-step harvest strategy that reduces exploitation rate on mature male abundance based on mature female abundance and ESB thresholds (Zheng et al. 1997). The Bering Sea snow crab harvest strategy includes a sliding control rule in which the exploitation rate on mature male biomass depends on the current-year estimate of total mature biomass (i.e., mature male biomass plus mature female biomass) relative to the long-term average of total mature biomass (Zheng et al. 2002). The Pribilof Islands blue king crab harvest strategy employs a threshold for opening the fishery based on total mature biomass (Zheng and Pengilly 2003).

In Canada, snow crab management does not include mature females as part of the annual TAC calculation, but includes an indicator-based approach that considers mature female clutch fullness and egg viability as indices for stock health to protect reproductive potential by initiating reductions in exploitation rates on males and fishing depth restrictions (Mullowney et al. 2018). The percentage of mature females carrying full clutches of viable eggs has generally remained high throughout the time series but mature female abundance has declined in recent years (DFO 2018). The low levels observed over the past five years are considered a biological concern, but population-level implications are uncertain: "The threshold level of mature female abundance below which larval supply would become limiting is unknown" (DFO 2018).

For EBS Tanner crab, mature female abundance trends are predictors of mature male population abundance. Females mature at a younger age and smaller size (Donaldson et al. 1981), and as a result, mature male population-level increases and decreases tend to lag behind those of mature females by 1-2 years (Figure 3). This temporal mismatch in maturation causes the reproductively important years to be offset for females and males of the same cohort. It is believed that mature male Tanner crab likely have 4-5 years of effective reproduction during their lifespan based on assumptions about gonad size (Zaleski and Tamone 2014), sperm allocation at age (Adams and Paul 1983), and post-terminal-molt lifespan (Sainte-Marie et al. 1995). A reduction of exploitation on males is likely appropriate when mature female abundance is at relatively low levels to ensure optimal mating opportunities for incoming mature female recruits, with the hope that reproductively important years for mature female recruits overlap with reproductively important years for males from prior cohorts (Figure 4). Furthermore, dampening exploitation of mature males in 1-2 years prior to a population decline (as predicted by mature female biomass trends) could preserve males for harvest in subsequent fisheries in an attempt to dampen the steepness of population decline trajectories.

HARVEST STRATEGY SCENARIOS

We compared 15 harvest strategies ranging in levels of female consideration and overall aggressiveness (Table 1). For all strategies, the directed fishery is prohibited if MMB/MMB_{AVE} is <25%, which is broadly consistent with the federal control rule where the instantaneous fishing mortality (F_{OFL}) used in the calculation of the OFL equals zero when B/B_{MSY} is <25%. With the exception of the ABC, exploitable legal male (ELM, defined as 100% of the new-shell 5-inch males plus 40% of the old-shell 5-inch males), and status quo, harvest strategies included a sloping control rule where the exploitation rate on mature male biomass (MMB) increases linearly based on the ratio of the current year MMB (or mature female biomass, MFB, HCR1) relative to the long-term average MMB (or MFB, HCR1) during 1982 to 2018 (MMB_{AVE}; Figure 4). The exploitation rate on mature males is capped when $MMB/MMB_{AVE} \geq 1$. Except for the ABC harvest strategy (HCR3), a maximum exploitation rate on ELM abundance (either 30% or 50% exploitation of ELM) exists to provide an additional level of protection against over harvesting legal males in years when legal male abundance is low relative to the entire size range of mature male abundance. This method is common in other BSAI crab state harvest strategies. Typically, this situation occurs when the population is increasing from a period of low production (i.e., a strong cohort of mature size males exists simultaneously as a senescing cohort of legal sized males). The ABC harvest strategy yields a TAC that equals the 125 mm (5 inch) male portion of the ABC, whereas the fixed ELM harvest strategies yield calculated TACs based on 30%, 40%, or 50% exploitation of ELM. Finally, we included a "status quo" harvest strategy, which approximates the current harvest strategy based on the 2011 update. The 2017 update (i.e., "female error band rule") was meant as a temporary adjustment until a large-scale revision is established. As such, the female error band control rule was not included as part of the status quo harvest strategy scenario. Proposed exploitation rates in the sloping MMB and fixed ELM harvest strategies described here are consistent with State of Alaska snow and Tanner crab management in the EBS and Gulf of Alaska (Bishop et al. 2011).

STOCK ASSESSMENT MODEL

The Tanner crab stock assessment model is a stage/size-based population dynamics model that incorporates sex (male, female), shell condition (new shell, old shell), and maturity state (immature, mature) as categories into which the overall stock is divided on a size-specific basis (Stockhausen 2019). Although Bering Sea Tanner crab is managed as two separate areas, it is considered a single stock and, because the stock assessment model is not spatially explicit, the OFL and ABC are calculated for the entire EBS. Crab enter the modeled population annually as immature new-shell recruits, which are generally smaller than 55 mm CW with an assumed equal (50:50) sex ratio. These recruits are added at the start of a new model year (July 1) to the population numbers-at-sex/shell condition/maturity state/size remaining from the previous year on July 1. These are then projected forward to Feb. 15 (0.625 yr) and reduced for the interim effects of natural mortality. Subsequently, the various fisheries that either target Tanner crab or catch them as bycatch are prosecuted as pulse fisheries (i.e., instantaneously). Catch by sex/shell condition/maturity state/size in the directed Tanner crab, snow crab, BBRKC, and groundfish fisheries is calculated based on fishery-specific stage/size-based selectivity curves and fully selected fishing mortalities and removed from the population. Account is taken of discard and discard mortality. The numbers of surviving immature, new-shell crab that will molt to maturity are then calculated based on sex/size-specific probabilities of maturing, and growth (via molt) is calculated for all surviving new-shell crab. Crab that were new-shell mature crab become old-shell mature crab (i.e., they don't molt), and old-shell crab remain old-shell. Population numbers are then adjusted for the effects of maturation, growth, and change in shell condition. Finally, population numbers are reduced for the effects of natural mortality operating from Feb. 15 to July 1 (0.375 yr) to calculate the population numbers (prior to recruitment) on July 1. Model parameters are estimated using a maximum likelihood approach, with Bayesian-like priors on some parameters and penalties for smoothness and regularity on others. Data components in the base model entering the likelihood include mature survey biomass, survey size compositions, retained catch, retained catch size compositions, bycatch mortality in the bycatch fisheries, and total catch size compositions in the bycatch fisheries.

MANAGEMENT STRATEGY EVALUATION

Overview

Current knowledge about how to consider female Tanner crab reproductive potential in the management of a male-only fishery is limited. The methods adopted here take into account results from an open workshop with biologists, managers, and industry stakeholders to evaluate gaps and identify steps to revise the State of Alaska harvest strategy for Tanner crab. The agreed-upon method of exploring harvest control rule alternatives was simulation modeling using the current federal Tanner crab assessment model (Stockhausen 2017), modified for Management Strategy Evaluation (MSE). The methods for this MSE have been developed iteratively and reviewed by an ad hoc *bairdi* committee of industry representatives, with opportunities for stakeholder input on simulated model outputs and selection of risk factors for analysis. The MSE had two primary components (Figure 5): (1) the operating model, which represents the system that is being managed, and (2) the harvest strategies. The harvest strategies consistent of two components: (i) an estimation method (also called a stock assessment method), which takes the monitoring data and provides estimates of biomass, abundance and other inputs to the harvest control rules, and (ii) the harvest control rules.

Each year of the projection phase of the MSE involves applying the estimation method using the historical data and the future data generated operating model to estimate numbers by sex, size, maturity state, and shell condition. These estimates are used to compute the Overfishing Level (OFL) and the Acceptable Biological Catch (ABC) using the OFL and ABC control rules as well as the TAC based on one of the harvest strategy scenarios. Calculation of the OFL and ABC requires an assumption regarding future fishing mortality due to the snow crab fishery, the groundfish fishery, and the fishery for red king crab in Bristol Bay; for consistency with actual practice, these values are set to average over the most recent 5 years. The TAC is fed back into the operating model, and the catch is removed from the population, the population numbers by size are updated based on mortality and growth, and recruitment is added. The process is repeated for 100 years and for 100 simulations. Although MSE generally involves a greater number of simulations, this project was constrained by processing time (each simulation replicate of a 100-year projection took ~6 h) and storage capacity (8,000 MB for each simulation). The outputs from the operating model are used to identify trends and evaluate "risk" in terms of sustainability and economic metrics.

The operating model

The operating model is based on the same assumptions as the stock assessment—that is, the population is represented by a sex/stage/shell condition/maturity stage-structured with a molt to maturity for both males and females. The values for the parameters of the operating model were set to those estimated during 2017 assessment. As such, the operating model mimics the best understanding of the population dynamics of the stock.

Several extensions to the model on which the stock assessment was based were necessary to allow the population to be projected into the future.

- Recruitment for future year y ($y > 2017$) was generated by selecting a year from 1974-2017 and setting the recruitment for year y to that estimated from the selected year (i.e., recruitment is generated under the assumption that recruitment is independent of male or female biomass). The same time-series of recruitment is used for each harvest control rule (HCR), increasing the comparability of the results among HCRs.
- Fishing mortality by the bycatch fleets is assumed to equal the average over 2013-2017 from the assessment.
- Fishing mortality for the directed fishery is selected so that the model estimate of the landed catch by directed fishing equals the TAC computed using the harvest strategy. This fishing mortality is obtained by solving the following equation:

$$\mathrm{C} = \sum_{f}\sum_{x}\sum_{z}\frac{F_{f,x,z}}{F_{x,z}}\left(1 - e^{-F_{x,z}}\right) * w_{x,z} * [e^{-M_x * \delta t * N_{x,z}}]$$

  where C is total catch (biomass), $F_{f,x,z}$ is the fishing mortality in fishery f on crab in 5 mm size bins z by sex (x), $F_{x,z} = \sum_f F_{f,x,z}$ is the total fishing mortality by sex on crab in size bin z, $w_{x,z}$ is the mean weight of crab in size bin z by sex, M_x is the sex-specific rate of natural mortality, δt is the time from July 1 to the time of the fishery (0.625 yr), and $N_{x,z}$ is the numbers by sex in size bin z on July 1, 2018, as estimated by the assessment model (Stockhausen 2019).
- The operating model generates future survey and fishery monitoring data that is used by the estimation method (see box 3 in Figure 3).

Harvest strategies

The 15 harvest control rules (HCRs) (Table 1) that determine Total Allowable Catches for the directed fishery are all based on the stock assessment used for the 2017 assessment. The HCRs calculate the exploitation rate on exploitable mature male biomass (E_{MMB}), defined as male individuals over 127 mm CW, which is used along with the estimates of numbers by size to compute a TAC. A cap on TAC was included in some harvest strategies to limit overharvest of industry-preferred size (>127 mm CW) males. This cap was determined by exploitable legal male biomass (ELM), defined as 100% new-shell 5-inch males plus 40% old-shell 5-inch males. Old-shell selectivity was held at 40% based on average historical old-shell selectivity trends in the directed fishery. The maximum TAC was set at a proportion of ELM biomass as:

$$\text{MaxTAC} = (\text{ELM} * w_{males,z}) * \text{CP}$$

where Max TAC is the product of exploitable legal male abundance (ELM) multiplied by weight at sex (males) at size (z) and a cap percentage (CP), which was set at either 50% or 30% depending on the harvest strategy scenario. Most of the HCRs accounted for the annual ratio of mature animals to long-term averages, mature biomass for males (MMB_{ave}), and females (MFB_{ave}) from 1982-2017.

HCR1 (Female-only ramp)

- E_{MMB} increases from 0.05 when the mature female biomass for year Y+1 ($MFB_{\text{Y+1}}$) equals $0.25\text{MFB}_{\text{ave}}$ to 0.2 when $MFB_{\text{Y+1}}$ is equal to or exceeds MFB_{ave} (Figure 6). The TAC is constrained not to exceed $0.5ELMB_{\text{Y+1}}$.

HCR2 (Male-only ramp)

- E_{MMB} increases from 0.05 when the mature male biomass for year Y+1 ($MMB_{\text{Y+1}}$) equals $0.25\text{MMB}_{\text{ave}}$ to x_{i} when $MMB_{\text{Y+1}}$= MMB_{ave} where x_{i} represents variants in the exploitation maximums (x_{i}=0.1, 0.15, 0.2, and 0.225) (Figure 7). The TAC is constrained not to exceed $0.5ELBM_{Y+1}$.

HCR3 (ABC)

- The TAC equals the portion of the ABC that consists of males greater than 125 mm CW.

HCR4 (Female Dimmer)

- HCR4_1 (Original)
  - E_{MMB} depends on $\text{MFB}/\text{MFB}_{\text{ave}}$. E_{MMB} increases from 0.05 when $MFB_{\text{Y+1}}$ = $0.25\text{MFB}_{\text{ave}}$ to 0.2 based on both the male and female biomass to respective average ratios. The female ratio determines the maximum exploitation rate (a value between 0.05 and 0.2), and the male ratio determines specific exploitation rate (Figure 8). The TAC is constrained not to exceed $0.5ELBM_{Y+1}$.
- HCR4_2 (Variant 1)
  - As in original, except E_{MMB} increases from 0.1 when MFB_{Y+1} = $0.25\text{MFB}_{\text{ave}}$ to 0.2.
- HCR4_3 (Variant 2)
  - As in variant 2, except that E_{MMB} increases from 0.1 when MFB_{Y+1} = $0.25\text{MFB}_{\text{ave}}$ to 0.225.
- HCR4_4 (Variant 3)
  - As in variant 2, except the TAC is constrained not to exceed $0.3ELBM_{Y+1}$.

HCR5 (Blocked Female Dimmer)

- E_{MMB} depends on blocked ranges of $\text{MFB}/\text{MFB}_{\text{ave}}$. E_{MMB} starts at 0.05 and increases to 0.1 when the female ratio is greater than 0.3 and less than 0.5, increases to 0.15 when the female ratio is greater than 0.5 and less than 0.7, and caps at 0.2 when the female ratio is greater than 0.7 (Figure 9). The TAC is constrained not to exceed $0.5ELBM_{Y+1}$.

HCR6 (ELM)

- The TAC is set based on exploitable legal male biomass. There are three variants for exploitation rate: 0.3 (HCR6_30), 0.4 (HCR6_40), or 0.5 (HCR6_50) of $ELBM_{Y+1}$.

HCR7 (Status Quo)

- E_{MMB} is set using a combination of the control rules from 2011 and 2017 (Zheng and Pengilly 2011; ADF&G 2017b).
    - The rule has updated periods for threshold calculations for consistency with the other HCRs (1982-2017) for MFB_{ave} and MMB_{ave}
    - Female maturity is defined morphologically by the abdominal flap
    - The error band based on survey variability in the 2017 harvest strategy for biomass estimates and male exploitation calculation was removed
    - The TAC will be set at half the calculated amount in years directly following a closure year.

$$\text{TAC} = (F_{\text{MSY}} * \text{ELM}) * (\frac{B}{B_{\text{ave}}} * 0.9)$$

where F_{MSY} is a proxy for fishing mortality corresponding to maximum sustainable yield.

Performance metrics

We compared the harvest strategies using a 2-tier approach, which considered conservation and economic criteria separately. The conservation criteria included the probability of the population being below the federal minimum stock size threshold (MSST; i.e., threshold for being "overfished" = $0.5B_{MSY}$), the probability of the retained catch plus bycatch mortality exceeding the federal OFL (estimated in the operating model), the probability of the retained catch plus bycatch mortality exceeding the federal ABC (OFL * 0.80), and the probability that MMB < B_{MSY}. The economic criteria included the probability of a fishery closure, average TAC, annual variability of TAC, the probability that TAC is above 10 and 20 million lb, and the probability that MMB < MMB_{AVE} (i.e., the probability that the exploitation rate is lower than the maximum in a given harvest strategy). Probabilities were calculated as the number of the total simulated years (100 forecast years * 100 runs = 10,000 simulated years) that were either above or below a given management quantity.

Historical TAC calculations

As a supplemental analysis, we computed the annual TAC for 1982-2019 using area-swept estimates from the NOAA EBS summer bottom trawl survey for a subset of the harvest strategies (the male-only HCR2 and female dimmer HCR4) harvest strategies (Figures 7 and 8). This portion of the analysis should be considered separately from the forecast simulations described above; it is meant to aid in further understanding the performance of the harvest strategies using real data, rather than simulated data in the MSE forecast simulations. Raw area-swept estimates were used as inputs for the TAC calculations and data for 1982-2018 was used to calculate historical averages (for B/B_{Ave} MMB and MFB calculations). Caution should be used when interpreting these results, because annual survey population estimates do not account for hypothetical removals determined by the various harvest strategies. Thus, the population estimates used do not respond to hypothetical fishery removals, which would impact subsequent population dynamics and associated abundance fluctuations. Because survey data are spatially discrete, we calculated TAC separately for areas east and west of 166° W long and present results for each area separately and combined.

PROJECTION RESULTS

Projection results and computed probabilities in conservation and economic risk matrices are summarized in Tables 2–5 but are qualitatively described in the following sections.

