Norton Sound Red King Crab Stock Assessment for the fishing year 2023

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Executive Summary

1. Stock. Red king crab, *Paralithodes camtschaticus*, in Norton Sound, Alaska.

2. Catches. This stock supports three important fisheries: summer commercial, winter commercial, and winter subsistence. Of those, the summer commercial fishery accounts for 85% of total harvest. The summer commercial fishery started in 1977. Catch peaked in the late 1970s with retained catch of over 2.9 million pounds. Since 1994, the Norton Sound crab fishery has operated as superexclusive. During the 2022 fishery season, **2,708** crab (**7,6834** lb) were harvested in the winter and **125,042** crab (**317,173** lb) were harvested in the summer commercial fishery. In the winter subsistence fishery **7,565** male crab (**15,130** lb) were caught and retained and **2,476** male crab (**2,476** lb) were unretained. In total, **135,315** crab (**338,989** lb) were harvested during the 2022 season. Estimated discard mortality ranged from **-272** lb to **199,797** lb. Total fishing mortality ranged from **0.34** to **0.54** million lb where the exceedance of the total catch ABC is dependent on the method used to estimate discard mortality. The CPT recommended discards mortality biomass of **22,092 lb** estimated from the Model 21.0 for calculation of total catch, which is 0.36 million lb. This was lower than total catch ABC of 0.40 million lb. Thus, overfishing did not occur during the 2022 season.

3. Stock Biomass. Norton Sound red king crab is monitored not in biomass but in abundance. For the assessment model, biomass is calculated by multiplying the average weight of each length class. Abundance of the Norton Sound red king crab stock has been monitored by trawl surveys since 1976 by NMFS (1976-1991), NOAA NBS (2010-2022), and ADF&G (1996-2021). Historical survey abundance of Norton Sound red king crab of carapace length greater than 63 mm (CL > 63 mm) ranged from 1.41 million to 5.90 million crab. In 2022 abundance of crab estimated from the NOAA NBS 2022 survey was 2.103 million crab with CV 0.37 (Table 3).

4. Recruitment. Recruitment is not monitored directly. It is inferred by the assessment model. Model-estimated recruitment since the 1980s has averaged ~0.70 million, ranging from 0.20 to 1.60 million.

5. Management performance.

Status and catch specifications (million lb)

Year	MSST	Biomass (MMB)	GHL	Retained Catch	Total Catch	OFL	ABC
2018	2.41	4.08	0.30	0.31	0.34	0.43	0.35
2019	2.24	3.12	0.15	0.08	0.08	0.24	0.19
2020	2.28	3.67	0.17	Conf.	Conf.	0.29	0.21
2021	2.25	5.05	0.31	0.007	0.007	0.63	0.35
2022	2.08	5.33	0.34	0.34	0.36	0.67	0.40
2023	2.65	5.29	TBD	TBD	TBD	0.643	0.450

Note
MSST was calculated as $B_{MSY}/2$
OFL-ABC 2018-2020 are retained only
2019, 2020: Total catch equals retained catch. Discarded catch was estimated only for the summer commercial fishery, but the summer commercial fishery did not occur.
OFL-ABE 20023 -retained only

Status and catch specifications (k t)

Year	MSST	Biomass (MMB)	GHL	Retained Catch	Total Catch	OFL	ABC
2018	1.09	1.85	0.13	0.14	0.15	0.20	0.16
2019	1.03	1.41	0.07	0.04	0.04	0.11	0.09
2020	1.04	1.66	0.08	Conf.	Conf.	0.13	0.09
2021	1.02	2.29	0.14	0.003	0.003	0.29	0.16
2022	0.95	2.42	0.15	0.15	0.16	0.30	0.18
2023	1.20	2.40	TBD	TBD	TBD	0.292	0.204

Conversion to Metric ton: 1 Metric ton (t) = 2.2046×1000 lb

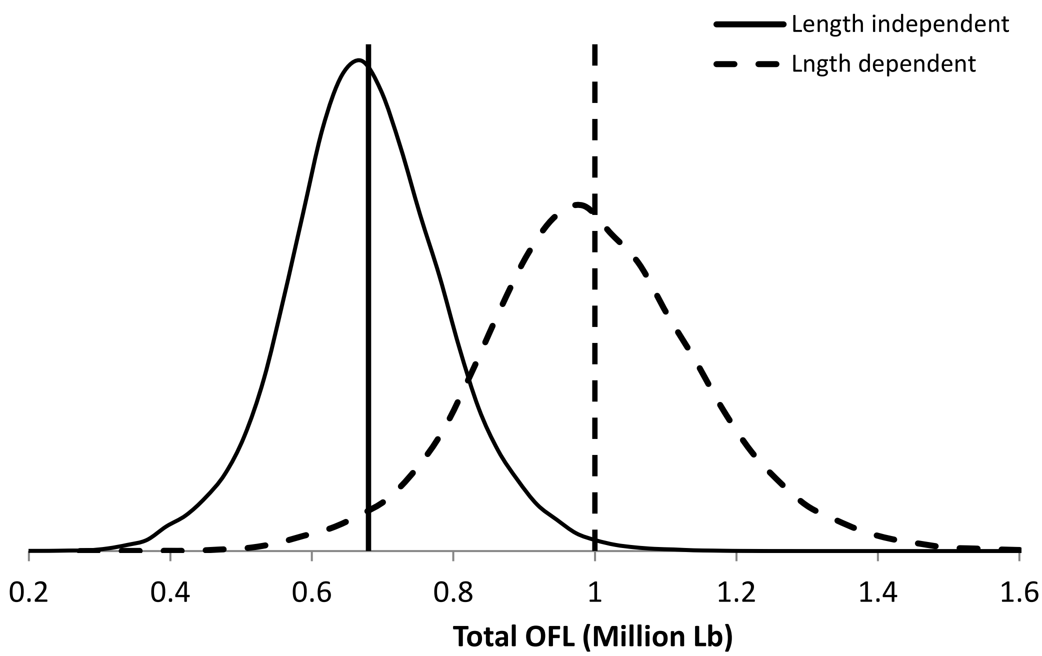
Biomass (million lb)

Year	Tier	B_{MSY}	Current MMB	B/B_{MSY} (MMB)	F_{OFL}	Years to define B_{MSY}	M	ABC Buffer	ABC
2018	4b	4.82	4.08	0.9	0.15	1980-2018	0.18	0.2	0.35
2019	4b	4.57	3.12	0.7	0.12	1980-2019	0.18	0.2	0.19
2020	4b	4.56	3.66	0.8	0.14	1980-2020	0.18	0.3	0.21
2021	4a	4.53	5.05	1.1	0.18	1980-2021	0.18	0.4	0.35
2022	4a	4.17	5.33	1.3	0.18	1980-2022	0.18	0.4	0.40
2023	4a	4.37	5.29	1.2	0.18	1980-2023	0.18	0.3	0.450

Biomass in k t

Year	Tier	B_{MSY}	Current MMB	B/B_{MSY} (MMB)	F_{OFL}	Years to define B_{MSY}	M	ABC Buffer	ABC
2018	4b	2.07	1.85	0.9	0.15	1980-2018	0.18	0.2	0.16
2019	4b	2.06	1.41	0.7	0.12	1980-2019	0.18	0.2	0.09
2020	4b	2.07	1.66	0.8	0.14	1980-2020	0.18	0.3	0.09
2021	4a	2.05	2.29	1.1	0.18	1980-2021	0.18	0.4	0.16
2022	4a	1.90	2.42	1.3	0.18	1980-2022	0.18	0.4	0.18
2023	4a	1.98	2.40	1.2	0.18	1980-2023	0.18	0.3	0.204

6. Probability Density Function of the OFL and mcmc estimates



7. The basis for the ABC recommendation.

For Tier 4 stocks, the default maximum ABC is based on P*=49% that is essentially identical to the OFL. The annual ABC buffer is determined by accounting for uncertainties in assessment and model results. **However, criteria for determining the level of ABC buffer are undefined.** The buffer was 10% from 2011 to 2014 (ABC = 90% OFL) that was increased to 20% (ABC = 80% OFL) in 2015, to 30% (ABC = 70% OFL) in 2020, and to 40% (ABC = 60% OFL) in 2021. In 2023 CPT recommended to reduce buffer to 30%

Year	ABC Buffer
2011-2014	10%
2015-2019	20%
2020	30%
2021-2022	40%
2023	30%

8. Summary of the results of any rebuilding analysis

   NA: NSRKC is not overfished.

A. Summary of Major Changes in 2023 assessment model

1. Changes to the management of the fishery.

   None.

2. Changes to the input data.

   Input data update through 2022:

   Winter subsistence, winter and summer commercial crab fishery harvest.
   Trawl surveys: abundance, length-shell compositions: NOAA NBS survey in Aug 2022.

3. Changes to the assessment methodology.

   Four assessment models are compared for September 2022 draft report, and the CPT-SSC selected the Model 21.0 for the final assessment for Jan 2023.

   a. **Model 21.0: Baseline model adopted in 2022 and for the final assessment 2023**
   b. Model 22.0: Model 21.0 + Shell based retention probability: work on earlier draft
   c. Model 22.1: Model 21.0 + individual *M* estimate: work on earlier draft
   d. Model 22.2: Model 22.0 + individual *M* estimate: work on earlier draft

4. Changes to the assessment results.
   None.

B. Response to SSC and CPT Comments

Following are SSC, CPT-SSC's requests/review (received in Jan 2022, Oct 2022) and authors' responses, arranged by topic. Requests are italicized.

I. NSRKC Biology-Ecology

Natural Mortality

SSC (Jan 2022): The biological context for natural mortality used in the model is still not well understood.
CPT (Jan 2022): Evaluate the appropriateness of the use of M=0.18 yr^{-1} for all red king crab stocks.

Author reply:

Whether or not biological context and justification of *M*=0.18 specification is appropriate for NSRKC as expressed by SSC, this *M* specification was originally set to be 0.2 for BSAI red king crab stock (NPFMC 1998) and was changed to 0.18 with Amendment 24 (NPFMC 2011). NSRKC assessment model is **REQUIRED** to use *M* = 0.18 unless CPT-SSC grants an exception, such as the CPT-SSC-accepted higher M for crabs of CL > 123mm.
Previous model alternatives exploring alternative *M* specifications (See section E, of history of model progression) and Model 22.1 and 22.2 of this year, suggest higher *M* could be more appropriate for NSRKC. CPT-SSC have been rejecting higher *M* specification for NSRKC, except for requesting more of the same analyses. Authors agree with CPT-SSC that biological context and appropriateness of the use of *M*=0.18 needs to be reevaluated not only for NSRKC but also for all RKC stocks. However, we believe that this should be conducted by CPT-SSC, not the NSRKC assessment authors who are non-member of CPT-SSC.

SSC (Jan 2022): Allowing for the estimation of M across all size classes

Author reply:

Alternative models 22.1 and 22.2 were provided, in earlier draft work. As predicted both models showed length-dependent increasing natural mortality with M of near 0 for CL < 84mm (Figure 3). However, neither model showed any visual improvements of model fits for trawl and commercial length distribution (Figures 8, 9).

SSC (Jan 2022): The authors should consult with regional managers to identify the potential for additional large crab mortality sources.

Author reply:

Contrary to the SSC's assertion, the ADF&G NSRKC stock assessment author works closely with Norton Sound crab research and management biologists. The assessment author is responsible for providing biometric support for design, analyses, and interpretation of ADF&G surveys, researches, and management, including NSRKC trawl survey and tagging studies. The ADF&G NSRKC crab biologists are members of Nome community and are acquainted with many local fishermen and staff of community organizations such as Norton Sound Economic

Development Corporation (NSEDC), and Kawerak, exchanging information and research ideas about crab biology and fisheries, including the model assumption of the additional large crab mortality and its source and validity. Thus far, neither the ADF&G nor the NSEDC biologists have identified any large crab mortality sources that the author has examined. NSRKC stock assessment author, research biologists, and managers welcome SSC bringing forward potential additional sources of mortality that can be evaluated.

Growth and Molting Probability

SSC (Jan 2022): Work directly with the scientists conducting the laboratory growth studies so that those data are collected in a way that informs the molting probability function in the stock assessment.

Authors reply:

The authors contacted Dr. Leah Zacher of NOAA AFSC Kodiak for consultation. Dr. Zacher expressed that directly applying lab obtained molting and growth data for assessment model may not be appropriate. NSRKC at the Kodiak lab are kept in water that is warmer than Norton Sound. Diet provided at the lab could be over or less nutritious than that of NSRKC *in situ*. NSRKC spend several months under ice (no light penetration) during winter, while they are not kept under dark condition in the lab. Those environmental difference could affect growth and molt timing that will differ from NSRKC *in situ*.

As for logistics of estimating molting probability and growth increments of the molted, at minimum 20 crab per size category or total of minimum 240 crabs need to be captured and shipped to the lab. The lab can spare a maximum of 2 holding tanks and each can hold a maximum of 20 crabs (total of 40 crabs). Catching 20-30 crabs especially for large crab (e.g., > 123 mm CL) could be challenging. In ideal conditions where all crabs are caught, shipped, healthy, and alive and no tank malfunctions occur, it would take 6 years to investigate.

II. NSRKC Assessment Surveys and Data

Discards

CPT (Jan 2022) Provide a table comparing discard estimates for all three current options (LNR2, subtraction, proportional), any new methods (survey-based), and estimates from the assessment model to better compare methods and identify years of concern.

CPT (Jan 2022) Evaluate how the spatial distribution of catch impacts the ability to estimate discards using Option 2 (survey length-compositions);

CPT-SSC (Oct 2022). Bring forward different methods for estimating discards (without survey data).

Authors reply:

As noted in the Appendix C, estimating of discards for NSRKC has TWO major issues.

1. Estimating discards (2012-2019) from **opportunistic observer surveys that were not intended to estimate discards**
2. Estimating discards (2020- present) **without observer surveys for evaluation of Annual Catch Limit overages.**

OFL and ABC for NSRKC stock has been **retained catch OFL and ABC** until 2020 because of **the lack of observer survey and thus no discards estimates**. In 2020 they were changed to **total catch OFL and ABC** based on 2012-2019 *ad hoc* observer surveys that was **not intended to estimate discards.** In the same year of 2020, **the *ad hoc* observer survey was terminated, and it is unlikely that observer survey will be resumed in the near future**. Given that OFL and ABC are total catch, CPT-SSC requested to bring forward methods for estimating discards **without** observer survey **for the purpose of determining annual catch limit (ACL) overage**.

Table: history of OFL-ABC designation for NSRKC.

Year	Discards survey	Discards/Total (retained + discards) Catch	OFL/ABC	Rationale
1997-2011	No survey	NA	Retained	No total catch = retained OFL
2012-2019	Opportunistic	*ad hoc*	Retained	No total catch = retained OFL
2020	No survey	NA	Total	Set total catch OFL **given that 2012-2019 are available**
2021- 2022	No survey	NA	Total	**Given that total catch OFL is set**, discards-total catch needs to be estimated **without survey data** for **determination of ACL overage.**

Author has provided various discards estimates (with survey data) since 2018 (Table 4, 5 Appendix C), and discards estimates without observer survey data since 2020 as requested by CPT-SSC (See Appendix C). However, CPT-SSC has not discussed or presented any **objective criteria** for selecting a method, which led no decisions for selecting the most appropriate method for NSRKC.

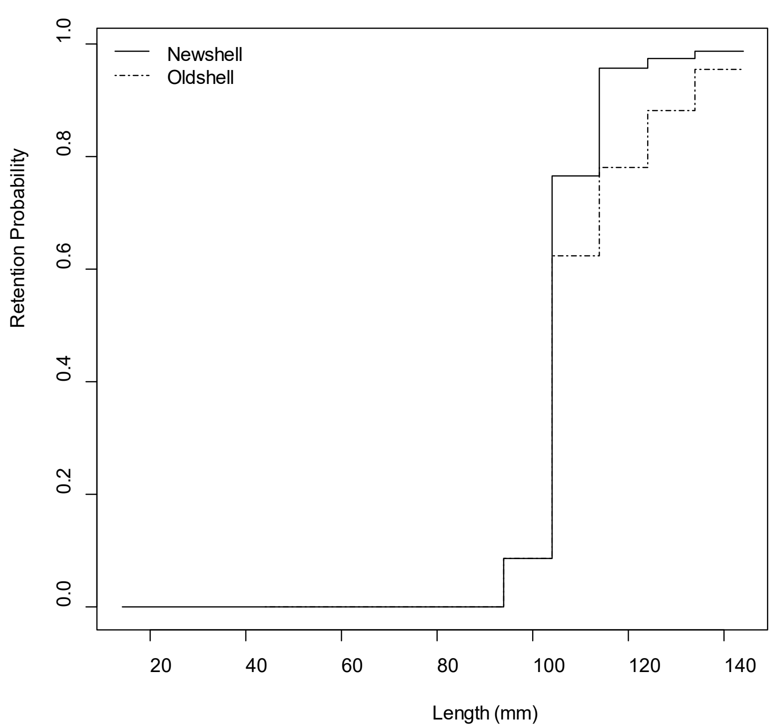
Regarding method for estimating discards without observer survey data, the author provided 21 methods and their estimates (Appendix C Table 12). Regarding the trawl survey method (Option 2), the majority of trawl length-composition sample came from area outside of commercial fishery grounds (See Figures A and B, Section D). This raises questions about representativeness of trawl survey length-shell composition, not only in this context of estimating discards, but also for using the data in the assessment model.

Regardless of a method selected for NSRKC, the fundamental question of jurisprudence needs to be addressed: **Should overage of the ACL be determined without data?** The discards mortality biomass estimated here is used **solely for determination of overage of the annual catch limit (ACL) that has significant regulatory consequences.** The opportunistic NSRKC observer survey was temporary and not return for foreseeable future. The jurisprudence applied for NSRKC will be a precedence that can be applied to other BSAI crab fisheries that termination of observer survey will be in consideration.

CPT(Jan 2022) Re-examine the evidence for shell condition-specific dis card rates and evaluate their implications for the assessment model (e.g., would this affect the overestimation of large crab).

Authors reply:

The following figure is an observed proportion of crab retained (retention probability) by shell condition from 2012-2019 observer data. The figure shows that oldshell crabs are less likely to be retained than newshell crab. An alternative model 22.0 includes separate retention probability for newshell and oldshell crab.



VAST

CPT (Jan 2022) Updates on the use of VAST for survey abundance estimation

Authors reply:
Dr. Jon Richar of NOAA received an approval from his supervisor to work on a VAST model for the Norton Sound trawl surveys. For the 2022 assessment, NOAA assigned VAST estimate of Norton Sound trawl survey to medium priority (per Dr. William Stockhausen NOAA). We look forward to his progress.

GMACS

CPT (Jan 2022) Develop a GMACS version of the NSRKC assessment model
SSC (Oct 2022) Provide an update on GMACS development for NSRKC stock for October 2023.

Authors reply:
Dr. Andre Punt and Matthieu Veron of the University of Washington are working towards developing GMACS version of the NSRKC assessment model. The author looks forward to their further development.

Standardized CPUE

CPT (Jan 2022) Calculate the arithmetic scale CV for lognormally-distributed data

Authors reply:

Table 1 includes arithmetic scale CV calculated as $CV = \sqrt{\exp(SE^2) - 1}$

III. NSRKC Assessment model

Include a table (if necessary) identifying any parameters estimated at a bound.

Authors reply:

The NSRKC Assessment model has two parameters that are estimated at a bound.: Trawl survey selectivity ($\log\_\phi_{st1}$), and parameters (r1, r2) that estimate recruit size proportion.

1. Trawl Survey selectivity parameter

   Trawl survey selectivity model is a one parameter logistic curve that reaches 1.0 at L_{max} (143.5 mm)

$$S_l = \frac{1}{1+e^{(\alpha(L_{\max}-L)+\ln(1/0.999-1))}}$$

where α = exp(log_ϕ_{st1}), L_{max} = 143.5 mm L (63.5-143.5mm)

Model estimated trawl survey selectivity is 1.0 across all size classes, or $e^{(\alpha(L_{\max}-L)+\ln(1/0.999-1))}$ ≈ 0 for all lengths, or α(L_{max}-L)+ln(1/0.999-1) = -∞ and α ≈ 0 or log_ϕ_{st1} = -∞. Thus, parameter will hit the boundary.

Alternative option is specifying S_l = 1.0 for all length classes; however, this also removes the model's ability to estimate S_l when all length classes are *not* 1.0.

2. The proportion of recruits

The proportion of recruits is a multinomial formula of n =3

$$p_l = \frac{\exp(r_l)}{1+\sum_{l=1}^{n-1}\exp(r_l)} \text{ for } l = 1,..,n-1$$

$$p_n = 1 - \frac{\sum_{l=1}^{n-1}\exp(r_l)}{1+\sum_{l=1}^{n-1}\exp(r_l)}$$

Model estimated recruit size proportions P_1, P_2, and P_3 are 0.5905, 0.4055, and 0.0040, respectively. This makes it extremely difficult for the model to estimate P_1 and P_2. Alternative option is assuming P_3 = 0; however, this also removes the model's ability to estimate P_3 when P_3 is far greater than 0.

Those parameters hitting boundaries would have little influence on the model. **We welcome CPT-SSC's suggestion for an alternative parameterization form that could avoid parameters hitting the boundaries.**

SSC(Oct 2022), Explore an inverse logistic (or other descending right limb pattern) selectivity to assess whether we may be missing larger crabs, due to either movement or gear selectivity.

Authors reply:

Author notes that this is a recurring request made by the SSC that have been explored since 2017. Please refer to the section E-1 for details.

CPT (Sept 2022) Place a prior on M in the smaller size bin in future explorations of models 22.1 and 22.2 to keep the M estimate above 0.

Authors reply:

Author did explore this but ultimately did not bring forward for review. When minimum M is set to *0.18*, *M* of the small crab sizes hit the boundary of 0.18 with no discernible difference in likelihoods and projections from models 22.1 and 22.2. Those two models were presented not as alternative assessment model, but to evaluate:1) whether model suggest length-dependent M, and 2) whether the length-dependent M would improve model fit to observed length-shell composition. The model exercise answered Yes to the first, and No to the second questions.

The assessment model creates abundance of smaller size classes (1, 2, 3) by mortality and growth and recruits with time invariant size proportions. Contribution of recruit is 100% for the smallest size class (64-73mm) and 80-95% for the second smallest size classes (74-83mm). The assessment model is not able to separate contribution from growth and mortality and that from recruit without setting a strict limit to either minimum *M* or the maximum recruit. The author sees no value for setting minimum *M* to 0.18.

CPT (Jan 2022) Provide a brief description and discussion of the convergence criteria and other methods used to evaluate model convergence to the global minimum. Use jittering to evaluate convergence

Authors reply:

We set ADMB convergence criteria to 1e-6, though this does not necessarily guarantee model convergence to the global minimum. Of 100 jittering (Table 14), 15 did not reach to convergence. 74 had likelihood 354.104 that are the same as the final model, and 11 had higher likelihood. Those suggest the model converged to the global minimum.

IV. NSRKC Management

OFL

CPT (Jan 2022) Present an evaluation of Tier 4 OFL calculations for NSRKC using the standard (single M) and length-dependent M approaches, and the associated assumptions and tradeoffs, for consideration by the CPT and SSC in the fall prior to the 2023 assessment.

SSC (Oct 2022) The SSC requests that the methodology for calculating FOFL based on a length-based M as requested by the CPT be clearly documented with supporting rationale.

Authors reply:

Standard calculation of OFL for Tier 4 crab is $F_{OFL,l} = \gamma M_l = \gamma 0.18$ for all lengths. However, this is not strictly applicable for NSRKC that has length-dependent *M*. The length-dependent *M* and F_{OFL} was recommended by CPT-SSC in January 2017 but was rejected primarily because it would produce higher OFL. As a compromise, OFL for NSRKC stock in the above equations was specified to length-independent $F_{OFL,l} = \gamma M_l = \gamma 0.18$ and length-dependent M_l for allocation of winter and summer fisheries.

This compromise works only when *M* is prespecified (e.g., *M* = 0.18) for the assessment model. However, when the biological justification of prespecified *M* is in question (this has been raised by CPT-SSC since 2019) and is estimated inside an assessment model, biological-scientific justification for selecting *M* for F_{OFL} needs to be clarified and specified. For instance, in 2021 Model 21.5 estimated two *M*s for lengths 64-123mm, and 124mm and above. In this case, should M for lengths 64-123mm be used for F_{OFL} specification? This is further complicated when M of each length is estimated within the model, such as Models 22.1 and 22.2 in which estimated M ranged from 0 to 0.7. Out of the 8 length-dependent *M*s, which *M* should be selected for F_{OFL} and what are the biological and scientific justifications? Regardless of which model is selected, a protocol for selecting a single *M* should be discussed and determined if size-independent *M* for F_{OFL} is preferred.

Length-dependent *M* and F_{OFL} would be more logical as this is a simple extension of the concept of the Tier 4 *OFL* specification. The biggest concerns raised by CPT-SSC were that length-dependent *M* for NSRKC would increase OFL from standard OFL, though the opposite could occur if estimated *M* were LOWER than 0.18. Recognizing scientific uncertainties in the determination of OFL, the FMP included the ABC Control Rule "*for setting the maximum permissible ABC for each stock as a function of the scientific uncertainty in the estimate of OFL and any other specified scientific uncertainty.*" The ABC-control rule allows CPT-SSC setting ABC-buffer they deem to be appropriate for each stock based on scientific uncertainties of OFL. If it is a concern that a length-dependent *M* increases the OFL, CPT-SSC should increase the ABC-buffer to a level that deems the most appropriate for NSRKC stock as CPT-SSC has increased ABC buffer of NSRKC from 10% in 2011 to 40% in 2021-2022. As an example, increasing ABC buffer to 60% for length-dependent OFL (OFL-l) is similar to ABC catch level as standard OFL.

	OFLst	ABCst-buffer	ABCst	OFL-l	ABC-l-buffer	ABC-l
21.0	0.70	40%	0.42	1.03	60%	0.41
22.0	0.67	40%	0.40	1.00	60%	0.40
22.1	0.63	40%	0.38	1.10	60%	0.44
22.2	0.63	40%	0.38	1.09	60%	0.44

The author recommends that CPT-SSC adopt length-dependent OFL and apply ABC control rule (increase ABC-buffer) that it deems appropriate for NSRKC stock.

The formula for calculation of a length-based *M OFL* has been noted in the section F.

C. Introduction

1. Species:

Red king crab, *Paralithodes camtschaticus*, in Norton Sound, Alaska.

2. General Distribution:

Norton Sound red king crab (NSRKC) is one of the northernmost red king crab populations that can support a commercial fishery (Powell et al. 1983). It is distributed throughout Norton Sound with a westward limit of 167-168º W. longitude, depths less than 30 m, and summer bottom temperatures above 4º C. The Norton Sound red king crab management area consists of two units: Norton Sound Section (Q3) and Kotzebue Section (Q4) (Menard et al. 2011). The Norton Sound Section (Q3) consists of all waters in Registration Area Q north of the latitude of Cape Romanzof, east of the International Dateline, and south of 66°N latitude (Figure 1). The Kotzebue Section (Q4) lies immediately north of the Norton Sound Section and includes Kotzebue Sound. Commercial fisheries have not occurred regularly in the Kotzebue Section. This report deals with the Norton Sound Section of the NSRKC management area.

3. Evidence of stock structure:

Based on variability at 15 SNP loci and in mtDNA sequences (COI, 665 bp), the NSRK stock belongs to the Okhotsk Sea–Norton Sound–Aleutian Islands evolutionary lineage (SNPs, FCT = 0.054; mtDNA FCT = 0.222) (Grant and Chen 2012). However, this does not indicate that NSRKC is a single stock. The study indicates it was incapable of detecting possible evolutionary stock differences within the NSRKC stock. No studies have investigated possible stock separation within the Norton Sound management area (Figure 1).

4. Life history characteristics relevant to management:

One of the unique life-history traits of NSRKC is that they spend their entire lives in shallow water since Norton Sound is generally less than 40 m in depth. Based on the 1976-2021 trawl surveys, NSRKC are found in areas with a mean depth range of 19 ± 6 (SD) m and bottom temperatures of 7.4º ± 2.5 (SD) C during summer. NSRKC are consistently abundant offshore of Nome.

NSRKC migrate between deep offshore and shallow inshore waters within Norton Sound. Timing of the inshore mating migration is unknown but is assumed to be during late fall to winter (Powell et al. 1983). Offshore migration occurs in late May - July (Bell et al. 2016). The results from a study funded by North Pacific Research Board (NPRB) during 2012-2014 suggest that older/large crab (> 104mm CL) may stay offshore in the winter, based on findings that large crab are not found nearshore during spring offshore migration periods (Jenefer Bell, ADF&G, *personal comm*). Molting is thought to occur in fall to winter late. Double shelled crabs were often observed in late August commercial catch (Joyce Song ADF&G *personal comm*). Laboratory observation showed that male crab molted in August – November and female crab molted in Jan-March (Leah Zacher and Jennifer Gardner NOAA-AFSC *personal comm*). Trawl surveys show that crab distributions are patchy and dynamic. Functional maturity of NSRKC male crab is as small as 79.4 mm CL (Leah Zacher NOAA Kodiak *personal comm*). Those small males could also fertilize eggs of ~ 4 females, which was comparable to the number of females larger (94-116 mm CL) crabs could fertilize. More interestingly, the largest crab (> 123 mm) was able to fertilize eggs of ~ 2 females.

5. Brief management history:

NSRKC fisheries consist of commercial and subsistence fisheries. The commercial red king crab fisheries occur in summer (June – August) and winter (December – May), and subsistence is open year-round. The majority of NSRKC is harvested during the offshore summer commercial fishery, whereas the winter commercial and subsistence fisheries occur nearshore through ice and take a much smaller harvest.

The distinguishing characteristic of the NSRKC fisheries is that all fisheries, surveys, researches, and management are conducted by local residents of Norton Sound. Commercial fisheries are designated as super-exclusive: a vessel registered for the Norton Sound crab fishery may not be used to take king crabs in any other registration areas. The ADF&G NSRKC crab research and management biologists are members of Nome community and are acquainted with many local fishermen (commercial and subsistence) and staff of community organizations such as Norton Sound Economic Development Corporation (NSEDC) and Kawerak Inc, exchanging information and research ideas about crab biology and fisheries management.

Summer Commercial Fishery

A large-vessel summer commercial crab fishery started in 1977 in the Norton Sound Section (Table 1) and continued from 1977 through 1990. No summer commercial fishery occurred in 1991 because there were no staff to manage the fishery. In March 1993, the Alaska Board of Fisheries (BOF) limited participation in the fishery to small boats. Then on June 27, 1994, a super-exclusive designation went into effect for the fishery. This designation states that a vessel registered for the Norton Sound crab fishery may not be used to take king crabs in any other registration areas during that registration year. A vessel moratorium was put into place before the 1996 season. This was intended to precede a license limitation program. In 1998, Community Development Quota (CDQ) groups were allocated a portion of the summer harvest; however, no CDQ harvest occurred until the 2000 season. On January 1, 2000, the North Pacific License Limitation Program (LLP) went into effect for the Norton Sound crab fishery. The program dictates that a vessel which exceeds 32 feet in length overall must hold a valid crab license issued under the LLP by the National Marine Fisheries Service. Changes in regulations and the location of buyers resulted in eastward movement of the harvest distribution in Norton Sound in mid-1990s. In Norton Sound, a legal crab is defined as ≥ 4 3/4-inch carapace width (CW, Menard et al. 2011), which is approximately equivalent to ≥ 104 mm carapace length (CL). In 2005 and 2006, commercial buyers, specifically Norton Sound Economic Development Corporation (NSEDC), accepted only legal crab of ≥ 5 inch CW. This preference became permanent in 2008.

Portions of the Norton Sound area are closed to commercial fishing for red king crab. Since the beginning of the commercial fisheries in 1977, waters approximately 5-10 miles offshore of southern Seward Peninsula from Port Clarence to St. Michael have been closed to protect nearshore subsistence fisheries and to act as a refuge for crab during the summer commercial crab fishery (Figure 2). The spatial extent of closed waters has varied historically, with the closure line being moved in to provide additional area to achieve harvest goals. In 2020 the BOF closed Norton Sound area east of 167 degrees W. longitude for the commercial summer crab fishery. In 2020 and 2021 NSEDC did not purchase NSRKC resulting in small or no harvest. In 2022, the summer commercial fishery resumed.

CDQ Fishery

The Norton Sound and Lower Yukon CDQ groups divide the NSRKC CDQ allocation. Only fishers designated by the Norton Sound and Lower Yukon CDQ groups are allowed to participate in this portion of the king crab fishery. Fishers are required to have a CDQ fishing permit from the Commercial Fisheries Entry Commission (CFEC) and register their vessel with the Alaska Department of Fish and Game (ADF&G) before beginning fishing. Fishers operate under the authority of each CDQ group. CDQ harvest share is 7.5% of the guideline harvest level (GHL), and can be prosecuted in both summer and winter seasons.

Winter Commercial Fishery

The winter commercial crab fishery uses hand lines and pots through the nearshore ice. On average 10 permit holders harvested 2,500 crab during 1978-2009. From 2007 to 2015 the winter commercial catch increased from 3,000 crab to over 40,000 (Table 2). In 2015 the winter commercial catch reached 20% of total crab catch. The BOF responded in May 2015 by amending regulations to allocate 8% of the total commercial GHL to the winter commercial fishery, which has been in effect since the 2017 season. The timing of the winter red king crab commercial fishing season has changed over time to address ice stability. It was originally from January 1 to April 30, amended in 1985 to from November 15 to May 15. In 2015 the period was changed to January 15 to April 30 after fisheries opened in Nov 15 in 2014, so that January 15 starting date was into effect in 2016. In 2021 it was further amended to February 1 to April 30.

Year	Opening period
1977-1984	Jan 01 – Apr 30
1985- 2014	Nov 15 – May 15
2015	Nov 15 – Apr 30
2016-2020	Jan 15 – Apr 30
2021 -	Feb 01 – Apr 30

Subsistence Fishery

The winter subsistence fishery has a long history; however, harvest information is available only since the 1977/78 season. The majority of subsistence crab harvest occurs in winter using hand lines and pots through nearshore ice. Average annual winter subsistence harvest is 5,281 crab (1977-2021). Subsistence harvesters need to obtain a permit before fishing and record daily effort and catch. There are no size or sex specific harvest limits; however, the majority of retained catch is males of near legal size.

Summer subsistence crab fishery harvest has been monitored since 2004 with an average harvest of 1,145 crab (2004-2020). The summer subsistence fishery was not included in the assessment model.

Harvest of both winter commercial and subsistence fisheries is also influenced by availability of stable ice conditions. Small harvests can occur due to poor ice condition, regardless of crab abundance.

1. Brief description of the annual ADF&G harvest strategy

Since 1997 NSRKC has been managed based on a GHL. From 1999 to 2011 the GHL for the summer commercial fishery was determined using model estimated predicted biomass: (1) 0% harvest rate of legal crab when estimated legal biomass < 1.5 million lb; (2) ≤ 5% of legal male biomass when the estimated legal biomass falls within the range 1.5-2.5 million lb; and (3) ≤ 10% of legal male biomass when estimated legal biomass >2.5 million lb. In 2012 the summer commercial fishery GHL was revised to (1) 0% harvest rate of legal crab when estimated legal biomass < 1.25 million lb; (2) ≤ 7% of legal male biomass when the estimated legal biomass falls within the range 1.25-2.0 million lb; (3) ≤ 13% of legal male biomass when the estimated legal biomass falls within the range 2.0-3.0 million lb; and (3) ≤ 15% of legal male biomass when estimated legal biomass >3.0 million lb.

In 2015 the BOF passed the following regulations regarding the winter commercial fisheries:

1) Revise GHL to include summer and winter commercial fisheries.
2) Set GHL for the winter commercial fishery (GHL_w) at 8% of the total GHL

NSRKC GHL is determined in early February after the final determination of ABC. GHL is determined not to exceed (e.g., 5-10% less) retained portion of the total catch ABC.

Table: Brief NSRK fishery management history

Year	Notable historical management changes
1976	The abundance survey started
1977	**Large vessel commercial fisheries began. Legal size was set to ≥ 5 inch CW**
1978	**Legal size was changed to ≥ 4.75 inch CW**
1991	Fishery closed due to staff constraints
1993	Fishery is restricted to small boat. The end of large vessel commercial fishery operation.
1994	Super exclusive designation went into effect.
1998	Community Development Quota (CDQ) allocation went into effect
1999	Guideline Harvest Level (GHL) went into effect
2000	North Pacific License Limitation Program (LLP) went into effect.
2002	Change in closed water boundaries (Figure 2)
2006	The Statistical area Q3 section expanded (Figure 1)
2008	Start date of the open access fishery changed from July 1 to after June 15 by emergency order. **Pot configuration requirement: at least 4 escape rings (> 4.5 inch diameter) per pot located within one mesh of the bottom of the pot, or at least ½ of the vertical surface of a square pot or sloping side-wall surface of a conical or pyramid pot with mesh size > 6.5 inches.**
2008	**Market preferred size of ≥ 5 inch CW became a standard commercial retained size.**
2012	The BOF adopted a revised GHL for summer fishery.
2016	Winter GHL for commercial fisheries was established and modified winter fishing season dates were implemented.
2020	The BOF closed summer commercial fishery E of 167 longitude
2021	Change winter fishery open date to February 1

2. Summary of the history of the B_{MSY}.

NSRKC is a Tier 4 crab stock. Direct estimation of the B_{MSY} is not possible. The B_{MSY} proxy is calculated as mean model estimated mature male biomass (MMB) from 1980 to present. Choice of this period was based on a hypothesized shift in stock productivity due to a climatic regime shift indexed by the Pacific Decadal Oscillation (PDO) in 1976-77.

D. Data

1. Summary of new information:

Winter commercial and subsistence fisheries:

The winter commercial fishery retained catch in 2022 was 2,708 crab (7,683.7 lb). Winter subsistence total male crab catch was 10,041 and retained male crab catch was 7,565, and total female catch was 645 and retained female was 65. In total, 10,646 crab were caught and 7,630 crab were retained (Table 2).

Summer commercial fishery:

The summer commercial fishery opened on 6/15/2022 and closed on 7/24/2022. A total of 125,042 crab (317,173 lb) were harvested (Table 1).

Standardized CPUE (Appendix B).

Standardized CPUE for the years of 1991, 2020, 2021 were not calculated because a commercial fishery was closed (1991) or no crab was harvested (2020, 2021).

Recalculate standardized CPUE: 3 periods:

1977-1992: Large Scale commercial fishery
1993-2007: Small boat commercial fishery
2008-2019: Small boat commercial fishery with high grading.

Discards
Estimate of discards is based on ratio method (Appendix C).

Summer Trawl Survey

Norton Sound portion of the NOAA NBS trawl survey was conducted in 2022. Total male crab abundance estimate (CL > 63mm) is 2,103 thousand with CV 0.37 (Table 3).

Available survey, catch, and tagging data

Available NSRKC data consist of the following: trawl survey that informs abundance and size composition, catch that informs size composition, and standardized CPUE that informs an index of abundance, and tag recovery that informs growth-transition.

Trawl survey

Trawl survey consists of 3 surveys: NMFS triennial survey: 1976-1992, ADF&G survey: 1996-2021, and NOAA NBS survey: 2010, 2017-2021.

NMFS triennial survey:

A Norton Sound trawl survey was initiated by NMFS in 1976 to assess stock status of crab and ground fish in Norton Sound and Kotzebue Sound. The survey established 10 nautical mile (nm) grid survey stations throughout the entire Norton Sound and 15 nm grids outside the Norton Sound area. The initial Norton Sound survey became the standard stations moving forward. The survey was conducted from mid-late August to September-October, except for 1979, which was in late July/early August. The survey used 83-112 Eastern Otter trawl gear, with tow distance of 1.3 – 1.7 nm (30 minutes tow). The survey was terminated in 1992.

ADF&G triennial -annual survey:

After the termination of the NMFS trawl survey, ADF&G began trawl surveys in 1996 using the same survey stations, but smaller boat and survey coverage. The survey started as triennially but became an annual survey in 2017. The survey usually occurs in late July – mid August, using 400 Eastern Otter trawl gear with tow distance of 1.0 nm. The survey used to have a re-tow protocol: when the first tow caught more than 5 legal red king crab, the station was re-towed. This protocol was dropped in 2012 in favor of more coverage.

NOAA biennial-annual NBS survey:

NOAA NBS trawl survey started in 2010, and biennially since 2017. The survey occurs in late July-mid August, similar to the ADF&G survey. The survey has 20 nm grid using 83-112 Eastern Otter trawl gear, with tow distance of 1.3 – 2.5 nm (30 min tow).

Abundance estimation method

Methods of estimating red king crab abundance differed among the three surveys and throughout time periods. Abundance estimates have been revised many times.

Abundance and CV of the NMFS 1976-1991 surveys were provided by NOAA (Jon Richer NOAA p*ersonal communication*). The abundance was estimated by averaging catch CPUE (#/nm^2) of all stations (including survey stations out of Norton Sound) that was multiplied by standard Norton Sound Area (7600 nm^2) (i.e., N = 7600*mean CPUE). The ADF&G survey abundance is calculated at each station (i.e., n= CPUE*100 nm^2) and summed across all surveyed stations (i.e., N = sum of 100*CPUEs) (Bell and Hamazaki 2019). Extent of the ADF&G survey coverage differed among years due to survey conditions, and survey abundance has not been standardized. NOAA NBS survey abundance is estimated by the author in similar manner as ADF&G survey with the data limited to the Norton Sound survey area that overlaps the ADF&G survey area (5841 nm^2) (Figure A).

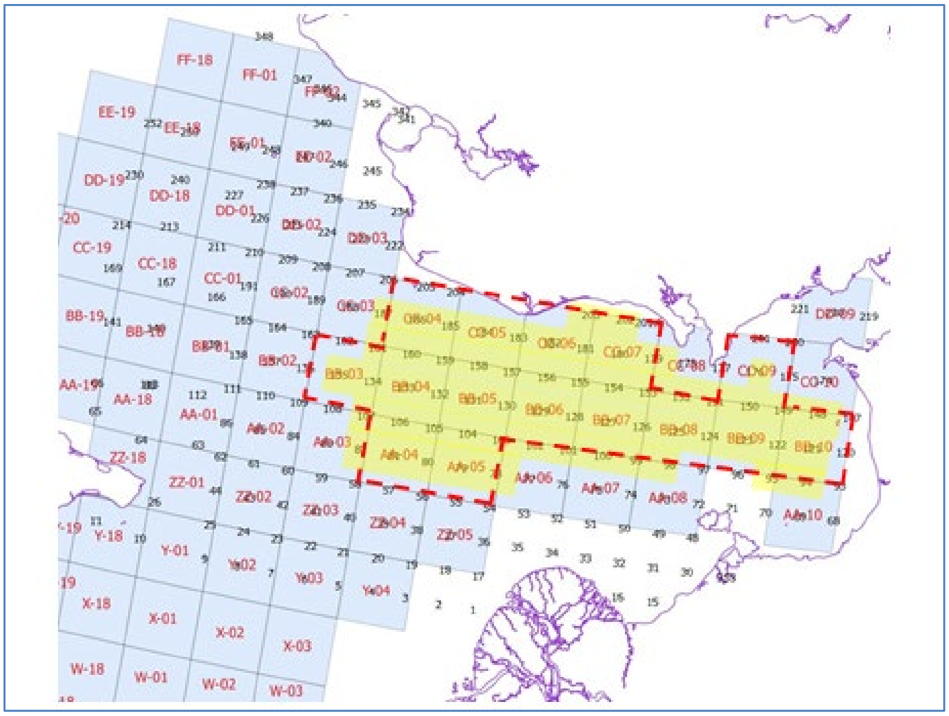


Figure A. ADF&G trawl survey coverage (yellow shade) and NOAA NBS trawl survey coverage where abundance estimates were made (red hashed line),

Catchability of NSRKC appears to differ among ADF&G, NMFS, and NOAA NBS trawl surveys. ADF&G trawl survey abundance tends to be higher than NMFS and NOAA NBS trawl survey even though NMFS and NOAA NBS survey coverages are greater than ADF&G. The assessment model assumes (recommendation by CPT-SSC) that survey q of ADF&G trawl survey be 1.0, which resulted in q = 0.7-0.8 for NMFS and 0.7-0.96 for NOAA NBS survey.

Trawl survey catches are highly patchy. The majority of catches occurred at 1 to 4 stations that caught 20% to 80% of crabs caught during the entire survey (Figure B). The most consistently abundant survey stations are near Nome (blue dots) outside of the summer commercial fishery area (red rectangular). Some offshore stations had high catches for a few years (orange dots: 1990s, yellow dots: 2020s) but they did not persist.

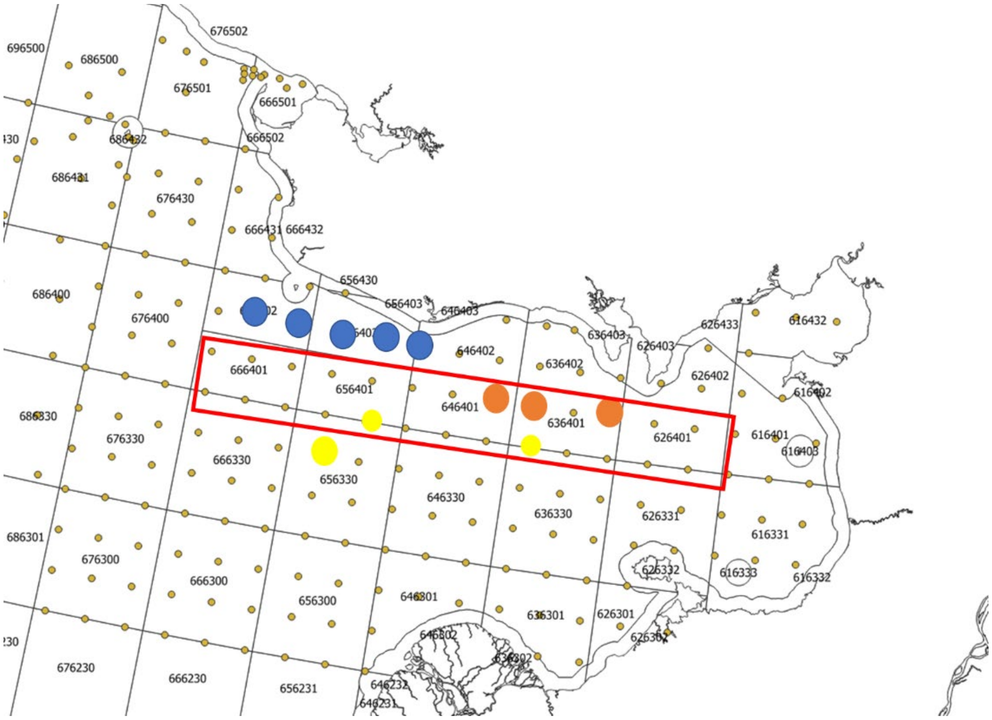


Figure B. Trawl survey stations where majority of catch occurred. Red rectangular indicates where the majority of summer commercial fishery occurs. Blue dots indicate the stations that had high catch consistently since 1976. Orange and yellow dots indicate high crab catch stations that occurred during the 1990s (orange) and 2020s (yellow).

Standardized CPUE

Standardized summer commercial fishery CPUE is included in the NSRKC assessment model as an index of NSRKC abundance that could supplement triennial trawl survey. In 2013, the CPUE standardization model was developed by Gretchen Bishop (ADF&G) (NPFMC 2013). Since then, the same model has been applied with updated data (Appendix B).

Tagging-recovery data

Norton Sound red king crab tagging was initially conducted in 1980 as a part of mark-recapture abundance survey (Brannian 1987). The study was conducted in 1980-1982 and 1985. From 1986 to 2012 crabs were tagged during the winter pot survey. The winter pot surveys tagged more smaller (sublegal) crabs; however, very few were recovered. Tagging resumed from 2012-2015 for a spring migration movement survey. In all the above studies, most of the tagged crabs were recovered by commercial fishermen, but subsistence fishermen also recovered a small number of tags.

Length-Shell proportion data

Length-shell data have been collected in every research and harvest monitoring survey. Of those, summer commercial harvest sampling, winter pot survey (terminated in 2012), and the trawl survey have been consistent.

Time series of the data used for the NSRKC assessment model are summarized in the following figure and table.

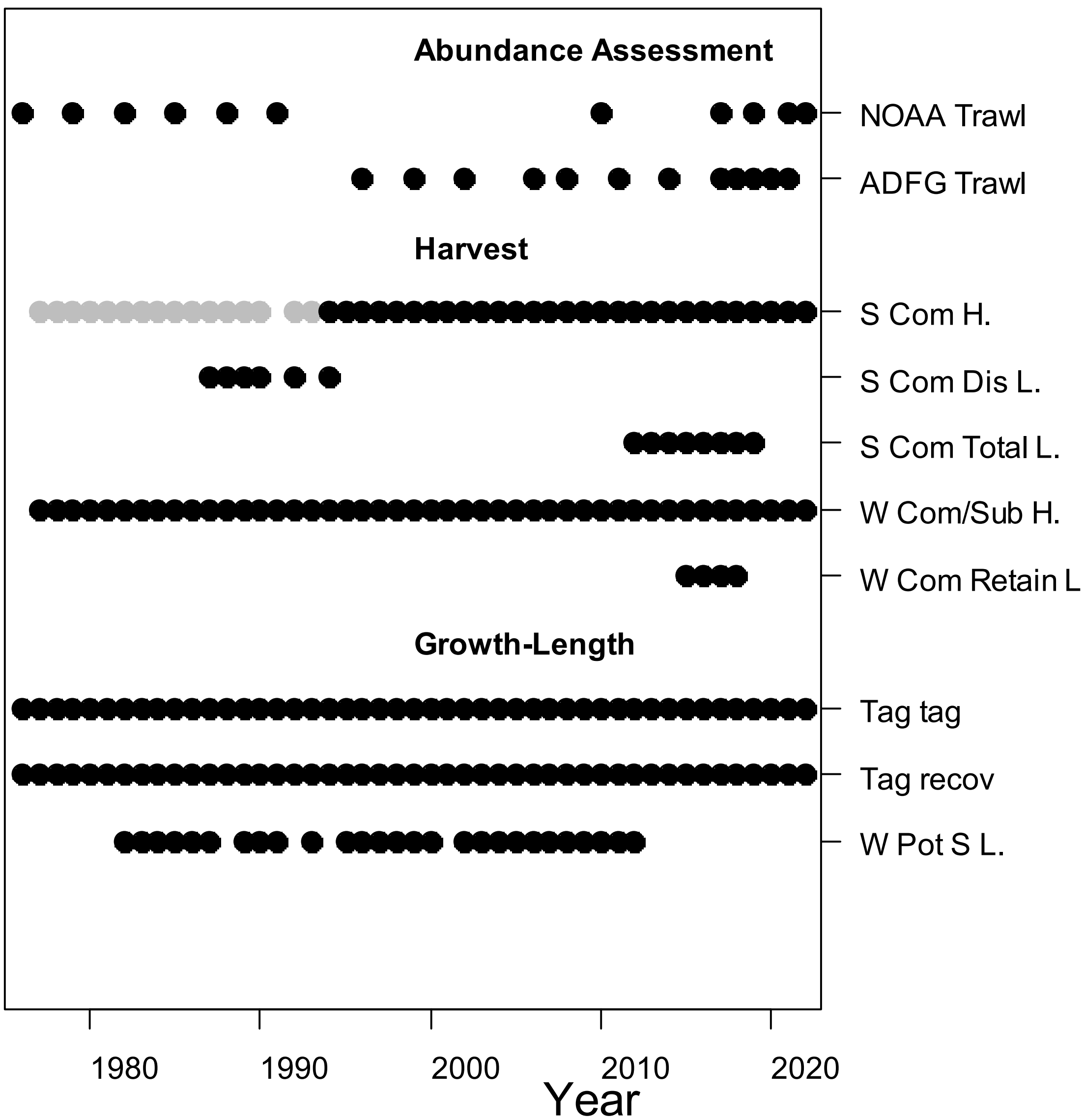


Table: a list of survey data

	Years	Data Types	Tables
Summer trawl survey	76,79,82,85,88,91,96, 99, 02,06,08,10,11,14,17-22	Abundance Length-shell comp	3 6
Winter pot survey	81-87, 89-91,93,95-00,02-12	Length-shell comp	7
Summer commercial fishery	77-90,92-22	Retained catch Standardized CPUE, Length-shell comp	1 1, Appendix B 4
Summer Com total catch	12-19	Length-shell comp	9
Summer Com Discards	87-90,92,94	Length-shell comp	8
Winter subsistence fishery	76-22	Total & Retained catch	2
Winter commercial fishery	78-22	Retained catch	2
	15-18	Retained Length-Shell	5
Tag recovery	80-19	Recovered tagged crab	10

Table: A list of data available but not used for assessment

Data	Years	Data Types	Reason for not used
Summer pot survey	80-82,85	Abundance Length proportion	Uncertainties on how estimates were made.
Summer preseason survey	95	Length proportion	Just one year of data
Summer subsistence fishery	2005-2019	retained catch	Too few catches, ignored.
Winter Pot survey	87, 89-91,93,95-00,02-12	CPUE	CPUE data unreliable.
Preseason Spring pot survey	2011-15	CPUE, Length proportion	Years of data too short
Postseason Fall pot survey	2013-15	CPUE, Length proportion	Years of data too short

Catches in other fisheries

In Norton Sound, the directed Pacific cod pot fishery was issued in 2018 under the CDQ permit. In 2018 and 2019 fishery seasons, a total of 8 and 13 kg (mortality applied) of NSRKC were taken in the groundfish fisheries (CPT 2020). However, all bycatch occurred to the west of 168.0 longitude where NSRKC survey has not been conducted. Norton Sound Fishery Management Area (Q3) extends to St. Lawrence Island and US-Russia border (Figure 1). In the absence of survey abundance extended to those area, it is questionable whether those bycatch mortalities should be included in the NSRKC population.

	Fishery	Data availability
Other crab fisheries	Does not exist	NA
Groundfish pot	Pacific cod	Y
Groundfish trawl	Does not exist	NA
Scallop fishery	Does not exist	NA

Other miscellaneous data:

- Tagging-recovery locations (2012-2019)
- Satellite tag migration tracking (NOAA 2016, ADF&G 2020-21)
- Spring offshore migration distance and direction (2012-2015)
- Monthly blood hormone level (indication of molting timing) (2014-2015)
- Functional maturity and mating success of captured crab (2021-)

Data aggregated:

- Length data were aggregated by 10 mm range, starting from 64-73 mm. Crab length greater than 133 mm were aggregated in >133 mm class.
- Shell condition data were aggregated from very new, and new to newshell, and from old, very old, and very very old to oldshell.
- Tag-recovery data were aggregated regardless of tagging years.

Data estimated outside the model:

- Summer commercial catch standardized CPUE (Table 1, Appendix B)
- Proportion of legal-size crab, estimated from trawl survey and observer data. (Table 13)
- Average weight of crab by length class (Table 13)

E. Analytic Approach

1. History of the modeling approach and issues:

The Norton Sound red king crab stock was assessed using a length-based synthesis model (Zheng et al. 1998). Since adoption of the model, the model had the following model mismatches:

1. Model projects higher abundance-proportions of large size class (> 123mm CL) of crab than observed. This problem was further exacerbated when natural mortality M was set to 0.18 from previous $M = 0.3$ in 2011 (NPFMC 2011).

2. Poor model fit to trawl survey abundance. This was further exacebrated when M = 0.18 was applied to all lengths.

3. Some model parameters hit boundaries

Those issues resulted in the model overestimating projected abundance. The following describes historical model adjustments attempted.

1. Model projects higher abundance-proportions of large size class (> 123mm CL) of crab.

   This issue has been solved by assuming (3-4 times) higher *M* for the large crab (i.e., *M* = 0.18 for length classes ≤ 123 mm, and higher *M* for > 123 mm) (NPFMC 2012, 2013, 2014, 2015, 2016, 2017, 2018). However, because this solution is biologically suspect, several alternative assumptions have been considered in the past.

   a. Large crabs move out of the survey and fishing area

      In modeling, this was dealt with by setting dome shaped survey and commercial catch selectivity (i.e., lower catchability for large crab). This modeling configuration resulted in estimating MMB two times higher than the default model, which indicates that true NSRKC abundance is twice larger than current trawl survey and commercial crab fishery indicate (NPFMC 2017). The NOAA NBS surveys (2010, 2017, 2019, 2021) did not find high numbers of red king crab outside Norton Sound. The large crab could also be nearshore where the commercial fishery is closed, and trawl survey is not conducted due to rocky bottom. However, spring tagging studies showed that most crab migrated from near shore to offshore (fishing) area (Jenefer Bell, ADF&G personal comm.). There was little evidence that large crabs stay in nearshore waters during summer.

   b. Molting and growth of NSRKC are slower. (i.e., model overestimating molting and growth probability: transition matrix)

      The model originally estimated the transition outside of the model. In 2014 the model was configured to estimate the transition matrix inside of the assessment model (NPFMC 2014). The transition matrix estimated inside of the model was similar to that estimated outside of the model. When length-specific molting probability was estimated individually, the shape of the probability curve was also similar to the default inverse logistic molting function (NPFMC 2016). A time varying molting function (random walk) process did not improve model fit. Laboratory studies showed that observed growth after molting was comparable to those from tag-recovery data, though sample size was limited and comparable tank-natural condition factors such as water temperature and food availability, were questionable (Leah Zacher of NOAA AFSC Kodiak personal comm),

c. Higher natural mortality (*M*) than assumed *M* = 0.18

   Profile analyses and estimating *M* across all length classes resulted in higher *M* (0.3-0.45) than default *M*=0.18 (NPFMC 2013, 2017). However, the model fit is slightly worse than the default model.

d. Higher natural mortality (*M* > 0.18) for small crab and large crab having higher mortality than small crab.

   This model configuration had the best fit to data (NPFMC 2017).

e. Gradual size dependent natural mortality.

   The default assessment model assumes abrupt *M* increase at size CL 124mm or greater. An alternative model suggested that *M* gradually increasing from size as low as 94 mm CL; however, the overall model fit did not greatly improve from the default model (NPFMC 2017). In 2022, CPT requested estimating *M* for each length class, which also suggested length-dependent natural mortality.

Natural mortality *M* specification was originally set to be 0.2 for BSAI red king crab stock, including NSRKC (NPFMC 1998) and was changed to 0.18 with Amendment 24 (NPFMC 2011), **which means that the NSRKC stock assessment model is REQUIRED to use *M*=0.18**. Since adoption of the model, the CPT-SSC has required reexamining the appropriateness of *M* specification for NSRKC; however, the CPT-SSC have been rejecting NSRKC having higher *M*, except for current model configuration.

2. Poor model fit to trawl survey abundance, especially NMFS survey (1976-1992) data

   The NSRKC assessment model suggest higher crab abundance during the 1976-1990s period. The model deals with this issue by including survey *q* (*q* < 1), or the model assumes the NMFS trawl surveys **underestimated** NSRKC abundance. However, this assumption is arbitrary, which is also affected by other model configurations. For instance, when *M* = 0.18 is assumed for all length classes, the model suggests that survey *q* for NMFS is greater than 1.0, or that the NMFS trawl surveys **overestimated** NSRKC abundance (Model 21.1). This indicates the trawl surveys overestimated NSRKC abundance (NPFMC 2022). Alternatively, assuming the NMFS survey *q* to be 1.0 resulted in ADF&G trawl survey *q* greater than 1.0 (i.e., trawl survey overestimates abundance), even though ADF&G trawl survey area is generally smaller than NMFS and NOAA NBS survey areas.

   This model fitting issue was also influenced by input sample sizes for size-shell compositions. Increasing the input sample size resulted in the model estimating lower abundance. Reducing the input sample sizes improved model fit to the trawl survey data but caused lower fit to size-shell composition data (NPFMC 2012, 2013, 2015).

Alternative model weighting methods (e.g., Francis 2012) have been tried, but those did not improve model fit.

3. Some model parameters hit boundaries.

There are two model parameters that hits boundaries: Trawl survey selectivity ($\log\_\phi_{st1}$), and the proportion of recruits (r1, r2).

3. Trawl Survey selectivity parameter

Trawl survey selectivity model is a one parameter logistic curve that reaches 1.0 at L_{max} (143.5 mm)

$$S_l = \frac{1}{1+e^{(\alpha(L_{\max}-L)+\ln(1/0.999-1))}}$$

where α = exp($\log\_\phi_{st1}$), L_{max} = 143.5 mm L (63.5-143.5 mm)

Model estimated trawl survey selectivity is 1.0 across all size classes. This means that $e^{(\alpha(L_{\max}-L)+\ln(1/0.999-1))} \approx 0$, $\alpha(L_{max}-L)+\ln(1/0.999-1) = -\infty$, $\alpha \approx 0$, and $\log\_\phi_{st1} = -\infty$. Hence, the parameter will hit the boundary.

Alternative option is assuming S_l = 1.0 for all length classes; however, this also removes the model's ability to estimate S_l when all length classes are NOT 1.0.

4. The proportion of recruits

The proportion of recruits is a multinomial formula of n =3

$$p_l = \frac{\exp(r_l)}{1+\sum_{l=1}^{n-1}\exp(r_l)} \quad \text{for } l = 1,..,n\text{-}1$$

$$p_n = 1-\frac{\sum_{l=1}^{n-1}\exp(r_l)}{1+\sum_{l=1}^{n-1}\exp(r_l)}$$

Model estimated recruit proportions for length classes 1, 2, 3 (P_1, P_2, P_3) are 0.592, 0403, and 0.003. $P_3 \approx 0$ makes it extremely difficult for the model to estimate P_1 and P_2., and **thus model parameters r1 and r2 (Tables 11, 12). Increasing the upper bound of the r parameters would still make r1 hit the boundary and make estimates of P_1, P_2, P_3 to be closer to P_1 = 0.60, P_2 = 0.40, and P_3=0.** Alternative option is assuming P_3 = 0; however, this also removes the model's ability to estimate P_3 when P_3 is far greater than 0.

Historical Model configuration progression:

2011 (NPFMC 2011)
1). *M* =0.18.
2). *M* of the last length class = 0.288.
3). Include summer commercial discards mortality = 0.2.
4). Weight of fishing effort = 20.
5). The maximum effective sample size for commercial catch and winter surveys = 100.

2012 (NPFMC 2012)
1) *M* of the last length class = 3.6×*M*.
2) The maximum effective sample size for commercial catch and winter surveys = 50.
3) Weight of fishing effort = 50.

2013 (NPFMC 2013)
3) Standardize commercial catch CPUE and replace likelihood of commercial catch efforts to standardized commercial catch CPUE with weight = 1.0.
4) Eliminate summer pot survey data from likelihood.
5) Estimate survey *q* of 1976-1991 NMFS survey with maximum of 1.0.
6) The maximum effective sample size for commercial catch and winter surveys = 20.

2014 (NPFMC 2014)
1) Modify functional form of selectivity and molting probability to improve parameter estimates (2 parameter logistic to 1 parameter logistic).
2) Include additional variance for the standardized CPUE.
3) Include winter pot survey CPUE (was removed from the final model due to lack of fit).
4) Estimate growth transition matrix from tagged crab recovery data.

2015 (NPFMC 2015)
1) Winter pot survey selectivity is an inverse logistic, estimating selectivity of the smallest length group independently.
2) Reduce weight of tag-recovery: W = 0.5.
3) Model parsimony: one trawl survey selectivity and one commercial pot selectivity.

2016 (NPFMC 2016)
1) Length range extended from 74 mm – 124 mm above to 64 mm – 134 mm above.
2) Estimate multiplier for the largest (> 123mm) length classes.

2017 (NPFMC 2017)
1) Change molting probability function from 1 to 2 parameter logistic. Assume molting probability not reaching 1 for the smallest length class.

2018 (NPFMC 2017) CPT-SSC suggested no model alternatives

2019 (NPFMC 2019)

1) Fit total catch length composition and estimate retention probability for summer and winter commercial fishery.
2) Include winter commercial retained length data.

2020 (NPFMC 2020) The CPT and SSC suggested no model alternatives

2021 (NPFMC 2021) Include discards data at the request of CPT and SSC
1) Models that bridge from the Model 19.0e to 21.0
2) Model 21.0 with natural mortality estimated by model.
3) Estimate size specific natural mortality.

2022 (NPFMC 2022)
1) Shell based retention probability
2) Estimate individual length class *M*

2. Model Description

a. Description of overall modeling approach:

The model is a male-only size structured model based on **abundance** that combines multiple sources of surveys, fishery catches and discards, and mark-recovery data using a maximum likelihood modeling framework to estimate population dynamics under fisheries. The model is an extension of the length-based model developed by Zheng et al. (1998) for NSRKC. A detailed description of the model is in Appendix A.

The model estimates abundances of male crab with CL ≥ 64 mm and with 10 mm length intervals (8 length classes, ≥ 134mm) because few crab measuring less than 64 mm CL were caught during surveys or fisheries.

The model assumes newshell crab as molted and oldshell crab as unmolted.

One critical characteristic of the model is that it does not estimate fishing mortality (*F*). Observed harvests were considered accurate and thus directly subtracted from the model estimated abundance.

The modeling scheme and data is described in the following figure.

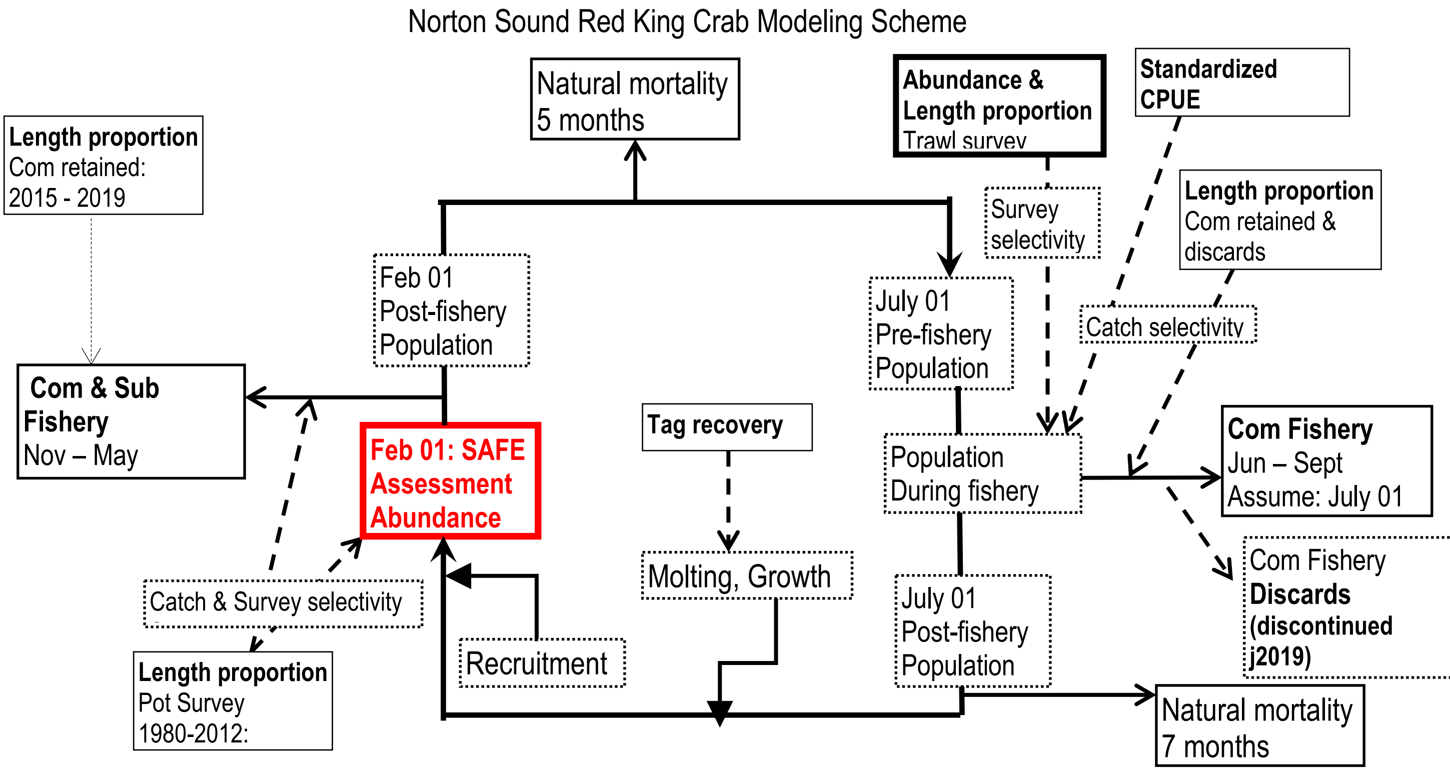


Figure C. Norton Sound red king crab model and data scheme. Bold type indicate data that were fitted to the model. Boxes in dotted line indicate model estimated parameters and quantities. Natural mortality, *M* was set to 0.18 except for CL greater than 123mm that was estimated in the model.

Timeline of calendar events and crab modeling events:

- **Model year starts February 1st to January 31st of the following year.**
- **Initial Population Date: February 1st, 1976, consisting of only newshell crab.**
- **Instantaneous fishing mortality: winter (February 1st) and summer (July 1st) fisheries**
- **Instantaneous molting and recruitment occur on July 1st**

Critical model assumptions

NSRKC Crab Biology

1. Instantaneous annual natural mortality (*M*) is 0.18 and increases at the size greater than 123 mm CL. *M* is constant over time.

See History of the modeling approach and issues section for detailed discussion regarding this assumption

2. Male crab size at maturity is 94mm CL.

Size at maturity of NSRKC is highly uncertain (NPFMC 2018, 2019, 2020, 2021). First, maturity has two categories (biological and functional). Biological maturity indicates that male red king crab can produce viable sperm, whereas functional maturity indicates that male red king crab are large enough to mate. The former can be determined using the presence/absence of spermatophores in the vas deferens, whereas the latter can be inferred by measuring mating pairs *in situ* or in lab experiments. The current NSRKC functional maturity size (>94 mm) was inferred from Bristol Bay red king crab by incorporating the fact that Norton Sound red king crab are smaller.

SSC suggested investigating size at functional maturity of other stocks, such as of Barents Sea red king crab (NPFMC 2021). However, it is unlikely that those metadata analyses would provide insights about size at functional maturity of Norton Sound red king crab because NSRKC is the smallest among red king crab stocks. Author was not able to find any other red king crab stocks that are comparable to the size of NSRKC.

Recent laboratory studies reported that NSRKC male crab as small as 79.4 mm CL can fertilize females. Those small males could also fertilize eggs of ~ 4 females, which was comparable to the number of females larger (94-116 mm CL) crabs could fertilize. More interestingly, the largest crab (> 123 mm) was able to fertilize eggs of ~ 2 females (Leah Zacher NOAA Kodiak *personal comm*). This functional maturity/matting success study is ongoing but does suggest that functional maturity of NSRKC is smaller than current model assumption of 94 mm CL.

Although determining size at functional maturity is important biologically, there is limited utility of this information for Tier 4 crab stock assessment. In Tier 4 stock assessment, size at maturity is used only for calculation of mature male biomass (MMB) and B_{MSY} (average MMB). Harvest control (F_{OFL}) is based on the ratio of projected MMB and B_{MSY} (projected MMB/B_{MSY}).

Level	Criteria	F_{OFL}
a	$B/B_{MSY^{prox}} > 1$	$F_{OFL} = \gamma M$
b	$\beta < B/B_{MSY^{prox}} \leq 1$	$F_{OFL} = \gamma M \, (B/B_{MSY^{prox}} - \alpha)/(1-\alpha)$
c	$B/B_{MSY^{prox}} \leq \beta$	$F_{OFL} = bycatch\ mortality\ \&\ directed\ fishery\ F = 0$

where B is a mature male biomass (MMB), B_{MSY} proxy is average mature male biomass over a specified time period, $M = 0.18$, $\gamma = 1$, $\alpha = 0.1$, and $\beta = 0.25$.

The MMB/B_{MSY} ratio is affected very little by changes of maturity size unless the ratio is very close to 1.0 (Tier 4a vs Tier 4b borderline). To illustrate this, we present 2022 assessment model results with various minimum size at maturity cutoffs, as follows.

Maturity size	94mm (default)	74mm	84mm	104mm	114mm	124mm	>134mm
B_{MSY} mil. lb	4.88	5.21	4.92	3.76	2.71	1.33	0.39
MMB(2022) mil. lb	5.21	5.91	5.61	4.42	2.86	1.03	0.27
MMB/B_{MSY}	1.16	1.13	1.14	1.18	1.06	0.77	0.70
Tier 4 level	a	a	a	a	a	b	b
F_{OFL}	0.18	0.18	0.18	0.18	0.18	0.13	0.12

As illustrated in the above table, changing minimum maturity size has little effect on MMB/B_{MSY} ratio and Tier 4 level designation. OFL and ABC are based on retained and unretained catch by size applied by F_{OFL}.

3. Molting occurs right after the summer fishery.

Molt timing of NSRKC was verified by field and laboratory survey. Double shelled crabs are often observed in September (Joyce Soong ADFG personal comm.), and crabs sent to Kodiak Lab molted in September-October (Leah Zacher NOAA personal comm).

4. Recruitment occurs in fall at the same time as molting.

In NSRKC assessment modeling, recruitment is not a function of mature males, but estimated model parameters entering to the immature length classes 64 mm - 93 mm. In modeling, this adjustment is done at the same time as molting-growth.

5. Molting probability is a descending logistic function of crab size. Molted crab become newshell and unmolted crab become oldshell crab.

Tag recovery data during the 2012-2014 study suggest lower molting probability for larger crabs. The table below shows the number of newshell crab tagged, released, and recaptured at 1 year of liberty. Crabs recaptured newshell is considered as molted and oldshell is considered as unmomolted.

Length Class	Newshell	Oldshell	% molted
1 (64-73mm)	3	0	100
2 (74-83mm)	30	0	100
3 (84-93mm)	64	5	93
4 (94-103mm)	113	9	93
5 (104-113mm)	44	36	56
6 (114-123mm)	22	21	51
7 (124-133mm)	5	10	22
8 (>133mm)	0	4	0

This assumes that shell condition observations are correct, which is difficult to verify objectively. For instance, in tag-recovery data (2012-2016) below, 125 crabs had no growth (+/- 3 mm) in one year of liberty. Of those, 100 crabs were released as newshell and 25 crabs were released as oldshell. If no growth is considered unmolted, all those crabs should be recaptured as oldshell. However, 29% of crabs released as newshell were recaptured as newshell crab and 48% of crabs released as oldshell were recaptured as newshell.

Released\Recovered	Newshell	Oldshell
Newshell	28	70
Oldshell	12	13

This could be caused by (1) inaccurate length measurement, (2) inaccurate shell condition assessment, or (3) no growth after molting.

6. Growth increment is a function of length, constant over time. Molted crab does not shrink.

   Tag recovery data showed that growth increment of large crab tend to be smaller than that of small crab (Figure D). The data also showed negative growth increment, at the largest length class.

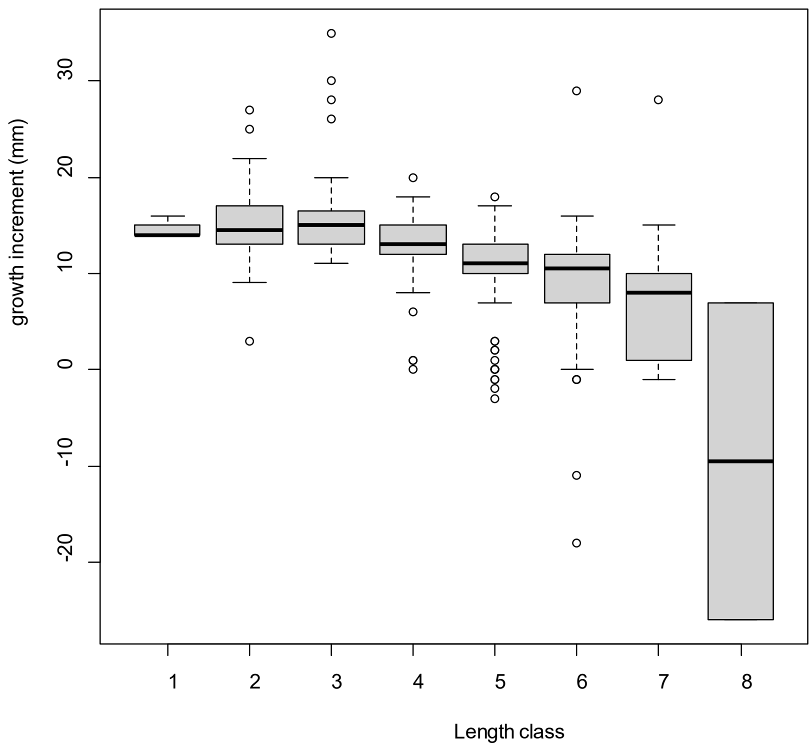


Figure D. Growth increment by tagged length class of molted (newshell recovered) crab with 1 year at liberty.

NSRKC Surveys

1. ADF&G trawl survey (1996-2021) abundance has the same scale as the population (i.e., catchability q = 1.0). Abundances by historical NMFS (1976-1991) and NOAA NBS (2010-present) survey are biased low (i.e., q < 1.0).

   Survey q =1.0 for ADF&G trawl survey and lower survey q for NOAA survey was adopted in 2013 assessment (NPFMC 2013). However, it is possible that ADF&G surveys are overestimates of abundance. Model estimated survey q for ADF&G trawl survey was greater than 1.0 (NPFMC 2013, 2019).

2. Size selectivity is an asymptotic one parameter logistic function of 1.0 at the length class 134 mm CL and the same across years and survey agencies.

$$S_l = \frac{1}{1 + e^{(\alpha(L_{\max} - L) + \ln(1/0.999 - 1))}}$$

This logistic function form was adopted during the crab workshop in 2005 to reduce model parameters and increase parameter estimation stability.

Although the surveys differ among NOAA (1976-1991), ADF&G (1996-2021), and NOAA NBS (2010-present) in terms of survey vessel and trawl net structure, selectivity of all surveys were assumed to be identical. Model fits separating and combining the surveys were examined in 2015; however, selectivity was essentially identical (1.0 across all size classes) (NPFMC 2015). For model parsimony, the SSC recommended using only one selectivity.

3. Winter pot survey selectivity is a dome shaped function: a combination of a reverse logistic function starting from length class 84 mm CL and model estimate for CL < 84 mm length classes. The selectivity is constant over time.

$$S_{w,l} = \frac{1}{1 + e^{\alpha(L-\beta)}}$$

This assumption is based on the low proportion of large crab that are caught in the nearshore area where winter surveys occur. This does not necessarily imply that the crab pots are less selective to large crabs. Alternatively, this may imply that fewer large crab migrate into nearshore waters in winter.

NSRKC Fisheries

1. Fisheries occur twice on July 01 and Feb 01 and are instantaneous.

2. Summer commercial fishery size selectivity is an asymptotic one parameter logistic function of length, with the selectivity in length class 134 mm CL set to 1. Selectivity is constant over time.

$$S_l = \frac{1}{1 + e^{(\alpha(L_{\max}-L)+\ln(1/0.999-1))}}$$

This logistic function form was adopted during the crab workshop in 2005 to reduce model parameters and parameter estimation stability. Although summer commercial fishery changed greatly between the periods (1977-1992, 1993-present) in terms of fishing vessel composition, and pot configuration, the selectivity of each period is assumed to be identical. Model fits of separating and combining the two periods were examined in 2015 and showed no difference between the two (NPFMC 2015). For model parsimony, the SSC recommended using only one selectivity.

3. Not all legal sized crabs are retained. Retention probability is an asymptotic logistic function.

Legal size of NSRKC is defined as carapace width (CW) greater than 4.75 inches that was conventionally equated as greater than 104 mm CL. Since 1996 ADF&G has started noting legal size crab based on carapace width in trawl, commercial fishery observer, and other miscellaneous surveys to complement the carapace length measurement. Originally, the proportion was based solely from the trawl survey. As more data are collected from commercial observer surveys, recent proportions are based on more observer data.