CONSERVATION CRITERIA

Long-term average MMB was higher for more conservative harvest strategies (Figure 10), which was largely a result of fewer animals being removed from the population. However, the probability of being overfished (probability of MMB<MSST) was zero for all policies (Figure 11). The probability that the TAC exceeded the OFL and ABC was greater than zero for 40% fixed ELM (HCR6_40), 50% fixed ELM (HCR6_50), and Status Quo (HCR7) (Figures 12 and 13). The fact that the computed TAC exceeded the federal overfishing threshold without the addition of bycatch mortality suggests that these are not viable options. When adding estimates of bycatch mortality to the TAC, the probability that the total fishery mortality (retained catch + discards) exceeds the OFL and ABC increased, with the male-only 20% (HCR2_R3), the male-only 22.5% (HCR2_R4), ABC (HCR5), female dimmer variant 1 (HCR4_2), female dimmer variant 2 (HCR4_3), 30% fixed ELM (HCR6_30), 40% fixed ELM (HCR6_40), 50% fixed ELM (HCR6_50), and Status Quo (HCR7) having >0.05 probabilities of exceeding the OFL (Table 2, Figure 12) and >0.14 probabilities of exceeding the ABC (Table 2, Figure 13). The probability that MMB falls below B_{MSY} (the stock size that results from fishing at F_{MSY}) generally increased with increasing exploitation rates on MMB or ELM (Table 2, Figure 14).

ECONOMIC CRITERIA

The probability of a fishery closure (i.e., when MMB < 0.25 * MMB_{AVE}) was <0.001 for all policies except for the status quo harvest strategy (0.014) (Figure 15). The TAC increased with increasing mean exploitation rates (Figure 16). Average long-term TAC ranged from 11.4 million lb under the female blocked dimmer (HCR5) to 23.6 million lb under the fixed 50% ELM harvest strategy (HCR6_50) (Table 3, Figure 17). Similar to overall trends in average long-term TAC, the probabilities that the average long-term TAC exceeded 10 or 20 million lb increased with increasing exploitation rates (Figure 18). Probabilities that the long-term average TAC was above 10 million lb was >0.60 for all harvest strategies except for male-only 10% ramp (HCR2_R1) and female blocked dimmer (HCR5) (Table 3). Probabilities that the long-term average TAC exceed 20 million lb ranged from 0.107 (male-only 10% ramp, HCR2_R1) to 0.501 (fixed 50% ELM, HCR6_50) (Table 3). Average annual variability in the TAC (calculated as the proportion of the TAC that changed from one year to the next) increased as the range of exploitation rate increased (Table 3, Figure 19). Accordingly, the male-only 10% ramp (HCR2_R1) had the lowest annual variability in TAC (0.187) with the exploitation rate ranging from 5% to 10%, whereas the male-only 22.5% ramp had an annual TAC variability of 0.309 with a range of exploitation rates from 5% to 22.5%. The blocked female dimmer (HCR5) had high annual TAC variability (0.395) because the shape of the exploitation ramp was not continuous as in the female dimmer (HCR4_1, variability of 0.297). Generally, the ratio of MMB to B_{MSY} (MMB/B_{MSY}), as an indicator for relative stock status, decreased with increasing TAC (Figure 20), as expected. Because the sloping control rules dictate that the exploitation rate on MMB is based on the current year estimate of MMB relative to the historical long-term average (MMB_{AVE}), we evaluated the probability that MMB is below MMB_{AVE} to predict how often the maximum exploitation rate on MMB is achieved for a given ramp. As expected, the probability that MMB is below MMB_{AVE} increased with increasing exploitation rate (Table 3, Figure 21).

The conservation and economic metrics were compiled and then grouped into three categories: conservation, catch, and catch stability (Table 4). We ranked the harvest strategies within each conservation and catch stability metric and averaged the ranks. The average ranks were scored relative to each other in each category (i.e., conservation, catch stability), as depicted in the decision tables (Table 5). Because of the high relative economic importance of TAC, we list average TAC in million lb for the "catch" category.

HISTORICAL TAC CALCULATION RESULTS

Recomputed historical TACs were comparable to actual TAC from 1982 to 1998, except for the male-only 10% ramp (HCR2_R1) which led to substantially lower TACs for 1989-1992 (Figure 22). Larger relative differences between "actual" TACs occurred across all harvest strategies in years from 1999 to 2019. Actual TACs for 1999-2019 averaged 2.8 million lb, while mean recomputed TACs ranged from 7.4 million lb (male 10% ramp, HCR2_R1) to 12.4 million lb (male 22.5% ramp, HCR2_R4). Since 1999, the fishery was closed for 11 out of 21 fishing seasons (52% closure rate), yet all harvest strategies evaluated yielded zero fishery closures during that same time period (Table 6). In general, inclusion of a female dimmer did not reduce the TACs in years with relatively high recomputed TACs (i.e., the peaks) calculated via male-only harvest strategies. Most TAC reductions induced by the female dimmer occurred during periods of declining population trajectories and periods of low population abundance (Figure 22). This effect was by design: to preserve mature males when mature females are in reduced abundance to optimize mating opportunities for incoming mature female recruits. Recomputed TACs were the same in some years for the more aggressive harvest strategies due to maximum exploitation rate on exploitable legal male abundance limitation. This effect was more common west of 166°W long. than east of 166°W long. (Figure 23), likely due to proportionately fewer crab molting to the industry preferred size (5 inches CW), which is expected as the size at maturity is smaller west of 166°W long. relative to the area east of 166° W long (Somerton 1981; Zheng 2008; Zheng and Pengilly 2011).

POLICY SELECTION

The policy selection options presented here have not provided a clear single policy choice; however, there is general alignment between State recommendations and industry stated preferences[1]. Through quantitative and qualitative review of the risk analyses, retrospective review, consideration of biological and environmental uncertainty, and discussions with stakeholders, we have provided some specific policy guidance as follows.

Our analysis suggests that the ABC (HCR3), fixed ELMs (HCR6_40 and HCR6_50) and Status Quo (HCR7) have the highest conservation risk with high probabilities of exceeding OFL and

[1] The ad-hoc Bairdi committee provided a summary of preferences to ADF&G Westward Region staff on December 20, 2019 and an updated summary of preferences, January 27, 2020. Industry preferences stated two clear objectives that addressed exploitation and stability: 1) robust harvesting of exploitable males when warranted, and 2) increasing stability by reducing or eliminating the likelihood of season closures. These preferences were clarified further as a desire "to harvest as many crab as possible when they are in their new shell condition and once they are above legal size, without harming the sustainability of the stock," and to have "a harvest strategy that minimizes disruption to markets and fishing businesses from fishery closures." The ad-hoc committee's HCR preferences were further specified to include two female dimmer variants and one of the male-only rules. A final noted HCR preference included stated support for the ELM cap rule at 50%.

ABC. The male-only 10% ramp (HCR2_R1) and female blocked dimmer (HCR5) have low probabilities of exceeding conservation thresholds but may not optimize yield. The MSE results suggest male-only ramps >10% (HCR2_R2, HCR2_R3, and HCR2_R4) and the female dimmer variants are likely to achieve the best trade-off between meeting conservation objectives and optimizing yield. These policies have low-moderate relative conservation risk and low-moderate relative annual TACs. Relative to male-only harvest strategies, simulations indicate that the female dimmer harvest strategies yielded comparable scores in economic metrics. Although HCR1 (exclusive female ramp) had relatively positive risk scores, it was removed from further consideration based on primary objectives to reduce the level of explicit female control within a revised Tanner crab harvest strategy.

Our analysis noted that remaining HCRs had relatively similar risk scores and retrospective outcomes. The remaining HCRs were a group of male-only ramps with a floor of 5% exploitation and ceiling ranges from 15% to 22.5%, and all of the candidate female dimmer rules. Regardless of the similar performance, the male-only rules as proposed would not explicitly include a female control component to account for an adequate level of female uncertainty and as such are inconsistent with the BOF policy on king and Tanner crab resource management (ADF&G 1990[2]). The male-only ramps (HCR2_X) were closely considered as viable options and provided a relative way to measure other HCRs, but we qualitatively focused further on female dimmer HCRs as viable options.

Although our analysis represents "best science", the population-level effect of including females as part of the state harvest strategy is nebulous based on the simulation results. Because the Bering Sea Tanner crab stock-recruit relationship has not been identified, like most crab stocks worldwide (Wahle 2003), annual recruitment in the forecast simulation was generated through random selection of recruit abundance from assessment estimates during the period 1975-2017. As such, mature male and/or female abundance did not influence recruitment strength in simulations and consequently the influence of spawner population size on simulated population dynamics was not fully captured. While this treatment of generating simulated recruitment is consistent with the lack of a stock-recruit relationship for Bering Sea Tanner crab, it could allow for some instances of biological impossibilities. For example, recruitment could be generated when mature females are completely absent from the simulated population. Depensation (lower than expected recruitment at low population levels, also known as the "Allee effect") could occur for Bering Sea Tanner crab if females cannot find mates when population size is below an unknown critical threshold, which could cause the population to collapse and fail to rebuild even after fishery closures. This limitation in our understanding of Bering Sea Tanner crab biology (i.e., complex mating dynamics) and the inability to capture recruitment mechanisms in forecast simulations must be recognized and warrants some level of consideration.

[2] Policy 2 states "Routinely monitor crab resources to provide information on abundance of females as well as prerecruit, recruit, and postrecruit males. This is necessary to detect changes in the population which may require adjustments in management to prevent irreversible damage to the reproductive potential of each stock and to better achieve the benefits listed above. Harvests must be conducted in a conservative manner in the absence of adequate information on stocks." Policy 6 states "Establish management measures in each fishing area based on the best available information. Stock and fishery characteristics, as well as available data, vary from area to area within Alaska. Actual management practices in each area will vary accordingly." Excluding female information does not use "the best available information" in each area (Policy 6), prevents the ability to "detect changes" in this portion of the population (Policy 2), and is inconsistent with an attempt to prevent "irreversible damage to the reproductive potential of each stock" (Policy 2). Policy 2 further directs ADF&G to implement a harvest policy in a "conservative manner in the in the absence of adequate information on stocks"; thus, failure to consider mature females implies a more conservative harvest strategy is appropriate.

Environmental uncertainty is another cause for a precautionary approach to Bering Sea Tanner crab fisheries management. Warming temperatures and reduced sea ice cover in the Bering Sea have dramatic and cascading effects on ecosystem-level processes (Siddon et al. 2018). Sea ice in the Bering Sea was at record low levels in 2018 and the summer cold pool, a body of cold (<2°C) subsurface water that occurs in the summer as a remnant of winter conditions that has important biological implications for crab and other benthic species, was nonexistent (Siddon et al. 2018). Future conditions are predicted to include continued warming temperature and reductions in sea ice cover (Hermann et al., 2016). The impacts of this change on Bering Sea crab stocks is unknown, but warming conditions are likely to affect Bering Sea Tanner crab through complex interactions of physiological (e.g., thermal stress, reduced calcification via ocean acidification; Swiney et al. 2015, Long et al. 2016) and ecological (e.g., shifts in adult spatial distribution, changing circulation patterns and associated larval transport, temporal mismatch of larvae and spring phytoplankton blooms) processes. Other Bering Sea crab stocks, including Bristol Bay red king crab and Bering Sea snow crab, were at or near the NOAA survey time-series nadir in recent years, suggesting contemporary environmental conditions are likely suboptimal for crab production in the Bering Sea. Our analysis did not include environmental forcing in any way, because this was beyond the scope of the forecast projections. In this regard, it is critical to recognize this source of uncertainty and the potential ramifications of overharvesting Bering Sea Tanner crab in a rapidly changing environment. Accordingly, we recommend a precautionary approach to managing Bering Sea Tanner crab.

The female dimmer (HCR4_X variants) is consistent with a precautionary approach and meets objectives outlined by researchers and stakeholders in the 2017 Tanner crab workshop, which was described succinctly as part of the final recommendation: "Workshop partners recommend an approach to revise the bairdi harvest strategy that improves the economic outlook to the industry and acknowledges the importance of the bairdi reproductive capacity to conserve the stock" (Goodman 2018). The female dimmer improves the "economic outlook to the industry": probability of fishery closures was zero in forecast simulations and the historical TAC calculations for 1999-2019 yielded zero closures with a substantial increase in average TAC over *actual* historical TACs. The female dimmer also acknowledges the importance of "reproductive capacity to conserve the stock" by dampening exploitation rate on mature male biomass when mature female biomass is at relatively low levels in order to optimize mating opportunities for incoming mature female recruits. In addition, because temporal trends in mature female biomass generally lead that of mature male biomass by 1-2 years and can be used as predictor for mature male biomass, a reduced exploitation rate prior to MMB population declines (as applied via the female dimmer) is a proactive approach to dampen fishery removals during periods of imminent conservation concern.

Based on further review, we consider HCR4_1 and HCR4_2 (both with 50% ELM maximum caps) as viable options. HCR4_3 is removed from consideration based on relatively higher risk of exceeding ABC/OFL, and retrospective review of exploitation reflecting ELM rates exceeding 50%. HCR4_4 is removed from further consideration because its ELM cap of 30% does not meet industry preferences. For these reasons, we recommend the original female dimmer (HCR4_1, Figure 8) or the first variant HCR4_2 (which has a ramp floor of 10%) for Bering Sea Tanner crab. Although the concept of the female dimmer (and its variants) is consistent with a precautionary approach, a 20% maximum exploitation on MMB and 50% maximum exploitation on ELM are liberal compared to actual historical removals and may result in substantially higher TACs on average.

Both HCR4_1 and HCR4_2 maximize exploitation when crab are most valuable to industry: during periods with a high proportion of 5-inch male crab in the new-shell condition. HCR4_1 sets the minimum exploitation rate at 5% of estimated mature male abundance, whereas HCR4_2 is more liberal and sets the minimum exploitation rate at 10% of mature male abundance. Relative to HCR4_1, the higher 10% minimum exploitation in female dimmer HCR4_2 increased average TAC by 4% in the MSE projections and 9% in the historical (1999-2019) TAC calculations and had lower annual TAC variability in the MSE. Although the MSE projections showed higher yield with low increases in relative risk, the 10% floor would allow for higher harvests when the population is declining or at low levels, with the highest exploitation rate differences occurring when mature male abundance approaches 25% of the long-term average (i.e., when in a depressed state). Further, crab at industry-preferred sizes tend to have higher proportions of individuals in the old-shell condition (i.e., less valuable to the fishery) during low population levels. As such, higher exploitation during these periods may be inconsistent with industry preferences. The female dimmer with a 5% minimum exploitation floor (HCR4_1) provides for lower exploitation during periods of conservation concern and affords improved conservation benefit to the stock overall.

For both female dimmer options we advance a single 50% ELM maximum cap. We note that while the recommended ELM cap is consistent with past management practices, a 50% ELM cap probably represents the upper bound of appropriate exploitation of industry preferred size crab. Because a lower proportion of mature males reach the industry preferred size west of 166°W long relative to east of 166°W long (Zheng 2008), the 50% ELM cap is expected to disproportionally limit TACs set west of 166° W long. A more in-depth evaluation of ELM control rules is warranted for the future.

These recommended harvest strategy options are consistent with MSA National Standards, FMP objectives, and the BOF policy on king and Tanner crab resources management.

ACKNOWLEDGEMENTS

We thank Nick Sagalkin and Chris Siddon for project oversight and the Bering Sea Fisheries Research Foundation (BSFRF) for funding this analysis. BSFRF is a nonprofit scientific research foundation and does not advocate for specific policy selection. The scientific results and conclusions, as well as any views or opinions expressed herein, are those of the author(s) and do not necessarily reflect those of NOAA or the Department of Commerce.

REFERENCES CITED

Adams, A., and A. Paul. 1983. Male parent size, sperm storage and egg production in the crab *Chionoecetes bairdi* (Decapoda, Majidae). International Journal of Invertebrate Reproduction, 6: 181-187.

ADF&G (Alaska Department of Fish and Game). 1990. Policy on king and Tanner crab resource management. ICES Document 90-04-FB.

ADF&G (Alaska Department of Fish and Game). 2017a. 2017-2019 King and Tanner Crab Commercial Fishing Regulations.

ADF&G (Alaska Department of Fish and Game). 2017b. Tanner crab harvest stragey substitute language. [*In*] Record Copy 8 (RC8) from Alaska Board of Fisheries May 2017 meeting.

Beverton, R. J. H., and S. J. Holt. 1957. On the dynamics of exploited fish populations. Fisheries Investigations (Series 2).

Bishop, G., J. Zheng, L. Slater, K. Spalinger, and R. Gustafson. 2011. The current status of the fisheries for *Chionoecetes* spp. (Decapoda, Oregoniidae) in Alaskan waters. Pages 109-126 [*In*] A. Asakura, editor. New frontiers in crustacean biology: proceedings of the TCS Summer Meeting, Tokyo, 20-24 September 2009. Brill, Leiden, The Netherlands.

Daly, B., C. Parada, T. Loher, S. Hinckley, A. Hermann, and D. Armstrong. *In press*. Impacts of climate change on red king crab larval advection in Bristol Bay: implications for recruitment variability. Fisheries Oceanography.

DFO (Fisheries and Oceans Canada). 2018. Assessment of Newfoundland and Labrador (Divisions 2HJ3KLNOP4R) snow crab. DFO Canadian Science Advisory Secretariat. Science Advisory Report 2018/024.

Donaldson, W., and B. Johnson. 1988. Some remarks on "Functional maturity and terminal molt of male snow crab, *Chionoecetes opilio*" by Conan and Comeau. Canadian Journal of Fisheries and Aquatic Sciences 45(8): 1499-1501.