Proportion of legal (CW>4.75 inch) crab in Trawl survey

size class	64	74	84	94	104	114	124	134
1996	0.00	0.00	0.00	0.18	0.93	1.00	1.00	1.00
1999	0.00	0.00	0.00	0.40	0.98	0.98	1.00	1.00
2002	0.00	0.00	0.00	0.28	0.97	1.00	1.00	1.00
2006	0.00	0.00	0.00	0.18	1.00	1.00	1.00	1.00
2008	0.00	0.00	0.00	0.19	0.96	1.00	1.00	1.00
2011	0.00	0.00	0.00	0.24	0.99	1.00	1.00	1.00
2014	0.00	0.00	0.00	0.21	0.98	1.00	1.00	1.00
2017	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00
2018	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00
2019	0.00	0.00	0.00	0.33	1.00	1.00	1.00	1.00
2020	0.00	0.00	0.00	0.22	1.00	1.00	1.00	1.00
Average	**0.00**	**0.00**	**0.00**	**0.25**	**0.98**	**1.00**	**1.00**	**1.00**

Proportion of legal (CW>4.75 inch) crab in Observer survey

size class	64	74	84	94	104	114	124	134
2012	0.00	0.01	0.02	0.22	0.90	1.00	1.00	1.00
2013	0.00	0.00	0.00	0.44	0.98	1.00	1.00	1.00
2014	0.00	0.00	0.00	0.22	0.91	1.00	1.00	1.00
2015	0.00	0.00	0.00	0.38	0.98	1.00	1.00	1.00
2016	0.00	0.00	0.00	0.46	1.00	1.00	1.00	1.00
2017	0.00	0.00	0.00	0.13	0.91	1.00	1.00	1.00
2018	0.00	0.00	0.00	0.16	0.95	0.99	1.00	1.00
2019	0.00	0.00	0.00	0.18	0.93	1.00	1.00	1.00
Average	**0.00**	**0.00**	**0.00**	**0.30**	**0.95**	**1.00**	**1.00**	**1.00**

The proportion of legal crab used in the assessment model is an average proportion based on observer survey data. In the assessment model, this proportion is used to estimate the number of retained crab in winter and summer commercial fisheries prior to 2008. It is assumed prior to 2008, all legal sized crab were retained.

Since 2008 commercially retained crab size is CW> 5.0 inches and retention probability is estimated from the observer survey.

The table below shows the proportion of legal vs. retained crab during the 2012-2019 observer survey, in response to request from the public.

Year		64	74	84	94	104	114	124	134
2012	Legal	0	0.01	0.02	0.22	0.9	1	1	1
	Retained	**0**	**0**	**0**	**0.05**	**0.46**	**0.63**	**0.64**	**0.85**
2013	Legal	0	0	0	0.44	0.98	1	1	1
	Retained	**0**	**0**	**0**	**0.14**	**0.86**	**0.99**	**1**	**1**
2014	Legal	0	0	0	0.22	0.91	1	1	1
	Retained	**0**	**0**	**0**	**0.04**	**0.74**	**0.97**	**0.99**	**1**
2015	Legal	0	0	0	0.38	0.98	1	1	1
	Retained	**0**	**0**	**0**	**0.11**	**0.74**	**0.91**	**0.94**	**0.89**
2016	Legal	0	0	0	0.46	1	1	1	1
	Retained	**0**	**0**	**0**	**0.13**	**0.89**	**0.99**	**1**	**1**
2017	Legal	0	0	0	0.12	0.91	1	1	1
	Retained	**0**	**0**	**0**	**0.02**	**0.75**	**0.99**	**1**	**1**
2018	Legal	0	0	0	0.16	0.95	0.99	1	1
	Retained	**0**	**0**	**0**	**0.14**	**0.92**	**0.99**	**1**	**0.99**
2019	Legal	0	0	0	0.18	0.93	1	1	1
	Retained	**0**	**0**	**0**	**0.15**	**0.93**	**1**	**1**	**1**

The proportion of legal sized crab retained from observer survey 2012-2019

Year	64	74	84	94	104	114	124	134
2012	0	0	0	0.23	0.51	0.63	0.64	0.85
2013	0	0	0	0.31	0.88	0.99	**1**	1
2014	0	0	0	0.19	0.82	0.97	0.99	1
2015	0	0	0	0.28	0.76	0.91	0.94	0.89
2016	0	0	0	0.28	0.89	0.99	1	1
2017	0	0	0	0.14	0.82	0.99	1	1
2018	0	0	0	0.87	0.98	1	1	0.99
2019	0	0	0	0.86	1	1	1	1

The above data justifies using logistic function as selection criteria.

Fishery	Model retention	Data
Summer:1977-2007	Logistic retention prob	Discard, retained size prop
Summer: 2008-2022	Logistic retention prob	Total, retained size prop
Winter: 1977-2007	Mean legal crab proportion	No data
Winter: 2008-2022	Logistic retention prob	Retained size prop
Winter: Subsistence	All crab > 94mm retained	No data (No legal size limit)

3. Winter commercial pot selectivity is the same as the selectivity of the winter pot survey.

   This assumption is based on the survey pot being similar to the one used for subsistence, and that many commercial fishermen are also subsistence harvesters. However, by regulation winter commercial king crab pots can be any dimension (5AAC 34.925(d)) and recent popularity of winter commercial fishery may have deviated this assumption.

4. Winter subsistence fishery retains crab size greater than 94 mm CL.

   This was based on the assumption that subsistence fishermen would keep crab smaller than legal crab size. By regulation, subsistence fishery had no size limit for retention. Size of crab caught by subsistence fishery has never been monitored.

5. Discards handling mortality rate for all fisheries is 20%.

   Discards mortality rate was specified by CPT. No empirical estimates are available.

Data quality assumptions

1. All size-shell composition data are collected accurately without systematic bias.

   Although this assumption is reasonable, it is difficult to verify the assumption objectively. For instance, in tag-recovery data (2012-2016), 125 crabs had no growth (+/- 3mm) in one year of liberty. Of those, 100 crabs were released as newshell and 25 crabs were released as oldshell. If no growth is considered unmolted, all those crabs should be recaptured as oldshell. However, 29% of crabs released as newshell were recaptured as newshell crab and 48% of crabs released as oldshell were recaptured as newshell.

Released\Recovered	Newshell	Oldshell
Newshell	29	71
Oldshell	12	13

   This could be caused by (1) inaccurate length measurement, (2) inaccurate shell condition assessment, or (3) no growth after molting.

2. Annual retained catch is accurate without error.

   In Norton Sound, almost all crabs caught by commercial fisheries are sold to NSEDC. Subsistence fishery harvest are self-reporting. Accuracy of self-reporting has never been evaluated.

Model data weighting

Survey data	Input sample size
Summer commercial, winter pot, and summer observer	minimum of 0.1 × actual sample size or 10
Summer trawl and pot survey	minimum of 0.5 × actual sample size or 20
Tag recovery	0.5× actual sample size

Recruitment SD: 0.5.

Discards CV: 0.3

"Implied" effective sample sizes were calculated as

$$n = \sum_l \hat{P}_{y,l}(1-\hat{P}_{y,l}) \Big/ \sum_l (P_{y,l} - \hat{P}_{y,l})^2$$

Where $P_{y,l}$ and $\hat{P}_{y,l}$ are observed and estimated length compositions in year *y* and length group *l*, respectively. Estimated implied effective sample sizes vary greatly over time.

Data-weighting for NSRKC model is aimed at achieving a balance between various data sets. The current model data weighting schemes, although arbitrary, were deemed appropriate by the CPT-SSC (NPFMC 2011, 2012, See Section E. 1. *Historical Model configuration progression* section). As illustrated in the figure below, increasing weight of size composition data (input sample size: from minimum) would lower model fit to the trawl survey abundance data.

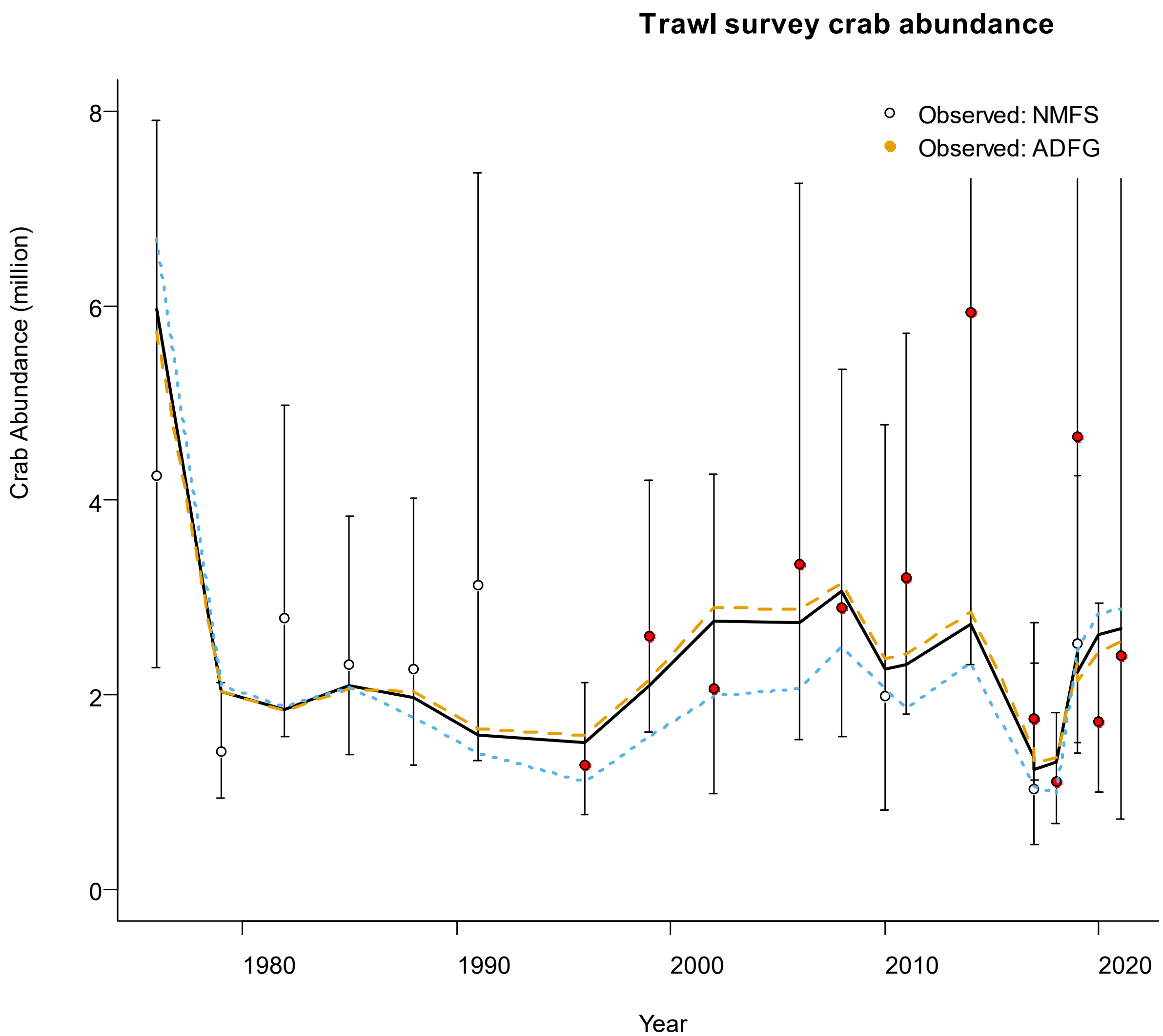


Figure E. Model 21.0 default input sample size (20: trawl, 10: others) (black) vs. increased input sample size (200, 100) (blue dash line), and reduce input size (10, 5) (red dash line).

Thus far, there is no objective criteria for determining the balance (i.e., how much a model should fit observed trawl abundance data vs. size composition data). The author has tried alternative weighting schemes (NPFMC 2019, 2020, 2021) and found current ones are most appropriate.

Changes of assumptions since last assessment:

None

3. Model Selection and Evaluation

a. Description of alternative model configurations.

For the 2023 draft assessment, the following alternative models are presented.

Model 21.0: Adopted by CPT-SSC for the 2022 final assessment.
Model 22.0: Model 21.0 with shell-dependent retention probability
Model 22.1: Model 21.0 with individual *M* estimated for all length classes
Model 22.2: Model 21.0 with individual *M* estimated for all length classes

Model	Retention probability	M	Parameters
21.0	1	0.18+est (L)	
22.0	2	0.18+est (L)	+4
22.1	1	Est	+8
22.2	2	Est	+12

Model 22.0 was proposed to compare efficacy of shell-dependent retention probability on model fit. The shell-dependent retention probability is expected to improve model fit to commercial retention length-shell proportion. This would improve model fit to trawl and total catch length-shell proportion as this allows more oldshell crabs caught in trawl survey. Models 22.1 and 22.2 are not alternatives but simply exploration if full length-dependent *M* would improve model ft to trawl survey length composition.

4. Results

As predicted, retention probability of oldshell crabs was lower than newshell crabs and individual estimates of *M* resulted in size-dependent increasing *M*. *M* was estimated to be nearly zero for length sizes 64-84 classes (Figure 3). Abundance of the first two length classes is a sum of crab that grew and survived from smaller length classes and independently added recruit (Appendix A equations 6,7). The model was not able to estimate *M* under this condition. Individual *M* estimates (Models 22.1, 22.2) also increased the abundance of recruits and thus total crab abundance and mature male biomass during the 1970-2010s (Figures 5, 6, Table 12), but had little influence on model fit to trawl and st. CPUE (Figure 16). This is because model would estimate higher q (Table 11).

Adding shell dependent retention probability (Model 21.0 vs. 22.0) did not reduce or improve retention or discards and total catch size composition (CLP, OBS), but improved trawl survey likelihood (TLP) by 3 points. Similarly, estimating individual *M* (Model 21.0 vs. 22.1) also lowered trawl survey likelihood by 3 points. Combined together, those reduced trawl survey likelihood by 5 points (Model 21.0 vs. 22.1). However, there was no observable difference in fits among all four models (Figures 8, 9).

In conclusion, size-dependent *M* and shell-dependent retention probability adds yet another failure of improving model fits since adoption of the NSRKC assessment model (Section E.1). The NSRKC assessment model has been failing to produce more oldshell crabs and fewer large-sized crabs to match observed size-shell proportions of the trawl survey and commercial retention. Those discrepancies cannot be explained by current understanding of NSRKC biology and fishery.

For selection of an assessment model for the final draft, the author recommends model 21.0 over 22.0. Although inclusion of shell-dependent retention probability is closer to the reality of the fishery, no change in model fit at the cost of additional 4 parameters would be against model parsimony.

In 2022 CPT and SSC recommended the model 21.0 for the final assessment model for 2023 OFL calculation.

Evaluation of negative log-likelihood values.

	Final	Sept 2022			
Model	**21.0**	**21.0**	**22.0**	**22.1**	**22.2**
Additional Parameters			+4	+8	+12
AIC change			+6	+5.4	+24
Total	354.1	347.9	346.1	342.6	341.1
TSA	11.0	11.0	10.8	10.5	10.5
DIS	3.4	3.5	4.5	3.3	3.6
St.CPUE	-14.8	-14.8	-14.9	-15.1	-15.0
TLP	134.0	129.0	126.4	125.5	123.7
WLP	39.6	39.5	39.3	39.3	39.1
CLP	49.5	49.3	48.5	48.7	48.9
OBS	24.3	24.3	25.0	24.9	25.1
WCLP	2.8	2.7	2.9	2.5	2.7
REC	19.4	19.5	19.6	20.1	20.1
TAG	85.0	83.9	83.9	82.9	83.4
Max gradient (e-6)	7.6	4.9	2009	14.7	4.55
RMSE Trawl	0.34	0.34	0.34	0.33	0.33
RMSE CPUE	0.44	0.44	0.44	0.44	0.44

TSA: Trawl Survey Abundance
St. CPUE: Summer commercial catch standardized CPUE
TLP: Trawl survey length composition:
WLP: Winter pot survey length composition
CLP: Summer commercial retention catch length composition
REC: Recruitment deviation
OBS: Summer commercial catch observer discards and total catch length composition
TAG: Tagging recovery data composition
WCLP: Winter commercial length-shell composition
DIS: Summer commercial discards abundance

F. Calculation of the OFL

1. Specification of the Tier level and stock status.

NSRKC stock is placed in Tier 4. It is not possible to estimate the spawner-recruit relationship, but some abundance and harvest estimates are available to build a computer simulation model that captures the essential population dynamics. Tier 4 stocks are assumed to have reliable estimates of current survey biomass and instantaneous *M*; however, the estimates of *M* for NSRKC stock are uncertain.

At the Tier 4 level the OFL is determined by the F_{MSY} proxy, B_{MSY} proxy, and estimated legal male abundance and biomass:

Level	Criteria	F_{OFL}
a	$B/B_{MSY^{prox}} > 1$	$F_{OFL} = \gamma M$
b	$\beta < B/B_{MSY^{prox}} \leq 1$	$F_{OFL} = \gamma M\,(B/B_{MSY^{prox}} - \alpha)/(1-\alpha)$
c	$B/B_{MSY^{prox}} \leq \beta$	$F_{OFL} = bycatch\ mortality\ \&\ directed\ \ fishery\ F = 0$

where B is a mature male biomass (MMB), B_{MSY} proxy is average mature male biomass over a specified time period, $M = 0.18$, $\gamma = 1$, $\alpha = 0.1$, and $\beta = 0.25$.

For NSRKC, MMB is defined as the biomass of males > 94 mm CL on February 01 (Appendix A). B_{MSY} proxy is

B_{MSY} proxy = average model estimated MMB from 1980-2023.

Estimated B_{MSY} proxy: 4.3726 million lb

Predicted mature male biomass in 2023 on February 01

Mature male biomass: 5.2872 million lb

Since the projected MMB is above B_{MSY} proxy,

The NSRKC status is Tire 4a

And F_{OFL} for calculation of the OFL is

$F_{OFL} = \gamma \cdot M$ for M is length invariant of 0.18 and $F_{OFL,l} = \gamma \cdot M_l$ for length-dependent M

2. Calculation formula of NSRKC OFL.

OFL of NSRKC is total OFL (OFL_T) that is a sum of the retained and unretained OFL (OFL_r, OFL_{nr}).

$$OFL_T = OFL_r + OFL_{ur}$$

where

$$OFL_r = retained\_B \cdot F_{OFL} \text{ and } OFL_{nr} = unretained\_B \cdot F_{OFL} \cdot hm$$

retained_B is a biomass of crab subject to fisheries that is a sum of the products of crab abundance ($N_{w,l}+ O_{w,l}$), fishery selectivity ($S_{s,l}$), retention probability ($S_{r,l}$), and average weight lb (wm_l) by length class (l).

$$retained\_B = \sum_l (N_{w,l,} + O_{w,l,}) S_{s,l} S_{r,l} wm_l$$

uretained_B is a biomass of crab subject to fisheries and is a sum of the products of crab abundance ($N_{w,l}+ O_{w,l}$), fishery selectivity ($S_{s,l}$), 1 minus retention probability ($S_{r,l}$), and average weight lb (wm_l) by length class (l).

$$unretained\_B = \sum_l (N_{w,l,} + O_{w,l,}) S_{s,l} (1 - S_{r,l}) wm_l$$

hm is handling mortality, default 0.2

The NSRKC fishery consists of two distinct fisheries: winter and summer. The two fisheries are discontinuous with 5 months (0.42 year) between the two fisheries during which natural mortality occurs. To estimate the OFL for the two fisheries, the CPT in 2016 recommended the following formula that the sum of winter and summer catch (*Hw*, *Hs*) equals total OFL (OFL = *Hw*+*Hs*) and that winter catch is a fraction (p) of total OFL: $H_w = p$·OFL, where ***p is predetermined fraction of*** the winter fishery to total fishery. In NSRKC fishery p = 0.16 is used.

$$H_w = B_w(1 - \exp(-x \cdot F_{OFL})),$$

$$H_s = B_s(1 - \exp((1-x) \cdot F_{OFL})), \text{ and}$$

$$B_s = (B_w - Hw)e^{-0.42 \cdot M}$$

where

B_w is the winter NSRKC biomass, B_s is the summer NSRKC biomass, and x is a fraction parameter,

Solving x of the above (see Appendix A for derivation), retained and unretained OFL is calculated as:

(1)

and

$$OFL_{nr} = unretained\_B_w \cdot FOFL_a \cdot hm$$

$$where \quad FOFL_a = \left(1 - e^{-(F_{OFl}+0.42M)} - (1 - e^{-0.42M}) \left(\frac{1 - p \cdot (1 - e^{-(F_{OFL}+0.42M)})}{1 - p \cdot (1 - e^{-0.42M})} \right) \right) \qquad (2)$$

Because *M* of NSRKC is length-dependent, the proper calculation of NSRKC OFL should account for length-dependent *M* as:

$$OFL_r = \sum_l \left[retained\_B_{w,l} \cdot FOFL_{a,l} \right]$$

$$where \quad FOFL_{a,l} = \left(1 - e^{-(F_{OF,l}+0.42M_l)} - (1 - e^{-0.42M_l}) \left(\frac{1 - p \cdot (1 - e^{-(F_{OFL,l}+0.42M_l)})}{1 - p \cdot (1 - e^{-0.42M_l})} \right) \right) \qquad (3)$$

and

$$OFL_{ur} = \sum_l \left[unretained\_B_{w,l} \cdot FOFL_{a,l} \right] \cdot hm$$

$$where \quad FOFL_{a,l} = \left(1 - e^{-(F_{OFL,l}+0.42M_l)} - (1 - e^{-0.42M_l}) \left(\frac{1 - p \cdot (1 - e^{-(F_{OFL,l}+0.42M_l)})}{1 - p \cdot (1 - e^{-0.42M_l})} \right) \right) \qquad (4)$$

where M_l is a size specific natural mortality,

Determination of Total catch OFL

Total catch OFL is calculable by adding retained and unretained portion of the OFL (i.e., Total OFL = $OFL_r + OFL_{nr}$). Standard calculation of OFL for Tier 4 crab is $F_{OFL} = \gamma M = \gamma 0.18$, which assumes that **natural mortality of a stock is F_{MSY} proxy or that OFL is proxy of a stock harvested at F_{MSY} (See Report of the Alaska Crab Stock Assessment Workshop May 13-14 2009).** However, this assumption is not strictly applicable for NSRKC that has length-dependent *M* because **F_{OFL} is NOT equal to natural mortality of the stock and OFL is not proxy of a stock harvested at F_{MSY}.**

The length-dependent *M* and F_{OFL} was recommended to CPT-SSC in January 2017 but was rejected primarily because it would produce higher OFL. As a compromise, OFL for NSRKC stock in the above equations was specified to length-independent $F_{OFL,l} = \gamma M_l = \gamma 0.18$ and length-dependent M_l for allocation of winter and summer fisheries (see equation2 3, 4, $FOFL_{a,l}$) . This compromise works only when *M* is prespecified (e.g., *M* = 0.18) for the assessment model. However, when the biological justification of prespecified *M* is in question (this has been raised by CPT-SSC since 2019) and is estimated inside an assessment model, biological-scientific justification for selecting *M* for F_{OFL} needs to be clarified and specified. For instance, in 2021

Model 21.5 estimated two *M*s for lengths 64-123mm, and 124mm and above. In this case, should *M* for lengths 64-123mm be used for F_{OFL} specification? This is further complicated when *M* of each length is estimated within the model, such as Models 22.1 and 22.2 in which estimated *M* ranged from 0 to 0.7. Out of the 8 length-dependent *M*s, which *M* should be selected for F_{OFL} and what are biological and scientific justifications? **If length-independent F_{OFL} is preferred, a protocol for selecting a single *M* should be established when *M* is length-dependent.**

Length-dependent *M* and F_{OFL} on the other hand, would be more logical and in line with the assumption of the Tier 4 *OFL* as **proxy of a stock harvested at F_{MSY}**. The biggest concerns raised by CPT-SSC were that length-dependent *M* for NSRKC would increase OFL from standard OFL, though the opposite could occur if estimated *M* were LOWER than 0.18. Recognizing scientific uncertainties in the determination of OFL, the FMP included ABC Control Rule "*for setting the maximum permissible ABC for each stock as a function of the scientific uncertainty in the estimate of OFL and any other specified scientific uncertainty.*" The ABC-control rule allows CPT-SSC setting ABC-buffer that they deem to be appropriate for each stock based on scientific uncertainties of OFL. Therefore, if a length-dependent M increases the OFL, the CPT-SSC would simply increase the ABC-butter to a level that it deems the most appropriate for NSRKC stock. In fact, ABC buffer of NSRKC has increased from 10% in 2011 to 40% in 2021-2022. For instance, increasing ABC buffer to 60% for length-dependent OFL is similar to ABC catch level as standard OFL. The author recommends that CPT-SSC adopt length-dependent OFL and apply ABC control rule (increase ABC-buffer) that it deems appropriate for NSRKC stock.

3. Determination of NSRKC OFL for the 2023 fishery season.

Projected NSRKC biomass catchable to fishery in 2023 is 5.563 million lb. Applying the equations 1-4

OFLs are as follows:

Length independent F_{OFL}.

Retained catch OFL (OFLr) = 0.643 million lb or 0.292 kt
Unretained catch OFL (OFLnr) = 0.037 million lb or 0.017 kt
Total catch OFL (OFL_T) = 0.680 million lb or 0.31 kt

Length dependent F_{OFL}.

Retained catch OFL (OFLr) = 0.965 million lb or 0.438 kt
Unretained catch OFL (OFLnr) = 0.037million lb or 0.017 kt
Total catch OFL (OFL_T) = 1.00 million lb or 0.45 kt

The CPT recommended OFL is retained OFL calculated with length independent F_{OFL}, 0.643 million lb or 0.292 kt

Table: Derivation of length-dependent and length-independent OFL

Length Class	64	74	84	94	104	114	124	134	Total
Newshell (abundance 10^3)	515.52	397.95	392.17	371.76	404.69	473.50	231.98	49.17	
Oldshell (abundance 10^3)	9.85	14.10	24.86	56.62	132.51	176.87	53.24	21.07	
S_l	0.12	0.33	0.63	0.86	0.99	1.00	1.00	1.00	
S_{lr}	0.00	0.00	0.00	0.02	0.90	1.00	1.00	1.00	
wm_l (lb)	0.52	0.82	1.20	1.70	2.32	2.99	3.69	4.37	
Retained (10^3 lb)	0	0	0	12	1072	1922	1048	307	4361
Unretained (10_3 lb)	33	111	317	620	121	0	0	0	1202
Length dependent M									
$M_{.l}$	0.18	0.18	0.18	0.18	0.18	0.18	0.62	0.62	
$FOFL_{.l}$	0.15	0.15	0.15	0.15	0.15	0.15	0.37	0.37	
$OFL_{.r.l}$ (x1000)	0	0	0	2	166	297	387	113	965
$OFL_{.nr.l}$ (x1000)	1	3	10	19	4	0	0	0	37
Length independent M									
M	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	
FOFL	0.15	0.15	0.15	0.15	0.15	0.15	0.13	0.13	
$OFL_{.r}$ (x1000)	0	0	0	2	166	297	138	40	643
$OFL_{.nr}$ (x1000)	1	3	10	19	4	0	0	0	37

G. Calculation of the ABC

1. Specification of the probability distribution of the OFL.

ABC is calculated as (1-ABC buffer)·OFL

In 2015 ABC buffer of Norton Sound Red King Crab was set to 20%, which was increased to 30% in 2020 and to 40% in 2021.
For 2023 fishery season, CPT recommended 30 % buffer.
ABC for the 2023 fishery is

ABC = 0.4501 million lb or 0.185 kt for length-independent and 0.60 million lb or 0.204 kt for length-dependent.

H. Rebuilding Analyses

Not applicable

I. Data Gaps and Research Priorities

The major data gap of NSRKC is an incomplete understanding of NSRKC biology, including natural mortality, and fate of oldshell and large crabs. Additionally, research should focus on female abundance and fecundity as well as their reproductive potential. As for management, the number and length-shell composition of unretained crab in fisheries are needed for calculation of total catch. Viability of unretained crab need to be researched to examine current default 20% mortality. Incorporation of local and traditional knowledge (LK/TK) and socio-economic impacts of NSRKC fisheries on the region, could bring further insights about NSRKC biology and management.

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Table 1. Historical summer commercial red king crab fishery harvest and economic performance, Norton Sound Section, eastern Bering Sea. Bold type shows data that are used for the assessment model.

	Guideline Harvest Level	Commercial Harvest (lb) [a, b]			Total Number (Open Access)			Total Pots		**ST CPUE**		Season Length		**Mid-day from July**
Year	(lb) [b]	Open Access	CDQ	**Number Harvest**	Vessels	Permits	Landings	Registered	Pulls	**CPUE**	**CV**	Days	Dates	
1977	[c]	517.787		**195,877**	7	7	13		5,457	**2.03**	**0.32**	60	[c]	**0.049**
1978	3,000.000	2,091.961		**660,829**	8	8	54		10,817	**3.87**	**0.16**	60	6/07-8/15	**0.142**
1979	3,000.000	2,931.672		**970,962**	34	34	76		34,773	**1.30**	**0.23**	16	7/15-7/31	**0.088**
1980	1,000.000	1,186.596		**329,778**	9	9	50		11,199	**1.64**	**0.27**	16	7/15-7/31	**0.066**
1981	2,500.000	1,379.014		**376,313**	36	36	108		33,745	**0.57**	**0.19**	38	7/15-8/22	**0.096**
1982	500.000	228.921		**63,949**	11	11	33		11,230	**0.25**	**0.15**	23	8/09-9/01	**0.151**
1983	300.000	368.032		**132,205**	23	23	26	3,583	11,195	**0.50**	**0.18**	3.8	8/01-8/05	**0.096**
1984	400.000	387.427		**139,759**	8	8	21	1,245	9,706	**1.13**	**0.19**	13.6	8/01-8/15	**0.110**
1985	450.000	427.011		**146,669**	6	6	72	1,116	13,209	**0.69**	**0.17**	21.7	8/01-8/23	**0.118**
1986	420.000	479.463		**162,438**	3	3		578	4,284	**2.24**	**0.47**	13	8/01-8/25	**0.153**
1987	400.000	327.121		**103,338**	9	9		1,430	10,258	**0.88**	**0.33**	11	8/01-8/12	**0.107**
1988	200.000	236.688		**76,148**	2	2		360	2,350	**2.16**	**0.41**	9.9	8/01-8/11	**0.110**
1989	200.000	246.487		**79,116**	10	10		2,555	5,149	**0.99**	**0.29**	3	8/01-8/04	**0.096**
1990	200.000	192.831		**59,132**	4	4		1,388	3,172	**2.03**	**0.32**	4	8/01-8/05	**0.099**
1991	340.000			**0**	No Summer Fishery									
1992	340.000	74.029		**24,902**	27	27		2,635	5,746	**1.47**	**0.47**	2	8/01-8/03	**0.093**
1993	340.000	335.790		**115,913**	14	20	208	560	7,063	**0.17**	**0.22**	52	7/01-8/28	**0.093**
1994	340.000	327.858		**108,824**	34	52	407	1,360	11,729	**1.02**	**0.09**	31	7/01-7/31	**0.044**
1995	340.000	322.676		**105,967**	48	81	665	1,900	18,782	**0.43**	**0.17**	67	7/01-9/05	**0.093**
1996	340.000	224.231		**74,752**	41	50	264	1,640	10,453	**1.08**	**0.13**	57	7/01-9/03	**0.101**
1997	80.000	92.988		**32,606**	13	15	100	520	2,982	**1.01**	**0.09**	44	7/01-8/13	**0.074**
1998	80.000	29.684	0.00	**10,661**	8	11	50	360	1,639	**1.14**	**0.09**	65	7/01-9/03	**0.110**
1999	80.000	23.553	0.00	**8,734**	10	9	53	360	1,630	**1.30**	**0.13**	66	7/01-9/04	**0.104**
2000	336.000	297.654	14.87	**111,728**	15	22	201	560	6,345	**0.97**	**0.10**	91	7/01- 9/29	**0.126**
2001	303.000	288.199	0	**98,321**	30	37	319	1,200	11,918	**2.08**	**0.11**	97	7/01- 9/09	**0.104**
2002	248.000	244.376	15.226	**86,666**	32	49	201	1,120	6,491	**0.76**	**0.26**	77	6/15-9/03	**0.060**
2003	253.000	253.284	13.923	**93,638**	25	43	236	960	8,494	**0.76**	**0.10**	68	6/15-8/24	**0.058**
2004	326.500	314.472	26.274	**120,289**	26	39	227	1,120	8,066	**1.65**	**0.09**	51	6/15-8/08	**0.033**
2005	370.000	370.744	30.06	**138,926**	31	42	255	1,320	8,867	**1.36**	**0.07**	73	6/15-8/27	**0.058**
2006	454.000	419.191	32.557	**150,358**	28	40	249	1,120	8,867	**0.64**	**0.12**	68	6/15-8/22	**0.052**
2007	315.000	289.264	23.611	**110,344**	38	30	251	1,200	9,118	**0.93**	**0.10**	52	6/15-8/17	**0.036**
2008	412.000	364.235	30.9	**143,337**	23	30	248	920	8,721	**0.89**	**0.23**	73	6/23-9/03	**0.079**
2009	375.000	369.462	28.125	**143,485**	22	27	359	920	11,934	**1.35**	**0.05**	98	6/15-9/20	**0.090**
2010	400.000	387.304	30	**149,822**	23	32	286	1,040	9,698	**0.92**	**0.04**	58	6/28-8/24	**0.074**
2011	358.000	373.990	26.851	**141,626**	24	25	173	1,040	6,808	**1.35**	**0.04**	33	6/28-7/30	**0.038**
2012	465.450	441.080	34.91	**161,113**	40	29	312	1,200	10,041	**1.54**	**0.05**	72	6/29-9/08	**0.093**
2013	495.600	373.278	18.585	**130,603**	37	33	460	1,420	15,058	**1.36**	**0.04**	74	7/3-9/14	**0.110**
2014	382.800	360.860	28.148	**129,657**	52	33	309	1,560	10,127	**0.71**	**0.04**	52	6/25-8/15	**0.052**
2015	394.600	371.520	29.595	**144,255**	42	36	251	1,480	8,356	**1.08**	**0.04**	26	6/29-7/24	**0.033**
2016	517.200	416.576	3,583	**138,997**	36	37	220	1,520	8,009	**1.33**	**0.05**	25	6/27-7/21	**0.025**
2017	496,800	411,736	0	**135,322**	36	36	270	1,640	9,401	**1.17**	**0.05**	30	6/26-7/25	**0.027**
2018	319,400	298,396	0	**89,613**	34	34	256	1,400	8,797	**1.00**	**0.05**	35	6/24-7/29	**0.030**
2019	150,600	73,784	1,239	**24,506**	24	26	146	1,096	5,438	**0.58**	**0.05**	62	6/25-9/03	**0.068**
2020	170,000	0	0	**0**	0	0	0	0	0			0	6/25-9/03	**NA**
2021	290.000	0	0	**0**	0	0	0	0	0			0	6/15-9/03	**NA**
2022	341.600	291,553	25,620	**121,323**	26	26	138		5,154	**1.51**	**0.07**	40	6/15-7/24	**0.014**

[a] Deadloss included in total. [b] Millions of pounds. [c] Information not available.

Table 2. Historical winter commercial and subsistence red king crab fisheries, Norton Sound Section, eastern Bering Sea. Bold typed data are used for the assessment model.

	Commercial			Subsistence					
Model Year	Year[a]	# of Fishers	# of Crab Harvested	Winter[b]	Permits Issued	Permits Returned	Permits Fished	Total Crab Caught[c]	Total Crab Retained[d]
1978	1978	37	**9,625**	1977/78	290	206	149	**NA**	**12,506**
1979	1979	1[f]	**221**[f]	1978/79	48	43	38	**NA**	**224**
1980	1980	1[f]	**22**[f]	1979/80	22	14	9	**NA**	**213**
1981	1981	0	**0**	1980/81	51	39	23	**NA**	**360**
1982	1982	1[f]	**17**[f]	1981/82	101	76	54	**NA**	**1,288**
1983	1983	5	**549**	1982/83	172	106	85	**NA**	**10,432**
1984	1984	8	**856**	1983/84	222	183	143	**15,923**	**11,220**
1985	1985	9	**1,168**	1984/85	203	166	132	**10,757**	**8,377**
1986	1985/86	5	**2,168**	1985/86	136	133	107	**10,751**	**7,052**
1987	1986/87	7	**1,040**	1986/87	138	134	98	**7,406**	**5,772**
1988	1987/88	10	**425**	1987/88	71	58	40	**3,573**	**2,724**
1989	1988/89	5	**403**	1988/89	139	115	94	**7,945**	**6,126**
1990	1989/90	13	**3,626**	1989/90	136	118	107	**16,635**	**12,152**
1991	1990/91	11	**3,800**	1990/91	119	104	79	**9,295**	**7,366**
1992	1991/92	13	**7,478**	1991/92	158	105	105	**15,051**	**11,736**
1993	1992/93	8	**1,788**	1992/93	88	79	37	**1,193**	**1,097**
1994	1993/94	25	**5,753**	1993/94	118	95	71	**4,894**	**4,113**
1995	1994/95	42	**7,538**	1994/95	166	131	97	**7,777**	**5,426**
1996	1995/96	9	**1,778**	1995/96	84	44	35	**2,936**	**1,679**
1997	1996/97	2[f]	**83**[f]	1996/97	38	22	13	**1,617**	**745**
1998	1997/98	5	**984**	1997/98	94	73	64	**20,327**	**8,622**
1999	1998/99	5	**2,714**	1998/99	95	80	71	**10,651**	**7,533**
2000	1999/00	10	**3,045**	1999/00	98	64	52	**9,816**	**5,723**
2001	2000/01	3	**1,098**	2000/01	50	27	12	**366**	**256**
2002	2001/02	11	**2,591**	2001/02	114	61	45	**5,119**	**2,177**
2003	2002/03	13	**6,853**	2002/03	107	70	61	**9,052**	**4,140**
2004	2003/04	2[f]	**522**[f]	2003/04[g]	96	77	41	**1,775**	**1,181**
2005	2004/05	4	**2,091**	2004/05	170	98	58	**6,484**	**3,973**
2006	2005/06	1[f]	**75**[f]	2005/06	98	97	67	**2,083**	**1,239**
2007	2006/07	8	**3,313**	2006/07	129	127	116	**21,444**	**10,690**
2008	2007/08	9	**5,796**	2007/08	139	137	108	**18,621**	**9,485**
2009	2008/09	7	**4,951**	2008/09	105	105	70	**6,971**	**4,752**
2010	2009/10	10	**4,834**	2009/10	125	123	85	**9,004**	**7,044**
2011	2010/11	5	**3,365**	2010/11	148	148	95	**9,183**	**6,640**
2012	2011/12	35	**9,157**	2011/12	204	204	138	**11,341**	**7,311**
2013	2012/13	26	**22,639**	2012/13	149	148	104	**21,524**	**7,622**
2014	2013/14	21	**14,986**	2013/14	103	103	75	**5,421**	**3,252**
2015	2014/15	44	**41,062**	2014/15	155	153	107	**9,840**	**7,651**
2016	2015/16	25	**29,792**	2015/16	139	97	64	**6,468**	**5,340**
2017	2017	43	**26,008**	2017	163	163	109	**7,185**	**6,039**
2018	2018	28	**9,180**	2018	123	120	82	**5,767**	**4,424**
2019	2019	6	**1,050**	2019	101	101	60	**2,080**	**1,545**
2020	2020	1	**conf**	2020	79	79	50	**813**	**548**
2021	2021	5	**320**	2021	103	103	76	**4,655**	**2,892**
2022	2022	8	**2,424**	2022				**10,686**	**7,630**

a Prior to 1985 the winter commercial fishery occurred from January 1 - April 30. As of March 1985, fishing may occur from November 15 - May 15.

b The winter subsistence fishery occurs during months of two calendar years (as early as December, through May).

c The number of crab actually caught, **including females**

d The number of crab retained is the number of crab caught and kept, **including females**

f Confidentiality was waived by the fishers.9963+

h Prior to 2005, permits were only given out of the Nome ADF&G office. Starting with the 2004-5 season, permits were given out in Elim, Golovin, Shaktoolik, and White Mountain.