Donaldson, W. E., R. T. Cooney, and J. R. Hilsinger. 1981. Growth, age and size at maturity of Tanner crab, *Chionoecetes bairdi* M. J. Rathbun, in the northern Gulf of Alaska (Decapoda, Brachyura). Crustaceana 40(3): 286-302.

Goodman, S. 2018. Summary information for the December 2017 workshop for bairdi Tanner crab hosted by the Bering Sea Fisheries Research Foundation (BSFRF).

Hermann, A. J., G. A. Gibson, N. A. Bond, E. N. Curchitser, K. Hedstrom, W. Cheng, M. Wang, E. D. Cokelet, P. J. Stabeno, and K. Aydin. 2016. Projected future biophysical states of the Bering Sea. Deep Sea Research Part II: Topical Studies in Oceanography 134: 30-47.

Incze, L., D. Armstrong, and S. L. Smith. 1987. Abundance of larval Tanner crabs (*Chionoecefes spp*.) in relation to adult females and regional oceanography of the southeastern Bering Sea. Canadian Journal of Fisheries and Aquatic Sciences 44(6): 1143-1156.

Incze, L. S., D. A. Armstrong, and D. L. Wencker. 1982. Rates of development and growth of larvae of *Chionoecetes bairdi* and *C. opilio* in the southeastern Bering Sea. Pages 191-218 [*In*] A. J. Paul, F. Gaffney, D. Haapa, J. Reeves, R. Baglin, and S. K. Davis, editors. Proceedings of the International Symposium on the Genus *Chionoecetes*. 3rd edition. Alaska Sea Grant College Program, University of Alaska Fairbanks, Anchorage.

Johnson, G. M. 2019. Population genetics of Tanner crab (Chionoecetes bairdi) in Alaskan waters. Master's thesis, University of Alaska Fairbanks.

Knutson, M. 2020. Reproductive potential of female eastern Bering Sea Tanner crab. Master's thesis, College of Fisheries and Ocean Sciences, University of Alaska Fairbanks.

Long, W. C., K. M. Swiney, and R. J. Foy. 2016. Effects of high pCO_2 on Tanner crab reproduction and early life history, Part II: carryover effects on larvae from oogenesis and embryogenesis are stronger than direct effects. ICES Journal of Marine Science 73(3): 836-848.

REFERENCES CITED (Continued)

Mullowney, D., K. Baker, E. Pedersen, and D. Osborne. 2018. Basis for a precautionary approach and decision making framework for the Newfoundland and Labrador snow crab (*Chionoecetes opilio*) fishery. Canadian Science Advisory Secretariat.

NMFS (National Marine Fisheries Service). 1996. Magnuson–Stevens Fishery Conservation and Management Act as amended through October 11, 1996. ICES Document NMFS-F/SPO-23.

NPFMC (North Pacific Fishery Management Council). 2007. Public review draft: environmental assessment for proposed Amendment 24 to the Fishery Management Plan for Bering Sea and Aleutian Islands King and Tanner crabs to revise overfishing definitions.

NPFMC (North Pacific Fishery Management Council). 2008. Environmental assessment for Amendment 24 to the Fishery Management Plan for Bering Sea and Aleutian Islands King and Tanner crabs to revise overfishing definitions.

NPFMC (North Pacific Fishery Management Council). 2011. Fishery Management Plan for Bering Sea/Aleutian Islands King and Tanner crabs.

Otto, R. S. 1989. An overview of Eastern Bering Sea king and Tanner crab fisheries. Pages 9-26 [*In*] S. K. Davis, G. H. Kruse, R. S. Otto, and T. C. Shirley, editors. Proceedings of the International Symposium on King and Tanner Crabs. 8th edition. Alaska Sea Grant College Program, University of Alaska Fairbanks, Anchorage.

Richar, J. I., G. H. Kruse, E. Curchitser, and A. J. Hermann. 2015. Patterns in connectivity and retention of simulated Tanner crab (*Chionoecetes bairdi*) larvae in the eastern Bering Sea. Progress in Oceanography 138(B): 475-485.

Ricker, W. E. 1954. Stock and recruitment. Journal of the Fisheries Research Board of Canada 11(5): 559-623.

Sainte-Marie, B., T. Gosselin, J.-M. Sévigny, and N. Urbani. 2008. The snow crab mating system: opportunity for natural and unnatural selection in a changing environment. Bulletin of Marine Science 83(1): 131-161.

Sainte-Marie, B., S. Raymond, and J.-C. Brêthes. 1995. Growth and maturation of the benthic stages of male snow crab, *Chionoecetes opilio* (Brachyura: Majidae). Canadian Journal of Fisheries and Aquatic Sciences 52(5): 903-924.

Siddon, E., S. Zador, and K. Aydin. 2018. Ecosystem status report eastern Bering Sea. North Pacific Fisheries Management Council, Anchorage.

Slater, L. M., J. Webb, and D. Pengilly. *In press*. Fecundity and egg production of eastern Bering Sea Tanner crab (*Chionoecetes bairdi*). PLOS ONE.

Somerton, D. 1981. Regional variation in the size of maturity of two species of Tanner crab (*Chionoecetes bairdi* and *C. opilio*) in the eastern Bering Sea, and its use in defining management subareas. Canadian Journal of Fisheries and Aquatic Sciences 38(2): 163-174.

Stockhausen, W. T. 2017. 2017 Stock Assessment anf Fishery Evaluiation Report for the Tanner Crab Fisheries of the Bering Sea and Aleutian Islands Regions. *In* Stock Assessment and Fishery Evaluation Report of the King and Tanner Crab Fisheries of the Bering Sea and Aleutian Islands Regions. North Pacific Fisheries Management Council, Anchorage.

Stockhausen, W. T. 2019. 2019 Stock assessment and fishery evaluation report for the Tanner crab fisheries of the Bering Sea and Aleutian Islands regions. [*In*] Stock assessment and fishery evaluation report of the king and Tanner crab fisheries of the Bering Sea and Aleutian Islands regions. North Pacific Fisheries Management Council, Anchorage, AK.

Swiney, K. M., W. C. Long, and R. J. Foy. 2015. Effects of high p CO2 on Tanner crab reproduction and early life history—Part I: long-term exposure reduces hatching success and female calcification, and alters embryonic development. ICES Journal of Marine Science 73(3): 825-835.

Tamone, S. L., M. M. Adams, and J. M. Dutton. 2005. Effect of eyestalk-ablation on circulating ecdysteroids in hemolymph of snow crabs, *Chionoecetes opilio*: physiological evidence for a terminal molt. Integrative and Comparative Biology 45(1): 166-171.

REFERENCES CITED (Continued)

Tamone, S. L., S. J. Taggart, A. G. Andrews, J. Mondragon, and J. K. Nielsen. 2007. The relationship between circulating ecdysteroids and chela allometry in male Tanner crabs: Evidence for a terminal molt in the genus *Chionoecetes*. Journal of Crustacean Biology 27(4): 635-642.

Wahle, R. A. 2003. Revealing stock-recruitment relationships in lobsters and crabs: is experimental ecology the key? Fisheries Research 65: 3-32.

Webb, J. 2014. Reproductive potential of snow (*Chionoecetes opilio*) and Tanner (*Chionoecetes bairdi*) crabs in Alaska. Doctoral dissertation, University of Alaska Fairbanks.

Webb, J., and J. Bednarski. 2010. Variability in reproductive potential among exploited stocks of Tanner crab (*Chionoecetes bairdi*) in southeastern Alaska. Management of exploited crab population under climate change. Pages 295-317 [*In*] G. H. Kruse, G. L. Eckert, R. J. Foy, R. N. Lipcius, B. Sainte-Marie, D. L. Stram, and D. Woodby, editors. Alaska Sea Grant College Program AK-SG-10-01. University of Alaska Fairbanks.

Webb, J. B., L. M. Slater, G. L. Eckert, and G. H. Kruse. 2016. The contribution of fecundity and embryo quality to reproductive potential of eastern Bering Sea snow crab (*Chionoecetes opilio*). Canadian Journal of Fisheries and Aquatic Sciences 73(12): 1800-1814.

Zaleski, M. A., and S. L. Tamone. 2014. Relationship of molting, gonadosomatic index, and methyl farnesoate in male snow crab (*Chionoecetes opilio*) from the eastern Bering Sea. Journal of Crustacean Biology 34(6): 764-772.

Zheng, J. 2008. Temporal changes in size at maturity and their implications for fisheries management for eastern Bering Sea Tanner crab. Journal of Northwest Atlantic Fishery Science 41: 137-149.

Zheng, J., G. Kruse, and M. Murphy. 1998. A length-based approach to estimate population abundance of Tanner crab, *Chionoecetes bairdi*, in Bristol Bay, Alaska. Pages 97-105 [*In*] G. S. Jamieson and A. Campbell, editors. Proceedings of the North Pacific Symposium on Invertebrate Stock Assessment and Management. Canadian Special Publication of Fisheries and Aquatic Sciences.

Zheng, J., and G. H. Kruse. 1998. Stock-recruitment relationships for Bristol Bay Tanner crab. Alaska Fishery Research Bulletin 5(2): 116-130.

Zheng, J., and G. H. Kruse. 1999. Overview of population dynamics and recommended harvest strategy for Tanner crabs in the eastern Bering Sea. Alaska Department of Fish and Game, Division of Commercial Fisheries, Regional Information Report No. 5J99-04, Juneau.

Zheng, J., and G. H. Kruse. 2003. Stock-recruitment relationships for three major Alaskan crab stocks. Fisheries Research 65: 103-121.

Zheng, J., M. C. Murphy, and G. H. Kruse. 1997. Analysis of harvest strategies for red king crab, *Paralithodes camtschaticus*, in Bristol Bay, Alaska. Canadian Journal of Fisheries and Aquatic Sciences 54(5): 1121-1134.

Zheng, J., and D. Pengilly. 2003. Evaluation of alternative rebuilding strategies for Pribilof Islands blue king crabs. Alaska Department of Fish and Game, Regional Information Report No. 5J03-10, Juneau.

Zheng, J., and D. Pengilly. 2011. Overview of proposed harvest strategy and minimum size limits for Bering Sea district Tanner crab. Alaska Department of Fish and Game, Special Publication No. 11-02, Anchorage.

Zheng, J., M. S. M. Siddeek, D. Pengilly, and D. Woodby. 2002. Overview of recommended harvest strategy for snow crabs in the eastern Bering Sea. Alaska Department of Fish and Game, Regional Information Report No. 5J02-03, Juneau.

Zheng, J., L. Slater, J. Webb, and G. Bishop. 2011. The current status of biological knowledge relating to the management of fisheries for Tanner (*Chionoecetes Bairdi* (Rathbun, 1924)) and snow crabs (*Chionoecetes Opilio* (Fabricius, 1788)) in Alaskan waters. Pages 127-138 [*In*] A. Asakura, editor. New frontiers in crustacean biology: proceedings of the TCS Summer Meeting, Tokyo, 20-24 September 2009. Brill, Leiden, The Netherlands.

TABLES

Table 1.–The fifteen harvest policies evaluated. All policies include a threshold for opening and closing the fishery based on mature male biomass (25% of MMB_{AVE}). Sloping or “ramp” control rules include an exploitation rate on mature male biomass described by the ramp upper and lower bounds. All but HCR3 and HCR7 include a maximum allowable exploitation rate on industry-preferred-size males (max TAC).

Policy	Description	Fixed vs ramp exploitation rate	Threshold for opening	Ramp lower bound	Ramp upper bound	Max TAC
HCR1	Female ramp	Ramp	25% MMB_{AVE}	5%	20%	50% ELM
HCR2_R1	Male only 20%	Ramp	25% MMB_{AVE}	5%	10%	50% ELM
HCR2_R2	Male only 20%	Ramp	25% MMB_{AVE}	5%	15%	50% ELM
HCR2_R3	Male only 20%	Ramp	25% MMB_{AVE}	5%	20%	50% ELM
HCR2_R4	Male only 20%	Ramp	25% MMB_{AVE}	5%	22.5%	50% ELM
HCR3	TAC = $ABC_{5\text{-inch}♂}$	Ramp (F_{MSY})	25% MMB_{AVE}	NA	NA	NA
HCR4_1	Female dimmer 20%	Ramp	25% MMB_{AVE}	5%	20%	50% ELM
HCR4_2	Female dimmer 20%	Ramp	25% MMB_{AVE}	10%	20%	50% ELM
HCR4_3	Female dimmer 22.5%	Ramp	25% MMB_{AVE}	10%	22.5%	50% ELM
HCR4_4	Female dimmer 22.5%	Ramp	25% MMB_{AVE}	10%	22.5%	30% ELM
HCR5	Female blocks	Ramp	25% MMB_{AVE}	5%	20%	50% ELM
HCR6_30	ELM 30%	Fixed	25% MMB_{AVE}	NA	NA	30% ELM
HCR6_40	ELM 40%	Fixed	25% MMB_{AVE}	NA	NA	40% ELM
HCR6_50	ELM 50%	Fixed	25% MMB_{AVE}	NA	NA	50% ELM
HCR7	Status Quo	Ramp (F_{MSY})	25% MMB_{AVE}	NA	NA	NA

Note: ABC = acceptable biological catch; ELM = exploitable legal male biomass

Table 2.–Summary of the conservation performance metrics. Units vary depending on the metric (see Table 4).

HCR	Description	Overfished probability[a]	Overfishing probability (OFL)[b]	Overfishing probability (ABC)[c]	Below B_{MSY} probability ($MMB<B_{MSY}$)	MMB_{AVE} (million lb)	MMB/B_{MSY} Ave ratio	Mean rank	Rank of mean ranks
1	female ramp	0.000	0.046	0.152	0.014	149	2.15	6.17	8
2_R1	male ramp 10	0.000	0.000	0.000	0.003	172	2.47	1.17	1
2_R2	male ramp 15	0.000	0.002	0.036	0.007	160	2.30	2.50	2
2_R3	male ramp 20	0.000	0.054	0.151	0.012	152	2.18	5.50	6
2_R4	male ramp 22.5	0.000	0.092	0.198	0.016	147	2.12	8.67	9
3	ABC	0.000	0.369	0.701	0.051	123	1.78	14.17	14
4_1	female dimmer	0.000	0.034	0.119	0.006	154	2.22	3.00	4
4_2	female dimmer	0.000	0.051	0.140	0.015	149	2.16	6.00	7
4_3	female dimmer	0.000	0.088	0.196	0.017	146	2.11	9.00	10
4_4	female dimmer	0.000	0.035	0.132	0.016	152	2.18	4.83	5
5	female blocks	0.000	0.042	0.091	0.006	170	2.47	2.50	2
6_30	ELM[d] 30	0.000	0.062	0.195	0.031	148	2.12	10.33	12
6_40	ELM 40	0.000	0.303	0.510	0.056	132	1.92	11.17	13
6_50	ELM 50	0.000	0.463	0.674	0.077	124	1.79	14.50	15
7	Status quo	0.000	0.157	0.251	0.015	142	2.08	9.33	11

[a] A stock is considered overfished when the mature male biomass (MMB) is less than the minimum stock size threshold (MSST, one half of B_{MSY}).
[b] OFL = overfishing level; numbers indicate the probability that the total catch (retained catch plus discard mortality) is greater than OFL
[c] ABC = acceptable biological catch; numbers indicate the probability that the total catch is greater than ABC
[d] ELM = exploitable legal male biomass

Table 3.–Summary of the economic performance metrics. Units vary depending on the metric (see Table 4).

HCR	Description	Closure probability[a]	Mean TAC (million lb)	TAC variability	Relative TAC (1)	Relative TAC (2)	Stock status[b]	Mean rank	Rank of mean ranks
1	female ramp	0.000	16.9	0.226	0.717	0.319	0.350	4.67	2
2_R1	male ramp 10	0.000	12.4	0.187	0.583	0.107	0.215	7.50	12
2_R2	male ramp 15	0.000	14.9	0.237	0.652	0.243	0.284	7.17	9
2_R3	male ramp 20	0.000	16.7	0.290	0.683	0.310	0.332	7.00	8
2_R4	male ramp 22.5	0.000	17.2	0.309	0.689	0.313	0.357	7.17	9
3	ABC[c]	0.000	21.9	0.246	0.884	0.480	0.481	4.00	1
4_1	female dimmer	0.000	15.9	0.297	0.615	0.307	0.302	8.33	13
4_2	female dimmer	0.000	16.5	0.255	0.687	0.301	0.341	7.17	9
4_3	female dimmer	0.000	17.3	0.274	0.691	0.316	0.362	6.00	5
4_4	female dimmer	0.000	16.6	0.272	0.710	0.283	0.337	6.67	6
5	female blocks	0.000	11.4	0.395	0.475	0.088	0.299	10.50	14
6_30	ELM[d] 30	0.000	16.9	0.251	0.782	0.269	0.370	6.67	6
6_40	ELM 40	0.000	20.0	0.279	0.868	0.377	0.482	5.50	4
6_50	ELM 50	0.000	23.6	0.290	0.932	0.501	0.541	5.00	3
7	Status quo	0.014	18.0	0.491	0.640	0.283	0.377	11.50	15

Note: Annual total allowable catch (TAC) variability is shown as proportional variation. Relative TAC (1) indicates the probability that TAC is greater than 10 million lb. Relative TAC (2) indicates the probability that TAC is greater than 20 million lb.

[a] Closures occur when mature male biomass (MMB) is below 25% of the long-term average MMB for years 1982–2017 (MMB_{AVE}). Numbers indicate the probability that closures will take place.

[b] Stock status indicates the probability that MMB is below MMB_{AVE}.

[c] ABC = acceptable biological catch

[d] ELM = exploitable legal male biomass

Table 4.–Criteria were grouped into three categories: conservation, catch, and catch stability. The below table shows the various metrics in each group.

Conservation		Catch		Catch Stability	
Metric	Unit	Metric	Unit	Metric	Unit
Overfished	Probability	TAC	Million lb	Fishery closures	Probability
Overfishing (OFL)	Probability			Annual TAC var	Proportion
Overfishing (ABC)	Probability			Relative TAC (1)	Probability
MMB	Million lb			Relative TAC (2)	Probability
MMB/MMB_{AVE}	Ratio			Stock status	Probability

Table 5.–Decision matrix based on mean policy ranks for conservation and catch stability categories. The catch category lists long-term average total allowable catch (TAC) rather than ranks.

HCR	Description	Conservation: mean ranks	Catch (TAC) in million lb	Catch stability: mean ranks
1	female ramp	6.2	16.9	4.0
2_R1	male ramp 10	1.2	12.4	6.2
2_R2	male ramp 15	2.5	14.9	6.0
2_R3	male ramp 20	5.5	16.7	6.6
2_R4	male ramp 22.5	8.7	17.2	7.4
3	ABC	14.2	21.9	4.4
4_1	female dimmer	3.0	15.9	7.6
4_2	female dimmer	6.0	16.5	6.4
4_3	female dimmer	9.0	17.3	6.2
4_4	female dimmer	4.8	16.6	6.0
5	female blocks	2.5	11.4	9.6
6_30	ELM 30	10.3	16.9	6.6
6_40	ELM 40	11.2	20.0	6.0
6_50	ELM 50	14.5	23.6	5.8
7	Status quo	9.3	18.0	13.0

Note: ABC = acceptable biological catch; ELM = exploitable legal male biomass

Table 6.–Average historical total allowable catch (TAC, in millions of pounds), differences between recomputed and actual historical (in millions of pounds), and numbers of fishery closure years for the male-only ramp (HCR2) and female dimmer (HCR4) variants for combined and separated areas east and west of 166° W long, 1999–2019.

					Combined East + West			East	West
HCR	Description	Ramp upper bound	Ramp lower bound	Max TAC	Average	Difference	Closures	Average	Average
Actual	Actual historical TAC			NA	2.8	NA	11	1.5	1.3
HCR2_R1	Male only 10%	10%	5%	50% ELM	7.4	4.8	0	3.0	4.4
HCR2_R2	Male only 15%	15%	5%	50% ELM	10.3	7.9	0	4.2	6.1
HCR2_R3	Male only 20%	20%	5%	50% ELM	11.9	9.6	0	5.1	6.8
HCR2_R4	Male only 22.5%	22.5%	5%	50% ELM	12.4	10.1	0	5.5	6.9
HCR4_1	Male 20% + fem dim	20%	5%	50% ELM	9.9	7.5	0	4.3	5.6
HCR4_2	Male 20% + fem dim	20%	10%	50% ELM	10.8	8.4	0	4.9	5.9
HCR4_3	Male 22.5% + fem dim	22.5%	10%	50% ELM	11.9	9.6	0	5.5	6.4
HCR4_4	Male 22.5% + fem dim	22.5%	10%	30% ELM	8.3	5.8	0	4.2	4.1

Note: HCR = harvest control rule; ELM = exploitable legal male biomass

FIGURES

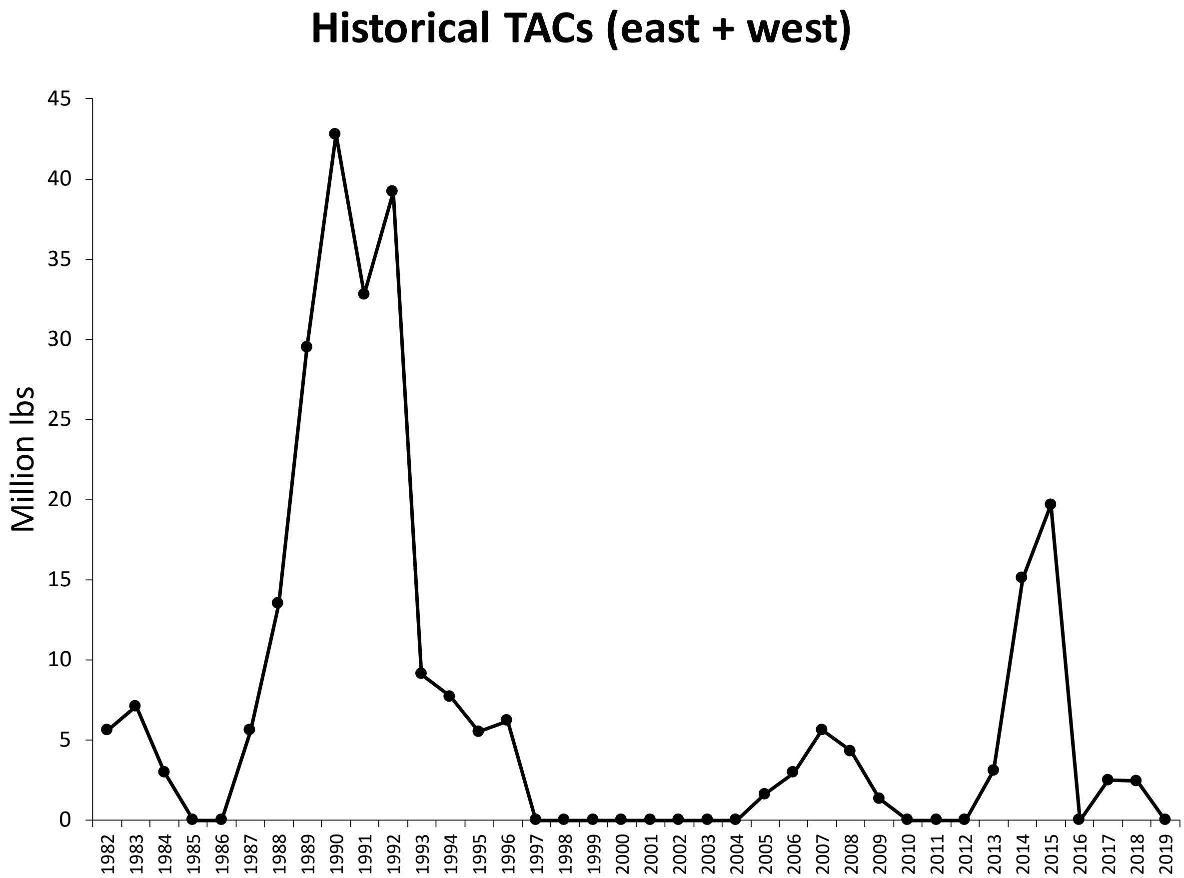


Figure 1.–Historical total allowable catch (TAC) of Bering Sea Tanner crab for the areas east and west of 166° W long combined.

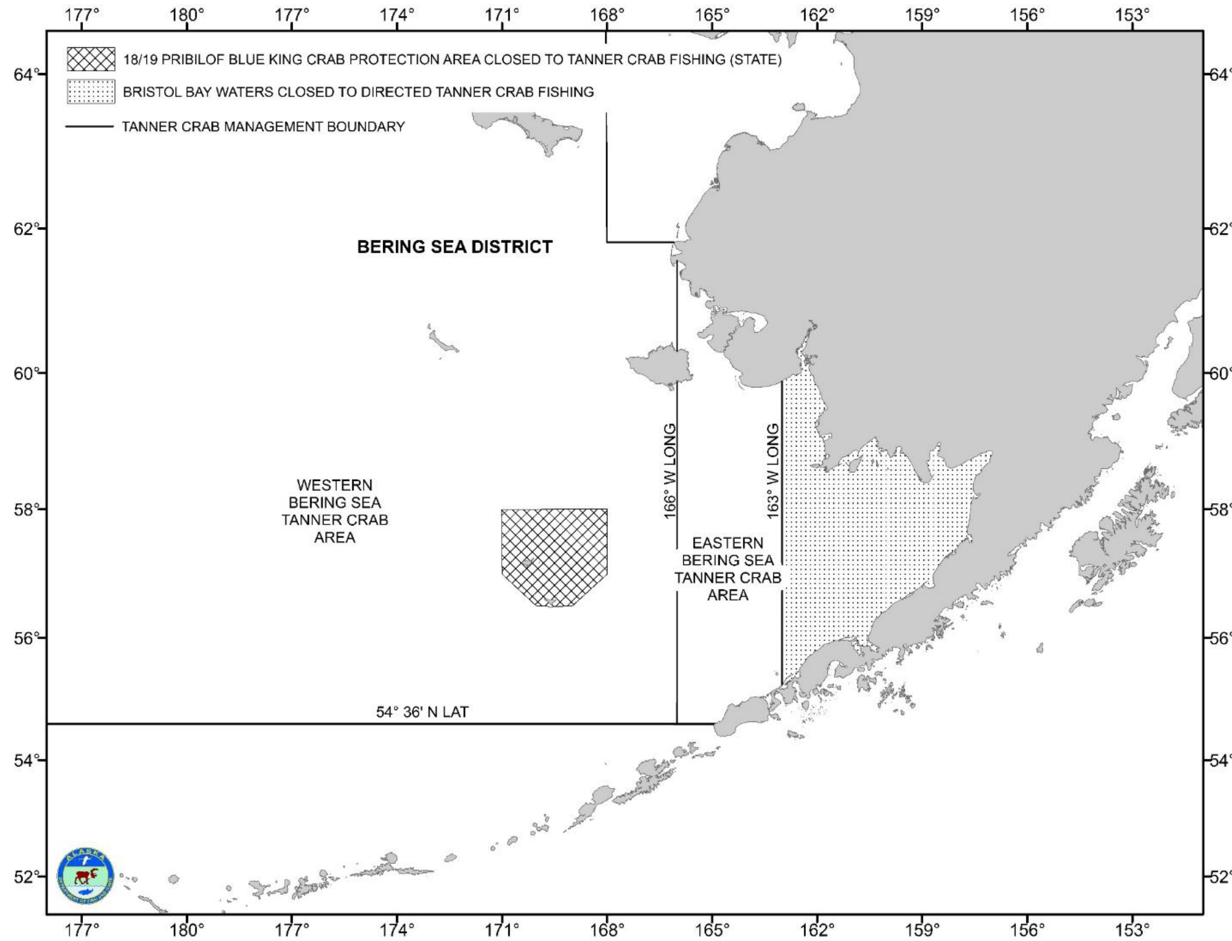


Figure 2.–Bering Sea District Tanner crab management area.

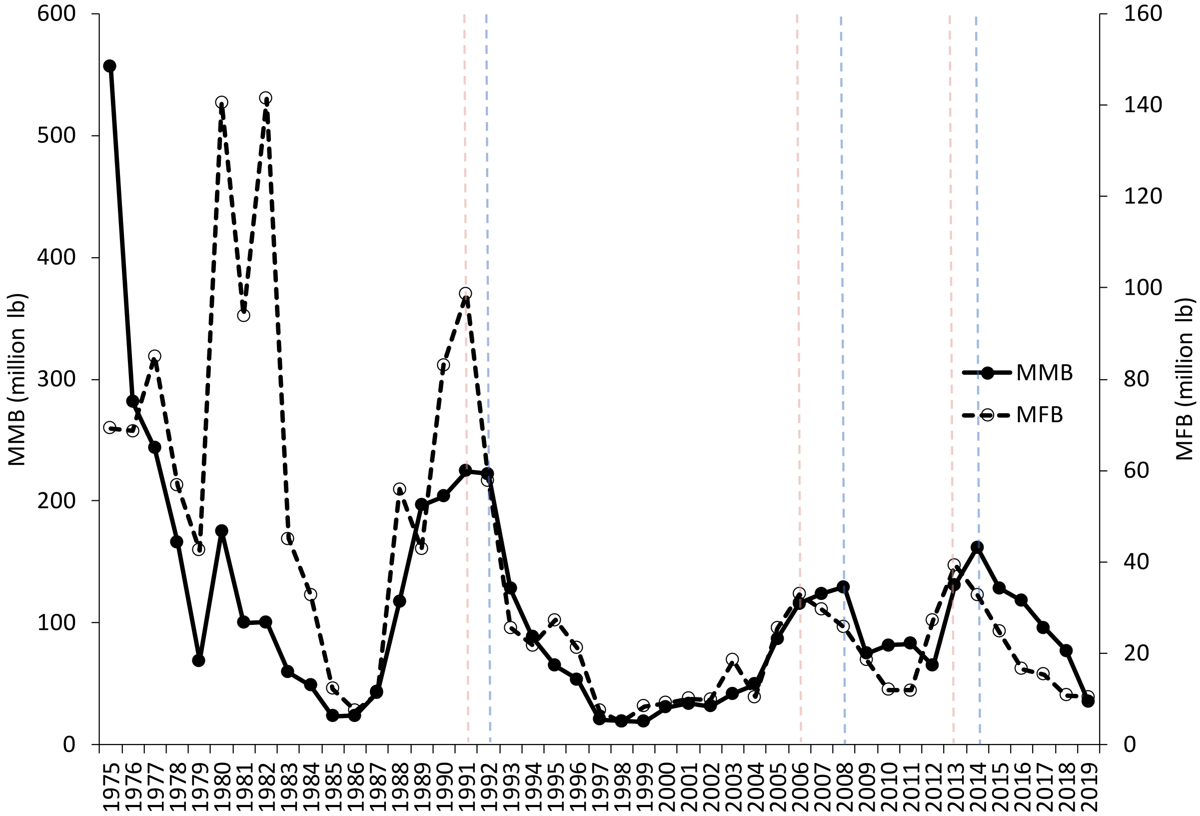


Figure 3.–Estimates of mature male biomass (MMB) and mature female biomass (MFB) based on National Oceanic and Atmospheric Administration (NOAA) eastern Bering Sea (EBS) summer bottom trawl survey area-swept data. Vertical pink dashed lines indicate approximate MFB biomass peaks, and vertical blue dashed lines indicate approximate MMB biomass peaks. The scales of the *y* axes differ between MMB and MFB to more clearly depict the 1-2 year lag of MMB trends.

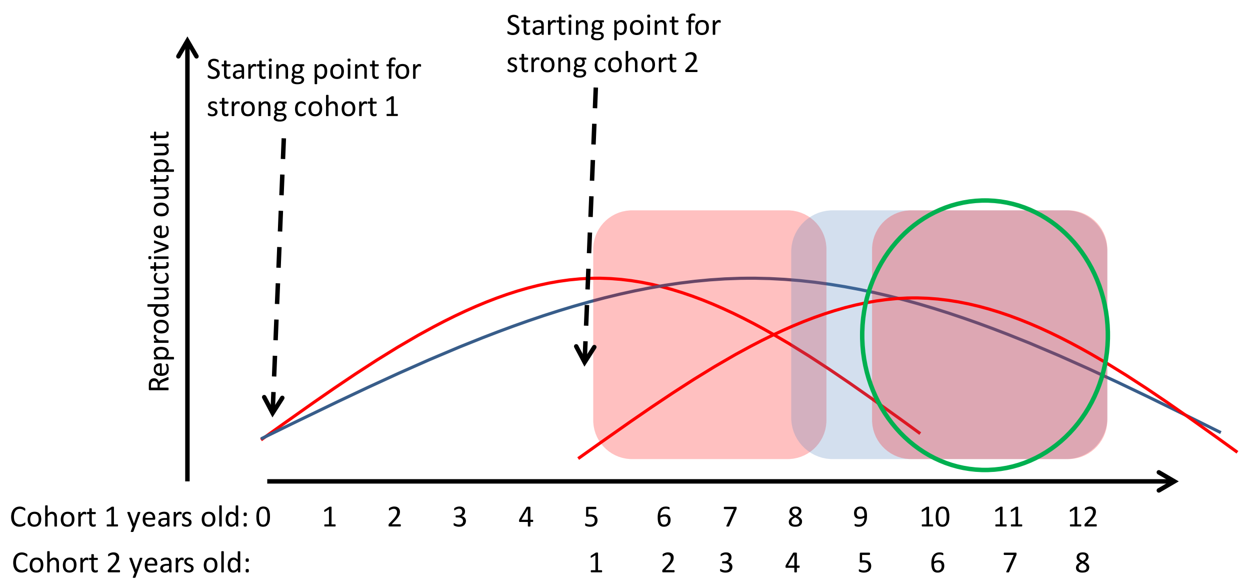


Figure 4.–Conceptual depiction of reproductively important years for mature female crabs (pink squares) and mature male crabs (blue squares). Red lines represent female relative reproductive output over time (*x* axis; units are years), and the blue line represents male relative reproductive output over time. The green circle indicates overlap of reproductively important years of males from hypothetical cohort 1 and females from hypothetical cohort 2.