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Table 3. Summary of Norton Sound red king crab trawl survey abundance estimates (x 1000) (CL ≥ 64mm). NMFS and ADF&G trawl survey abundance estimate is based on 10×10 nm² grids, and NBS trawl survey is based on 20×20 nm² girds. Bold typed data are used for the assessment model.

Year	Dates	Survey Agency	Survey method	Abundance ≥64 mm		Female			% clutch full 95% CI
					CV	N	% barren	% clutch full	
1976	9/02 – 9/25	NMFS	Trawl	**4301.8**	**0.31**	181	2.6	66.7	62.4-71.0
1979	7/26 - 8/05	NMFS	Trawl	**1457.4**	**0.22**	42	25.0	79.9	64.8-94.8
1980	7/04 - 7/14	ADF&G	Pots	2092.3	N/A				
1981	6/28 - 7/14	ADF&G	Pots	2153.4	N/A				
1982	7/06 - 7/20	ADF&G	Pots	1140.5	N/A				
1982	9/05 - 9/11	NMFS	Trawl	**3548.9**	**0.25**	269	0	84.3	81.5-87.2
1985	7/01 - 7/14	ADF&G	Pots	2320.4	0.08				
1985	9/16 -10/01	NMFS	Trawl	**2424.9**	**0.26**	151	0	87.5	NA
1988	8/16 - 8/30	NMFS	Trawl	**2702.3**	**0.29**	219	1.0	80.7	77.3-84.2
1991	8/22- 8/30	NMFS	Trawl	**3132.5**	**0.43**	105	0	69.3	57.7-80.8
1996	8/07 - 8/18	ADF&G	Trawl	**1283.0**	**0.25**	168	30.8	71.9	65.9-77.9
1999	7/28 - 8/07	ADF&G	Trawl	**2608.0**	**0.24**	81	4.7	80.4	76.0-84.7
2002	7/27 - 8/06	ADF&G	Trawl	**2056.0**	**0.36**	168	4.7	76.8	73.4-80.2
2006	7/25 - 8/08	ADF&G	Trawl	**3336.0**	**0.39**	194	3.6	67.3	63.2-71.5
2008	7/24 - 8/11	ADF&G	Trawl	**2894.2**	**0.31**	116	3.3	56.1	48.5-61.7
2010	7/27 - 8/09	NBS	Trawl	**1980.1**	**0.44**	28	0	70.2	63.8-78.5
2011	7/18 - 8/15	ADF&G	Trawl	**3209.3**	**0.29**	135	9.8	67.2	61.7-72.6
2014	7/18 - 7/30	ADF&G	Trawl	**5934.6**	**0.47**	60	0	60.4	54.3-66.6
2017	7/28 - 8/08	ADF&G	Trawl	**1762.1**	**0.22**	43	21.4	71.6	60.0-82.7
2017	8/18 - 8/29	NBS	Trawl	**1035.8**	**0.40**	58	0	80.0	72.5-87.5
2018	7/22 - 7/29	ADF&G	Trawl	**1108.9**	**0.25**	424	15.8	76.3	59.7-83.5
2019	7/17-7/29	ADF&G	Trawl	**4660.8**	**0.60**	386	47.8	50.6	43.1-56.4
2019	8/04-8/07	NBS	Trawl	**2532.4**	**0.26**	94	17.6	47.9	36.8-58.9
2020	7/31-8/14	ADF&G	Trawl	**1716.5**	**0.27**	186	4.5	66.2	61.6-70.8
2021	7/19-8/03	ADF&G	Trawl	**2400.0**	**0.60**	90	3.4	59.8	54.9-64.6
2021	7/29-8/07	NBS	Trawl	**2370.0**	**0.43**	139	2.6	61.1	58.8-63.4
2022	8/03-8/12	NBS	Trawl	**2103.0**	**0.37**	387	3.5	66.5	64.2-68.7

Abundance of NMFS survey was estimated by NMFS, by multiplying the mean CPUE (# NRKC/nm²) across all hauls (including re-tows) to a standard survey area (7600nm²). Abundance of ADF&G and NBS survey was estimated by ADF&G by multiplying CPUE (# NRKC/nm²) of each station to the grid represented by the station and summing across all surveyed station (ADF&G: 4700 – 5200nm². NBS 5841 nm²).

%barren is calculated by dividing the number of mature females with no eggs by total number of mature females.

Mean and 95% CI of % clutch full is calculated among non-barren mature females. Clutch fullness of each non-barren female was assigned by fullness index that was converted to percentage in the table below.

Clutch fullness index of both NMFS-NBS and ADF&G were converted as follows

NMFS and NBS Code	NMFS and NBS Fullness	Assigned %	ADF&G code	ADF&G Fullness	Assigned %
2	0-1/8	6.25	3	1-29%	15
3	1/8-1/4	18.75	4	30-59%	45
4	1/4 – 1/2	27.5	5	60-89%	75
5	1/2 – 3/4	62.5	6	90-100%	95
6	3/4 – 1	87.5			
7	>1	100			

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Table 4. Summer commercial retained catch length-shell compositions.

		New Shell								Old Shell							
Year	Sample	64-73	74-83	84-93	94-103	104-113	114-123	124-133	134+	64-73	74-83	84-93	94-103	104-113	114-123	124-133	134+
1977	1549	0	0	0	0.00	0.42	0.34	0.08	0.05	0	0	0	0.00	0.06	0.04	0.01	0.00
1978	389	0	0	0	0.01	0.19	0.47	0.26	0.04	0	0	0	0.00	0.01	0.01	0.01	0.00
1979	1660	0	0	0	0.03	0.23	0.38	0.26	0.07	0	0	0	0.00	0.03	0.00	0.00	0.01
1980	1068	0	0	0	0.00	0.10	0.31	0.37	0.18	0	0	0	0.00	0.00	0.01	0.02	0.01
1981	1784	0	0	0	0.00	0.07	0.15	0.28	0.23	0	0	0	0.00	0.00	0.05	0.12	0.09
1982	1093	0	0	0	0.04	0.19	0.16	0.22	0.29	0	0	0	0.00	0.01	0.02	0.03	0.03
1983	802	0	0	0	0.04	0.41	0.36	0.06	0.03	0	0	0	0.00	0.04	0.01	0.02	0.02
1984	963	0	0	0	0.10	0.42	0.28	0.06	0.01	0	0	0	0.01	0.07	0.05	0.01	0.00
1985	2691	0	0	0.00	0.06	0.31	0.37	0.15	0.02	0	0	0	0.00	0.03	0.03	0.01	0.00
1986	1138	0	0	0	0.03	0.36	0.39	0.12	0.02	0	0	0	0.00	0.02	0.04	0.02	0.00
1987	1985	0	0	0	0.02	0.18	0.29	0.27	0.11	0	0	0	0.00	0.03	0.06	0.03	0.01
1988	1522	0	0.00	0	0.02	0.20	0.30	0.18	0.04	0	0	0	0.01	0.06	0.10	0.07	0.02
1989	2595	0	0	0	0.01	0.16	0.32	0.17	0.05	0	0	0	0.00	0.06	0.12	0.09	0.02
1990	1289	0	0	0	0.01	0.14	0.35	0.26	0.07	0	0	0	0.00	0.04	0.07	0.05	0.01
1991																	
1992	2566	0	0	0	0.02	0.20	0.27	0.14	0.09	0	0	0	0.00	0.08	0.13	0.06	0.02
1993	17804	0	0	0	0.01	0.23	0.39	0.23	0.03	0	0	0	0.00	0.02	0.04	0.03	0.01
1994	404	0	0	0	0.02	0.09	0.08	0.07	0.02	0	0	0	0.02	0.19	0.25	0.20	0.05
1995	1167	0	0	0	0.04	0.26	0.29	0.15	0.05	0	0	0	0.01	0.05	0.07	0.06	0.01
1996	787	0	0	0	0.03	0.22	0.24	0.09	0.05	0	0	0	0.01	0.12	0.14	0.08	0.02
1997	1198	0	0	0	0.03	0.37	0.34	0.10	0.03	0	0	0	0.00	0.06	0.04	0.03	0.01
1998	1055	0	0	0	0.03	0.23	0.24	0.08	0.03	0	0	0	0.02	0.11	0.14	0.08	0.03
1999	562	0	0	0	0.06	0.29	0.24	0.18	0.09	0	0	0	0.00	0.02	0.05	0.04	0.00
2000	17213	0	0	0	0.02	0.30	0.39	0.11	0.02	0	0	0	0.00	0.05	0.07	0.04	0.01
2001	20030	0	0	0	0.02	0.22	0.37	0.21	0.07	0	0	0	0.00	0.02	0.05	0.02	0.01
2002	5219	0	0	0	0.04	0.23	0.28	0.25	0.07	0	0	0	0.00	0.03	0.04	0.03	0.01
2003	5226	0	0	0	0.02	0.37	0.32	0.12	0.03	0	0	0	0.00	0.02	0.05	0.05	0.01
2004	9606	0	0	0	0.01	0.38	0.39	0.11	0.03	0	0	0	0.00	0.03	0.03	0.01	0.01
2005	5360	0	0	0	0.00	0.25	0.47	0.16	0.02	0	0	0	0.00	0.02	0.05	0.02	0.01
2006	6707	0	0	0	0.00	0.18	0.35	0.17	0.02	0	0	0	0.00	0.05	0.14	0.07	0.01
2007	6125	0	0	0	0.01	0.36	0.34	0.14	0.03	0	0	0	0.00	0.02	0.06	0.03	0.01
2008	5766	0	0	0	0.00	0.35	0.35	0.06	0.01	0	0	0	0.00	0.09	0.09	0.04	0.01
2009	6026	0	0	0	0.01	0.34	0.33	0.11	0.02	0	0	0	0.00	0.08	0.08	0.02	0.01
2010	5902	0	0	0	0.01	0.39	0.36	0.10	0.01	0	0	0	0.00	0.05	0.05	0.02	0.00
2011	2552	0	0	0	0.00	0.32	0.40	0.12	0.02	0	0	0	0.00	0.06	0.06	0.02	0.00
2012	5056	0	0	0	0.00	0.24	0.46	0.18	0.02	0	0	0	0.00	0.03	0.04	0.02	0.00
2013	6072	0	0	0	0.00	0.24	0.37	0.24	0.06	0	0	0	0.00	0.01	0.04	0.02	0.00
2014	4682	0	0	0	0.01	0.28	0.24	0.18	0.07	0	0	0	0.00	0.04	0.09	0.07	0.02
2015	4173	0	0	0	0.01	0.48	0.28	0.10	0.03	0	0	0	0.00	0.02	0.03	0.03	0.01
2016	1543	0	0	0	0.00	0.25	0.47	0.16	0.03	0	0	0	0.00	0.02	0.02	0.03	0.01
2017	3412	0	0	0	0.00	0.18	0.39	0.21	0.03	0	0	0	0.01	0.03	0.12	0.05	0.01
2018	2609	0	0	0	0.00	0.11	0.32	0.32	0.08	0	0	0	0	0.01	0.08	0.08	0.02
2019	1136	0	0	0	0.01	0.32	0.23	0.13	0.03	0	0	0	0	0.02	0.10	0.14	0.03
2020																	
2021																	
2022	2981	0	0	0	0.02	0.46	0.30	0.03	0.00	0	0	0	0.00	0.12	0.05	0.01	0.00

Table 5. Winter commercial catch length-shell compositions.

		New Shell								Old Shell							
Year	Sample	64-73	74-83	84-93	94-103	104-113	114-123	124-133	134+	64-73	74-83	84-93	94-103	104-113	114-123	124-133	134+
2015	576	0	0	0	0.07	0.50	024	0.06	0.01	0	0	0	0.01	0.04	0.03	0.03	0.01
2016	1016	0	0	0	0.03	0.45	0.31	0.03	0.00	0	0	0	0.01	0.09	0.04	0.02	0.01
2017	540	0	0	0	0.00	0.20	0.30	0.13	0.02	0	0	0	0.00	0.08	0.19	0.06	0.02
2018	401	0	0	0	0.00	0.11	0.25	0.27	0.05	0	0	0	0	0.04	0.16	0.10	0.02

Table 6. Summer Trawl Survey length-shell compositions.

			New Shell								Old Shell							
Year	Survey	Sample	64-73	74-83	84-93	94-103	104-113	114-123	124-133	134+	64-73	74-83	84-93	94-103	104-113	114-123	124-133	134+
1976	NMFS	1326	0.01	0.02	0.10	0.19	0.34	0.18	0.02	0.00	0.00	0.00	0.01	0.02	0.03	0.04	0.01	0.01
1979	NMFS	220	0.01	0.01	0.00	0.02	0.05	0.05	0.03	0.01	0.01	0.00	0.01	0.04	0.14	0.40	0.19	0.03
1982	NMFS	327	0.22	0.07	0.16	0.23	0.17	0.03	0.00	0.00	0.00	0.00	0.01	0.02	0.03	0.02	0.02	0.03
1985	NMFS	350	0.11	0.11	0.19	0.17	0.16	0.06	0.01	0.00	0.00	0.00	0.00	0.02	0.05	0.08	0.05	0.01
1988	NMFS	366	0.16	0.19	0.12	0.13	0.11	0.06	0.03	0.00	0.00	0.00	0.01	0.01	0.03	0.07	0.05	0.03
1991	NMFS	340	0.18	0.08	0.02	0.03	0.06	0.03	0.01	0.01	0.03	0.06	0.02	0.08	0.16	0.14	0.09	0.02
1996	ADF&G	269	0.29	0.21	0.13	0.09	0.05	0.00	0.00	0.01	0.00	0.00	0.03	0.03	0.04	0.04	0.04	0.03
1999	ADF&G	283	0.03	0.01	0.10	0.29	0.26	0.13	0.03	0.01	0.00	0.00	0.00	0.03	0.05	0.04	0.02	0.00
2002	ADF&G	244	0.09	0.12	0.14	0.11	0.02	0.03	0.02	0.01	0.01	0.03	0.07	0.10	0.09	0.09	0.05	0.02
2006	ADF&G	373	0.18	0.26	0.21	0.11	0.06	0.04	0.02	0.00	0.00	0.00	0.00	0.02	0.04	0.04	0.01	0.00
2008	ADF&G	275	0.12	0.15	0.21	0.11	0.10	0.03	0.02	0.01	0.00	0.01	0.04	0.06	0.08	0.01	0.04	0.00
2010	NOAA	69	0.01	0.04	0.06	0.17	0.06	0.03	0.00	0.00	0.00	0.03	0.09	0.20	0.19	0.07	0.03	0.01
2011	ADF&G	315	0.13	0.11	0.09	0.11	0.18	0.14	0.03	0.01	0.00	0.00	0.01	0.02	0.09	0.04	0.03	0.00
2014	ADF&G	387	0.08	0.15	0.24	0.18	0.09	0.02	0.01	0.01	0.00	0.00	0.03	0.10	0.05	0.04	0.01	0.00
2017	ADF&G	116	0.14	0.12	0.05	0.09	0.10	0.04	0.00	0.00	0.01	0.02	0.02	0.02	0.07	0.18	0.04	0.00
2017	NOAA	58	0.09	0.10	0.14	0.05	0.05	0.05	0.05	0.03	0.03	0.00	0.03	0.05	0.03	0.19	0.05	0.03
2018	ADF&G	73	0.37	0.10	0.11	0.03	0.01	0.03	0.04	0.01	0	0.07	0.01	0.04	0.03	0.03	0.10	0.03
2019	ADF&G	307	0.55	0.30	0.03	0	0.00	0.00	0.00	0	0.00	0.00	0.01	0.02	0.01	0.02	0.03	0.01
2019	NOAA	135	0.36	0.30	0.08	0.04	0.01	0	0.01	0.01	0.04	0.01	0.04	0.02	0.01	0.01	0.04	0.01
2020	ADF&G	111	0.13	0.22	0.30	0.06	0.05	0.01	0	0	0.03	0.08	0.05	0.02	0.02	0.02	0	0.01
2021	ADF&G	158	0.06	0.17	0.22	0.22	0.22	0.04	0.01	0.01	0	0	0.01	0	0.02	0.01	0.01	0.01
2021	NOAA	82	0.05	0.16	0.21	0.16	0.10	0.02	0	0	0.01	0.05	0.11	0.06	0.06	0.01	0	0
2022	**NOAA**	378	0.16	0.17	0.11	0.10	0.07	0.03	0.01	0.01	0.02	0.02	0.07	0.08	0.087	0.05	0.02	0.01

Table 7. Winter pot survey length-shell compositions.

			New Shell								Old Shell							
Year	CPUE	Sample	64-73	74-83	84-93	94-103	104-113	114-123	124-133	134+	64-73	74-83	84-93	94-103	104-113	114-123	124-133	134+
1981/82	NA	719	0.00	0.10	0.23	0.21	0.07	0.02	0.02	0.00	0.00	0.05	0.11	0.11	0.04	0.02	0.02	0.00
1982/83	24.2	2583	0.03	0.08	0.28	0.28	0.21	0.07	0.01	0.00	0.00	0.00	0.00	0.00	0.02	0.01	0.01	0.01
1983/84	24.0	1677	0.01	0.16	0.26	0.23	0.15	0.06	0.01	0.00	0.00	0.00	0.00	0.02	0.06	0.03	0.01	0.01
1984/85	24.5	789	0.02	0.09	0.25	0.35	0.16	0.06	0.01	0.00	0.00	0.00	0.00	0.01	0.03	0.02	0.00	0.00
1985/86	19.2	594	0.04	0.12	0.17	0.24	0.19	0.08	0.01	0.00	0.00	0.00	0.00	0.01	0.06	0.04	0.01	0.00
1986/87	5.8	144	0.00	0.06	0.15	0.19	0.07	0.04	0.00	0.00	0.00	0.00	0.01	0.04	0.30	0.11	0.03	0.00
1987/88																		
1988/89	13.0	500	0.02	0.13	0.15	0.13	0.19	0.17	0.03	0.00	0.00	0.00	0.00	0.00	0.05	0.08	0.03	0.00
1989/90	21.0	2076	0.00	0.05	0.21	0.26	0.18	0.12	0.06	0.01	0.00	0.00	0.00	0.00	0.03	0.06	0.02	0.00
1990/91	22.9	1283	0.00	0.01	0.09	0.29	0.27	0.10	0.01	0.00	0.00	0.00	0.00	0.00	0.03	0.12	0.07	0.02
1992/93	5.5	181	0.00	0.01	0.03	0.06	0.13	0.12	0.03	0.00	0.00	0.00	0.00	0.02	0.19	0.27	0.10	0.05
1993/94																		
1994/95	6.2	858	0.01	0.06	0.08	0.10	0.26	0.23	0.07	0.01	0.00	0.00	0.00	0.00	0.03	0.07	0.06	0.02
1995/96	9.9	1580	0.06	0.14	0.20	0.19	0.11	0.07	0.03	0.00	0.00	0.00	0.00	0.01	0.06	0.07	0.03	0.01
1996/97	2.9	398	0.07	0.21	0.22	0.11	0.15	0.11	0.05	0.01	0.00	0.00	0.00	0.00	0.02	0.03	0.01	0.01
1997/98	10.9	881	0.00	0.14	0.41	0.27	0.05	0.02	0.00	0.00	0.00	0.00	0.01	0.02	0.03	0.02	0.02	0.01
1998/99	10.7	1307	0.00	0.02	0.12	0.36	0.36	0.08	0.01	0.00	0.00	0.00	0.00	0.01	0.02	0.01	0.01	0.00
1999/00	6.2	575	0.02	0.09	0.10	0.16	0.33	0.18	0.03	0.00	0.00	0.00	0.00	0.00	0.05	0.02	0.01	0.00
2000/01	3.1	44																
2001/02	13.0	828	0.05	0.29	0.26	0.17	0.06	0.06	0.04	0.01	0.01	0.00	0.01	0.01	0.00	0.01	0.00	0.00
2002/03	9.6	824	0.02	0.10	0.22	0.28	0.18	0.06	0.02	0.00	0.00	0.01	0.01	0.02	0.02	0.03	0.02	0.01
2003/04	3.7	296	0.00	0.02	0.16	0.26	0.32	0.14	0.01	0.00	0.00	0.00	0.01	0.02	0.02	0.01	0.02	0.01
2004/05	4.4	405	0.00	0.07	0.14	0.18	0.22	0.19	0.07	0.00	0.00	0.00	0.00	0.00	0.04	0.06	0.01	0.00
2005/06	6.0	512	0.00	0.14	0.23	0.21	0.16	0.05	0.02	0.00	0.00	0.01	0.01	0.02	0.04	0.07	0.03	0.01
2006/07	7.3	159	0.07	0.14	0.19	0.35	0.13	0.04	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.04	0.00	0.00
2007/08	25.0	3552	0.01	0.14	0.25	0.17	0.14	0.07	0.01	0.00	0.01	0.04	0.07	0.03	0.03	0.01	0.01	0.00
2008/09	21.9	525	0.00	0.07	0.13	0.35	0.20	0.08	0.01	0.00	0.00	0.00	0.00	0.00	0.04	0.10	0.00	0.00
2009/10	25.3	578	0.01	0.05	0.13	0.21	0.24	0.11	0.02	0.00	0.00	0.00	0.01	0.06	0.10	0.05	0.01	0.00
2010/11	22.1	596	0.02	0.08	0.13	0.20	0.17	0.13	0.05	0.00	0.00	0.00	0.01	0.03	0.11	0.05	0.01	0.00
2011/12	29.4	675	0.03	0.11	0.23	0.19	0.12	0.13	0.04	0.00	0.00	0.00	0.00	0.01	0.05	0.05	0.03	0.00

Table 8. Summer commercial 1987-1994 observer discards length-shell compositions.

		New Shell								Old Shell							
Year	Sample	64-73	74-83	84-93	94-103	104-113	114-123	124-133	134+	64-73	74-83	84-93	94-103	104-113	114-123	124-133	134+
1987	1146	0.06	0.19	0.32	0.33	0.03	0.00	0.00	0.00	0.00	0.00	0.02	0.04	0.00	0.00	0.00	0.00
1988	722	0.01	0.04	0.15	0.48	0.14	0.00	0.00	0.00	0.00	0.01	0.03	0.10	0.04	0.00	0.00	0.00
1989	1000	0.07	0.19	0.24	0.22	0.03	0.00	0.00	0.00	0.02	0.03	0.07	0.11	0.03	0.00	0.00	0.00
1990	507	0.08	0.23	0.27	0.27	0.04	0.00	0.00	0.00	0.02	0.02	0.02	0.05	0.01	0.00	0.00	0.00
1992	580	0.11	0.17	0.30	0.29	0.03	0.00	0.00	0.00	0.01	0.02	0.02	0.04	0.01	0.00	0.00	0.00
1994	850	0.07	0.06	0.11	0.15	0.02	0.00	0.00	0.00	0.07	0.07	0.15	0.24	0.05	0.00	0.00	0.00

Table 9. Summer commercial observer total catch length-shell compositions.

		New Shell								Old Shell							
Year	Sample	64-73	74-83	84-93	94-103	104-113	114-123	124-133	134+	64-73	74-83	84-93	94-103	104-113	114-123	124-133	134+
2012	3055	0.10	0.05	0.08	0.15	0.15	0.17	0.06	0.01	0.00	0.00	0.00	0.03	0.08	0.09	0.03	0.00
2013	4762	0.19	0.16	0.09	0.10	0.16	0.16	0.09	0.01	0.00	0.00	0.00	0.00	0.01	0.02	0.01	0.00
2014	3506	0.02	0.05	0.13	0.22	0.22	0.12	0.08	0.03	0.00	0.00	0.00	0.02	0.03	0.03	0.02	0.01
2015	1671	0.01	0.04	0.09	0.23	0.37	0.14	0.05	0.01	0.00	0.00	0.00	0.01	0.02	0.02	0.01	0.00
2016	2114	0.01	0.01	0.03	0.12	0.29	0.36	0.08	0.02	0.00	0.00	0.00	0.01	0.03	0.03	0.02	0.00
2017	2748	0.02	0.03	0.03	0.06	0.19	0.33	0.18	0.02	0.00	0.00	0.00	0.00	0.02	0.07	0.03	0.01
2018	1628	0.03	0.06	0.12	0.11	0.09	0.17	0.18	0.04	0.00	0.00	0.01	0.01	0.15	0.07	0.08	0.02
2019	236	0.13	0.06	0.06	0.13	0.08	0.05	0.01	0.01	0	0	0.00	0.04	0.11	0.14	0.14	0.05

Table 10. The observed proportion of tagged crab by each size class released and recovered after 1 -3 year of liberty 1980-2019 periods.

Year at liberty 1

	64-73	74-83	84-93	94-103	104-113	114-123	124-33	> 134	n
64-73	0	0.2	0.8	0	0	0	0	0	5
74-83		0	0.44	0.47	0.09	0	0	0	47
84-93			0	0.32	0.62	0.05	0.01	0	146
94-103				0.03	0.62	0.34	0.01	0.00	317
104-113					0.31	0.59	0.09	0	241
114-123						0.42	0.47	0.11	210
124-133							0.69	0.31	81
>134								1	26

Year at liberty 2

	64-73	74-83	84-93	94-103	104-113	114-123	124-33	> 134	n
64-73	0	0	0.09	0.55	0.36	0	0	0	11
74-83		0	0	0.11	0.85	0.04	0	0	113
84-93			0	0.04	0.32	0.61	0.03	0	114
94-103				0.02	0.36	0.41	0.20	0	94
104-113					0.06	0.71	0.22	0	108
114-123						0.17	0.72	0.11	65
124-133							0.36	0.64	25
>134								1	8

Year at liberty 3

	64-73	74-83	84-93	94-103	104-113	114-123	124-33	> 134	n
64-73	0	0	0	0	0.5	0.5	0	0	22
74-83	0	0	0	0	0.26	0.66	0.082	0	73
84-93	0	0	0	0.04	0.26	0.53	0.17	0	53
94-103	0	0	0	0	0.06	0.67	0.27	0	52
104-113	0	0	0	0	0	0.26	0.62	0.12	34
114-123	0	0	0	0	0	0	0.79	0.21	14
124-133	0	0	0	0	0	0	0.1	0.9	10
>134	0	0	0	0	0	0	0	1	1

Table 11. Summary of bounds and model estimated parameters for a length-based population model of Norton Sound red king crab. Parameters with "log_" indicate log scaled parameters

Parameter	Parameter description	Lower	Upper
log_q_1	Commercial fishery catchability (1977-93)	-20.5	20
log_q2	Commercial fishery catchability (1994-2007)	-20.5	20
log_q3	Commercial fishery catchability (2008-2019)	-20.5	20
log_N_{76}	Initial abundance	2.0	15.0
R_0	Mean Recruit	2.0	12.0
log_σ_R^2	Recruit standard deviation	-40.0	40.0
a_{1-7}	Intimal length proportion	0	10.0
$r_{1,2}$	Proportion of length class 1 for recruit	0	5.0
log_α	Inverse logistic molting parameter	-5.0	-1.0
log_β	Inverse logistic molting parameter	1.0	5.5
log_ϕ_{st1}	Logistic trawl selectivity parameter	-5.0	1.0
log_ϕ_{wa}	Inverse logistic winter pot selectivity parameter	-5.0	1.0
log_ϕ_{wb}	Inverse logistic winter pot selectivity parameter	0.0	6.0
$Sw_{1,2}$	Winter pot selectivity of length class 1,2	0.1	1.0
log_ϕ_l	Logistic commercial catch selectivity parameter	-5.0	1.0
log_ϕra	Logistic summer commercial retention selectivity Newshell (1976-2007, 2008-2022)	-5.0	1.0
log_ϕrb	Logistic summer commercial retention selectivity Newshell (1976-2007, 2008-2022)	0.0	6.0
log_ϕrao	Logistic summer commercial retention selectivity Oldshell (1976-2007, 2008-2022)	-5.0	1.0
log_ϕrbo	Logistic summer commercial retention selectivity Oldshell (1976-2007, 2008-2022)	0.0	6.0
log_ϕwra	Logistic winter commercial retention selectivity p	-5.0	1.0
log_ϕwrb	Logistic winter commercial retention selectivity	0.0	6.0
w^2_t	Additional variance for standard CPUE	0.0	6.0
m1-8	Natural mortality multipliers	0	5.0
q.1	Survey q for NMFS trawl 1976-91	0.1	1.0
q.2	Survey q for NMFS NBS trawl 2010,17,19	0.1	1.0
σ	Growth transition sigma	0.0	30.0
β_1	Growth transition mean	0.0	20.0
β_2	Growth transition increment	0.0	20.0

*: Parameter was unestimable because model estimated trawl survey selectivity was 1.0 across all size classes.

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	21.0 Final		21.0		22.0		22.1		22.2	
Name	Estimate	std.dev	Estimate	std.dev	Estimate	std.dev	Estimate	std.dev	Estimate	std.dev
log_q_1	-7.315	0.195	-7.313	0.195	-7.297	0.196	-7.358	0.197	-7.343	0.198
log_q_2	-6.721	0.166	-6.721	0.166	-6.724	0.166	-6.699	0.169	-6.697	0.169
log_q_3	-6.807	0.156	-6.811	0.156	-6.790	0.153	-6.811	0.159	-6.814	0.159
log_N_{76}	9.136	0.139	9.133	0.139	9.124	0.138	9.331	0.165	9.318	0.165
R_0	6.454	0.082	6.449	0.083	6.450	0.083	6.485	0.126	6.482	0.126
a_1	1.016	4.460	1.038	4.456	1.068	4.474	0.983	4.420	0.982	4.439
a_2	1.016	4.460	1.763	4.190	1.787	4.209	1.693	4.165	1.685	4.183
a_3	1.749	4.191	3.497	3.932	3.520	3.952	3.519	3.906	3.525	3.924
a_4	3.492	3.932	3.979	3.910	4.000	3.930	3.998	3.884	4.006	3.901
a_5	3.978	3.910	4.246	3.901	4.287	3.922	4.227	3.875	4.259	3.893
a_6	4.243	3.902	3.506	3.930	3.520	3.950	3.482	3.905	3.498	3.922
a_7	3.503	3.930	2.062	4.198	2.077	4.212	1.881	4.177	1.891	4.190
r1	**5.000**	**0.002**	**5.000**	**0.002**	**5.000**	**0.002**	**5.000**	**0.003**	**5.000**	**0.003**
r2	4.624	0.163	4.617	0.167	4.610	0.168	4.651	0.190	4.648	0.191
log_a	-2.750	0.090	-2.729	0.089	-2.711	0.089	-2.690	0.091	-2.685	0.090
log_b	4.835	0.016	4.834	0.015	4.827	0.015	4.824	0.015	4.821	0.015
log_ϕ_{st1}	**-5.000**	**0.028**	**-5.000**	**0.032**	**-5.000**	**0.033**	**-5.000**	**0.070**	**-5.000**	**0.067**
log_ϕ_{wa}	-2.392	0.421	-2.398	0.422	-2.410	0.427	-2.322	0.466	-2.343	0.475
log_ϕ_{wb}	4.773	0.067	4.771	0.069	4.770	0.071	4.805	0.056	4.802	0.060
Sw1	0.061	0.033	0.060	0.033	0.060	0.033	0.072	0.038	0.071	0.038
Sw2	0.425	0.146	0.425	0.147	0.423	0.149	0.480	0.151	0.474	0.153
Sw3	0.731	0.234	0.727	0.236	0.718	0.238	0.778	0.216	0.769	0.222
log_ϕ_l	-2.063	0.044	-2.061	0.044	-2.039	0.045	-2.036	0.048	-2.037	0.048
log_ϕra1	-0.856	0.143	-0.855	0.143	-0.809	0.157	-0.881	0.145	-0.839	0.159
log_ϕrb1	4.641	0.008	4.641	0.008	4.637	0.009	4.645	0.009	4.641	0.010
log_ϕra2	-0.491	0.278	-0.497	0.276	0.906	560.740	-0.500	0.280	-0.361	0.491
log_ϕrb2	4.653	0.013	4.654	0.013	4.606	8.653	4.654	0.014	4.645	0.025
log_ϕrao1					-1.036	0.448			-1.099	0.469
log_ϕrbo1					4.661	0.019			4.667	0.020
log_ϕrao2					-1.969	0.704			0.849	524.780
log_ϕrbo2					4.711	0.040			4.685	0.860
log_ϕwra	-0.948	0.566	-0.949	0.564	-0.945	0.573	-0.970	0.561	-0.983	0.552
log_ϕwrb	4.654	0.038	4.654	0.038	4.653	0.039	4.654	0.038	4.655	0.038
w^2_t	0.142	0.040	0.142	0.040	0.141	0.040	0.139	0.039	0.140	0.039
q.1	0.713	0.128	0.716	0.128	0.723	0.129	0.634	0.117	0.641	0.118
q.2	0.871	0.173	0.891	0.191	0.883	0.189	0.861	0.185	0.861	0.184
σ	3.815	0.208	3.824	0.208	3.792	0.211	3.809	0.214	3.782	0.216
β_1	11.788	0.696	11.808	0.697	11.668	0.714	11.960	0.754	11.868	0.760
β_2	7.813	0.171	7.806	0.171	7.850	0.176	7.786	0.186	7.816	0.188
m1							0.000	0.000	0.000	0.002
m2							0.000	0.754	0.000	0.000
m3							0.928	0.593	1.005	0.754
m4							1.249	0.395	1.268	0.593
m5							1.224	0.294	1.107	0.396
m6							1.680	0.339	1.708	0.296
m7							3.033	0.574	3.041	0.340
m8	3.815	0.208	3.428	0.266	3.427	0.266	3.746	0.214	3.752	0.574

Table 12. Annual abundance estimates of legal crab (million crab) and mature male biomass (Feb 01) (MMB, million lb) for Norton Sound red king crab estimated by a length-based analysis.

MMB

Year	Model 21.0 final	Model 21.0	Model 22.0	Model 22.1	Model 22.2
1976	17.33	17.45	17.29	21.02	20.84
1977	19.15	19.24	19.06	22.27	22.11
1978	16.71	16.76	16.61	18.61	18.50
1979	11.86	11.90	11.79	12.88	12.80
1980	6.42	6.44	6.37	6.95	6.90
1981	4.36	4.38	4.34	4.71	4.67
1982	3.40	3.42	3.38	3.77	3.73
1983	4.30	4.33	4.28	4.79	4.73
1984	5.04	5.07	5.01	5.61	5.53
1985	5.70	5.73	5.65	6.32	6.22
1986	6.05	6.09	5.99	6.65	6.54
1987	5.96	5.99	5.88	6.48	6.37
1988	5.88	5.91	5.81	6.36	6.27
1989	5.62	5.65	5.57	6.02	5.96
1990	5.31	5.33	5.28	5.66	5.62
1991	5.00	5.02	4.99	5.32	5.29
1992	4.76	4.78	4.76	5.01	5.00
1993	4.45	4.47	4.47	4.65	4.64
1994	3.85	3.87	3.87	3.99	3.99
1995	3.29	3.30	3.32	3.39	3.40
1996	2.90	2.91	2.94	2.99	2.99
1997	2.88	2.90	2.93	2.97	2.98
1998	3.49	3.52	3.54	3.63	3.63
1999	4.38	4.42	4.44	4.59	4.59
2000	4.62	4.66	4.68	4.76	4.77
2001	4.18	4.21	4.23	4.23	4.24
2002	3.98	4.01	4.03	4.04	4.05
2003	4.07	4.10	4.14	4.18	4.19
2004	4.08	4.11	4.16	4.21	4.22
2005	3.81	3.83	3.89	3.92	3.93
2006	3.57	3.60	3.66	3.70	3.71
2007	3.74	3.78	3.84	3.95	3.95
2008	4.26	4.31	4.38	4.55	4.54
2009	4.72	4.78	4.87	5.08	5.07
2010	4.92	4.98	5.10	5.28	5.28
2011	4.60	4.65	4.77	4.88	4.89
2012	4.15	4.19	4.28	4.35	4.36
2013	3.96	3.99	4.05	4.17	4.16
2014	4.36	4.40	4.44	4.69	4.67
2015	4.91	4.96	5.01	5.30	5.30
2016	4.50	4.54	4.61	4.77	4.78
2017	3.67	3.70	3.76	3.78	3.80
2018	2.82	2.85	2.88	2.83	2.85
2019	2.39	2.42	2.43	2.37	2.37
2020	3.00	3.08	3.08	3.04	3.04
2021	4.45	4.64	4.65	4.57	4.57
2022	5.31	5.52	5.52	5.30	5.31
2023	5.29	5.39	5.39	5.05	5.06

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Legal abundance (x million) (≥ 104 mm CL)

Year	Model 21.0 Final	Model 21.0	Model 22.0	Model 22.1	Model 22.2
1976	5.02	7.39	7.33	8.98	8.89
1977	6.15	7.14	7.08	8.32	8.25
1978	5.22	5.59	5.54	6.23	6.19
1979	3.51	3.77	3.74	4.09	4.07
1980	1.83	2.02	2.01	2.19	2.18
1981	1.15	1.46	1.45	1.59	1.58
1982	0.84	1.34	1.33	1.50	1.48
1983	1.14	1.76	1.74	1.97	1.94
1984	1.40	2.03	2.00	2.27	2.24
1985	1.60	2.25	2.21	2.51	2.47
1986	1.76	2.31	2.27	2.56	2.51
1987	1.71	2.22	2.18	2.43	2.39
1988	1.70	2.15	2.12	2.35	2.32
1989	1.62	2.01	1.99	2.18	2.16
1990	1.51	1.90	1.89	2.05	2.04
1991	1.43	1.78	1.77	1.92	1.91
1992	1.36	1.68	1.68	1.79	1.78
1993	1.27	1.57	1.57	1.65	1.65
1994	1.10	1.35	1.36	1.42	1.42
1995	0.93	1.16	1.17	1.21	1.22
1996	0.80	1.05	1.06	1.10	1.10
1997	0.78	1.09	1.10	1.13	1.13
1998	0.89	1.40	1.40	1.47	1.47
1999	1.24	1.74	1.75	1.83	1.83
2000	1.40	1.71	1.72	1.77	1.77
2001	1.22	1.49	1.50	1.52	1.52
2002	1.09	1.46	1.47	1.50	1.50
2003	1.11	1.54	1.56	1.61	1.61
2004	1.17	1.53	1.55	1.60	1.60
2005	1.11	1.40	1.42	1.45	1.46
2006	0.98	1.34	1.36	1.41	1.41
2007	0.99	1.48	1.50	1.58	1.57
2008	1.16	1.71	1.74	1.84	1.84
2009	1.32	1.88	1.92	2.04	2.03
2010	1.44	1.90	1.94	2.04	2.04
2011	1.37	1.69	1.73	1.80	1.80
2012	1.18	1.51	1.54	1.59	1.59
2013	1.07	1.51	1.52	1.60	1.59
2014	1.13	1.76	1.77	1.91	1.90
2015	1.41	1.95	1.97	2.11	2.11
2016	1.38	1.66	1.68	1.76	1.76
2017	1.11	1.27	1.29	1.31	1.32
2018	0.81	0.97	0.98	0.97	0.98
2019	0.65	0.86	0.86	0.85	0.85
2020	0.68	1.26	1.26	1.26	1.26
2021	1.19	1.92	1.93	1.92	1.92
2022	1.58	2.13	2.13	2.06	2.06
2023	1.54	1.98	1.98	1.88	1.88

Table 13. Summary of observed catch (million lb) for Norton Sound red king crab.

Year	Summer Com	Winter Com	Winter Sub	Discards Winter Sub	Total
1977	0.52	0.000	0.000	0	0.520
1978	2.09	0.024	0.025	0.008	2.147
1979	2.93	0.001	0.000	0	2.931
1980	1.19	0.000	0.000	0	1.190
1981	1.38	0.000	0.001	0	1.381
1982	0.23	0.000	0.003	0.001	0.234
1983	0.37	0.001	0.021	0.006	0.398
1984	0.39	0.002	0.022	0.005	0.419
1985	0.43	0.003	0.017	0.002	0.452
1986	0.48	0.005	0.014	0.004	0.503
1987	0.33	0.003	0.012	0.002	0.347
1988	0.24	0.001	0.005	0.001	0.247
1989	0.25	0.000	0.012	0.002	0.264
1990	0.19	0.010	0.024	0.004	0.228
1991	0	0.010	0.015	0.002	0.027
1992	0.07	0.021	0.023	0.003	0.117
1993	0.33	0.005	0.002	0	0.337
1994	0.32	0.017	0.008	0.001	0.346
1995	0.32	0.022	0.011	0.002	0.355
1996	0.22	0.005	0.003	0.001	0.229
1997	0.09	0.000	0.001	0.001	0.092
1998	0.03	0.002	0.017	0.012	0.061
1999	0.02	0.007	0.015	0.003	0.045
2000	0.3	0.008	0.011	0.004	0.323
2001	0.28	0.003	0.001	0	0.284
2002	0.25	0.007	0.004	0.003	0.264
2003	0.26	0.017	0.008	0.005	0.290
2004	0.34	0.001	0.002	0.001	0.344
2005	0.4	0.006	0.008	0.003	0.417
2006	0.45	0.000	0.002	0.001	0.453
2007	0.31	0.008	0.021	0.011	0.350
2008	0.39	0.015	0.019	0.009	0.433
2009	0.4	0.012	0.010	0.002	0.424
2010	0.42	0.012	0.014	0.002	0.448
2011	0.4	0.009	0.013	0.003	0.425
2012	0.47	0.025	0.015	0.004	0.514
2013	0.35	0.061	0.015	0.014	0.440
2014	0.39	0.035	0.007	0.002	0.434
2015	0.40	0.099	0.019	0.005	0.523
2016	0.42	0.080	0.011	0.001	0.512
2017	0.41	0.078	0.012	0.001	0.501
2018	0.30	0.029	0.008	0.001	0.338
2019	0.08	0.032	0.003	0.001	0.116
2020	0	Conf.	0.001	0.000	Conf
2021	0	0.0	0.004	0.002	0.006
2022	0.32	0.070	0.006	0.003	0.400

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Table 14: Jittering

replicate	likelihood	gradient	replicate	likelihood	gradient
1	354.104	9.14E-07	51	354.104	8.95E-07
2	354.104	1.62E-07	52	NA	236.9975
3	NA	455.0636	53	354.276	2.55E-07
4	354.104	2.62E-07	54	354.104	2.18E-08
5	354.104	5.66E-06	55	354.104	1.01E-07
6	354.104	2.31E-07	56	354.104	1.37E-07
7	354.104	5.16E-07	57	354.104	4.34E-08
8	354.104	2.82E-06	58	354.104	1.25E-07
9	354.104	1.92E-07	59	354.104	1.76E-06
10	354.104	2.60E-07	60	354.104	8.71E-07
11	NA	2401.038	61	354.104	1.57E-07
12	354.104	1.37E-06	62	354.104	1.93E-05
13	354.104	1.68E-07	63	NA	473.9493
14	354.104	2.52E-05	64	354.104	3.14E-06
15	354.104	1.15E-07	65	354.104	1.48E-07
16	354.104	1.91E-07	66	NA	9507.34
17	354.104	5.10E-07	67	354.104	1.05E-06
18	354.104	9.89E-07	68	354.104	2.01E-06
19	354.104	2.41E-07	69	354.104	1.35E-07
20	354.104	1.10E-07	70	354.104	3.74E-07
21	354.104	1.86E-06	71	354.104	3.67E-05
22	354.276	2.15E-06	72	354.104	6.39E-07
23	NA	1195.454	73	354.104	9.06E-07
24	354.104	2.13E-06	74	354.104	5.95E-08
25	354.104	3.12E-07	75	354.104	9.48E-07
26	354.104	9.78E-07	76	NA	599.3275
27	354.276	3.14E-07	77	354.104	1.57E-07
28	354.104	2.34E-06	78	354.104	3.51E-07
29	392.5614	2.22E-07	79	354.104	8.87E-07
30	354.104	1.29E-07	80	NA	273.8769
31	354.104	1.55E-07	81	354.104	8.59E-07
32	354.104	1.24E-07	82	NA	456.4396
33	354.104	7.70E-08	83	354.104	5.80E-07
34	354.104	1.73E-06	84	526.8582	19309.28
35	354.104	9.09E-07	85	NA	8669.331
36	354.104	1.29E-07	86	354.104	7.01E-06
37	NA	1410.093	87	380.6761	1471.876
38	354.104	8.00E-07	88	354.104	1.37E-05
39	NA	935.3707	89	354.104	0.000188
40	NA	686.2179	90	354.104	8.68E-06
41	NA	146.6267	91	354.104	6.13E-07
42	354.104	1.06E-06	92	354.104	4.83E-05
43	746.0123	40821.97	93	354.104	4.69E-08
44	354.104	7.75E-07	94	354.104	2.39E-06
45	354.104	9.81E-07	95	459.8175	14739.71
46	354.104	4.38E-05	96	354.276	3.95E-05
47	354.276	2.07E-07	97	354.104	4.02E-07
48	354.104	4.67E-08	98	354.104	1.45E-07
49	354.104	1.16E-07	99	354.104	1.14E-06
50	NA	881.402	100	392.5614	8.37E-08

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Figure 1. King crab fishing districts and sections of Statistical Area Q.

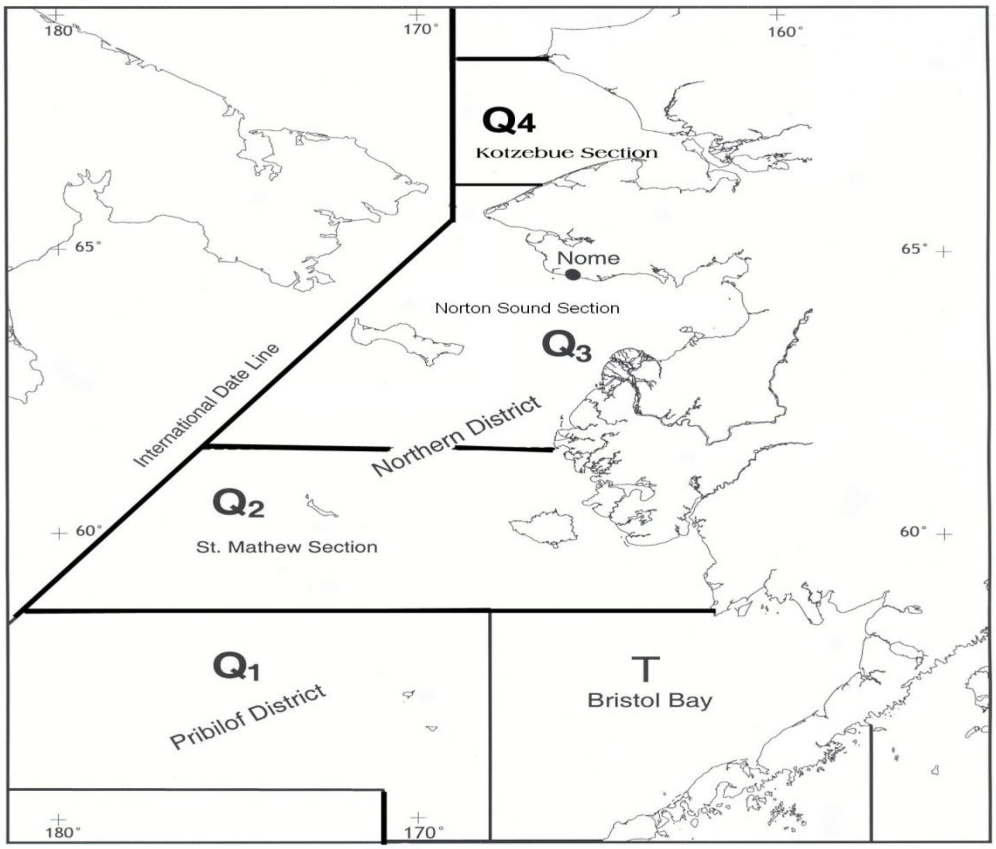

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Figure 2. Closed water regulations in effect for the Norton Sound commercial crab fishery. Line around the coastline delineates the 3-mil state waters zone.

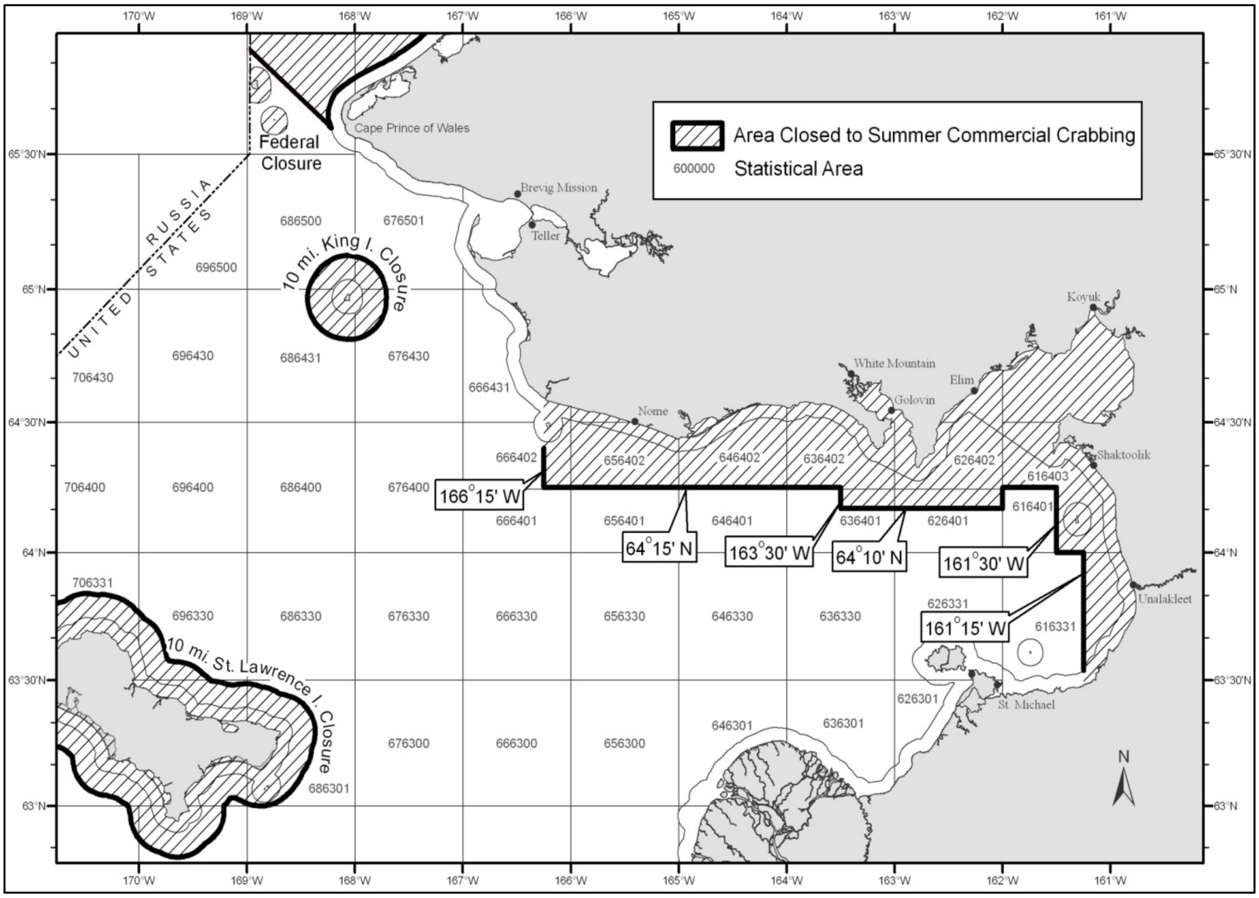

Figure 3. Model estimated natural mortality, annual molting probability, selectivity for trawl survey, winter pot survey, and summer commercial fishery, and retention probability for winter commercial and summer commercial (newshell and oldshell (for models 22.0 and 22.1). X-axis is carapace length (mm).

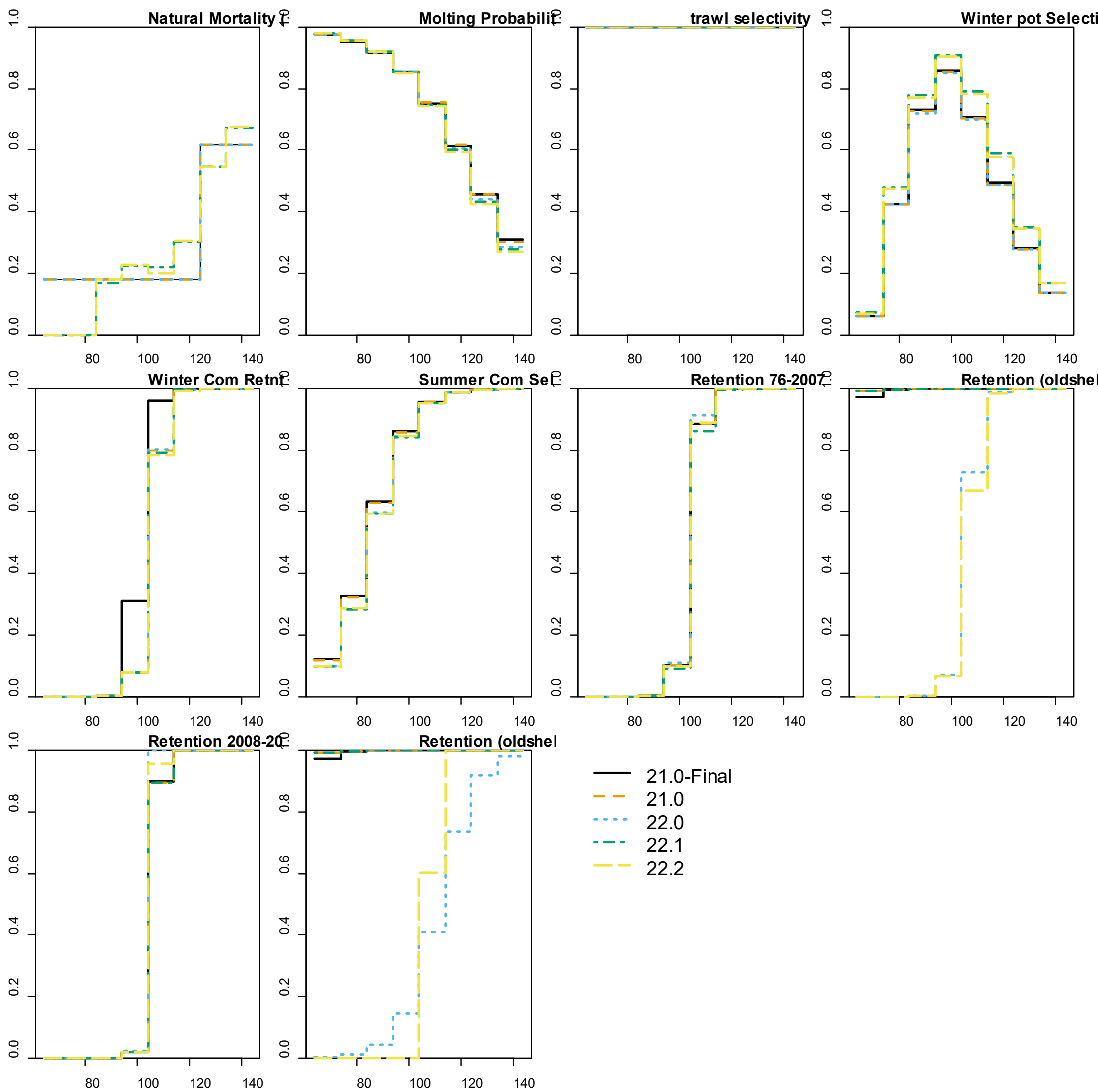

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Figure 4. Model estimated transition probability for each size classes.

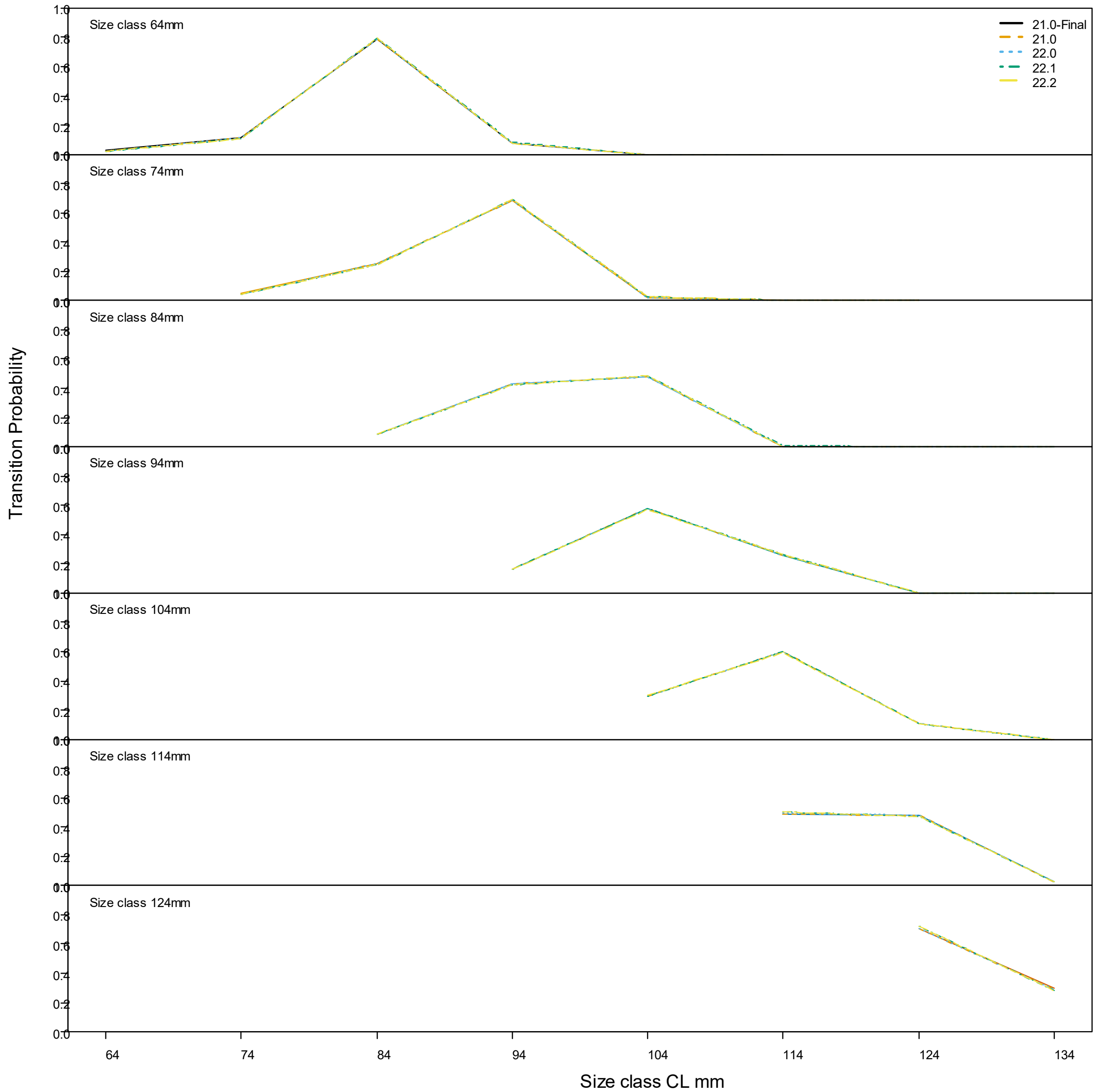

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Figure 5. Model estimated abundances of total, legal (CL>104 mm) and recruit (CL 64-94 mm) males during1976-2022.

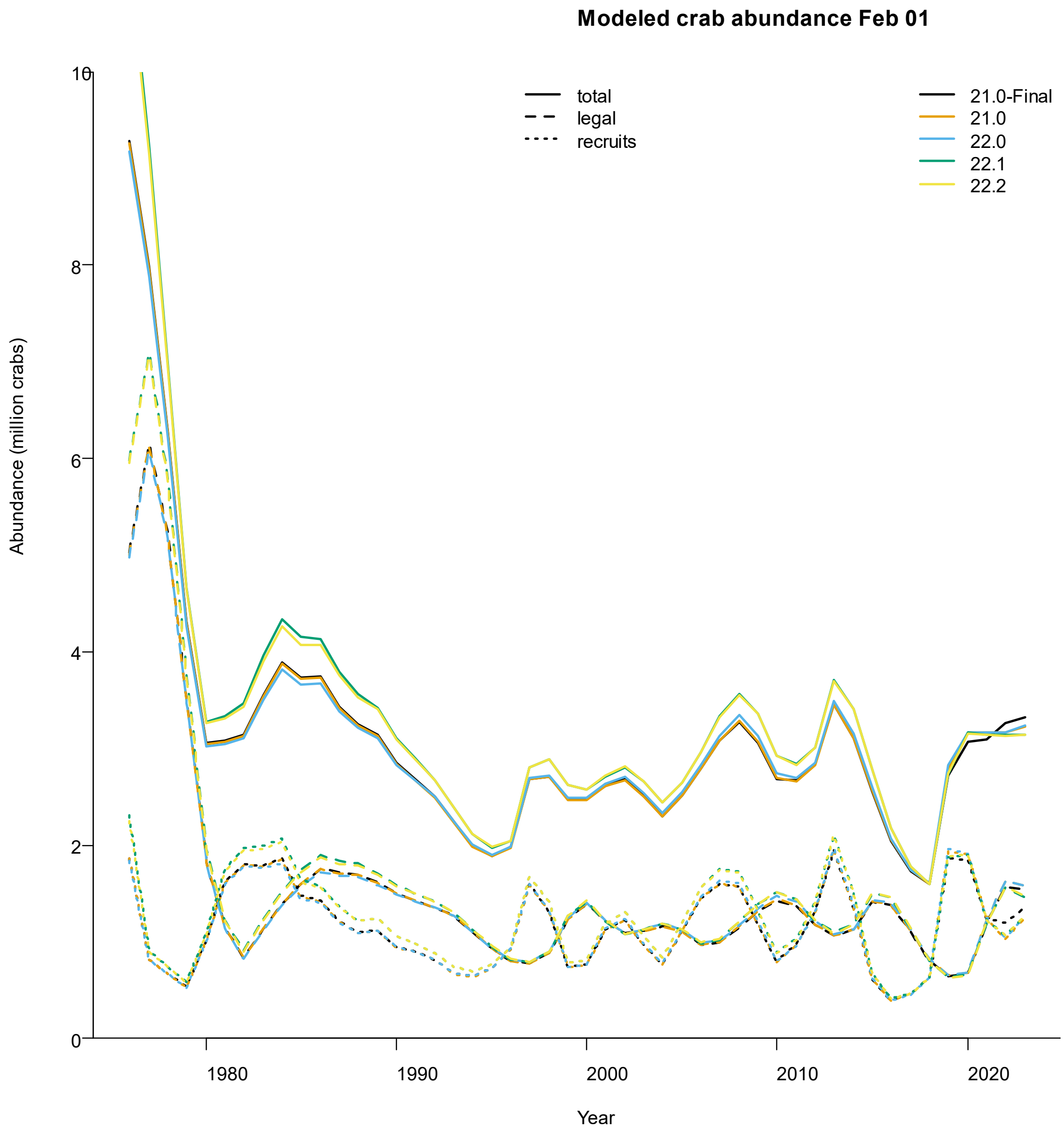

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Figure 5. Estimated MMB during 1976-2023. Horizontal line Bmsy (Average MMB of 1980-2023).

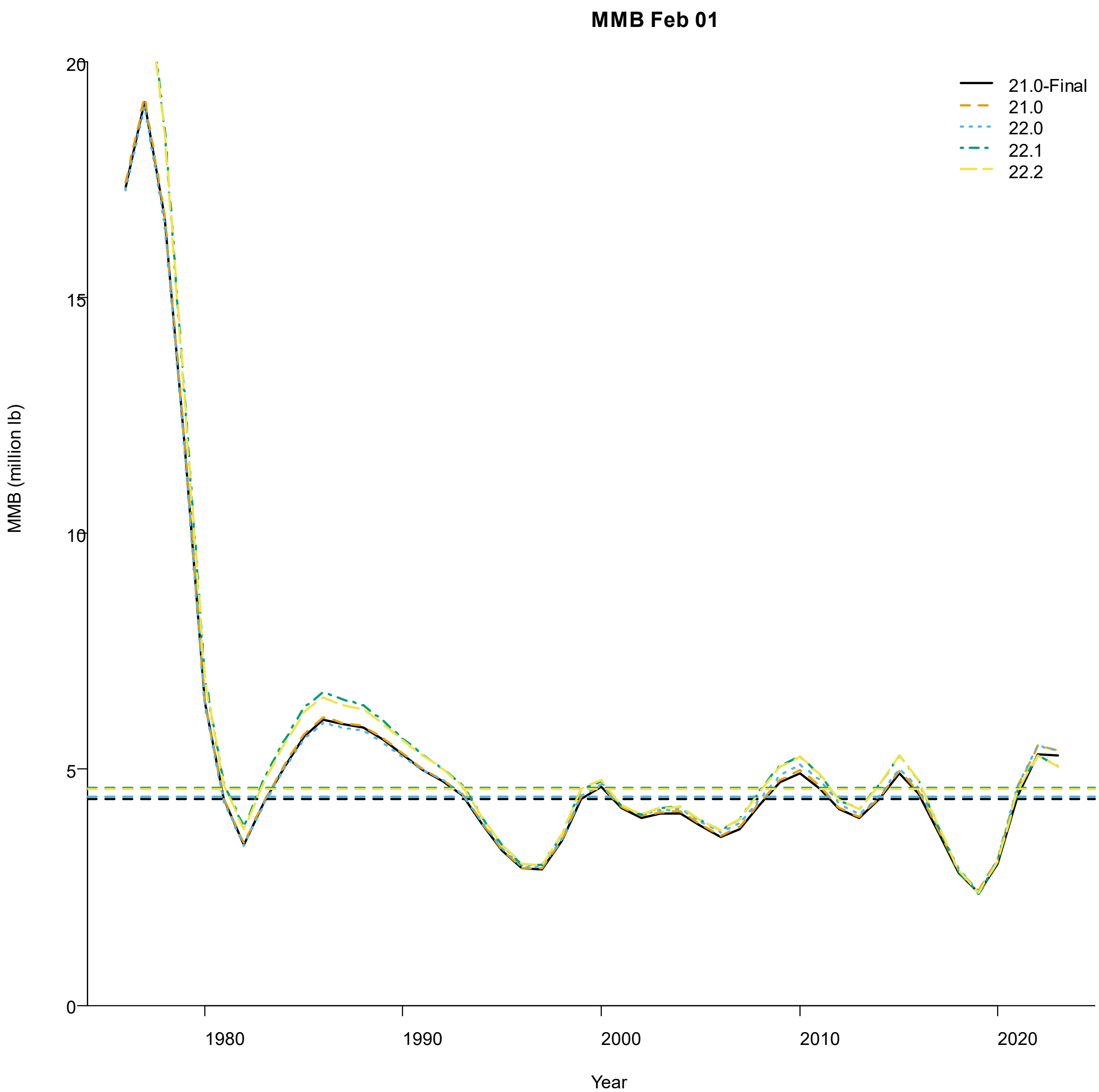

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Figure 6. Observed (open circle) (White: NMFS, Red: ADF&G) and model trawl survey male abundances with 95% lognormal Confidence Intervals (crab ≥ 64 mm CL).

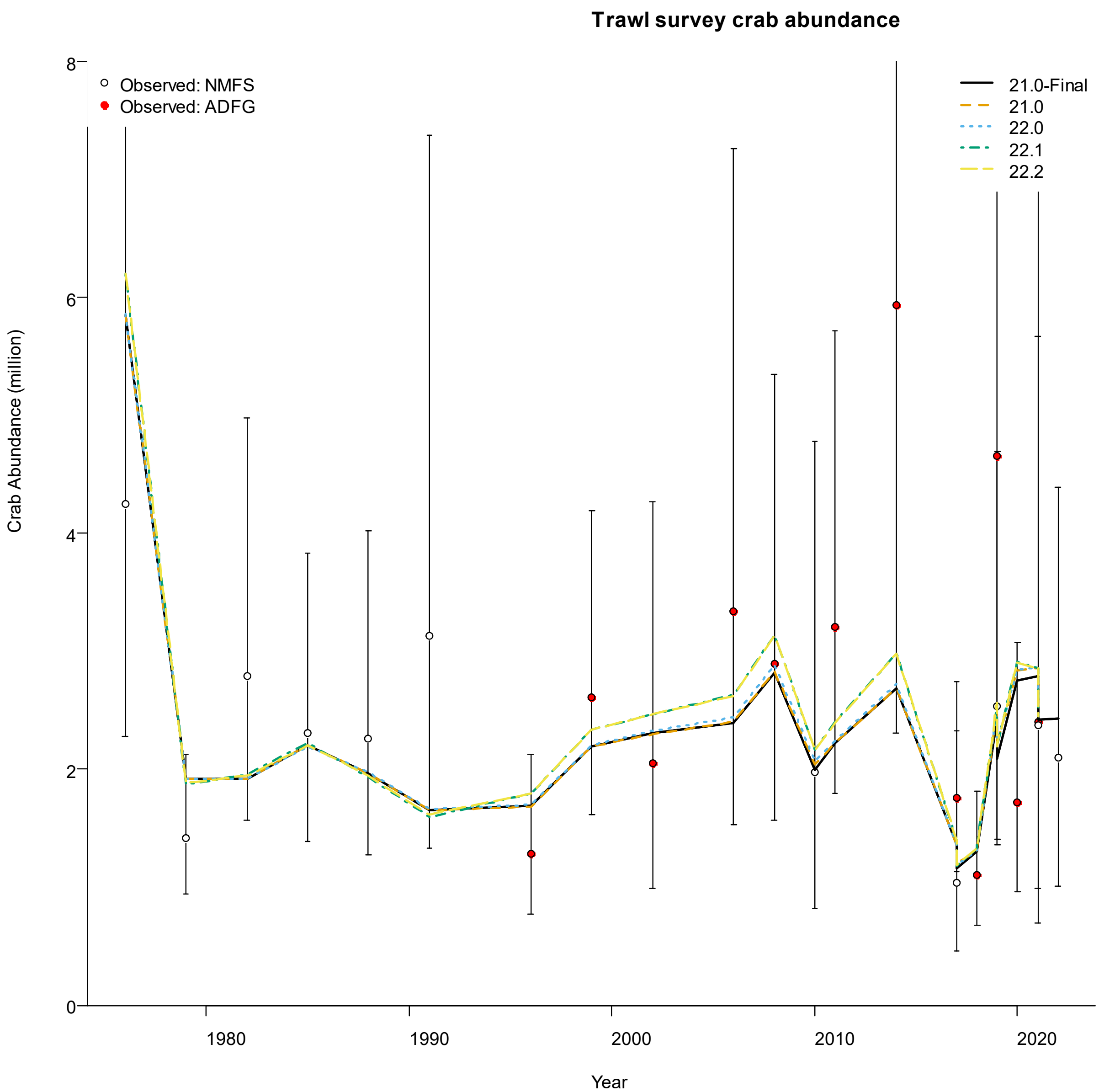

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Figure 7. Observed (open circle) with 95% lognormal Confidence Intervals with additional variance (gray), and model estimated standardized CPUE.

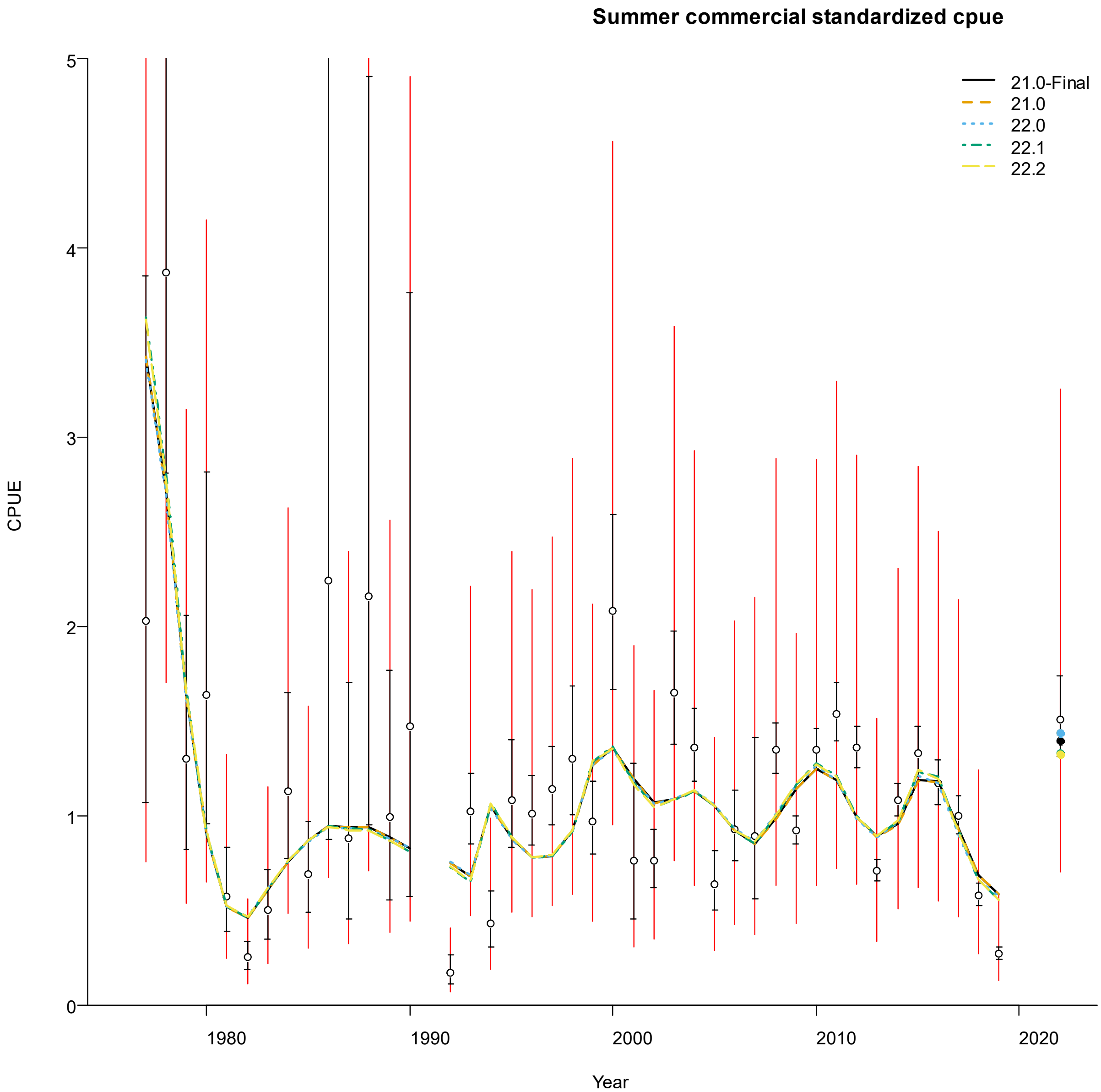

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Figure 8. Predicted (line) vs. observed (bar New Shell: blue, Old Shell: green) length class proportions for the summer commercial harvest 1977-2022.

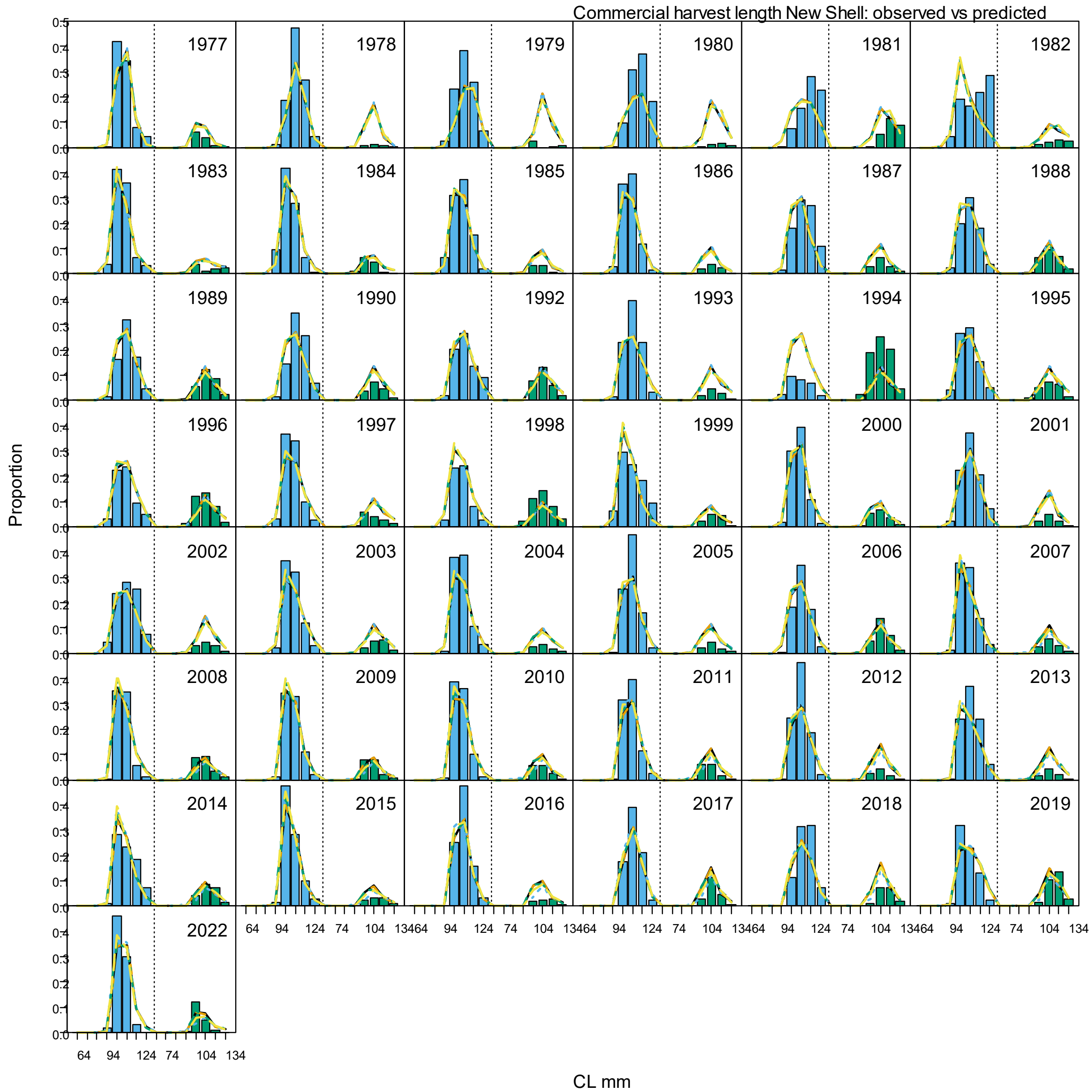

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Figure 9. Predicted (line) vs. observed (bar New Shell: blue, Old Shell: green) length class proportions for trawl survey 1976-2022.