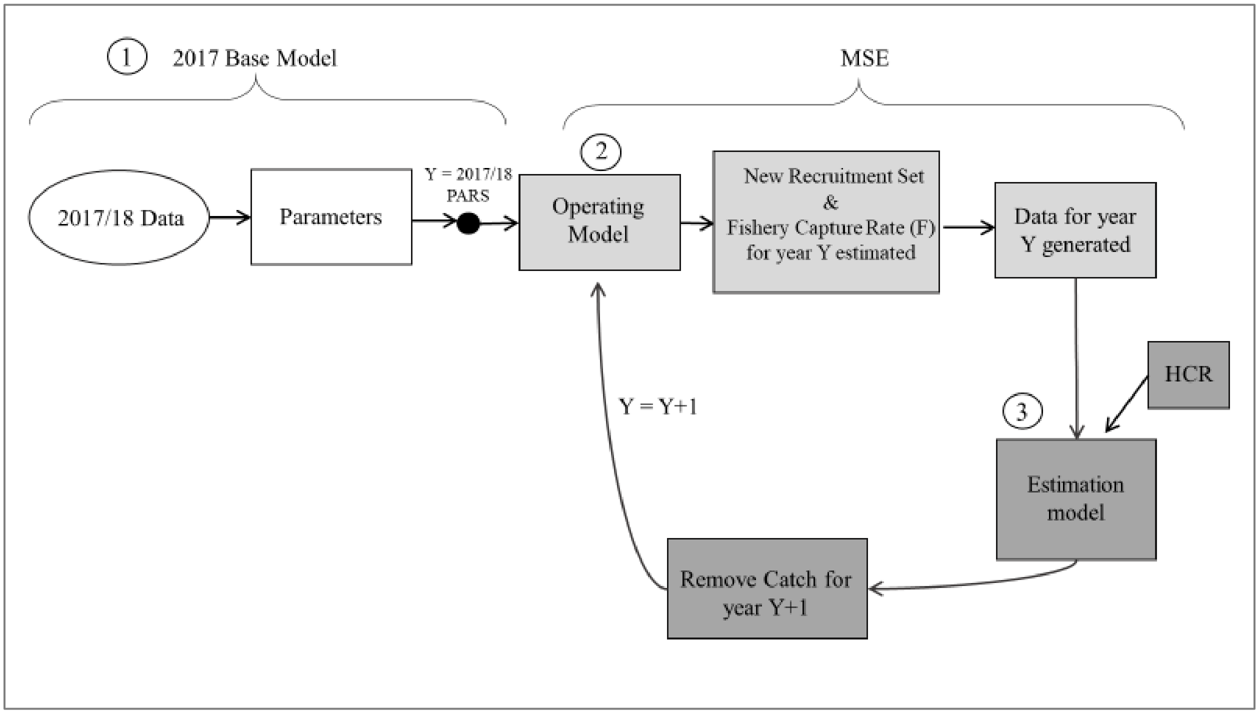


Figure 5.–Flow chart showing the inputs for each part of the management strategy evaluation (MSE), starting with the original estimation (1) using the 2017 Tanner crab assessment model (TCSAM02), which feeds initial parameters into the operating model (2), which in turn calculates total fishing mortality and generates recruitment and survey data. These data feed into the estimation model (3), which determines the TAC based on the HCR scenario, which then is fed back to the operating model (2), where the cycle continues for 100 years.

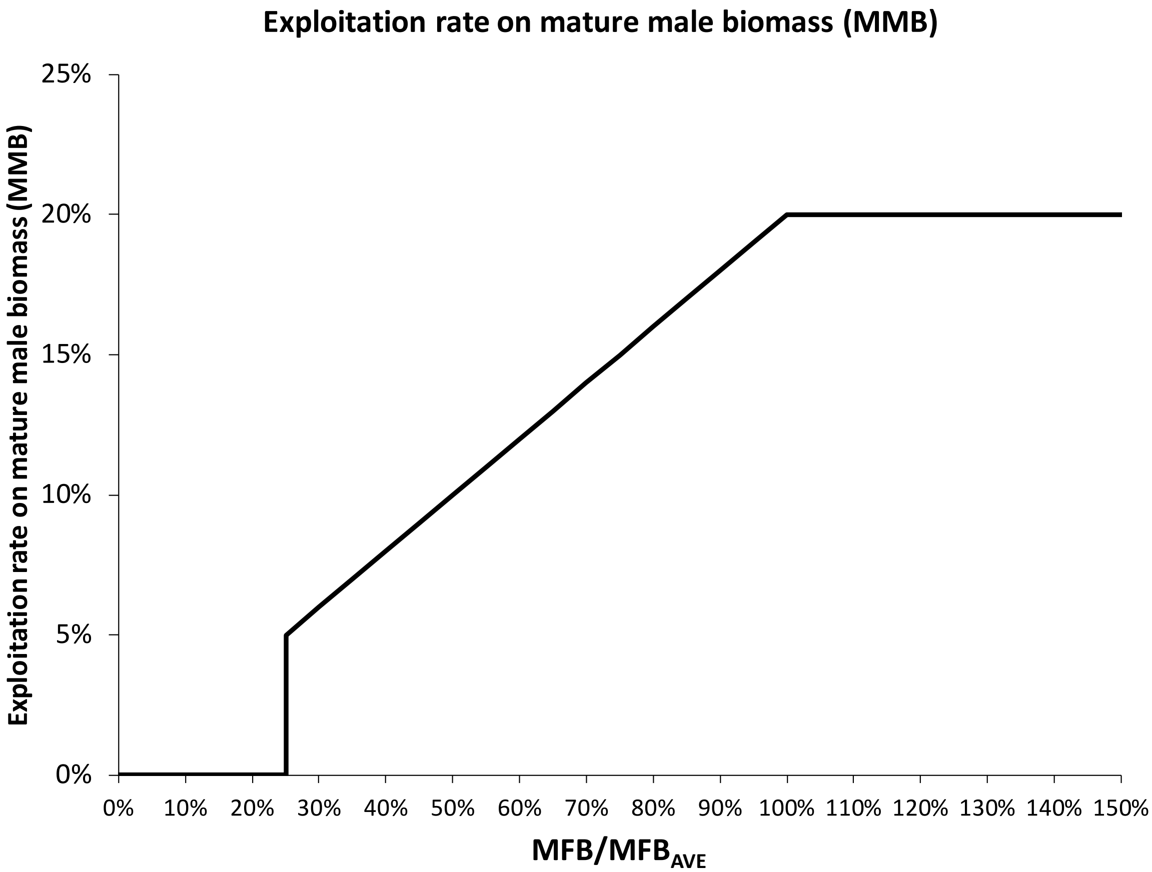


Figure 6.–Exploitation rates on mature male biomass (MMB) for HCR1 based on the current year mature female biomass (MFB) relative to MFB_{AVE} (the mean value of MFB for the period 1982–2017).

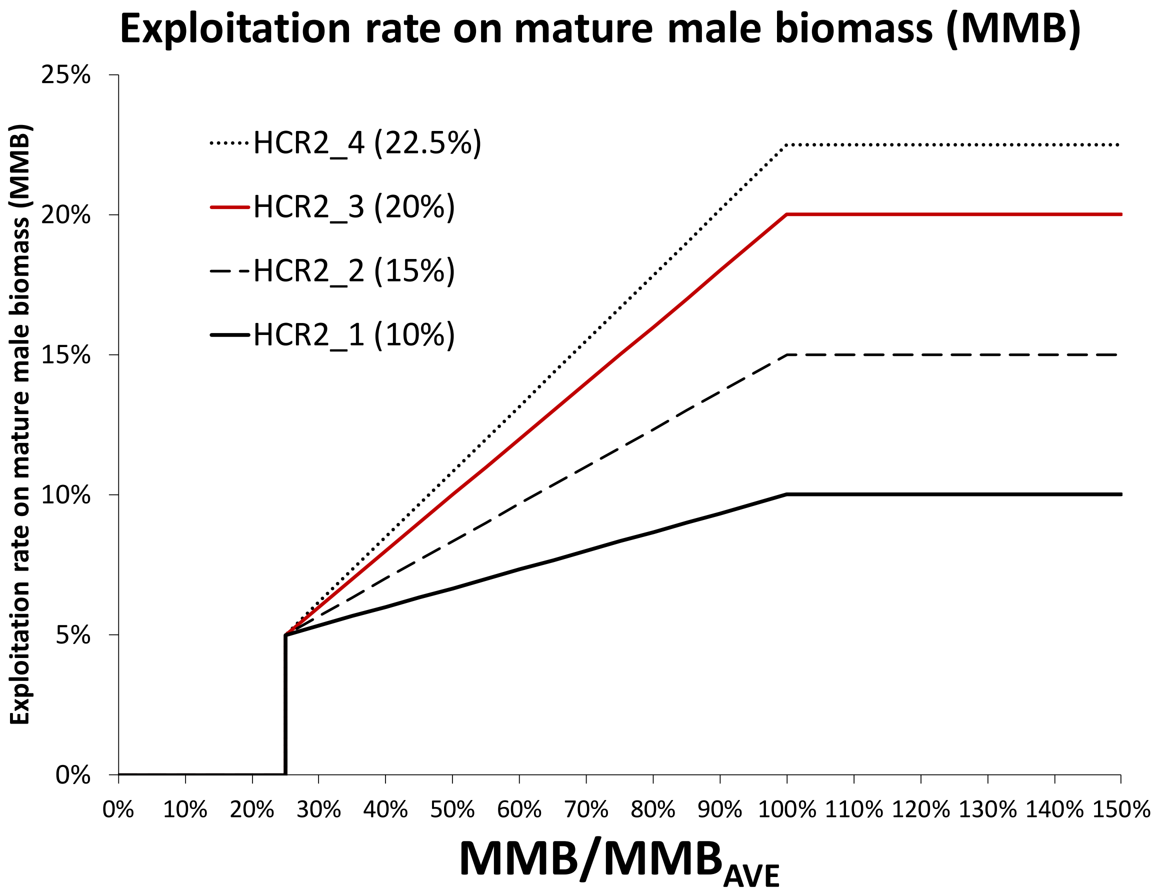


Figure 7.–Exploitation rates on mature male biomass (MMB) for HCR2. For each sloping control rule (“ramp”), the exploitation rate is determined based on the current year MMB relative to MMB_{AVE} (the mean value of MMB for the period 1982–2017).

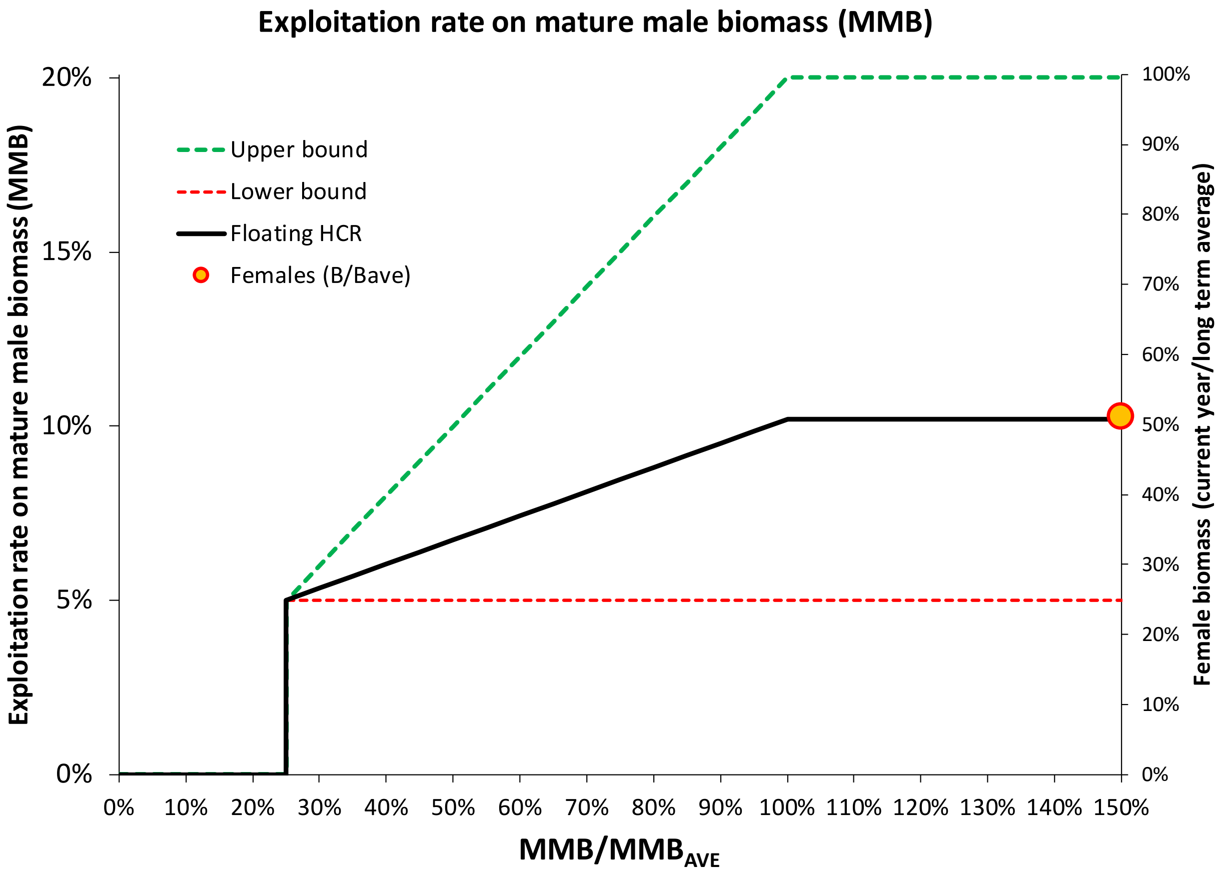


Figure 8.–Exploitation rates on mature male biomass (MMB) for HCR4 (female dimmer). The maximum exploitation rate is first determined by the current year mature female biomass (MFB) relative to MFB_{AVE} (the mean value of MFB for the period 1982–2017). The exploitation rate on MMB then is determined based on the current year MMB relative to MMB_{AVE} (the mean value of MMB for the period 1982–2017).

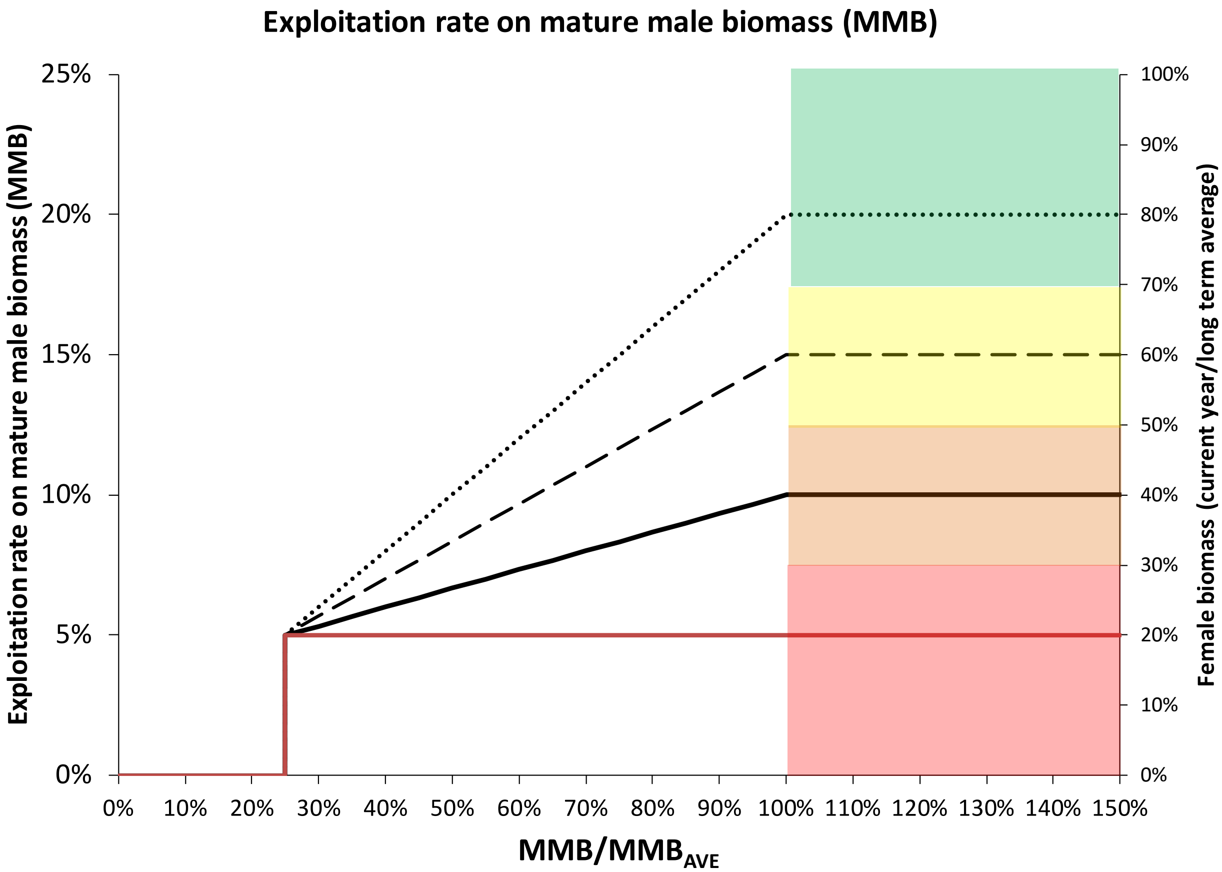
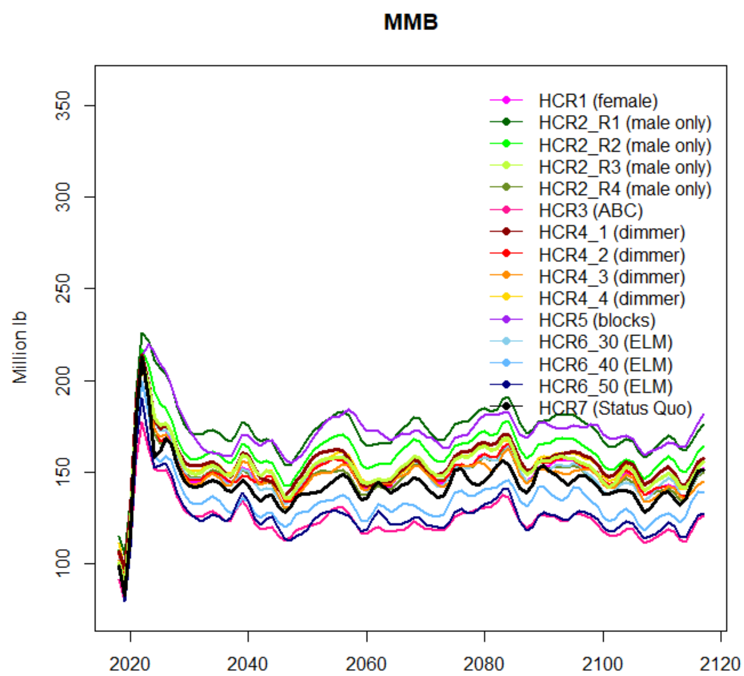


Figure 9.–Exploitation rates on mature male biomass (MMB) for HCR4 (female blocks). The ramp used in a given year is first determined by the current year mature female biomass (MFB) relative to MFB_{AVE} (the mean value of MFB for the period 1982–2018). When MFB/MFB_{AVE} is less than 30%, a 5% exploitation rate is applied to MMB. When MFB/MFB_{AVE} is between 30% and 50%, the maximum exploitation rate is 10% on MMB. When MFB/MFB_{AVE} is between 50% and 70%, the maximum exploitation rate is 15% on MMB. When MFB/MFB_{AVE} is over 70%, the maximum exploitation rate is 20% on MMB. Once the ramp is determined, the exploitation rate on MMB is then determined based on the current year MMB relative to MMB_{AVE} (the mean value of MMB for the period 1982–2017).