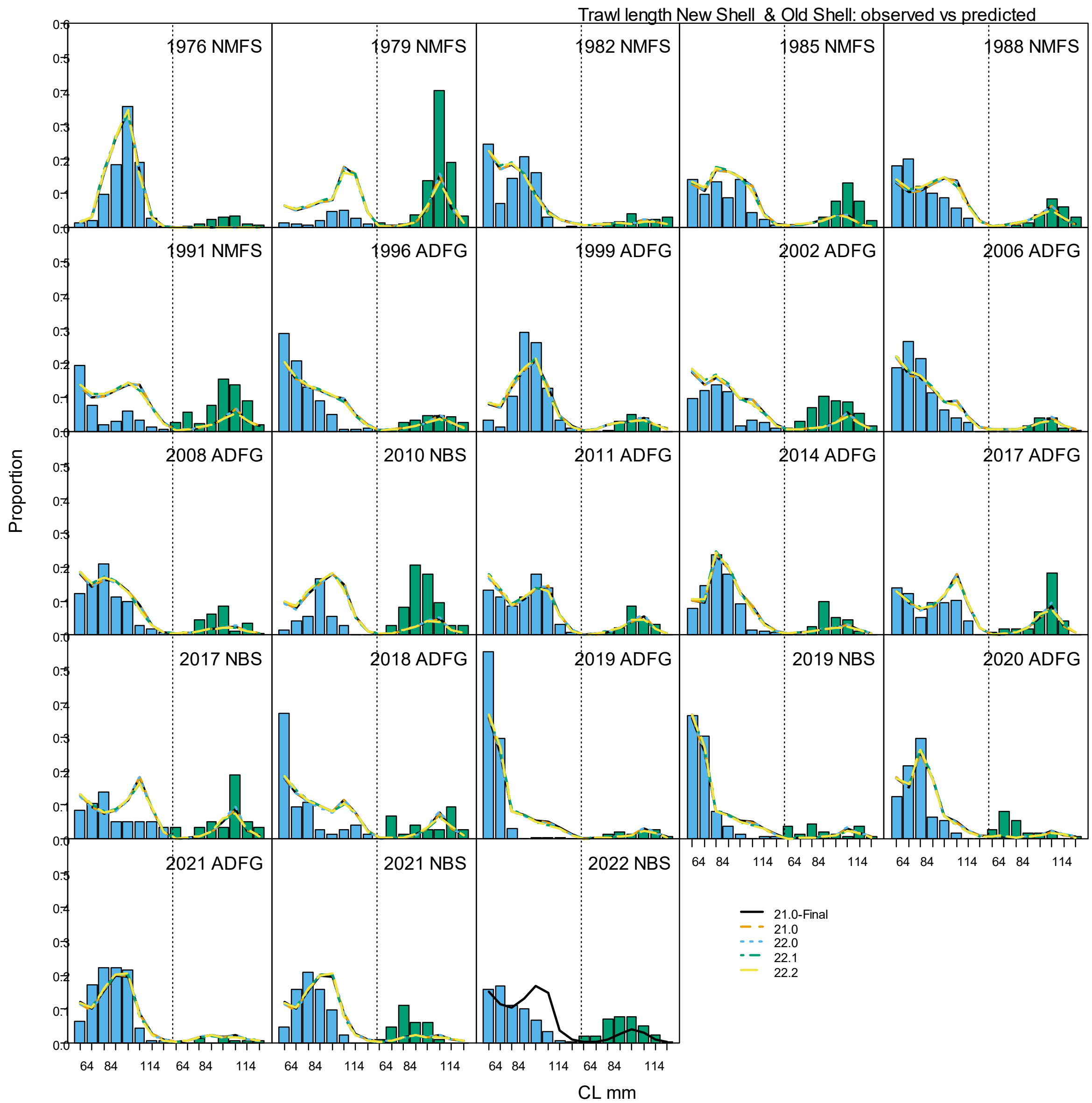

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Figure 10. Predicted (line) vs. observed (bar New Shell: blue, Old Shell: green) length class proportions for winter pot survey 1982-2012.

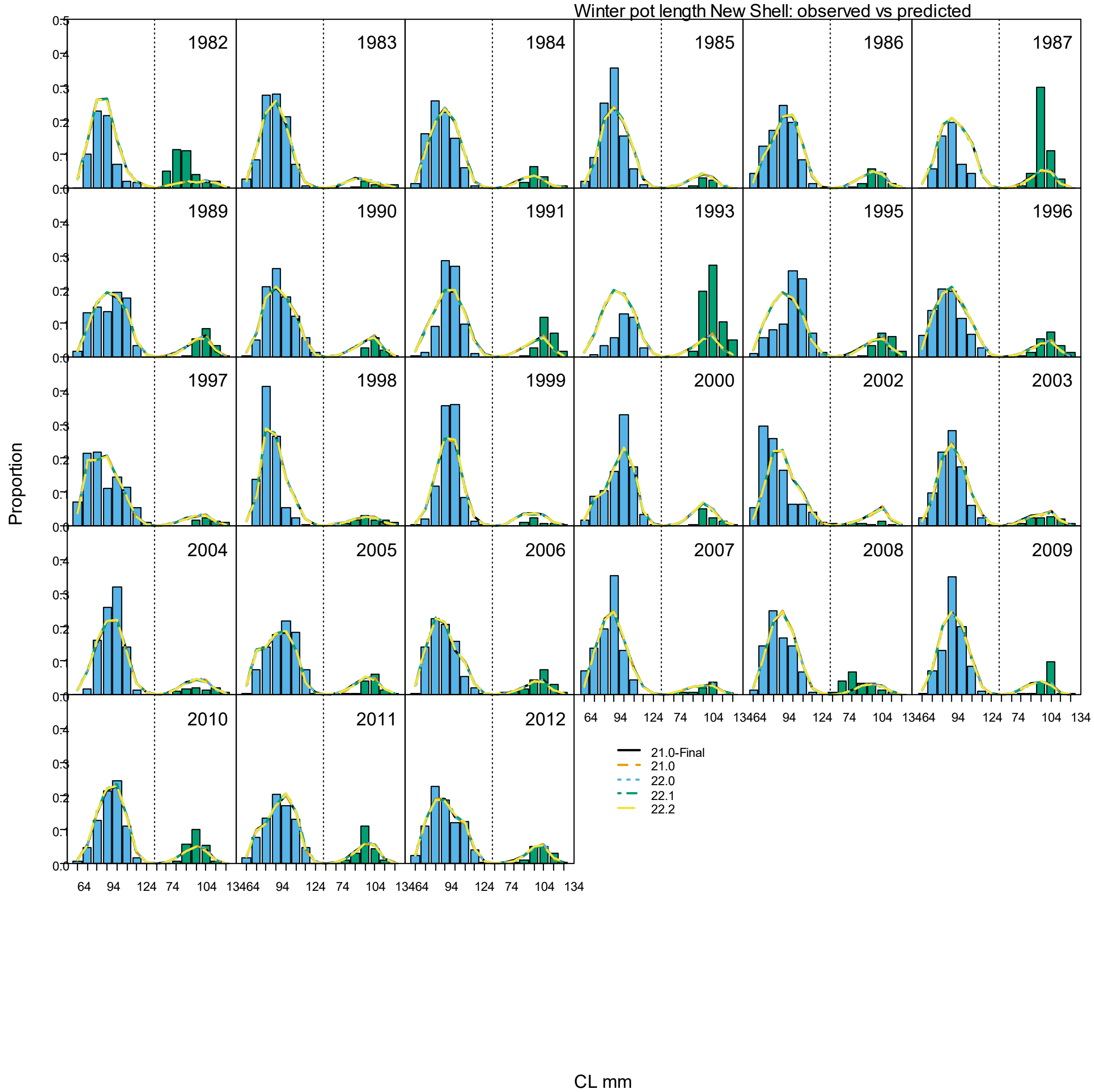

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Figure 11. Predicted (line) vs. observed (bar New Shell: left blue, Old Shell: right green) length class proportions for summer commercial total and discards (1987-1994, 2012-2019) and winter commercial retained fishery 2015-2018

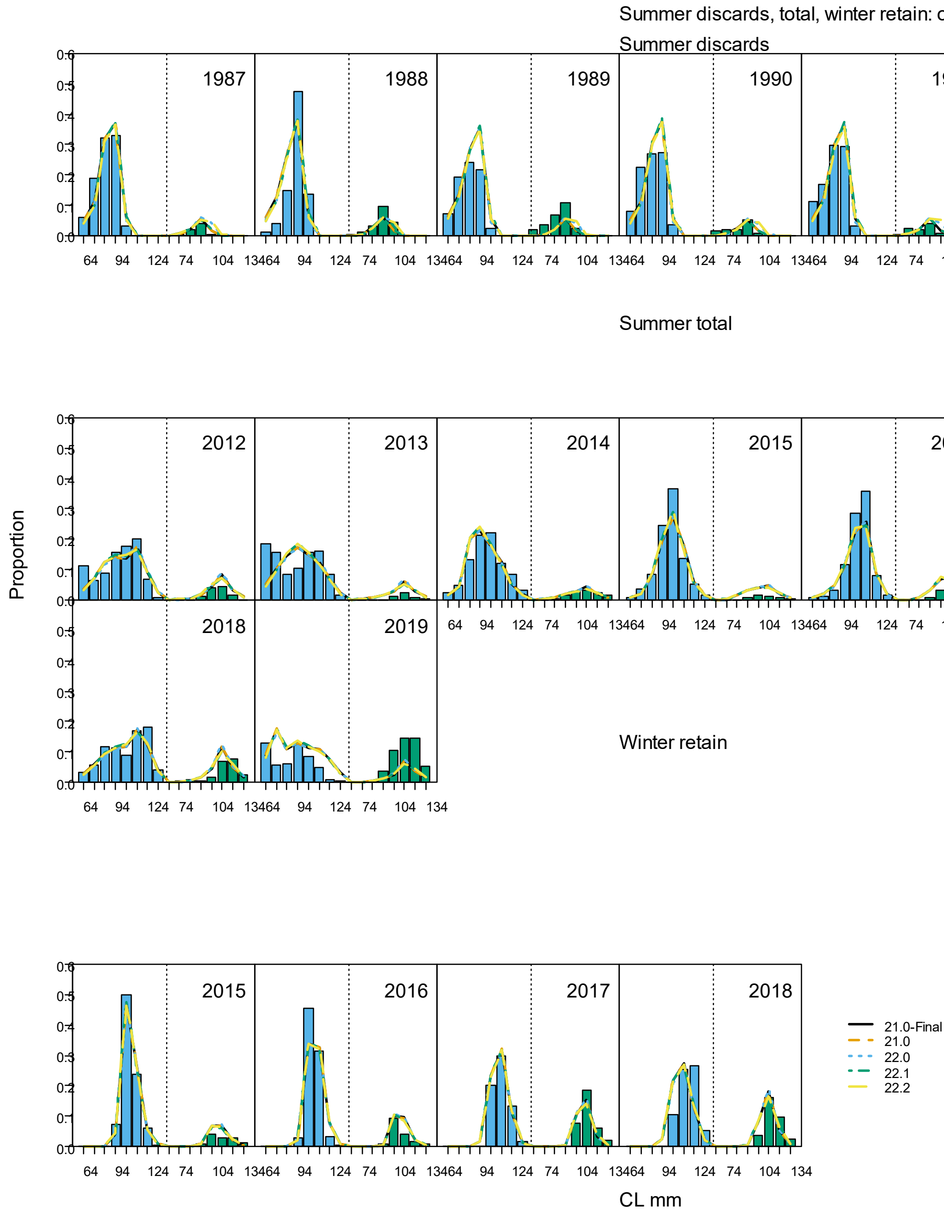

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Figure 12. Predicted (line) vs. observed (bar) length class proportions for tag recovery data.

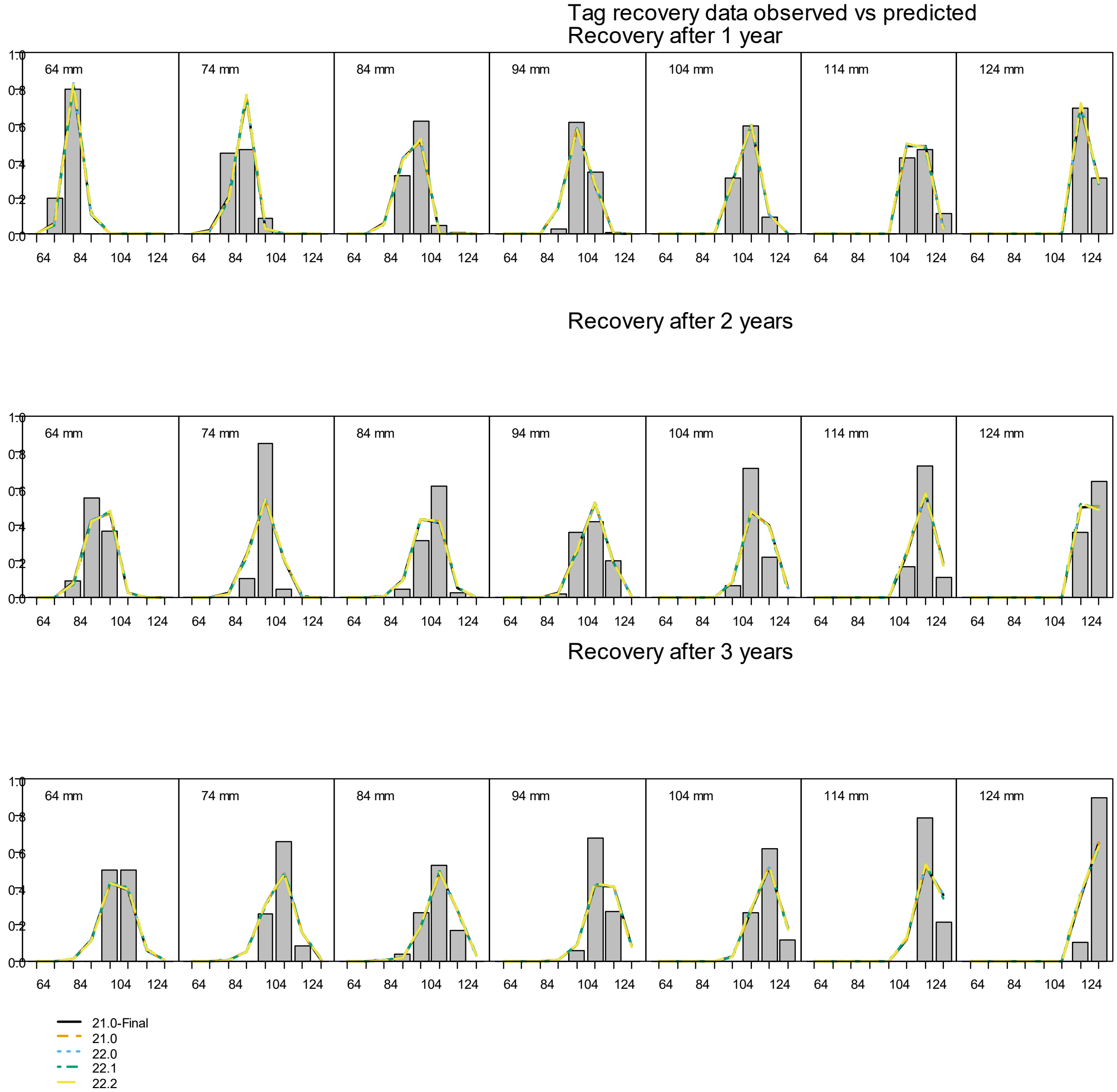

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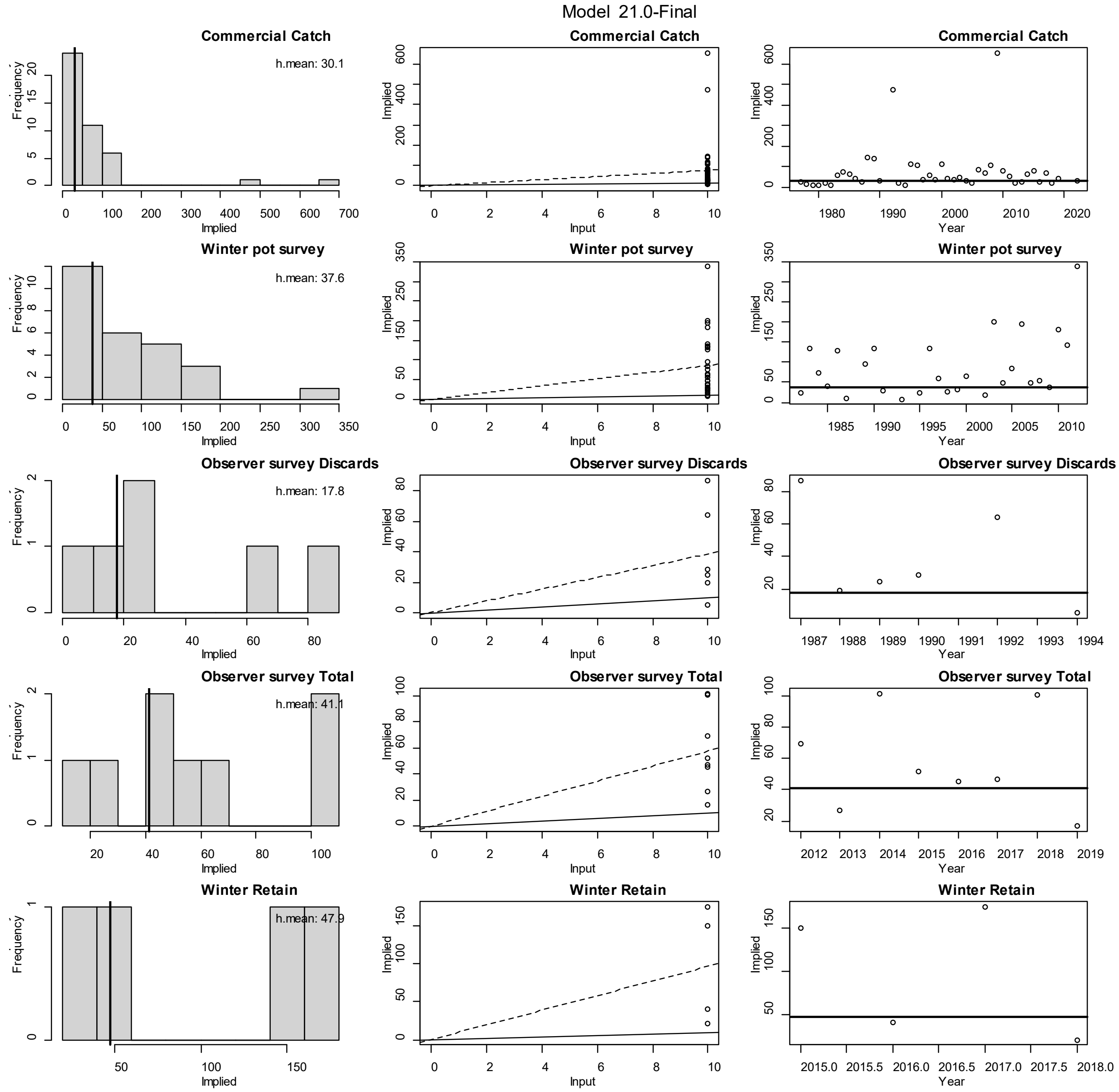
Figure 13. Input vs. model implied effective sample size. Figures in the first column show implied effective sample size (x-axis) vs. frequency (y-axis). Vertical solid line is the harmonic mean of implied sample size. Figures in the second column show input sample sizes (x-axis) vs. implied effective sample sizes (y-axis). Dashed line indicates the linear regression slope, and solid line is 1:1 line. Figures in the third column show years (x-axis) vs. implied effective sample sizes (y-axis). Horizontal solid line is the harmonic mean of implied sample size.



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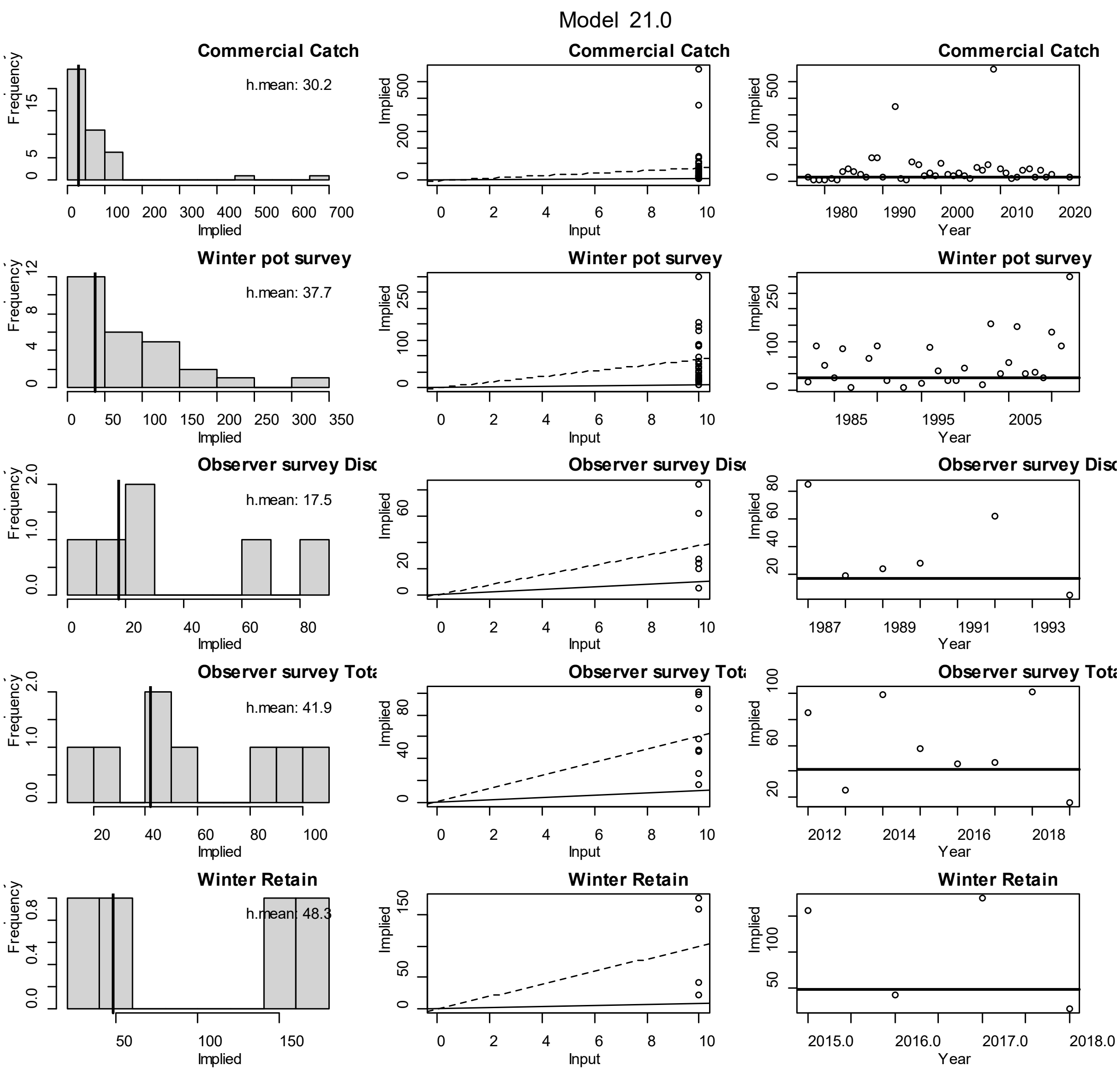

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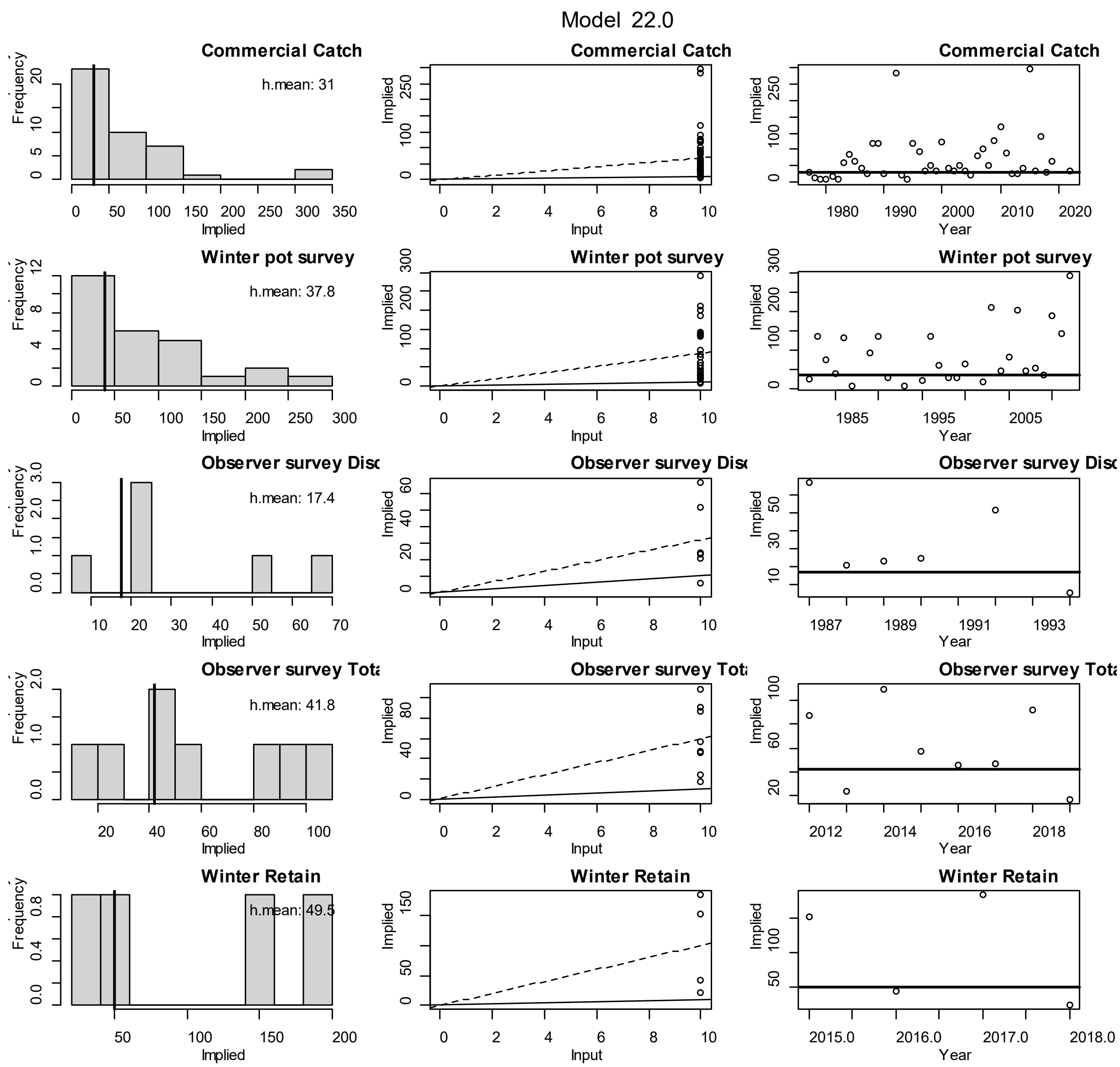

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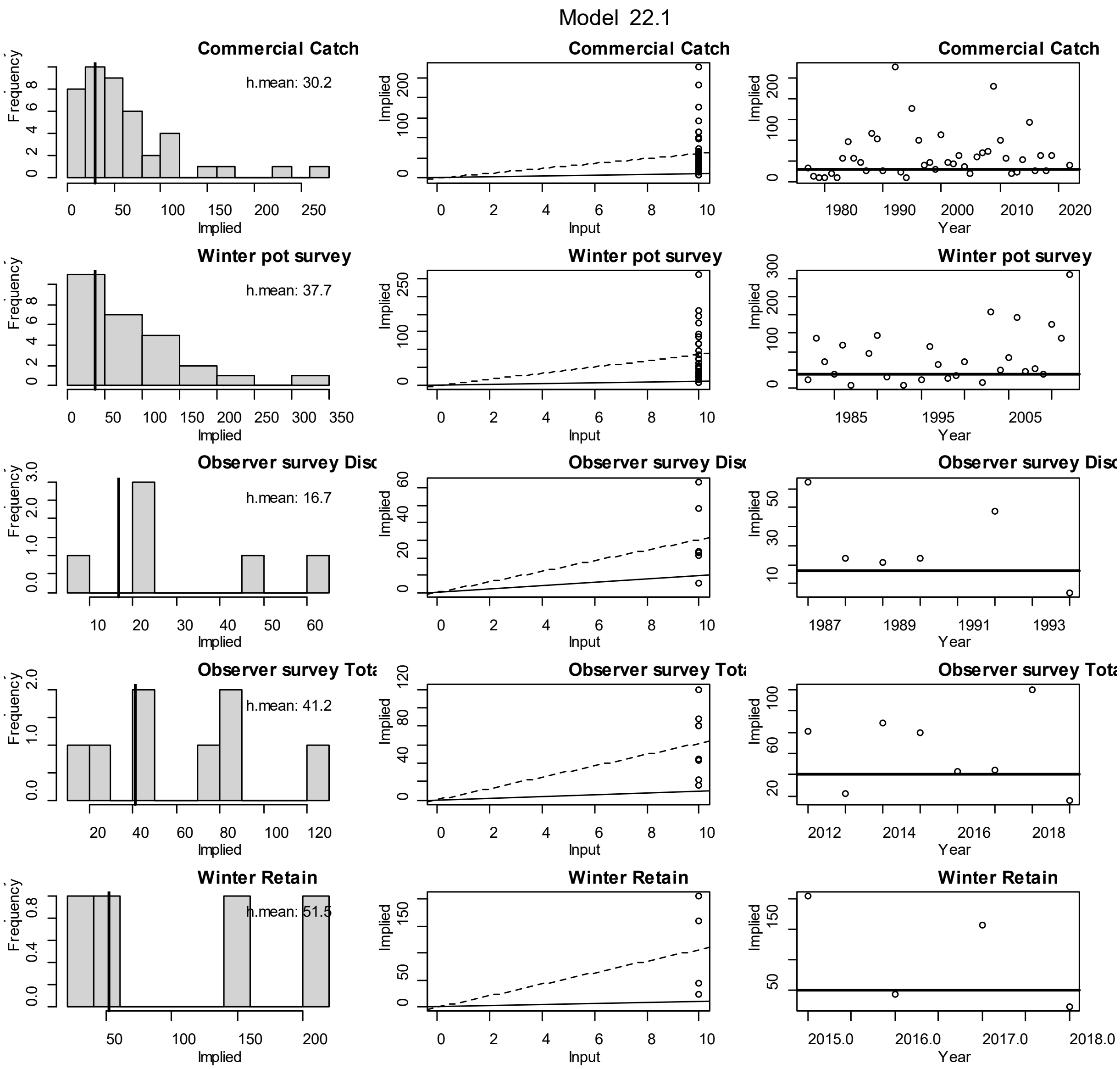

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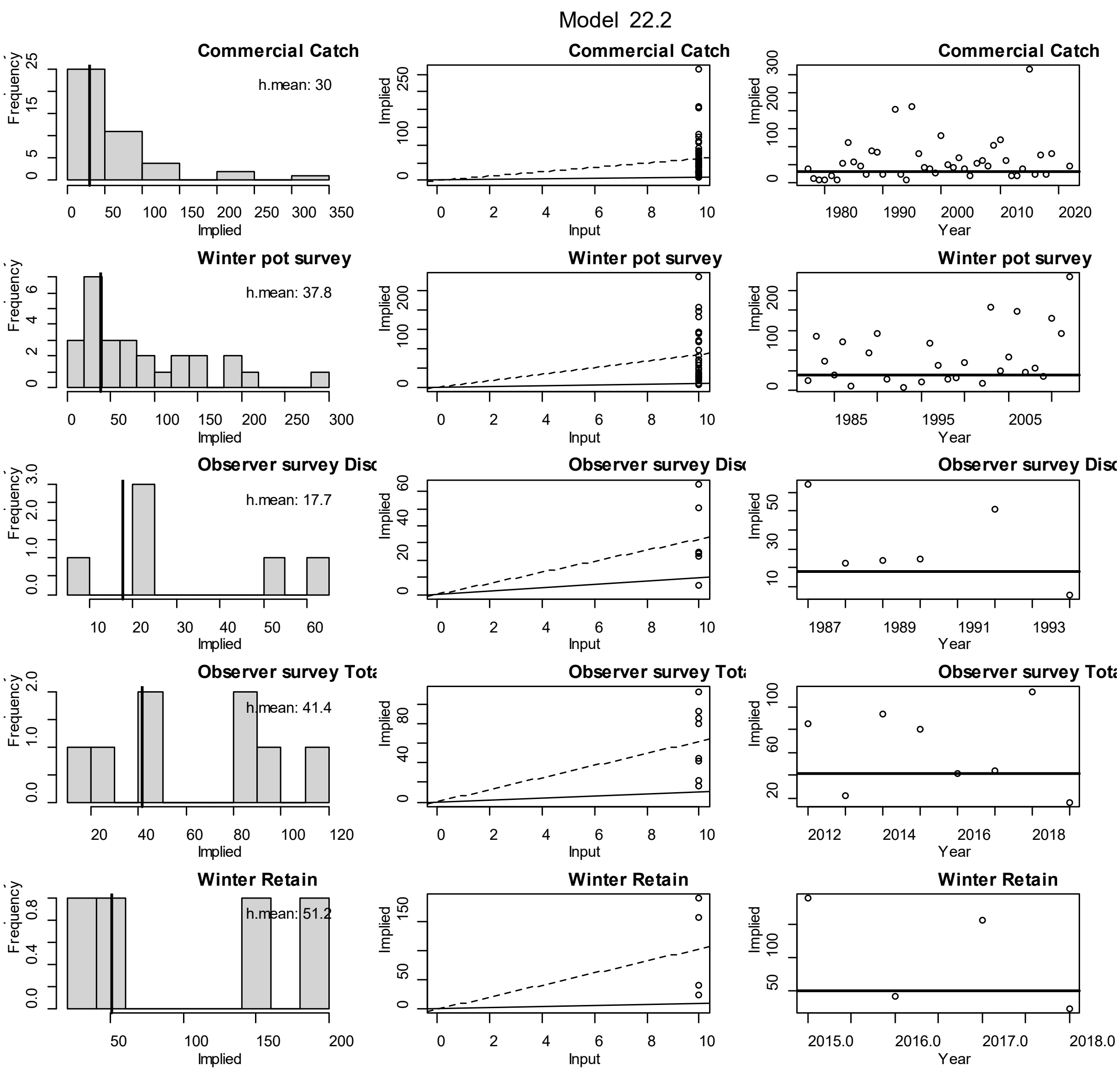
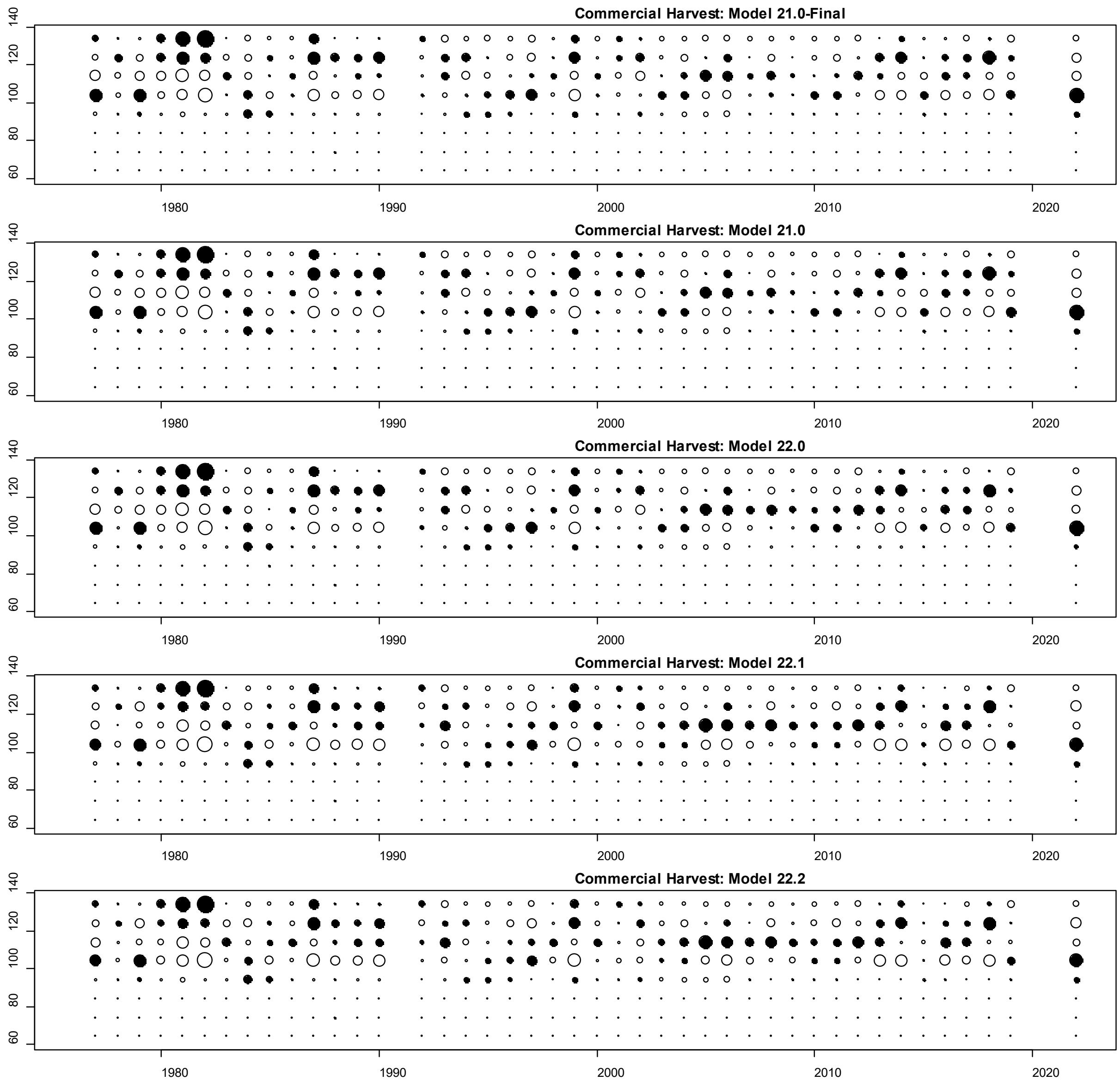


Figure 14. Bubble plots of predicted and observed length proportions.
Black circles indicate model underestimates compared to observed, and white circles indicate model overestimates compared to observed. Size of circle indicates degree of deviance (larger circle = larger deviance). In ideal model fit case, distribution of sizes and colors of circles should be random (i.e., no systematic model misfits).