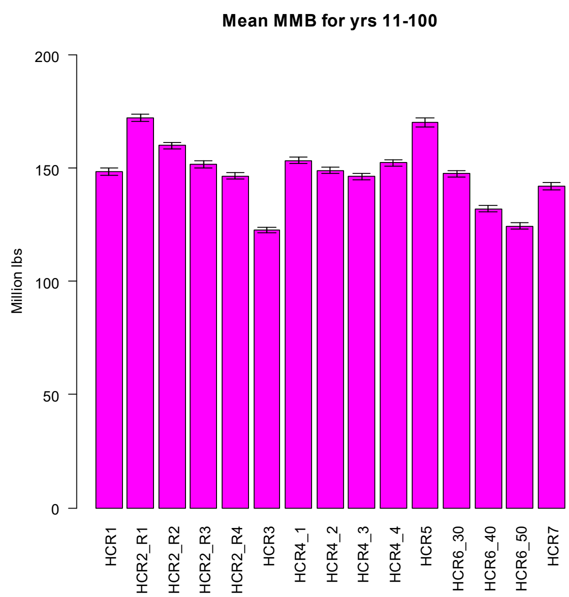


Figure 10.–Average (over simulation) mature male biomass (MMB) by year for each policy for simulation years 1 to 100 (top) and long term (years 11 to 100, bottom).

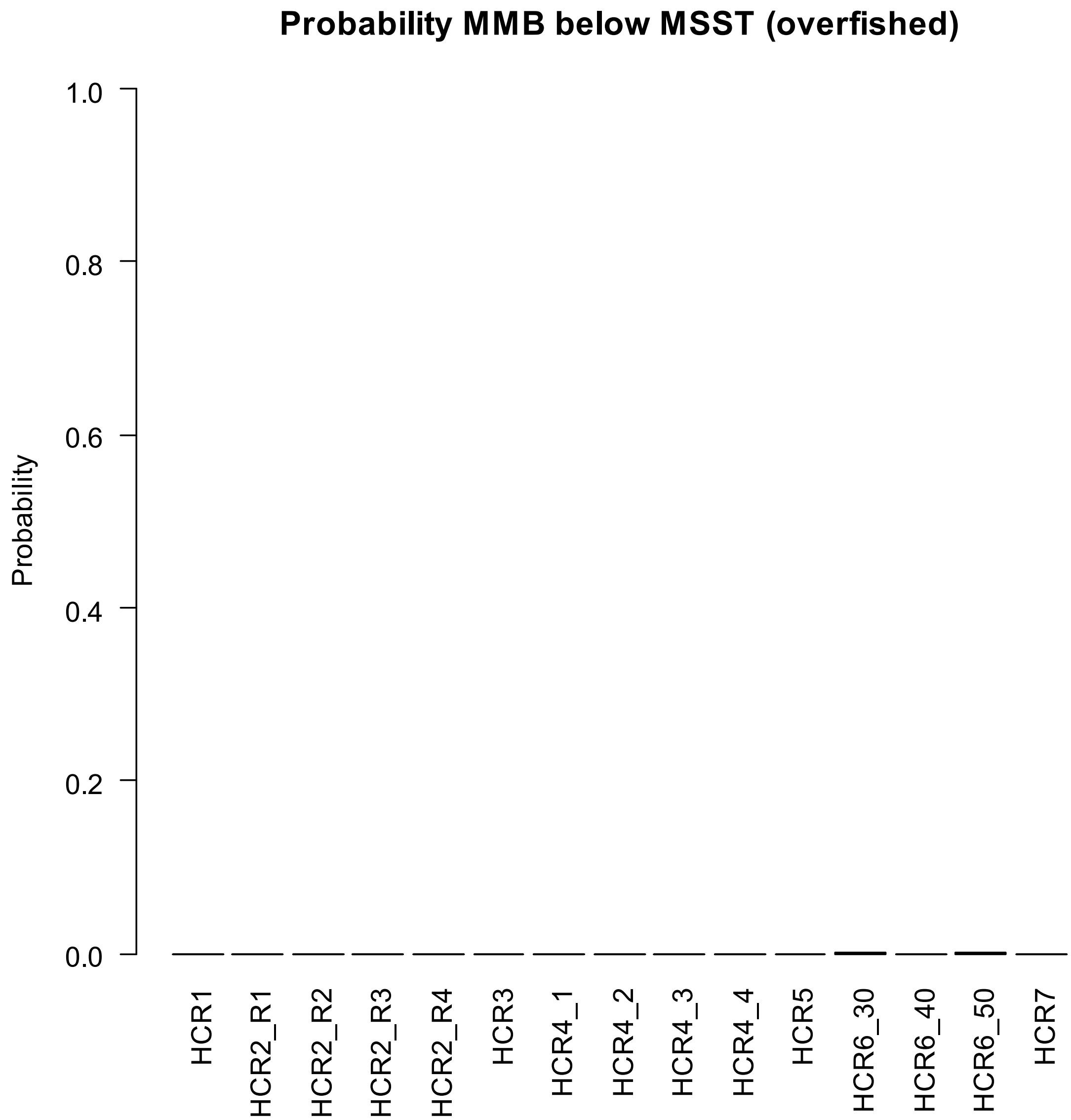
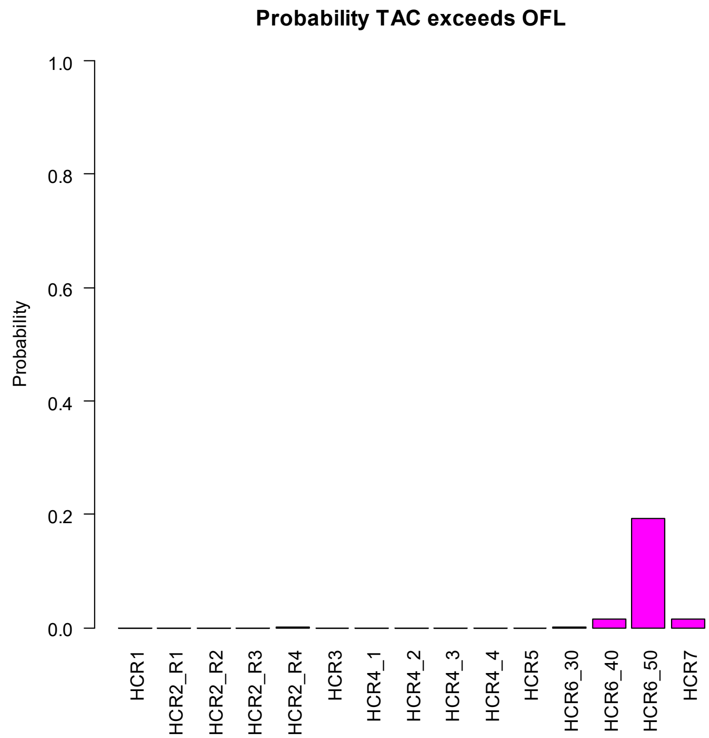


Figure 11.–Probability that MMB is less than the federal minimum stock size threshold (MSST) for each policy. Probabilities are equal to or close to zero for all policies.



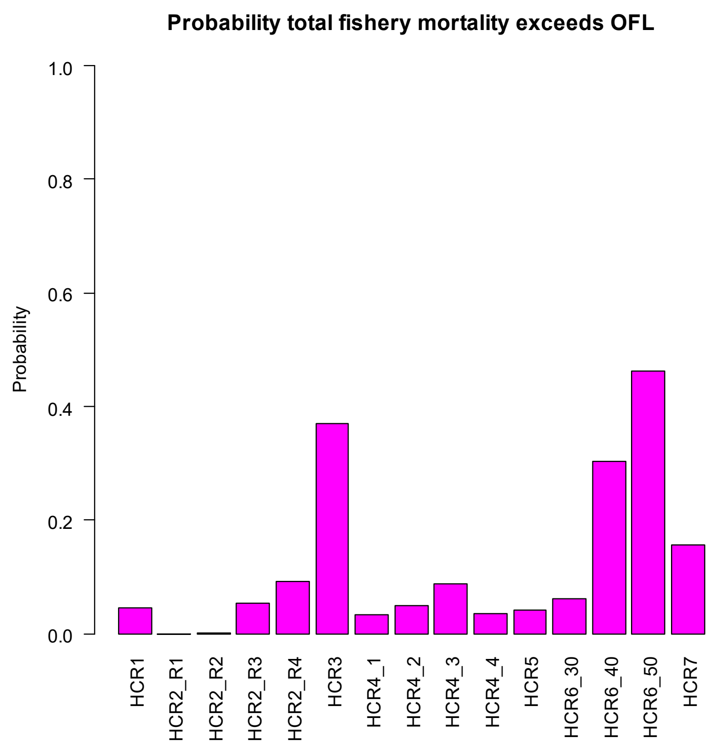


Figure 12.–Probability that total allowable catch (TAC, top) and total fishery mortality (catch + discard mortality, bottom) exceed the federal overfishing limit (OFL) for each policy.

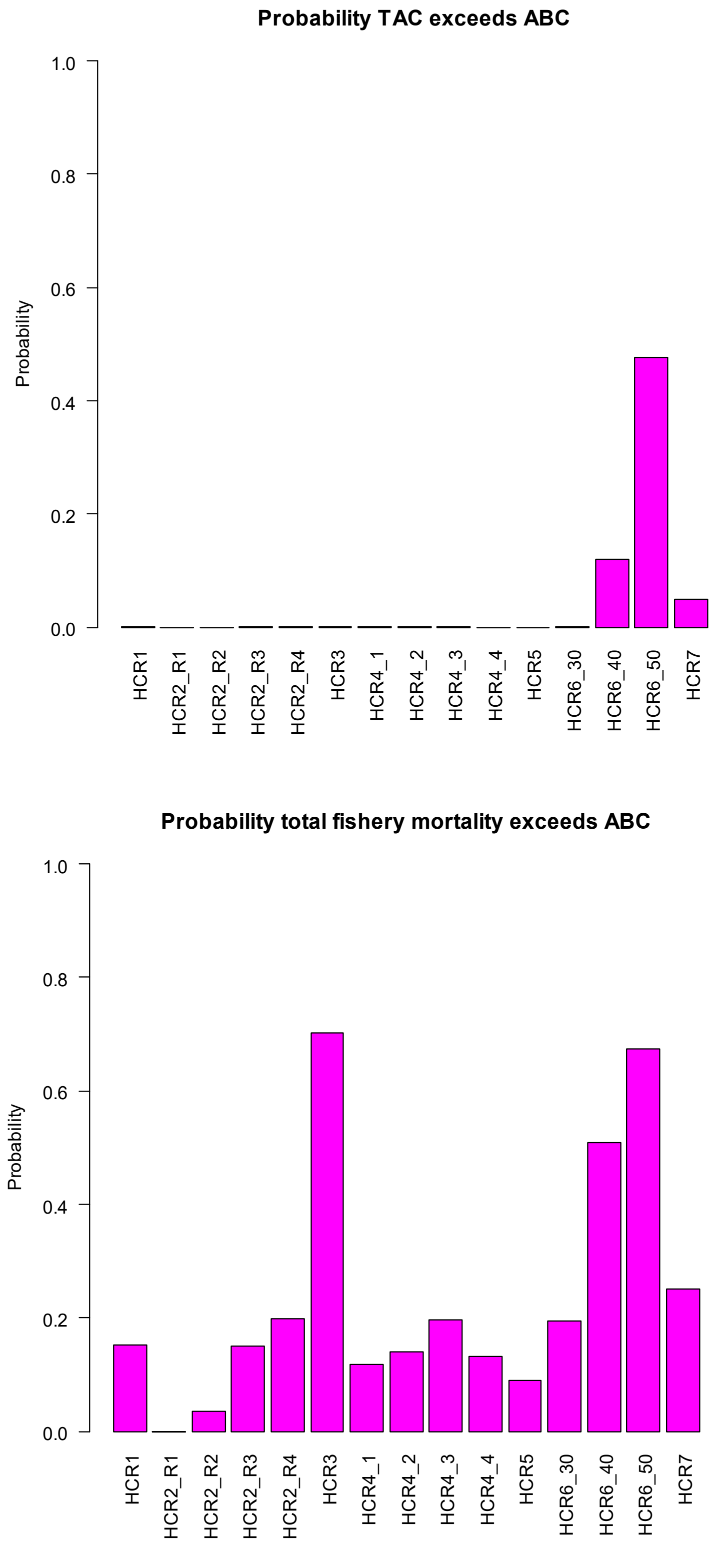


Figure 13.–Probability that total allowable catch (TAC, top) and total fishery mortality (catch + discard mortality, bottom) exceed the federal acceptable biological catch (ABC) for each policy.

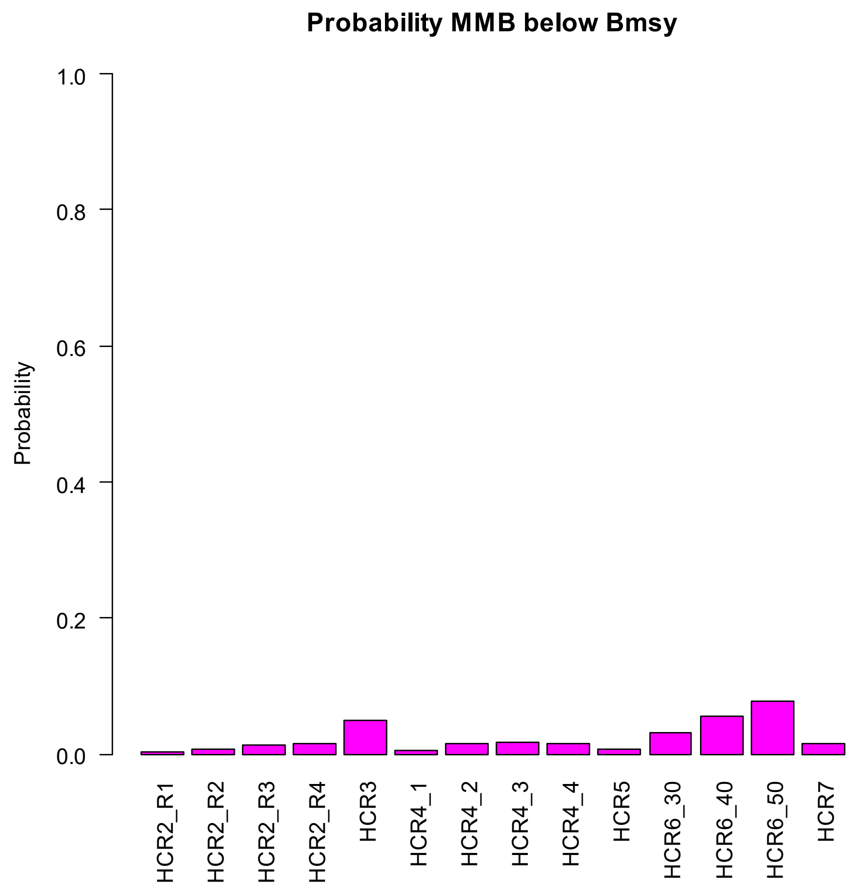


Figure 14.–Probability that mature male biomass (MMB) is below B_{35} (a proxy for B_{MSY}) for each policy.