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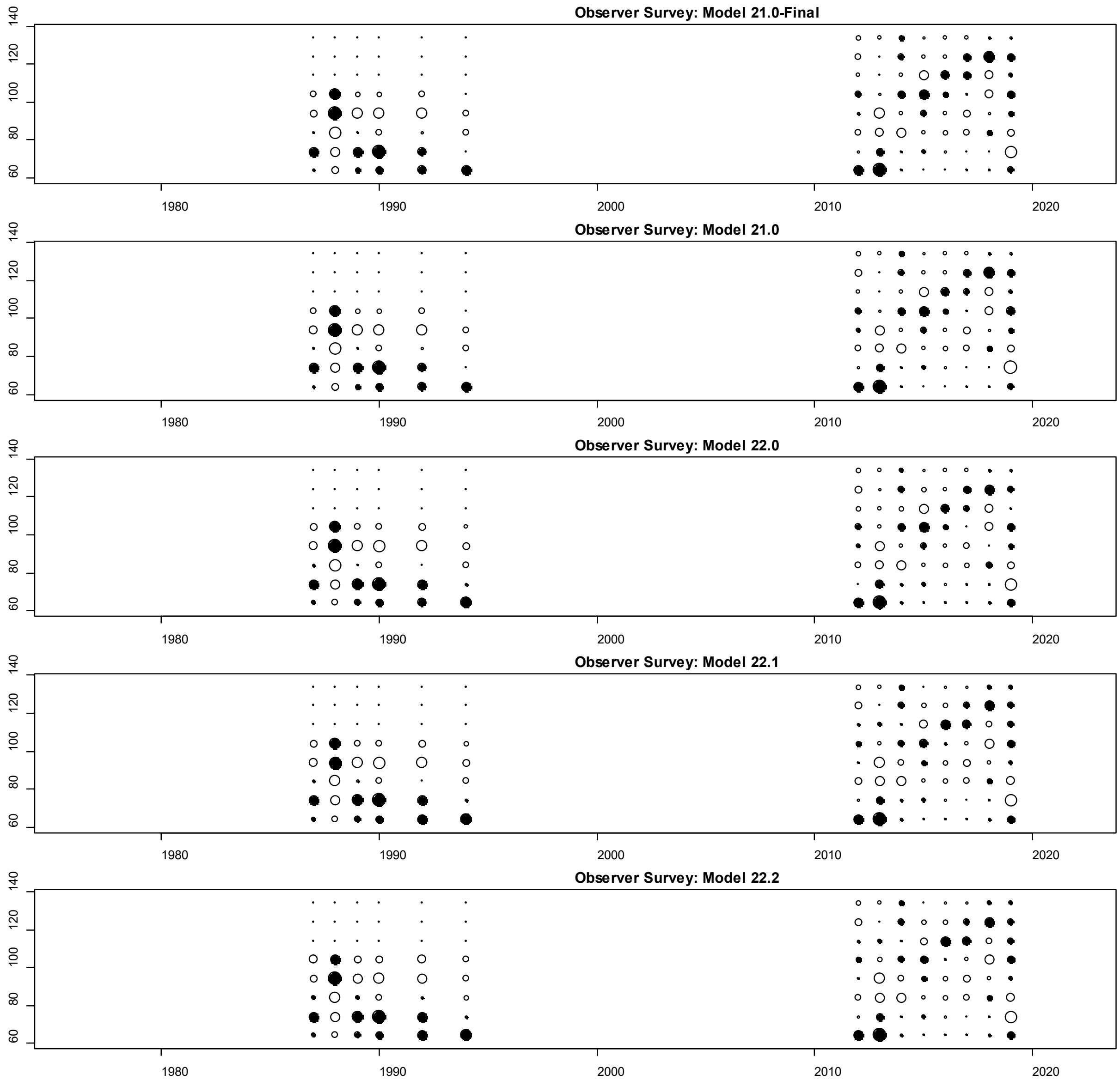

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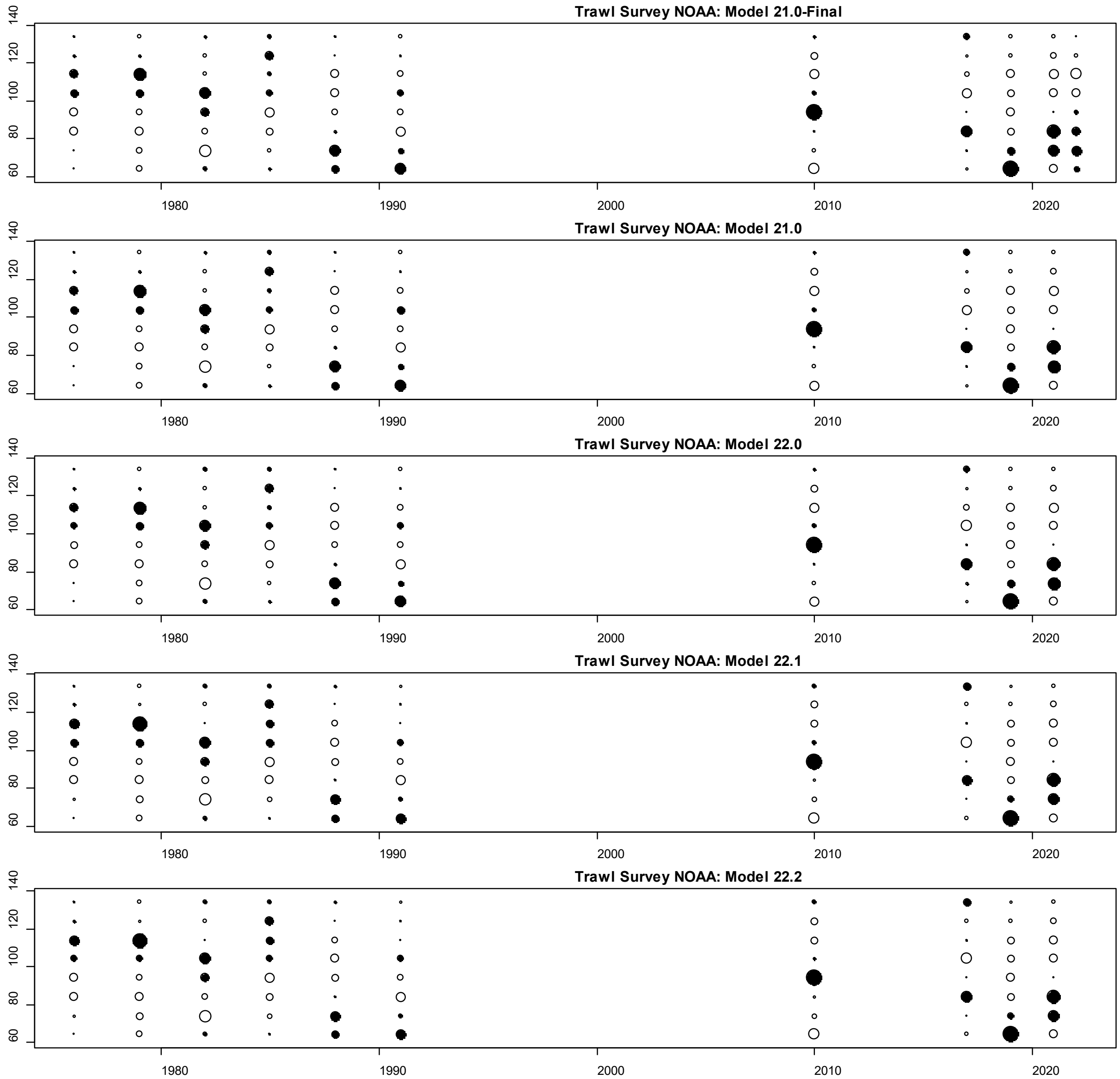

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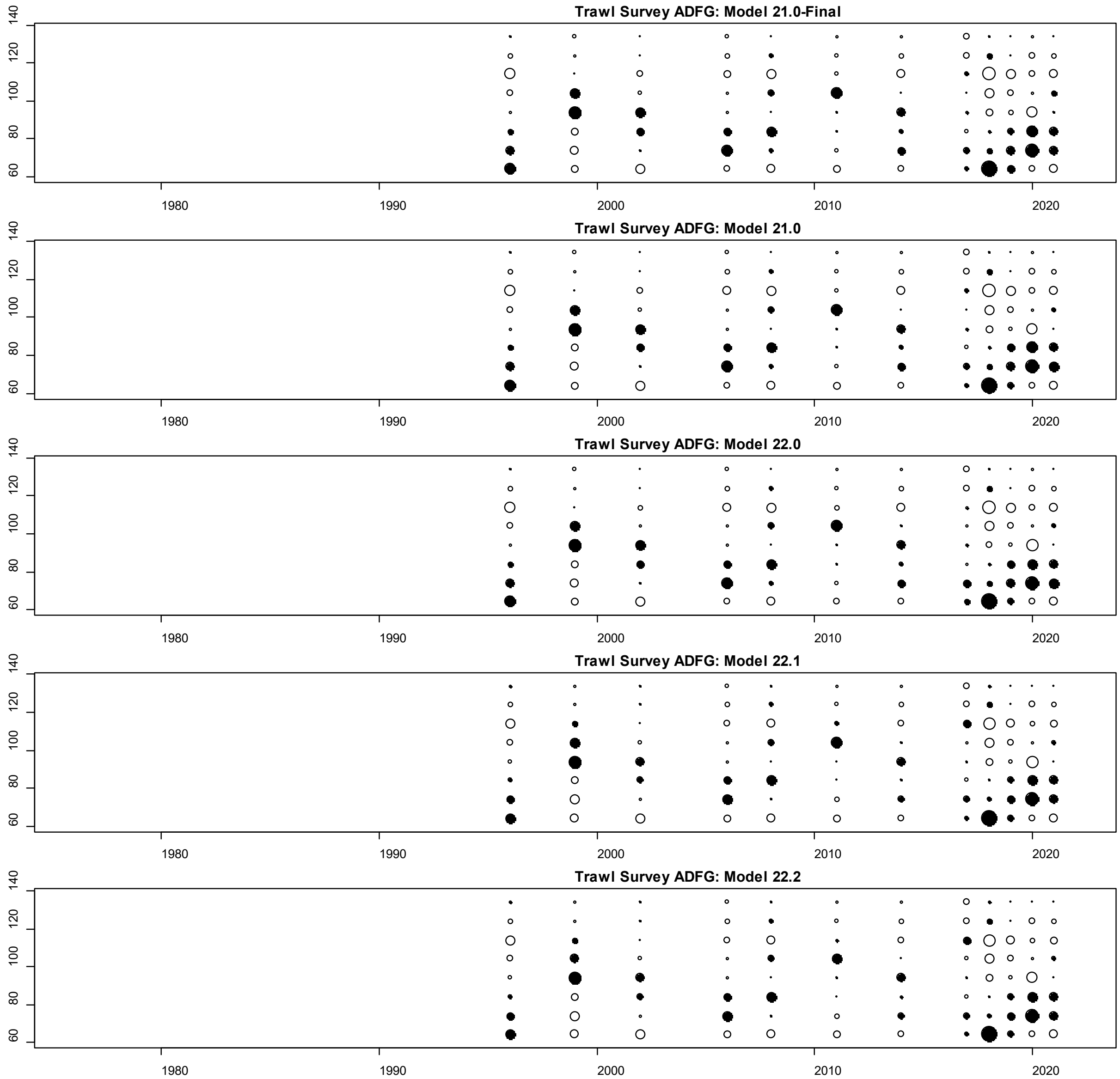

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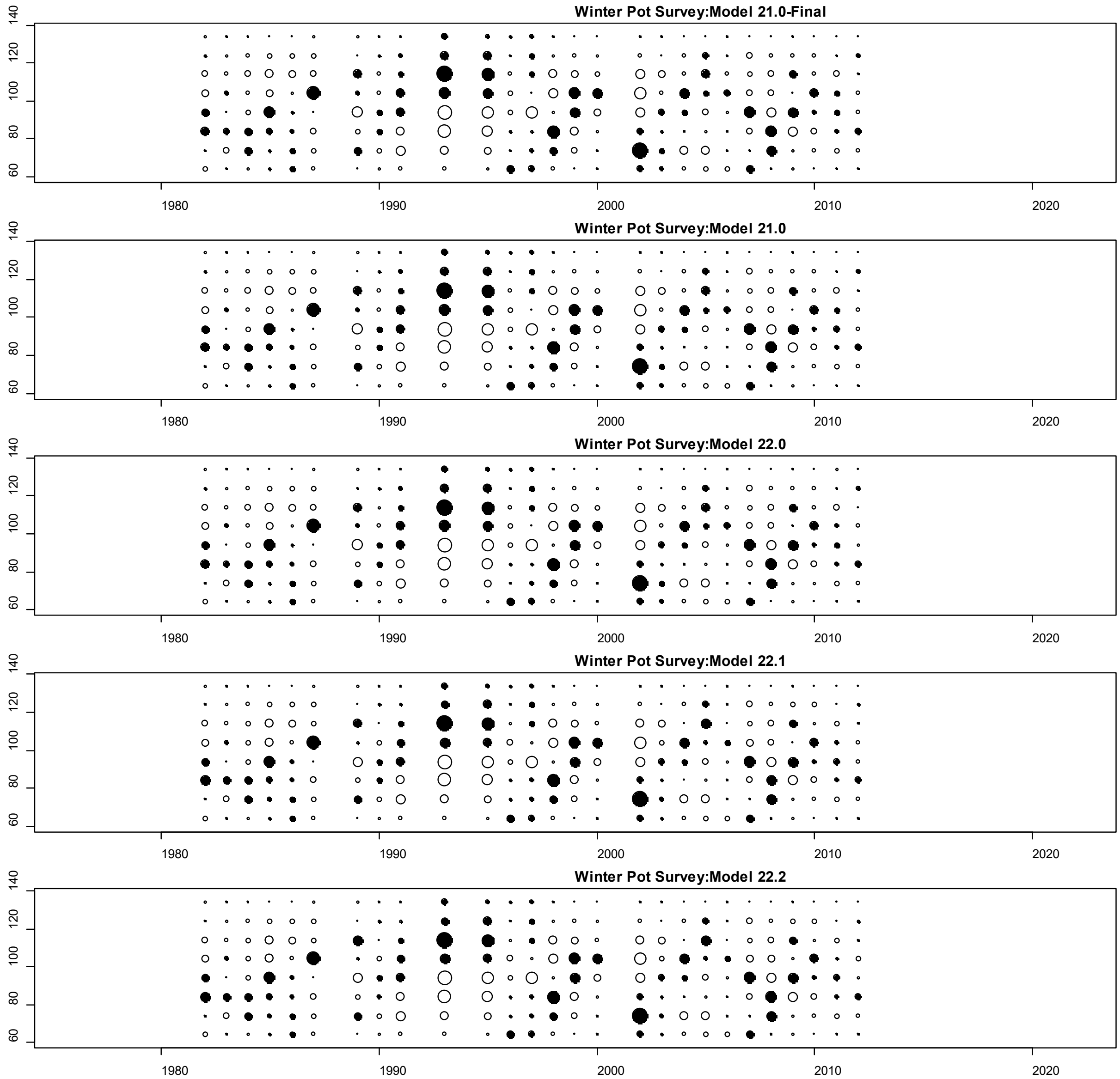

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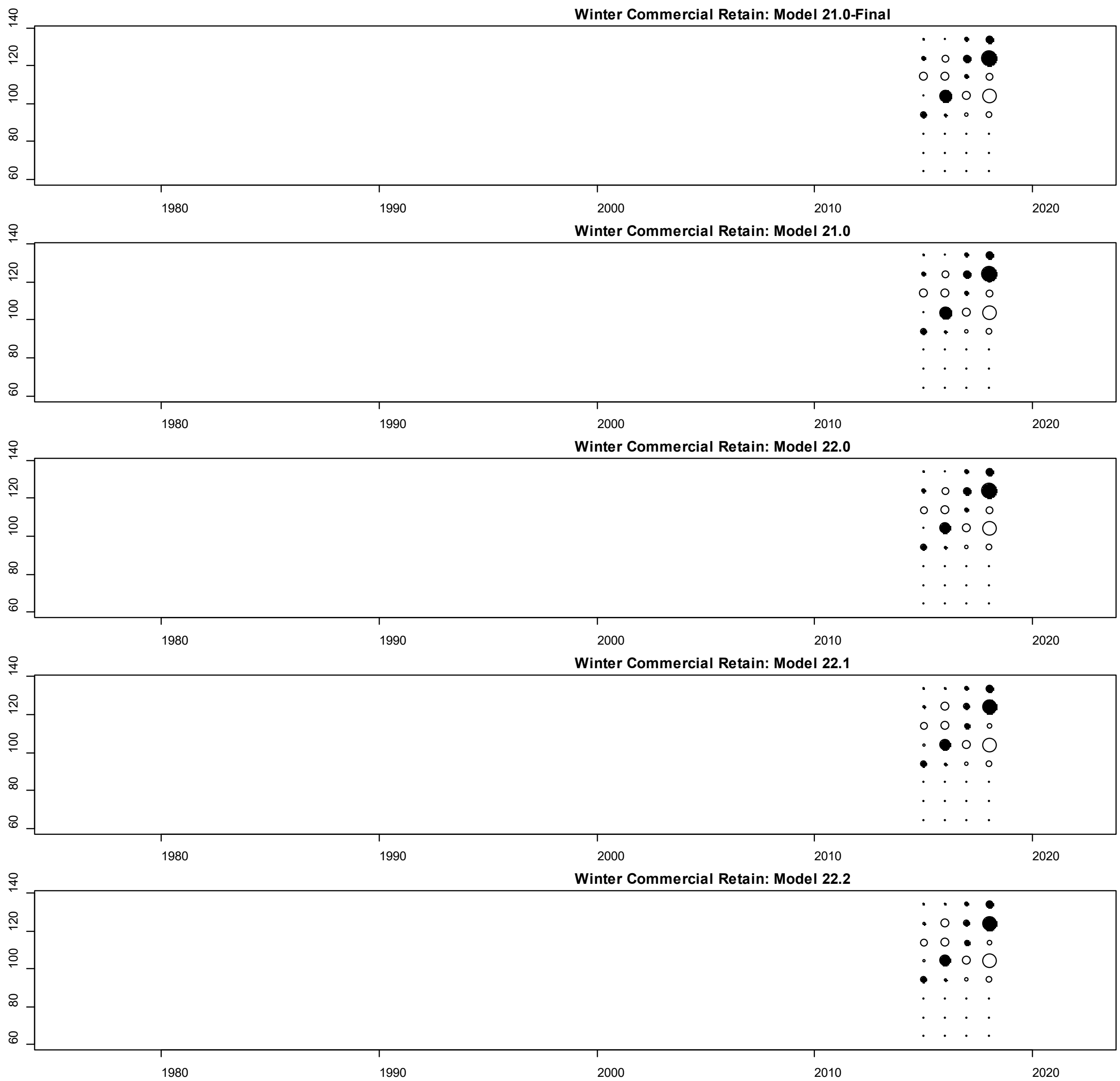

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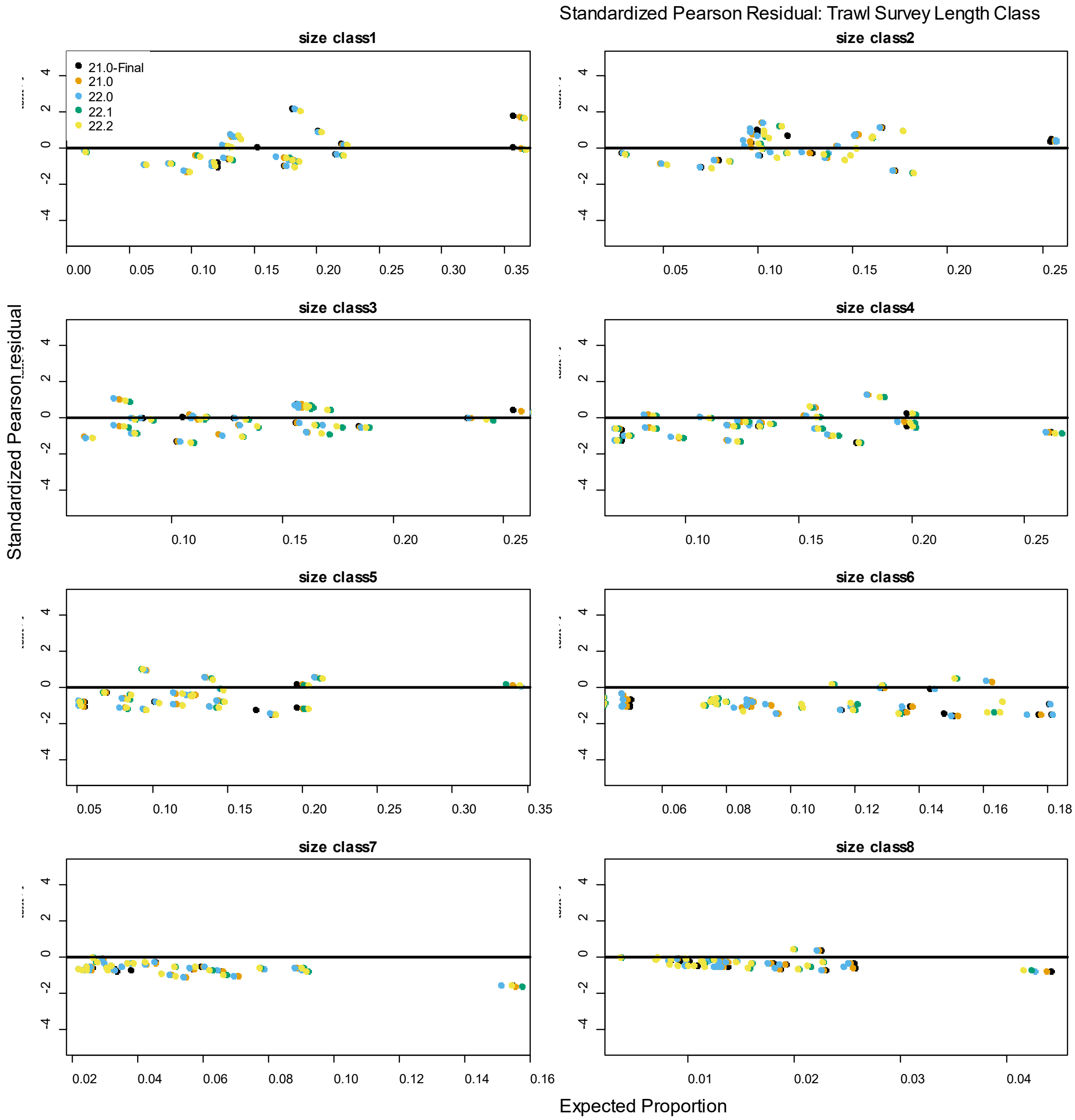
Figure 15. Standardized Pearson residual plots for trawl survey, summer commercial retained catch, winter pot survey, and observer for length size classes 1-8.



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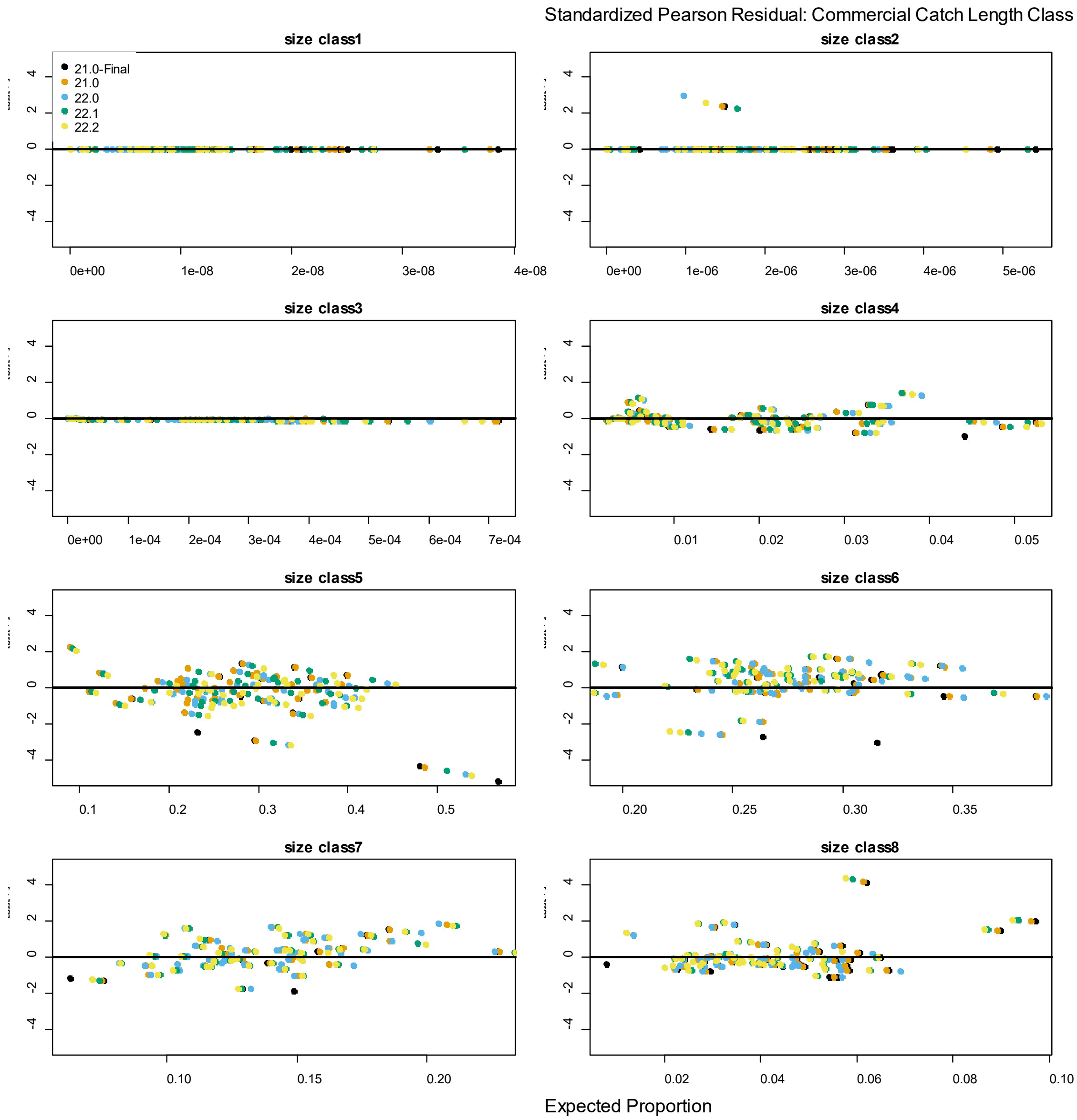

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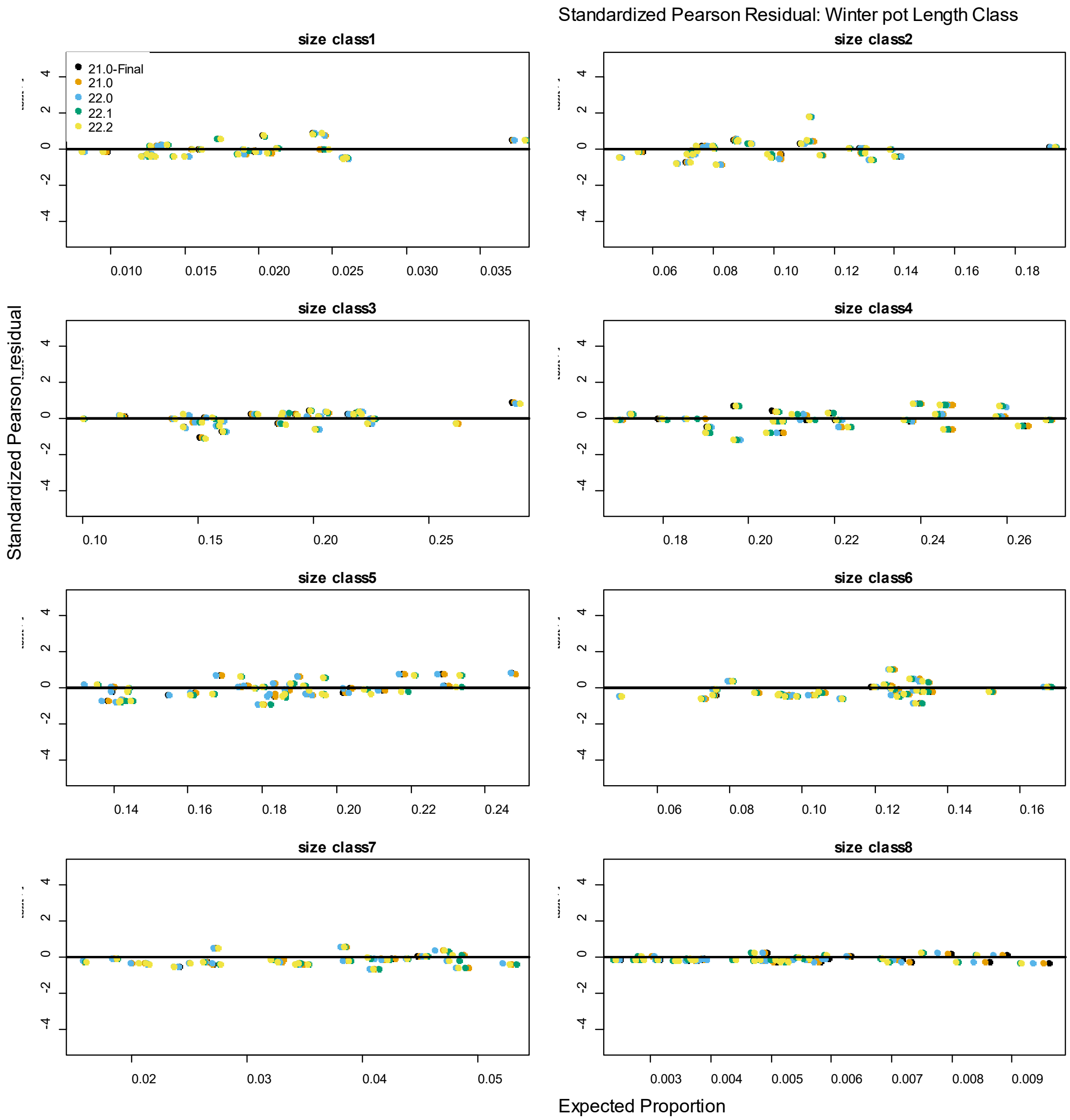

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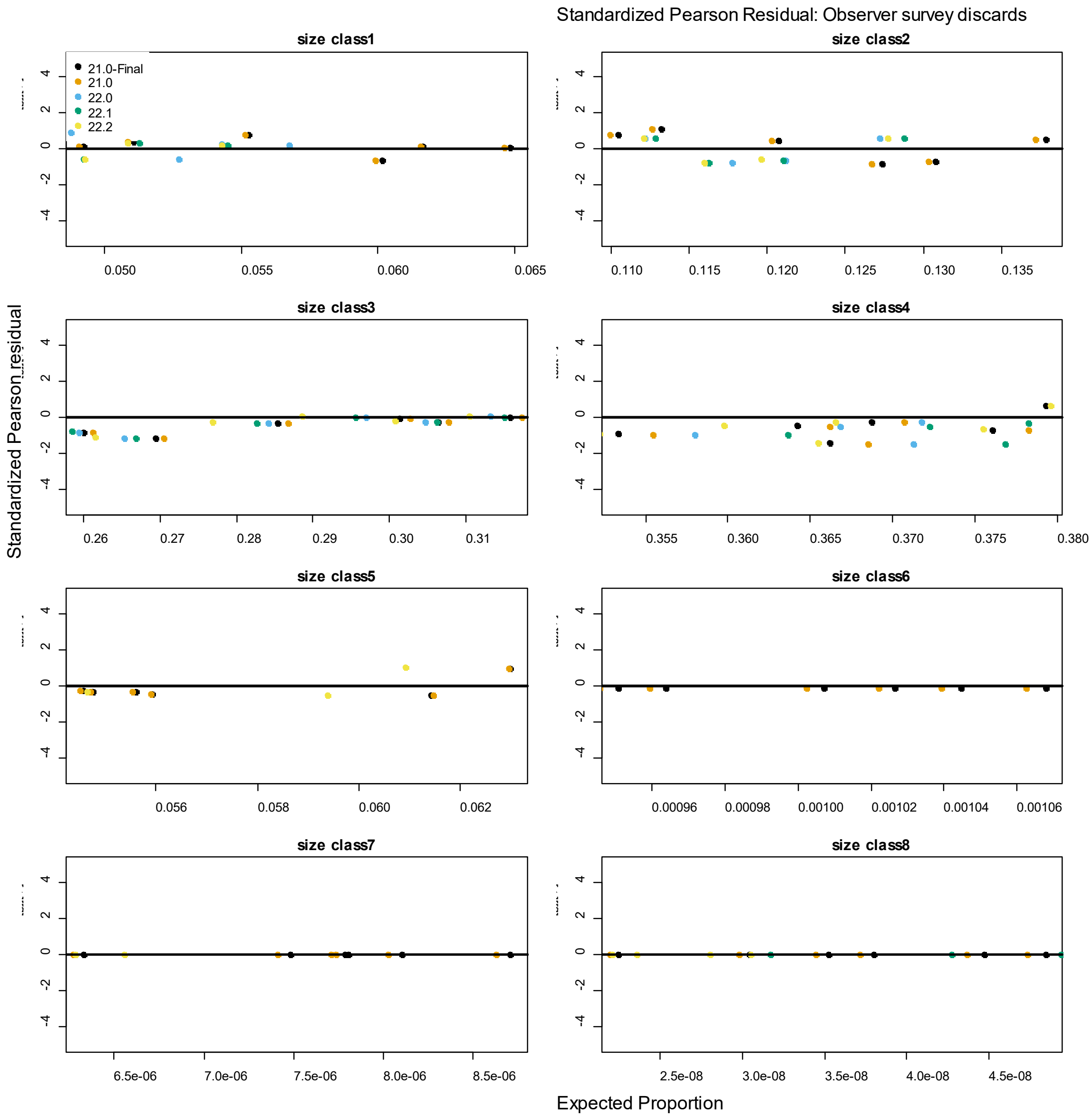

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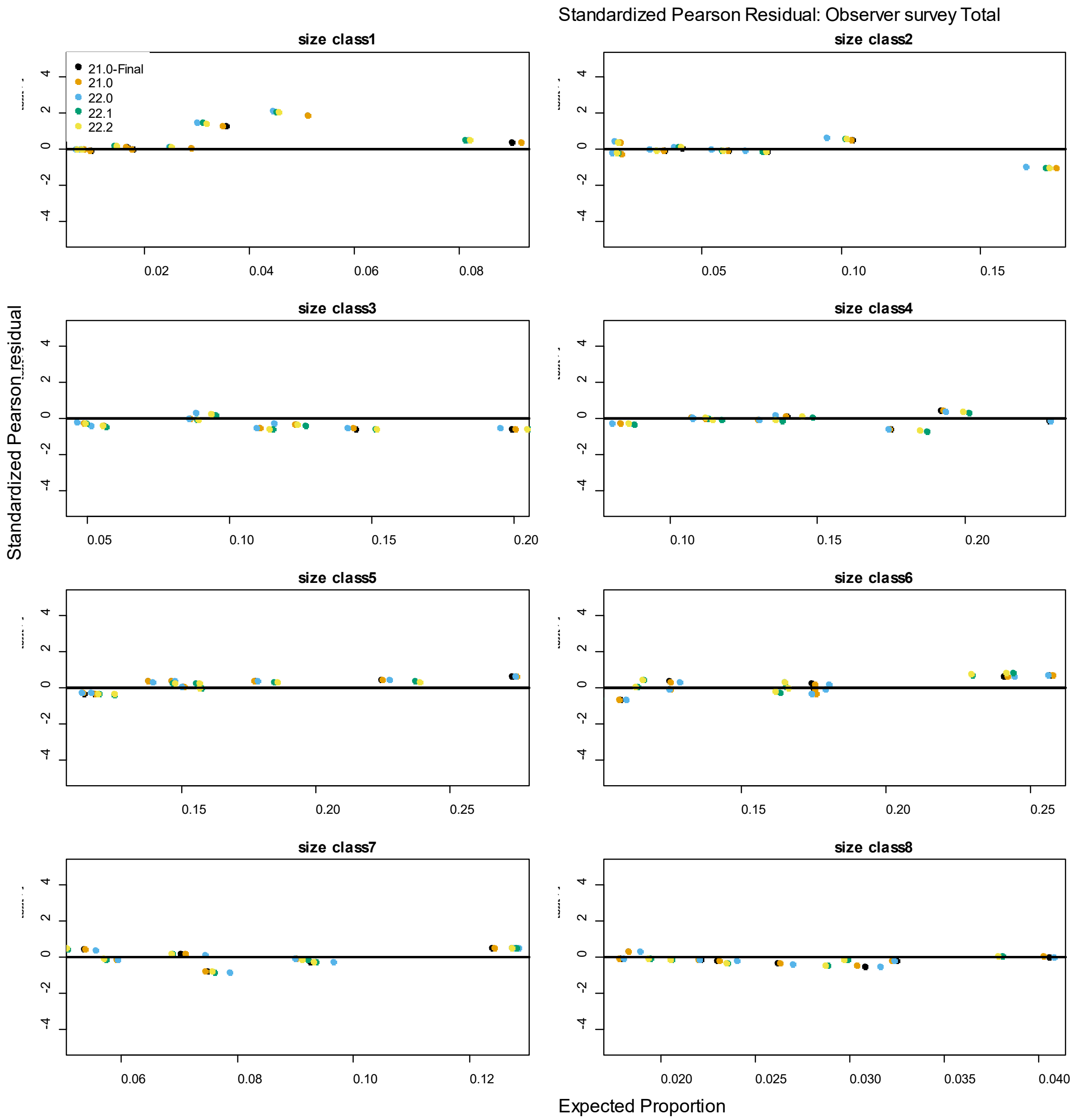

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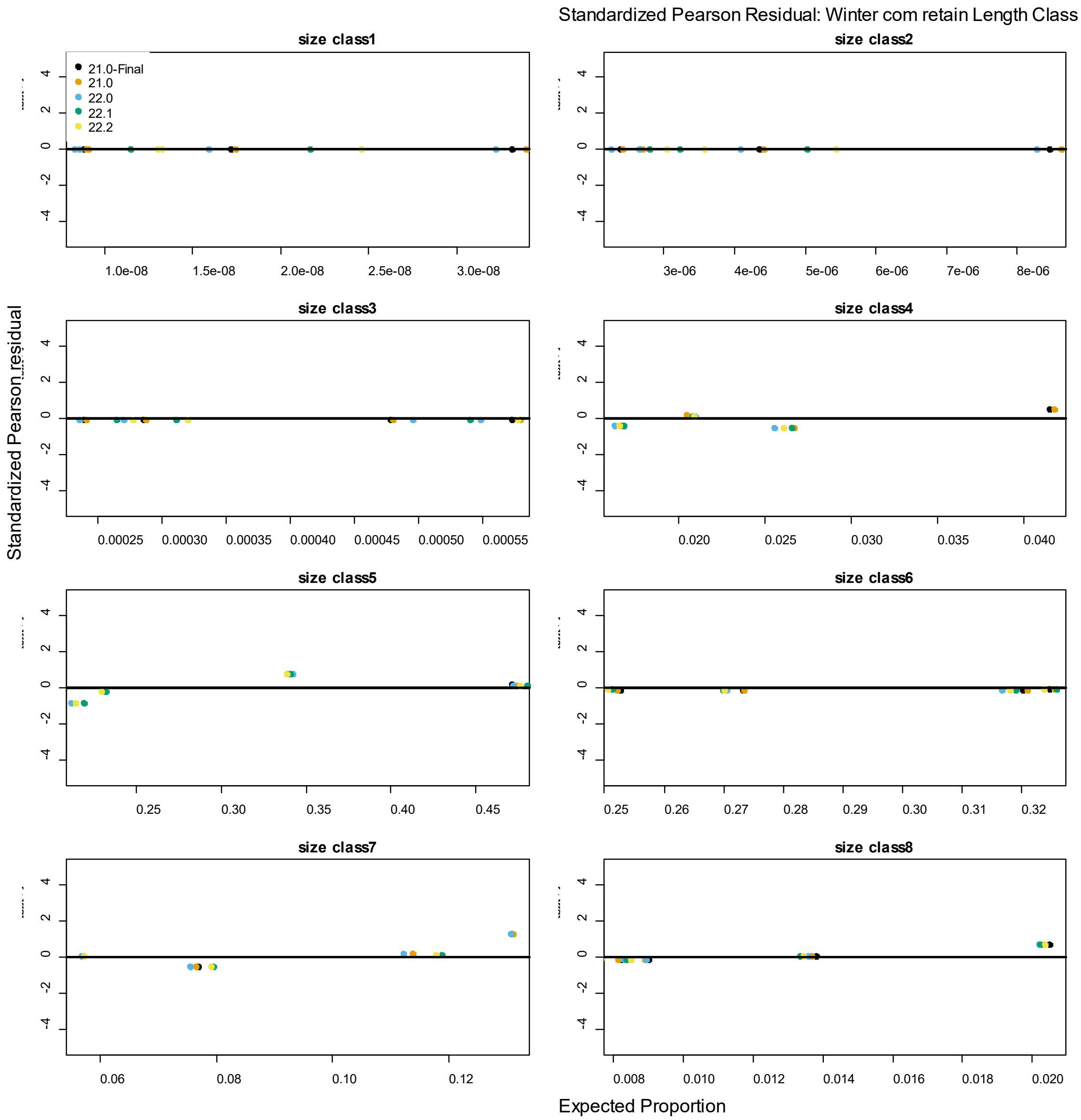
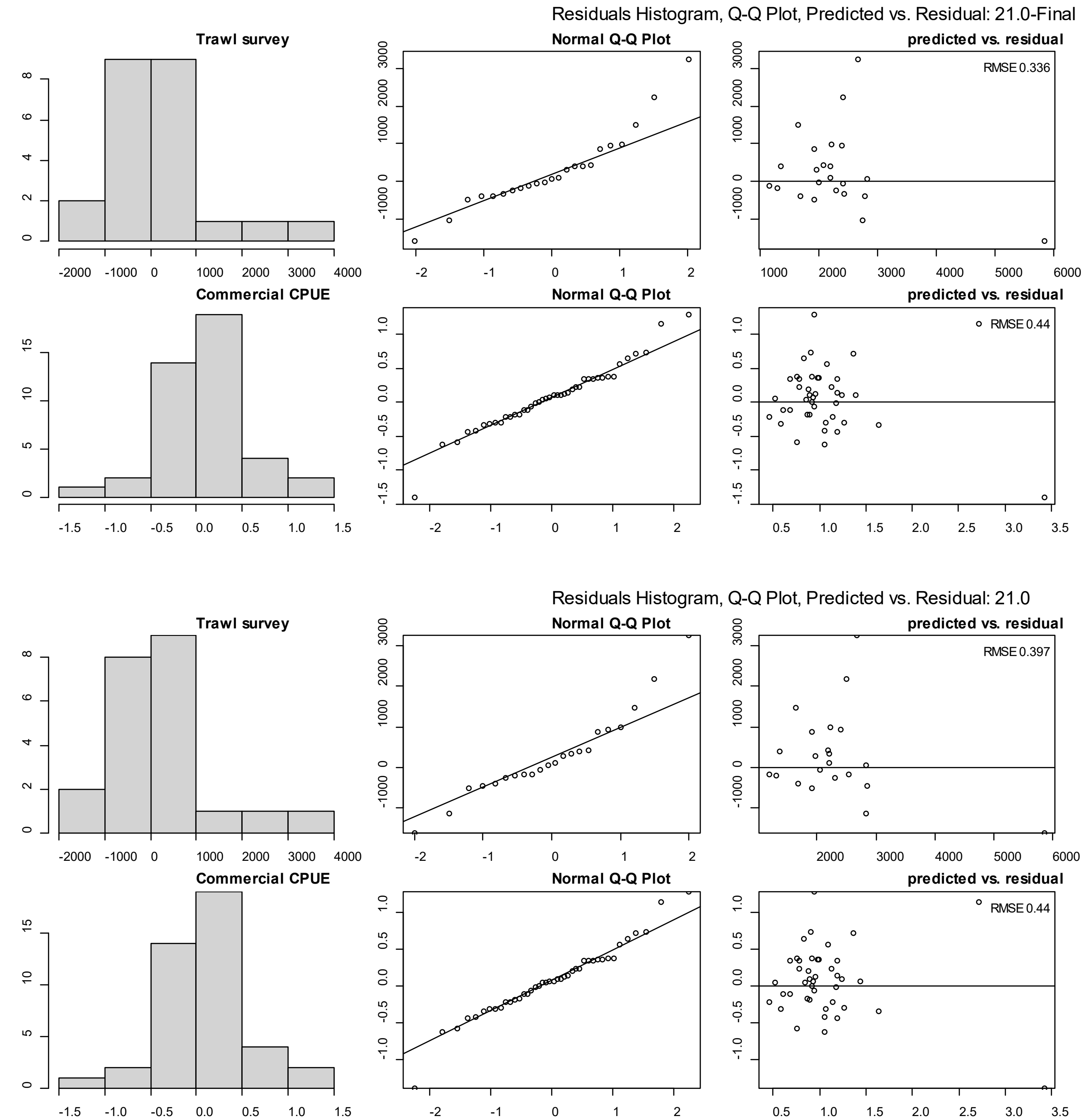


Figure 16. QQ Plot of Trawl survey and Commercial CPUE.