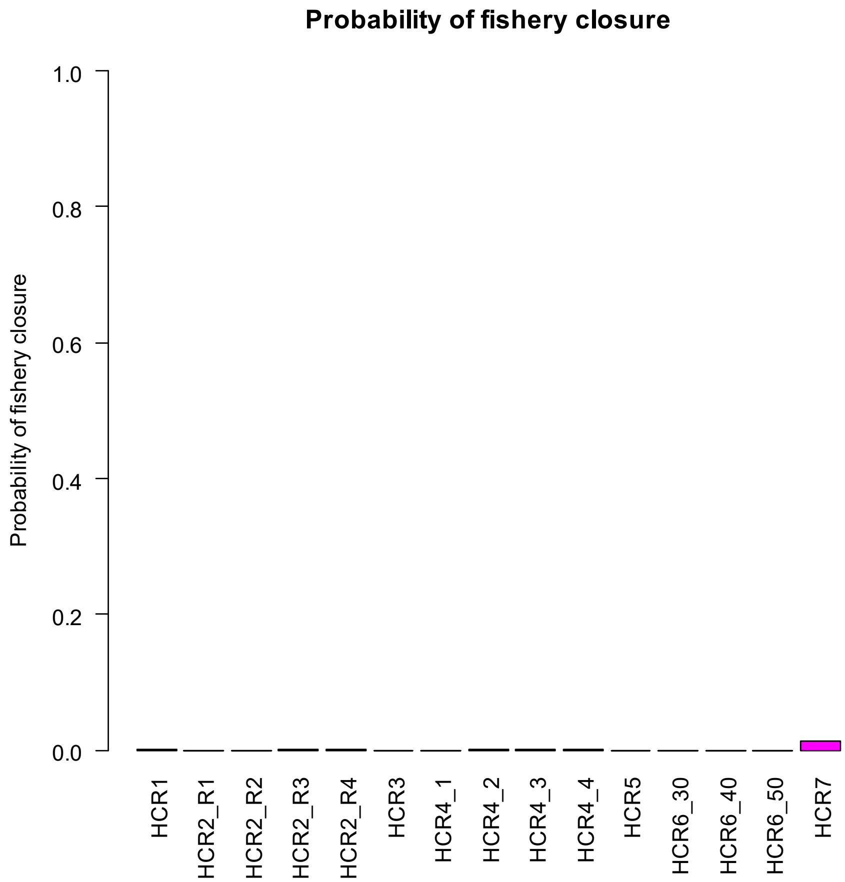


Figure 15.–Probability of fishery closures (when estimated mature male abundance [MMB] is below 25% of the estimated operating model historical long-term average MMB from 1982–2017) for each policy.

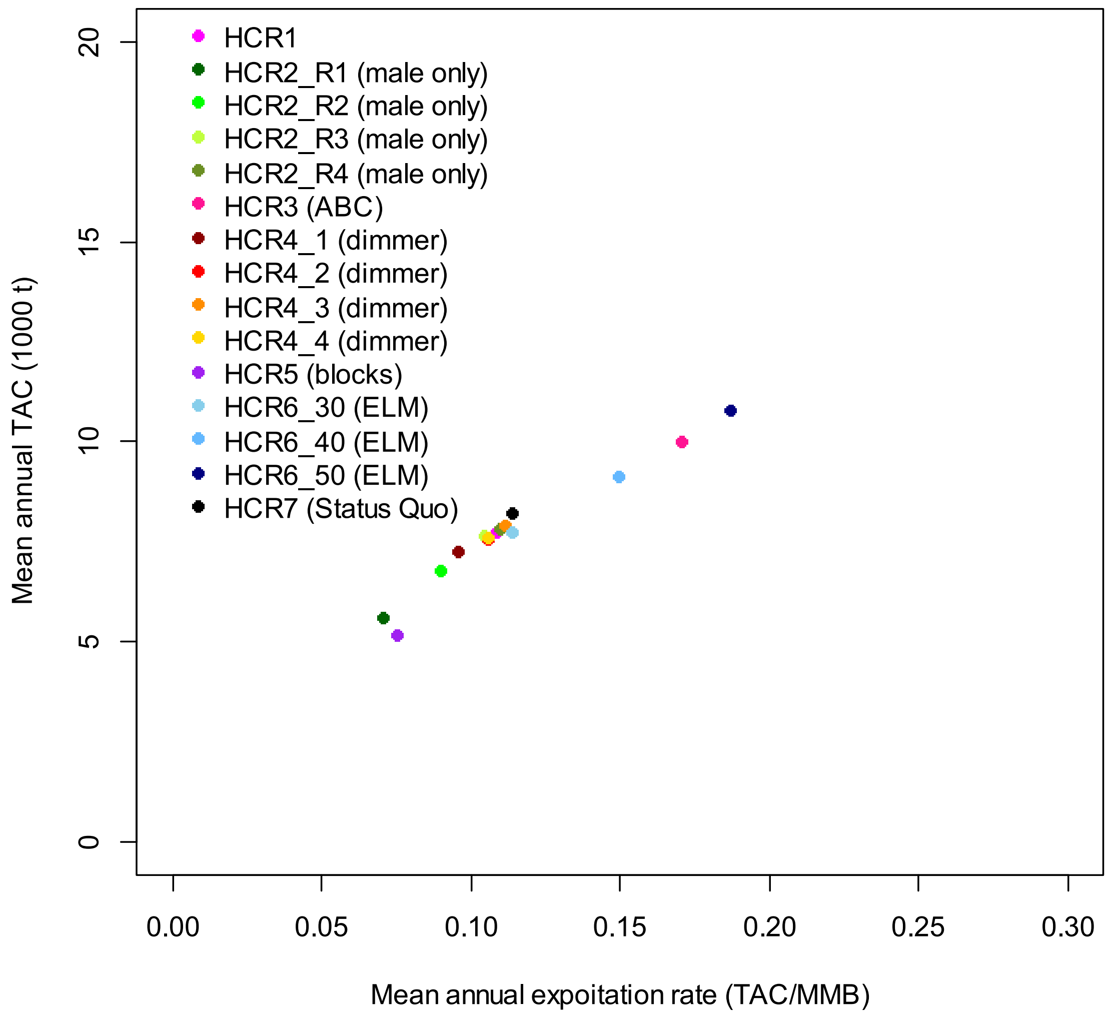
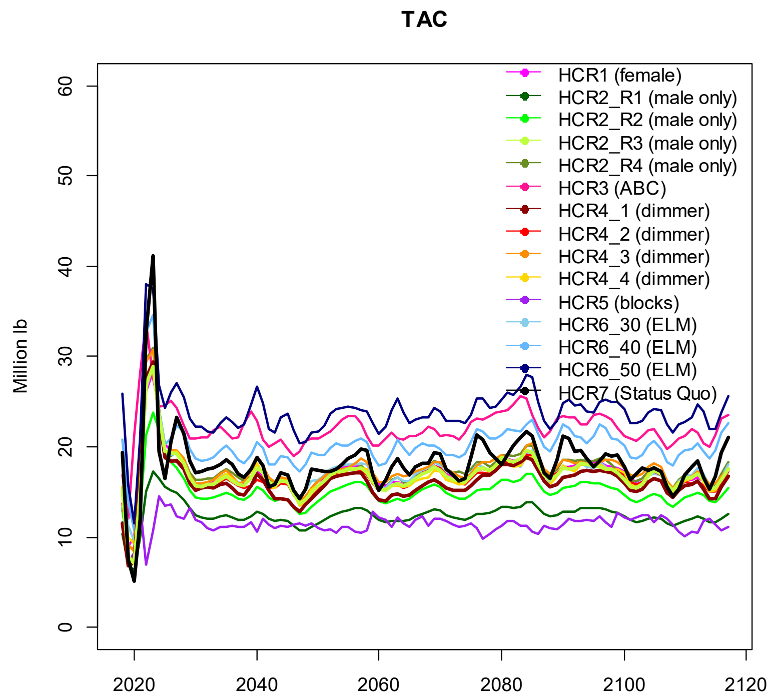


Figure 16.–Predicted long-term average total allowable catch (TAC) at each exploitation rate as defined by TAC divided by mature male biomass (MMB).



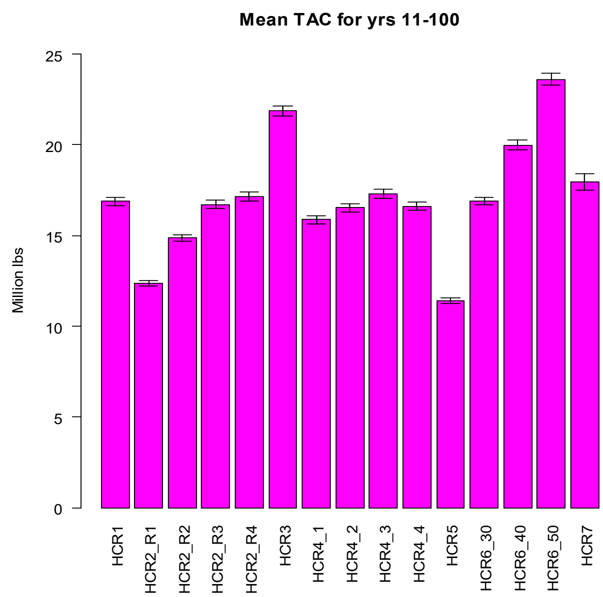


Figure 17.–Average total allowable catch (TAC) for each policy for simulation years 1 to 100 (top) and long term (years 11 to 100, bottom).

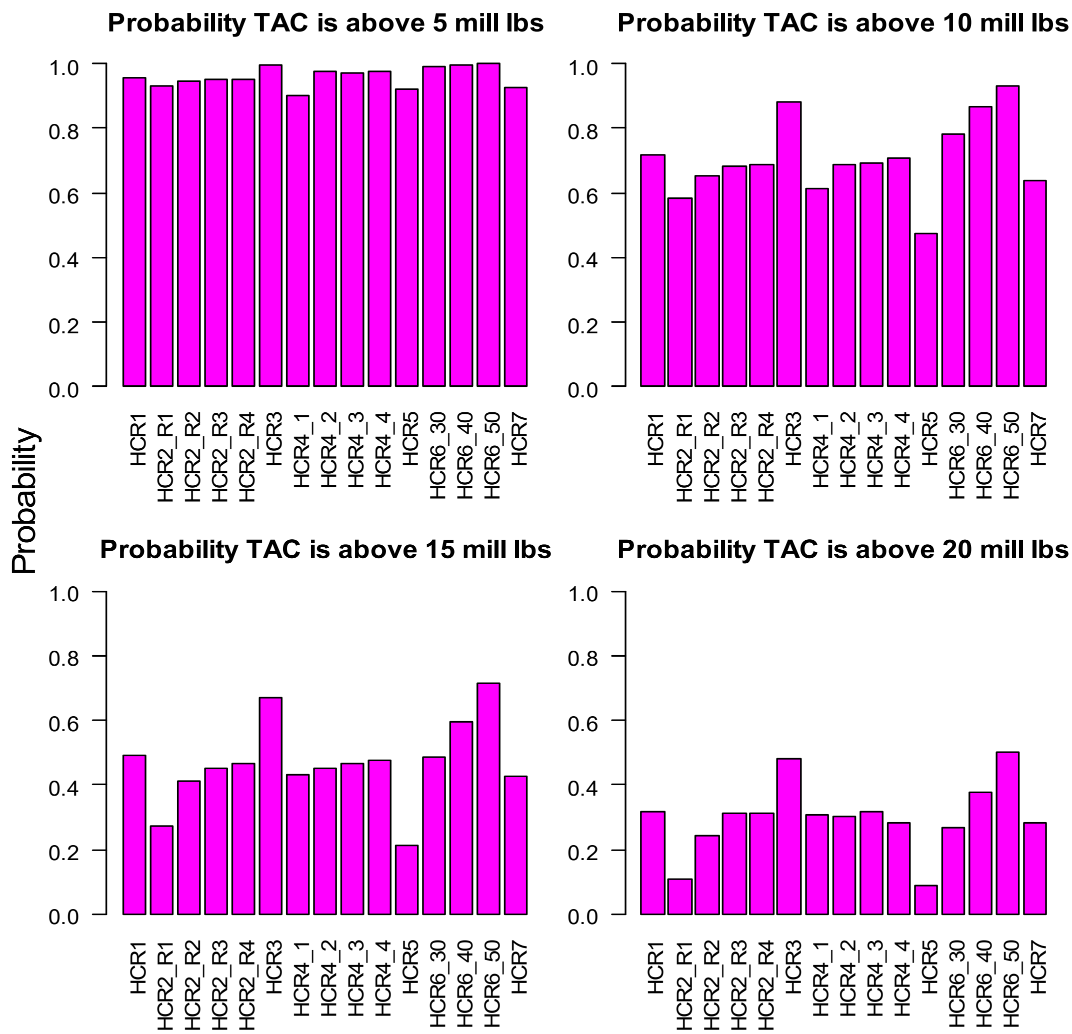


Figure 18.–Probability that the total allowable catch (TAC) is above 5, 10, 15, and 20 million lb.

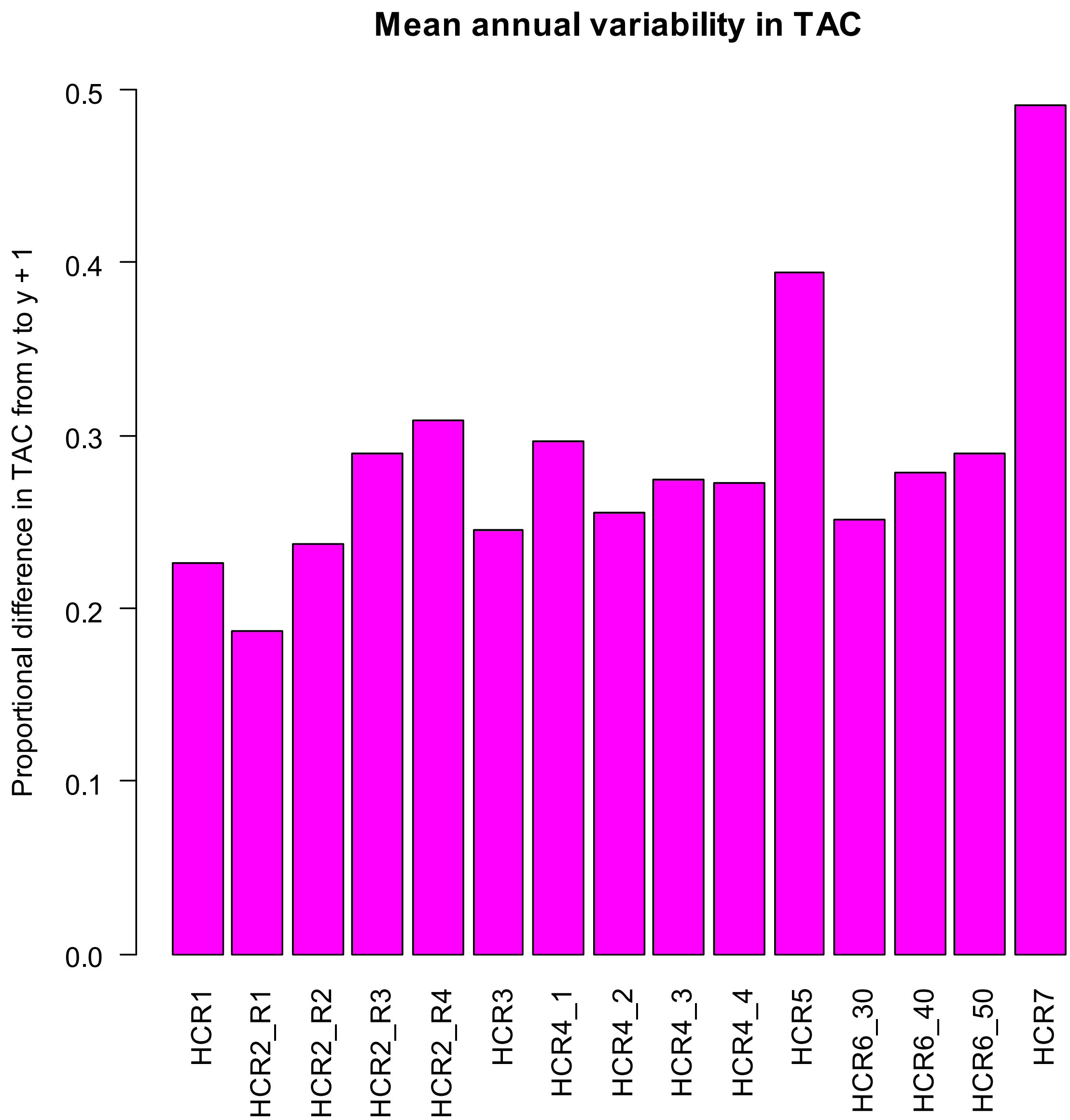


Figure 19.–Average annual variability in total allowable catch (TAC), as defined by the proportion of the TAC that changed from one year to the next.

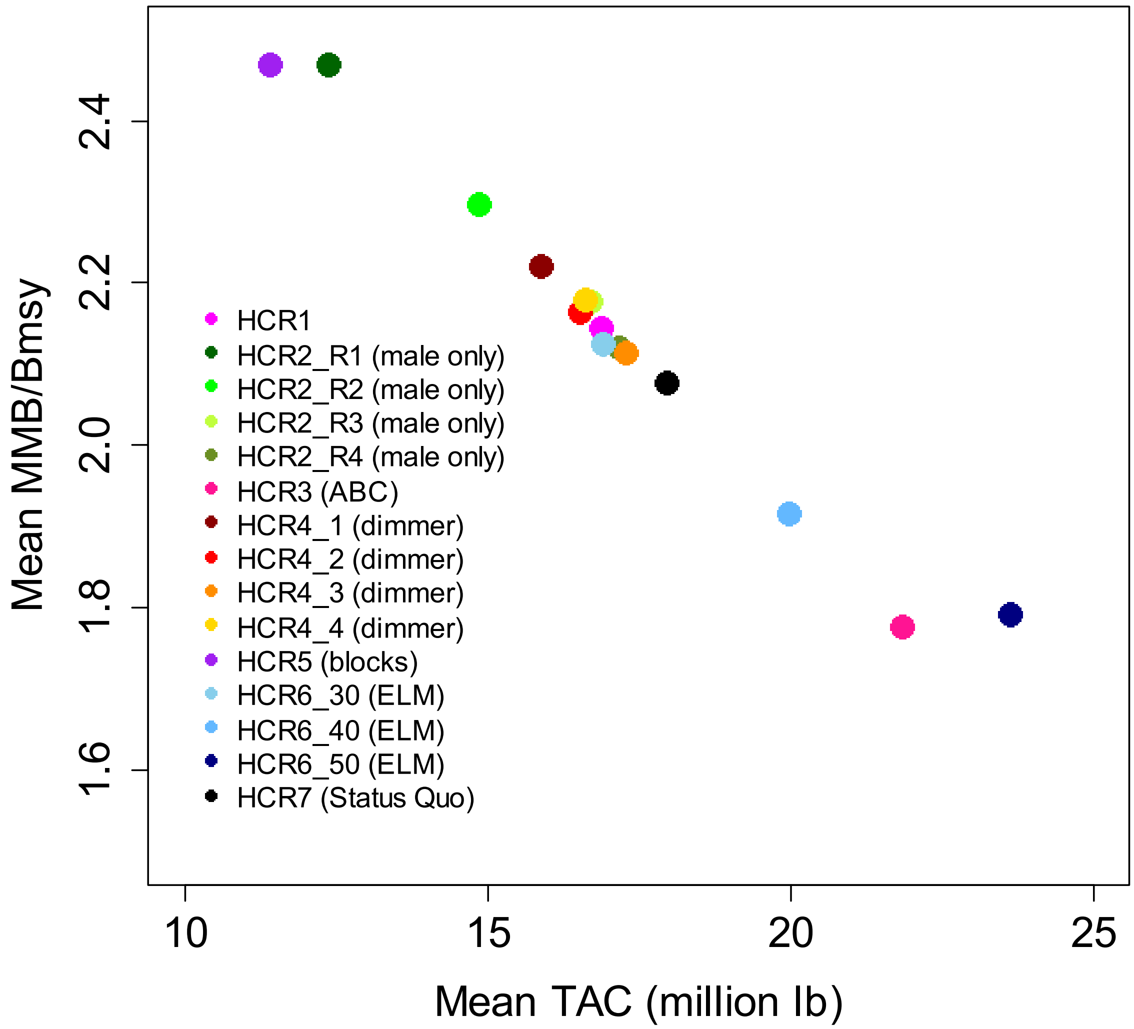


Figure 20.–Predicted long-term stock status (MMB/B_{MSY}) for each long-term average total allowable catch (TAC).

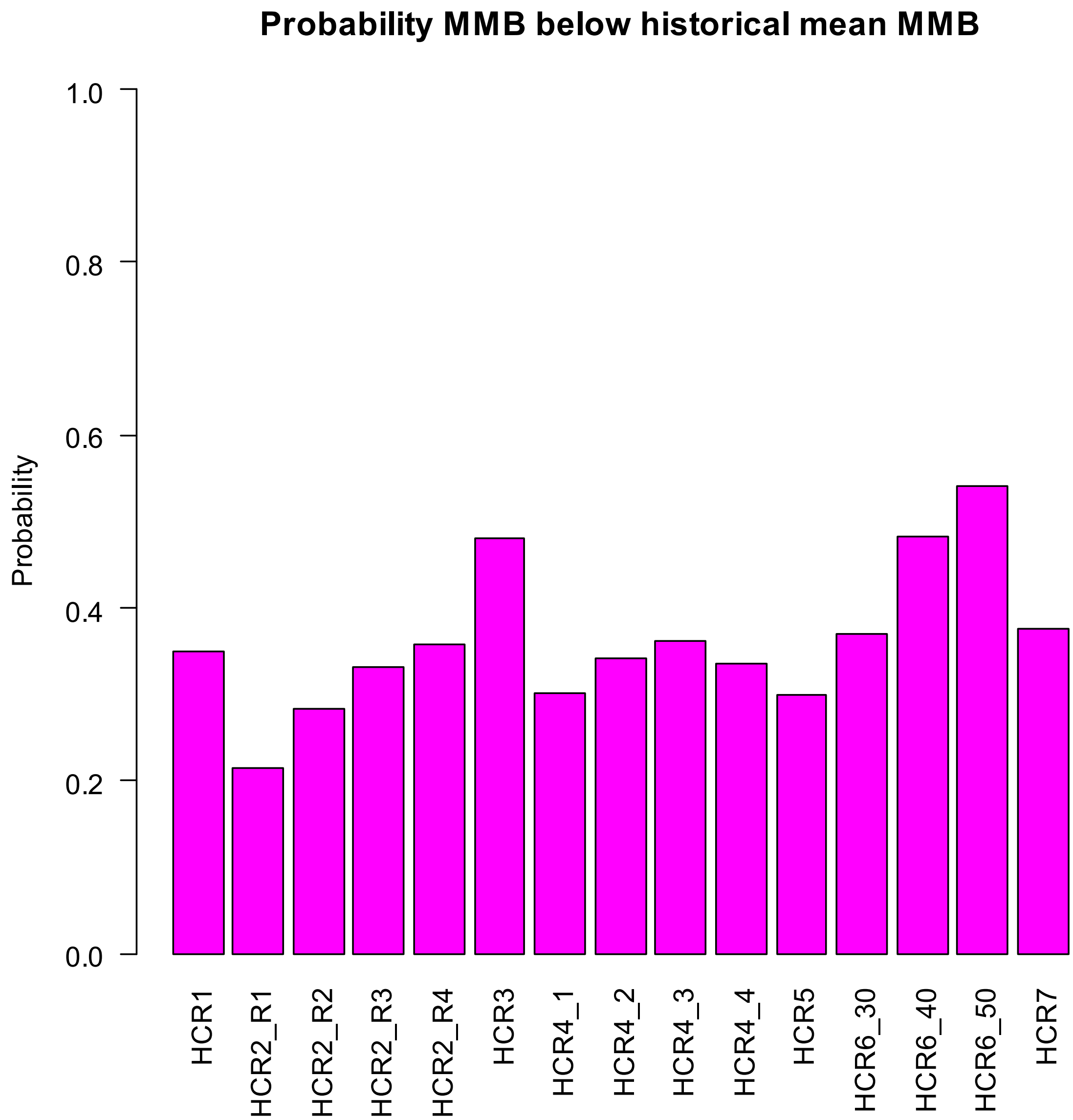
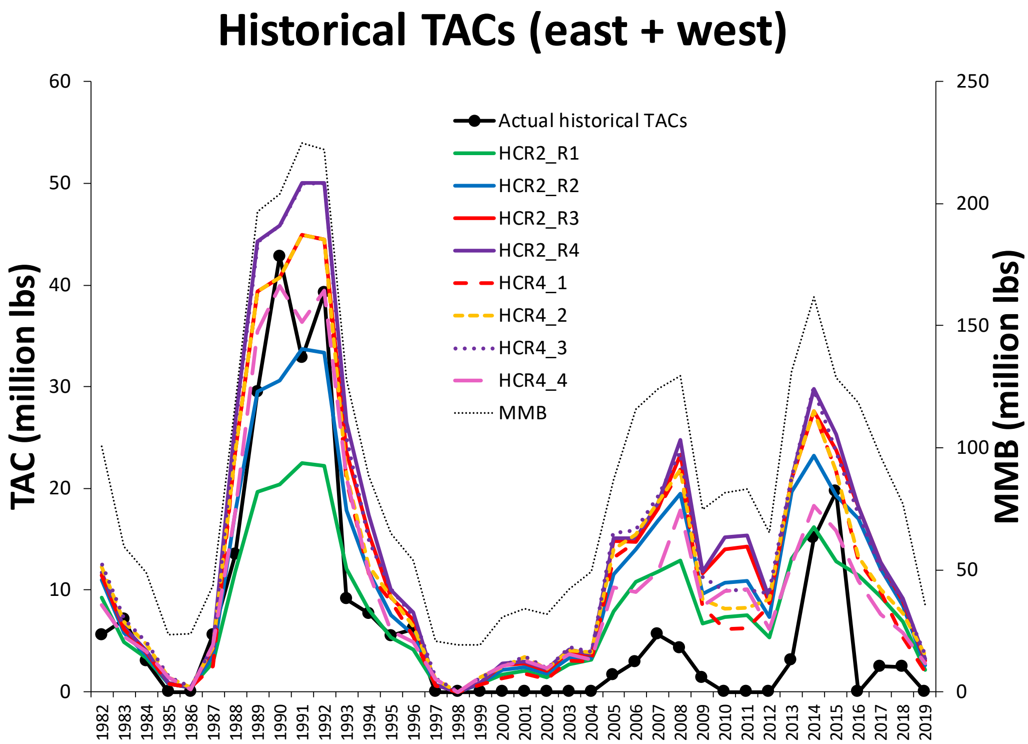


Figure 21.–Probability that the projected mature male biomass (MMB) is below average historical estimates of MMB for 1982–2017 (MMB_{AVE}).



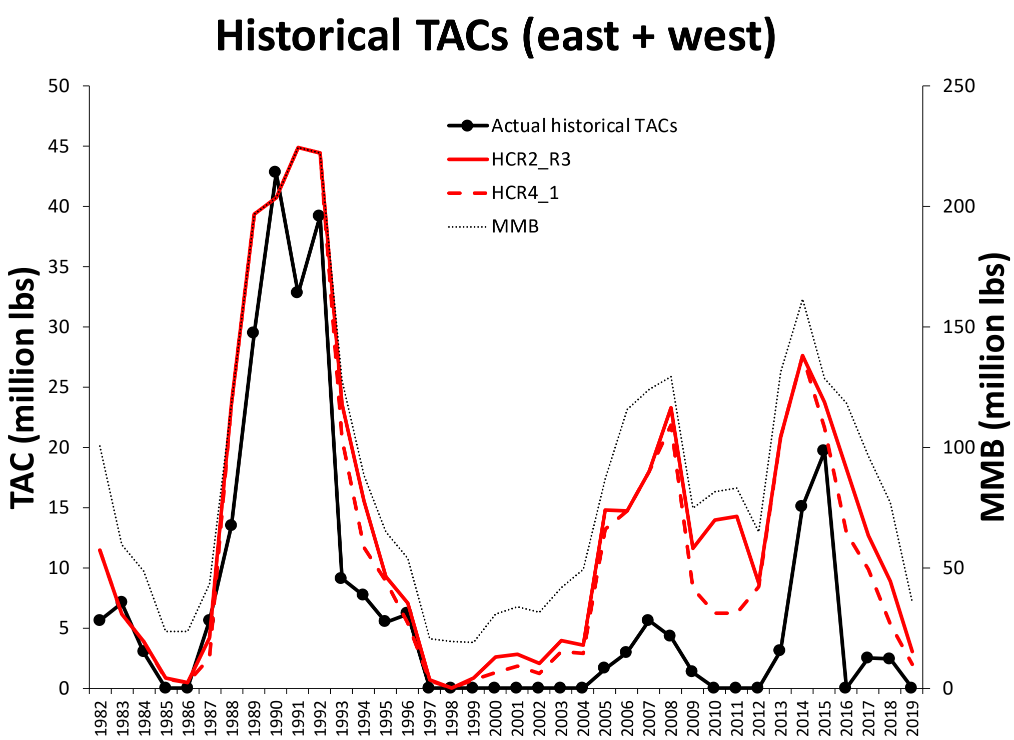
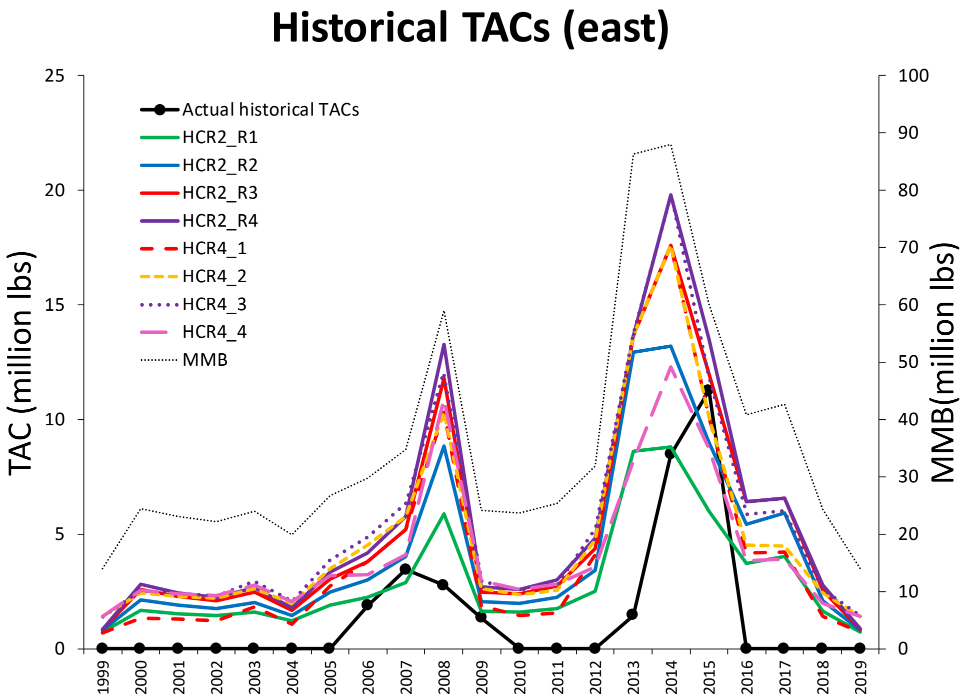


Figure 22.–Historical total allowable catch (TAC) for the male-only ramp (HCR2) and female dimmer (HCR4) variants using National Oceanic and Atmospheric Administration (NOAA) eastern Bering Sea (EBS) summer bottom trawl survey area-swept estimates for management areas east and west of 166° W long combined (top). Historical TACs for the 20% male-only ramp (HCR2_R3) and 20% female dimmer (HCR4_1, bottom).



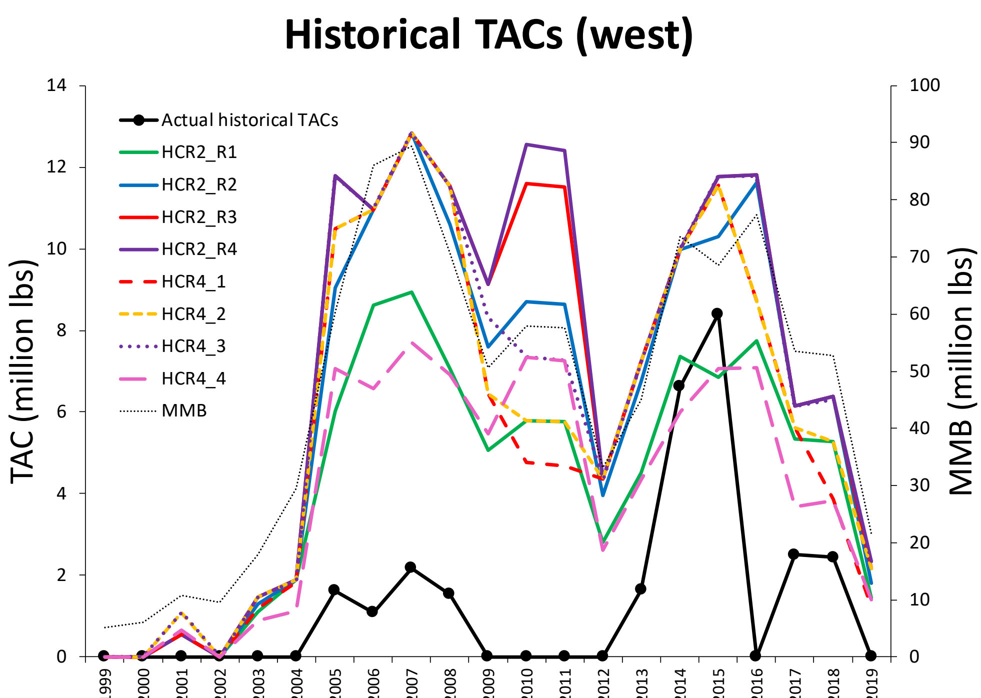


Figure 23.–Historical total allowable catch (TAC) for the male-only ramp (HCR2) and female dimmer (HCR4) variants using National Oceanic and Atmospheric Administration (NOAA) eastern Bering Sea (EBS) summer bottom trawl survey area-swept estimates for management areas east (top) and west (bottom) of 166° W long.