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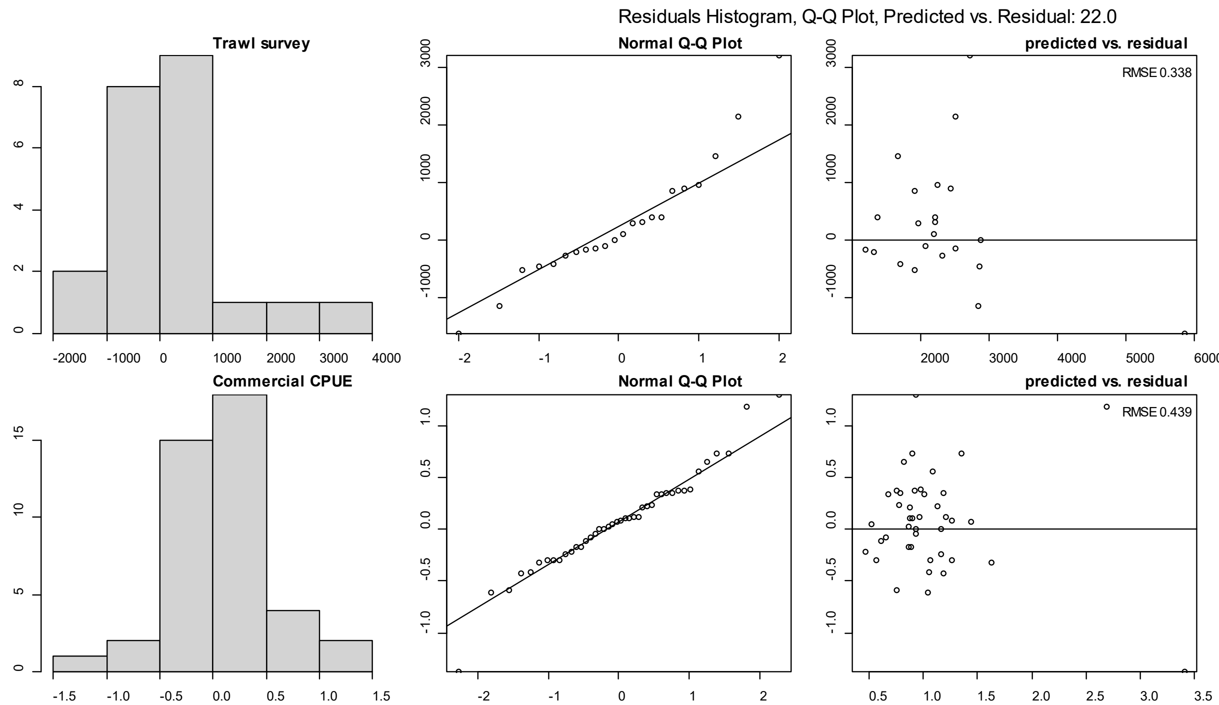

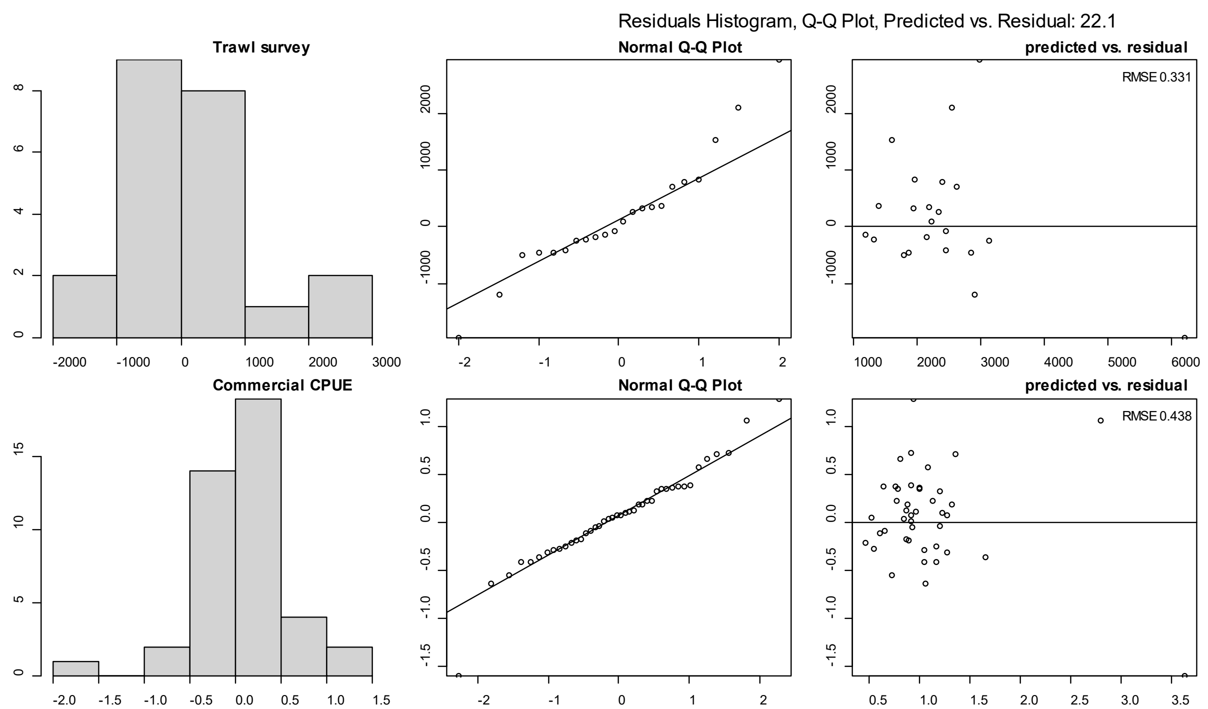

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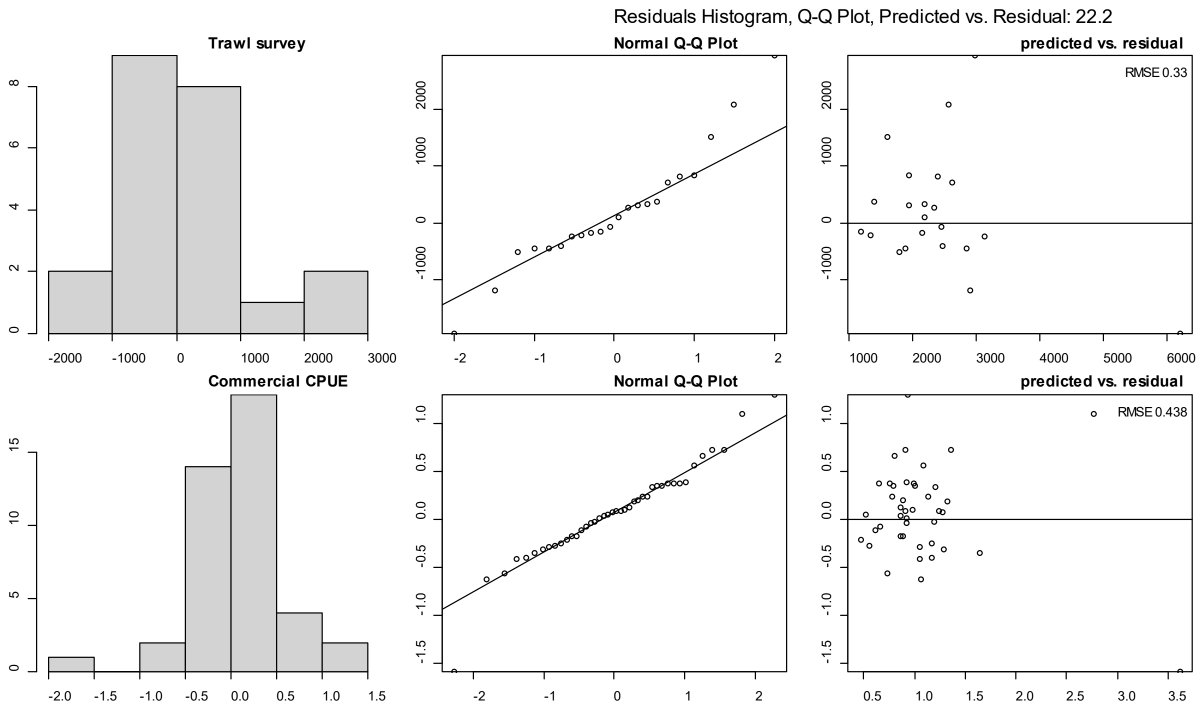

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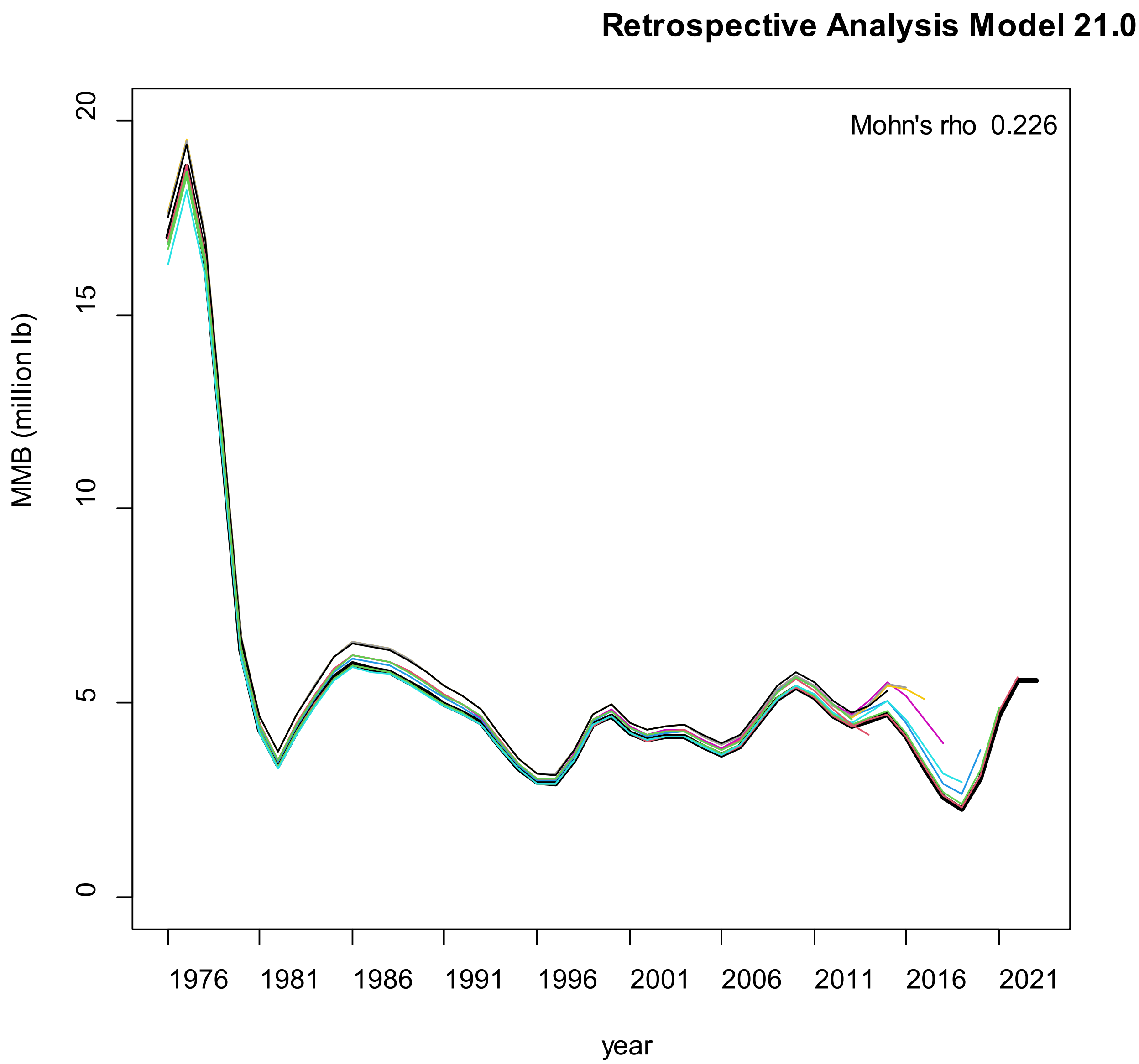
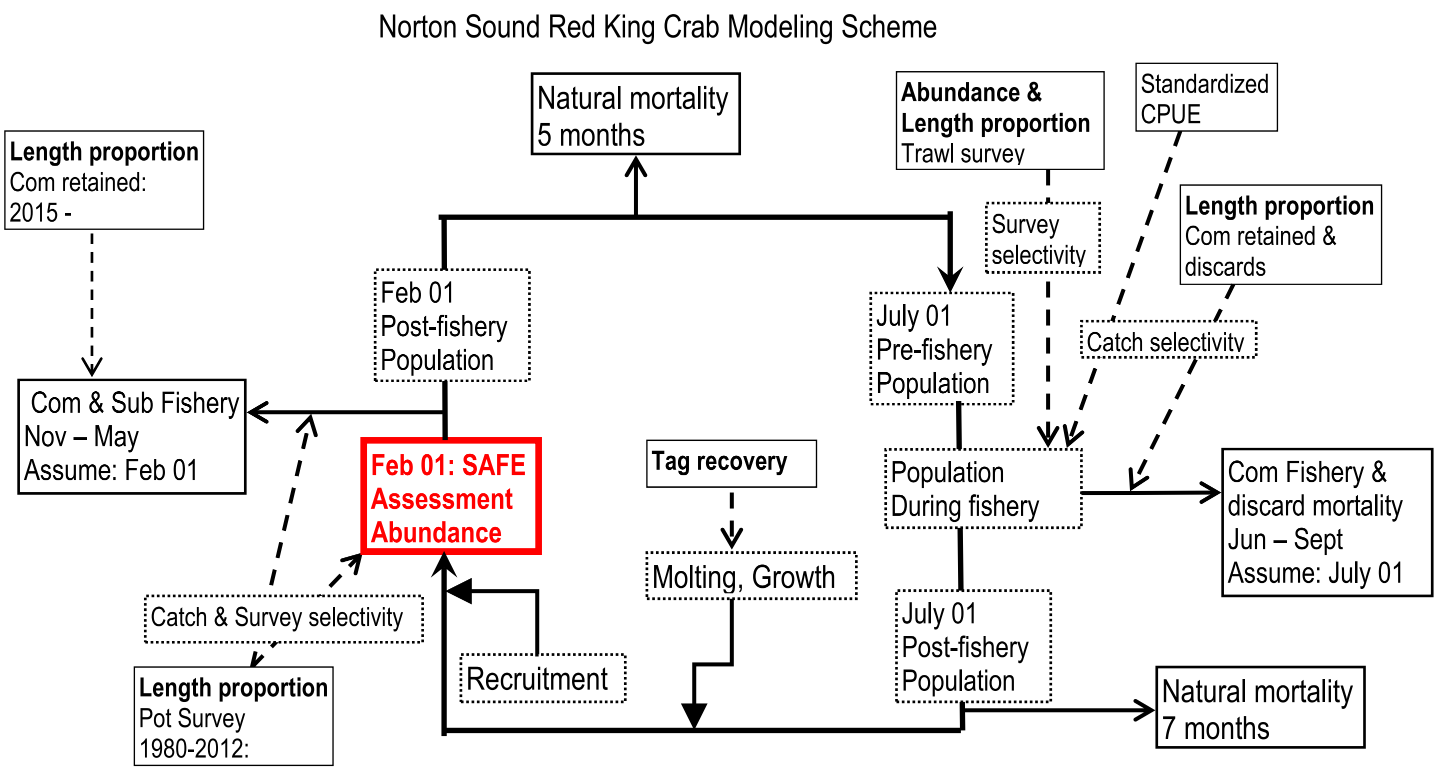


Figure 17. Retrospective Analyses of Norton Sound Red King Crab MMB from 2012 to 2023. Solid black line: 2023 assessment model results.

Appendix A. Description of the Norton Sound Red King Crab Model

a. Model description.

The model is an extension of the length-based model developed by Zheng et al. (1998) for Norton Sound red king crab. The model has 8 male length classes with model parameters estimated by the maximum likelihood method. The model estimates abundances of crab with CL ≥64 mm and with 10-mm length intervals (8 length classes, ≥134 mm) because few crab measuring less than 64 mm CL were caught during surveys or fisheries and there were relatively small sample sizes for trawl and winter pot surveys. The model treats newshell and oldshell male crab separately but assumes they have the same molting probability and natural mortality.



Timeline of calendar events and crab modeling events:

- **Model year starts February 1st to January 31st of the following year.**
- **Initial Population Date: February 1st 1976, consisting of only newshell crab.**
- **All winter fishery catch occurs on February 1st**
- **All summer fishery catch occurs on July 1st**
- **During 1976-2004, all legal crab caught in Commercial are retained.**

- **During 2004-2005, only commercially marketable legal crab caught in Commercial crabs are retained (i.e., high grading of crab ≥ 5 in CW).**
- **Winter Subsistence fishery retains all mature crab.**
- **Molting and recruitment occur on July 1st**

Initial pre-fishery summer crab abundance on February 1st 1976:

Abundance of the initial pre-fishery population was assumed to consist of newshell crab to reduce the number of parameters, and estimated as

$$N_{w,1,1} = p_l e^{\log\_N_{76}} \quad (1)$$

where length proportion of the first year (p_l) was calculated as

$$p_l = \frac{\exp(a_l)}{1+\sum_{l=1}^{n-1}\exp(a_l)} \text{ for } l = 1,..,n\text{-}1$$
$$p_n = 1 - \frac{\sum_{l=1}^{n-1}\exp(a_l)}{1+\sum_{l=1}^{n-1}\exp(a_l)} \quad (2)$$

for model estimated parameters a_l.

Crab abundance on July 1st :

Summer (01 July) crab abundance of newshell and oldshell are of survivors of Winter (Feb 01) population from winter commercial and subsistence crab fisheries, and natural mortality from 01Feb to 01July.

$$N_{s,l,y} = (N_{w,l,y} - C_{w,y}P_{w,n,l,y} - C_{p,t}P_{p,n,l,y} - D_{w,n,l,y} - D_{p,n,l,y})e^{-0.42M_l}$$
$$O_{s,l,y} = (O_{w,l,y} - C_{w,y}P_{w,o,l,y} - C_{p,y}P_{p,o,l,y} - D_{w,o,l,y} - D_{p,o,l,y})e^{-0.42M_l} \quad (3)$$

where

$N_{s,l,y}$, $O_{s,l,y}$: summer abundances of newshell and oldshell crab in length class l in year y ,
$N_{w,l,y}$, $O_{w,l,y}$: winter abundances of newshell and oldshell crab in length class l in year y,
$C_{w,t,y}$, $C_{p,t}$: total winter commercial and subsistence catches in year t,

$P_{w,n,l,y}$, $P_{w,o,l,y}$: Proportion of newshell and oldshell length class l crab in year y, harvested by winter commercial fishery,
$P_{p,n,l,y}$, $P_{p,o,l,y}$: Proportion of newshell and oldshell length class l crab in year y, harvested by winter subsistence fishery,
$D_{w,n,l,y}$, $D_{w,o,l,y}$: Discard mortality of newshell and oldshell length class l crab in winter commercial fishery in year y,
$D_{p,n,l,y}$, $D_{p,o,l,y}$: Discard mortality of newshell and oldshell length class l crab in winter subsistence fishery in year y,
M_l : instantaneous natural mortality in length class l,
0.42 : proportion of the year from Feb 1 to July 1 is 5 months.

Length proportion compositions of winter commercial retained catch ($P_{w,n,l,y}$, $P_{w,o,l,y}$) in year t were estimated as:

1976-2007

$$P_{w,n,l,y} = N_{w,l,y} S_{w,l} P_{\lg,l} / \sum_{l=1} [(N_{w,l,y} + O_{w,l,y}) S_{w,l} P_{\lg,l}]$$

$$P_{w,o,l,y} = O_{w,l,y} S_{w,l} P_{\lg,l} / \sum_{l=1} [(N_{w,l,y} + O_{w,l,y}) S_{w,l} P_{\lg,l}] \qquad (4)$$

2008-present

$$P_{cw,n,l,y} = N_{w,l,t} S_{w,l} S_{wr,l} / \sum_{l} [(N_{w,l,y} + O_{w,l,y}) S_{w,l} S_{wr,l}]$$

$$P_{cw,o,l,y} = O_{w,l,t} S_{w,l} S_{wr,l} / \sum_{l} [(N_{w,l,y} + O_{w,l,y}) S_{w,l} S_{wr,l}]$$

where
$P_{lg,l}$: the proportion of legal males in length class l ,
$S_{w,l}$: Selectivity of winter fishery pot.
$S_{wr,l}$: Retention probability of winter fishery

In the above, we assumed that all legal crabs were retained during 1976-2007 periods, and high grading has occurred since 2008 season.

The subsistence fisheries do not have a size limit; however, immature crab (< 94 mm) are generally not retained. Thus, we assumed proportion of length composition $l = 1$ and 2 as 0, and estimated length compositions ($l \geq 3$) as follows

$$P_{p,n,l,y} = N_{w,l,y} S_{w,l} / \sum_{l=3} [(N_{w,l,y} + O_{w,l,y}) S_{w,l}]$$

$$P_{p,o,l,y} = O_{w,l,y} S_{w,l} / \sum_{l=3} [(N_{w,l,y} + O_{w,l,y}) S_{w,l}] \qquad (5)$$

Crab abundance on Feb 1st :

The assessment model assumes that molting and growth occur immediately after summer fishery harvests, and that recruitment would occur between July 01 and Feb 01 of the next year. That is, the following events occur: (1) summery fishery, (2) summer fishery discards mortality, (3) molting and recruitment, and (4) natural mortality between July 01 and Feb 01. Those are formulated as follows:

Newshell Crab- Abundance of newshell crab of year *t* and length-class *l* ($N_{w,l,y}$) year-y consist of: (1) new and oldshell crab that survived the summer commercial fishery and molted, and (2) recruitment ($R_{l,y}$):

$$N_{w,l,y+1} = \sum_{l'=1}^{l'=l} G_{l',y}[(N_{s,l',y} + O_{s,l',y})e^{-y_c M_l} - C_{s,y-1}(P_{s,n,l',y} + P_{s,o,l',y}) - D_{l',y}]m_{l'} e^{-(0.58-y_c)M_l} + R_{l,y} \quad (6)$$

Oldshell Crab- Abundance of oldshell crabs of year *y* and length-class *l* ($O_{w,l,y}$) consists of the non-molting portion of survivors from the summer fishery:

$$O_{w,l,y+1} = [(N_{s,l,y} + O_{s,l,y})e^{-y_c M_l} - C_{s,y}(P_{s,n,l,y} + P_{s,o,l,y}) - D_{l,y}](1 - m_l)e^{-(0.58-y_c)M_l} \quad (7)$$

where

$G_{l',l}$: a growth matrix representing the expected proportion of crabs growing from length class l' to length class l
$C_{s,y}$: total summer catch in year y
$P_{s,n,l,y}$, $P_{s,o,l,y}$: proportion of summer catch for newshell and oldshell crab of length class l in year y,
$D_{l,y}$: summer discard mortality of length class l in year y,
m_l : molting probability of length class l,
y_c : the time in year from July 1 to the mid-point of the summer fishery,
0.58: Proportion of the year from July 1st to Feb 1st : 7 months = 0.58 year,
$R_{l,y}$: recruitment into length class l in year y.

Discards

Discards are crabs that were caught in summer and winter commercial and winter subsistence fisheries but were not retained.

Summer and winter commercial discards

In summer ($D_{l,t}$) and winter ($D_{w,n,l,t}$, $D_{w,o,l,t}$) commercial fisheries, sublegal males (<4.75 inch CW and <5.0 inch CW since 2008) are discarded. Those discarded crabs are subject to handling mortality. The number of discards was not directly observed, and thus was estimated from the model as: Observed Catch x (estimated abundance of crab that are not caught by commercial pot)/(estimated abundance of crab that are caught by commercial pot)

Model discard mortality in length-class *l* in year *y* from the summer and winter commercial pot fisheries is given by

$$D_{l,y} = C_{s,y} \frac{N_{s,l,y} S_{s,l} (1 - S_{r,n,l}) + O_{s,l,y} S_{s,l} (1 - S_{r,o,l})}{\sum_l (N_{s,l,y} S_{r,n,l} + O_{s,l,y} S_{r,o,l}) S_{s,l}} hm_s \qquad (8)$$

1977 – 2007 2008 – 2022

$$D_{w,n,l,y} = C_{w,y} \frac{N_{w,l,y} S_{w,l} (1 - P_{lg,l})}{\sum_l (N_{w,l,y} + O_{w,l,y}) S_{w,l} P_{lg,l}} hm_w \quad D_{w,n,l,y} = C_{w,t} \frac{N_{w,l,y} S_{w,l} (1 - S_{wr,l})}{\sum_l (N_{w,l,y} + O_{w,l,y}) S_{w,l} S_{wr,l}} hm_w \qquad (9)$$

1977 – 2007 2008 – 2022

$$D_{w,o,l,y} = C_{w,y} \frac{O_{w,l,y} S_{w,l} (1 - P_{lg,l})}{\sum_l (N_{w,l,y} + O_{w,l,y}) S_{w,l} P_{lg,l}} hm_w \quad D_{w,o,l,y} = C_{w,y} \frac{O_{w,l,y} S_{w,l} (1 - S_{wr,l})}{\sum_l (N_{w,l,y} + O_{w,l,y}) S_{w,l} S_{wr,l}} hm_w \qquad (10)$$

where

hm_s: summer commercial handling mortality rate assumed to be 0.2,
hm_W: winter commercial handling mortality rate assumed to be 0.2,
$S_{s,l}$: Selectivity of the summer commercial fishery,
$S_{w,l}$: Selectivity of the winter commercial fishery,
$S_{r,l}$: Retention selectivity of the summer commercial fishery,
$S_{wr,l}$: Retention selectivity of the winter commercial fishery,

Winter subsistence discards

Discards (unretained) from the winter subsistence fishery are reported in a permit survey ($C_{d,y}$), though its size composition is unknown. We assumed that subsistence fishers discard all crabs of length classes 1 -2.

$$D_{p,n,l,y} = C_{d,y} \frac{N_{w,l,y} S_{w,l}}{\sum_{l=1}^{2} (N_{w,l,y} + O_{w,l,y}) S_{w,l}} hm_w \qquad (11)$$

$$D_{p,o,l,y} = C_{d,y} \frac{O_{w,l,y} S_{w,l}}{\sum_{l=1}^{2} (N_{w,l,y} + O_{w,l,y}) S_{w,l}} hm_w \qquad (12)$$

where

$C_{d,y}$: Winter subsistence discards

Recruitment

Recruitment of year y, R_y, is a stochastic process around the geometric mean, R_0:

$$R_y = R_0 e^{\tau_t}, \tau_y \sim N(0, \sigma_R^2) \qquad (13)$$

R_t of the last year was assumed to be an average of previous 5 years: $R_y = (R_{y-1} + R_{y-2} + R_{y-3} + R_{y-4} + R_{y-5})/5$.

R_t was assumed to be newshell crab of immature (< 94 mm) length classes 1 to r:

$$R_{r,y} = p_r R_y \qquad (14)$$

where p_r takes multinomial distribution, same as equation (2)

Molting Probability

Molting probability for length class l, m_l, was estimated as an inverse logistic function of length-class mid carapace length (L) and parameters (α, β) where β corresponds to L_{50}.

$$m_l = \frac{1}{1 + e^{\alpha(L-\beta)}} \qquad (15)$$

Trawl net and summer commercial pot selectivity

Trawl and summer commercial pot selectivity was assumed to be a logistic function of mid-length-class, constrained to be 0.999 at the largest length-class (L_{max}):

$$S_l = \frac{1}{1 + e^{(\alpha(L_{\max} - L) + \ln(1/0.999 - 1))}} \qquad (16)$$

Winter pot selectivity,

Winter pot selectivity was assumed to be a dome-shaped with logistic function of length-class mid carapace length (L) and parameters (α, β) where β corresponds to L_{50}.

$$S_{w,l} = \frac{1}{1 + e^{\alpha(L-\beta)}} \qquad (17)$$

Selectivity of the first 3 length classes $S_{w,s}$ (S= l_1, l_2, l_3) were individually estimated.

Retention probability: Winter commercial, summer commercial

Winter and summer commercial retention probability was assumed to be a logistic function of length-class mid carapace length (*L*) and parameters (*α*, *β*) where *β* corresponds to L_{50}.

$$S_{r,l} = \frac{1}{1+e^{\alpha(L-\beta)}} \tag{17}$$

Growth transition matrix

The growth matrix $G_{l',l}$ (the expected proportion of crab molting from length class l' to length class l) was assumed to be normally distributed:

$$G_{l',l} = \begin{cases} \dfrac{\int_{lm_l-h}^{lm_l+h} N(L \mid \mu_{l'}, \sigma^2)dL}{\sum_{l=1}^{n} \int_{lm_l-h}^{lm_l+h} N(L \mid \mu_{l'}, \sigma^2)dL} & \text{when } l \geq l' \\ 0 & \text{when } l < l' \end{cases} \tag{18}$$

where

$$N(x \mid \mu_{l'}, \sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(L-\mu_{l'})^2}{\sigma^2} \right)$$

$$lm_l = L_1 + st \cdot l$$

$$\mu_l = L_1 + \beta_0 + \beta_1 \cdot l$$

Observation model

Summer trawl survey abundance

Modeled trawl survey abundance of year *y* ($B_{st,y}$) is July 1st abundance subtracted by summer commercial fishery harvest occurring from July 1st to the mid-point of summer trawl survey, multiplied by natural mortality occurring between the mid-point of commercial fishery date and trawl survey date, and multiplied by trawl survey selectivity. For the first year (1976) trawl survey, the commercial fishery did not occur.

$$\hat{B}_{st,y} = \sum_l [(N_{s,l,y} + O_{s,l,y})e^{-y_c M_l} - C_{s,y} P_{c,y} (P_{s,n,l,y} + P_{s,o,l,y})] e^{-(y_{st}-y_c)M_l} S_{st,l} \tag{19}$$

where

y_{st}: the time in year from July 1 to the mid-point of the summer trawl survey,
y_c: the time in year from July 1 to the mid-point for the catch before the survey, ($y_{st} > y_c$: Trawl survey starts after opening of commercial fisheries),
$P_{c,y}$: the proportion of summer commercial crab harvested before the mid-point of trawl survey date.
$S_{st,l}$: Selectivity of the trawl survey.

Winter pot survey CPUE (**depleted**)

Winter pot survey cpue (f_{wy}) was calculated with catchability coefficient q and exploitable abundance:

$$\hat{f}_{wy} = q_w \sum_l [(N_{w,l,y} + O_{w,l,y}) S_{w,l}] \tag{20}$$

Summer commercial CPUE

Summer commercial fishing CPUE (f_y) was calculated as a product of catchability coefficient q and mean exploitable abundance, A_t minus one half of summer catch, C_t:

$$\hat{f}_y = q_i (A_y - 0.5 C_y) \tag{21}$$

Because the fishing fleet and pot limit configuration changed in 1993, q_1 is for fishing efforts before 1993, q_2 is from 1994 to present.

Where A_y is exploitable legal abundance in year t, estimated as

$$A_y = \sum_l [(N_{s,l,y} + O_{s,l,y}) S_{s,l} S_{r,l}] \tag{22}$$

Summer pot survey abundance (**depleted**)

Abundance of y-th year pot survey was estimated as

$$\hat{B}_{p,y} = \sum_l [(N_{s,l,y} + O_{s,l,y}) e^{-y_p M_l}] S_{p,l} \tag{23}$$

Where

y_p: the time in year from July 1 to the mid-point of the summer pot survey.

Length composition

Summer commercial retained catch

Length compositions of the summer commercial catch for new and old shell crabs $P_{s,n,l,y}$ and $P_{s,o,l,y}$, were modeled based on the summer population, selectivity, and retention probability

$$\hat{P}_{s,n,l,y} = N_{s,l,y} S_{s,l} S_{r,o,l} / A_t$$
$$\hat{P}_{s,o,l,y} = O_{s,l,y} S_{s,l} S_{r,o,l} / A_t \qquad (24)$$

Retention probability is separated into two periods: 1977–2007 and 2008–2020 indicating before and after the start of high grading.

Summer commercial fishery discards (1977-1993)

Prior to 1993, Observer survey data contained length-shell composition of only discards.

Length/shell compositions of observer discards were modeled as

$$\hat{P}_{b,n,l,y} = N_{s,l,y} S_{s,l} (1 - S_{r,n,l}) / \sum_l [N_{s,l,y}(1 - S_{r,n,l}) + O_{s,l,y}(1 - S_{r,o,l})] S_{s,l}$$
$$\hat{P}_{b,o,l,y} = O_{s,l,y} S_{s,l} (1 - S_{r,o,l}) / \sum_l [N_{s,l,y}(1 - S_{r,n,l}) + O_{s,l,y}(1 - S_{r,o,l})] S_{s,l} \qquad (25)$$

Summer commercial fishery total catch (2008-present)

The 2012–2019 Observer survey had total as well as retained and discard length-shell composition, and total catch length-shell composition was fitted.

Length/shell compositions of observer total catch was modeled as

$$\hat{P}_{t,n,l,y} = N_{s,l,y} S_{s,l} / \sum_l [(N_{s,l,y} + O_{s,l,y}) S_{s,l}]$$
$$\hat{P}_{t,o,l,y} = O_{s,l,y} S_{s,l} / \sum_l [(N_{s,l,y} + O_{s,l,y}) S_{s,l}] \qquad (26)$$

Summer trawl survey

Proportions of newshell and oldshell crab, $P_{st,n,l,y}$ and $P_{st,o,l,y}$ were given by

$$\hat{P}_{st,n,l,y} = \frac{[N_{s,l,y} e^{-y_c M_l} - C_{s,y} P_{c,y} \hat{P}_{s,n,l',y}] e^{-(y_{st} - y_c) M_l} S_{st,l}}{\sum_l [(N_{s,l,y} + O_{s,l,y}) e^{-y_c M_l} - C_{s,y} P_{c,y} (\hat{P}_{s,n,l',y} + \hat{P}_{s,o,l',y})] e^{-(y_{st} - y_c) M_l} S_{st,l}} \qquad (27)$$

$$\hat{P}_{st,o,l,y} = \frac{[O_{s,l,y} e^{-y_c M_l} - C_{s,y} \hat{P}_{s,o,l',y} P_{c,y}] e^{-(y_{st}-y_c)M_l} S_{st,l}}{\sum_l [(N_{s,l,y} + O_{s,l,y}) e^{-y_c M_l} - C_{s,y} P_{c,y} (\hat{P}_{s,n,l,y} + \hat{P}_{s,o,l,y})] e^{-(y_{st}-y_c)M_l} S_{st,l}}$$

Winter pot survey

Winter pot survey length compositions for newshell and oldshell crab, $P_{sw,n,l,t}$ and $P_{sw,o,l,t}$ ($l \geq 1$) were calculated as

$$\begin{aligned} \hat{P}_{sw,n,l,y} &= N_{w,l,y} S_{w,l} / \sum_l [(N_{w,l,y} + O_{w,l,y}) S_{w,l}] \\ \hat{P}_{sw,o,l,y} &= O_{w,l,y} S_{w,l} / \sum_l [(N_{w,l,y} + O_{w,l,y}) S_{w,l}] \end{aligned} \quad (28)$$

Winter commercial retained

Winter commercial retained length compositions for newshell and oldshell crab, $P_{cw,n,l,t}$ and $P_{cw,o,l,t}$ ($l \geq 1$) were calculated as

$$\begin{aligned} \hat{P}_{cw,n,l,y} &= N_{w,l,y} S_{w,l} S_{wr,l} / \sum_l [(N_{w,l,y} + O_{w,l,y}) S_{w,l} S_{wr,l}] \\ \hat{P}_{cw,o,l,y} &= O_{w,l,y} S_{w,l} S_{wr,l} / \sum_l [(N_{w,l,y} + O_{w,l,y}) S_{w,l} S_{wr,l}] \end{aligned} \quad (29)$$

*Spring Pot survey 2012-2015 (**depleted**)*

Spring pot survey length compositions for newshell and oldshell crab, $P_{sw,n,l,t}$ and $P_{sw,o,l,t}$ ($l \geq 1$) were assumed to be similar to crab population caught by winter pot survey

$$\begin{aligned} \hat{P}_{sp,n,l,y} &= N_{s,l,y} S_{w,l} / \sum_l [(N_{s,l,y} + O_{s,l,y}) S_{w,l}] \\ \hat{P}_{sp,o,l,y} &= O_{s,l,y} S_{w,l} / \sum_l [(N_{s,l,y} + O_{s,l,y}) S_{w,l}] \end{aligned} \quad (30)$$

Estimates of tag recovery

The proportion of released tagged length class *l'* crab recovered after *t-th* year with length class of *l* by a fishery of *s-th* selectivity (S_l) was assumed to be proportional to the growth matrix, catch selectivity, and molting probability (m_l) as

$$\hat{P}_{l',l,t,s} = \frac{S_l \cdot [X^t]_{l',l}}{\sum_{l=1}^{n} S_l \cdot [X^t]_{l',l}} \quad (31)$$

where X is a molting probability adjusted growth matrix with each component consisting of

$$X_{l',l} = \begin{cases} m_{l'} \cdot G_{l',l} & \text{when } l' \neq l \\ m_l \cdot G_{l',l} + (1\text{-}m_i) & \text{when } l' = l \end{cases} \tag{32}$$

c. Likelihood components.

Under assumptions that measurement errors of annual total survey abundances and summer commercial fishing efforts follow lognormal distributions, and each type of length composition has a multinomial error structure (Fournier and Archibald 1982; Methot 1989), the log-likelihood function is

$$\begin{aligned}
&\sum_{i=1}^{i=4}\sum_{y=1}^{y=n_i} K_{i,t}\left[\sum_{l=1}^{l=n} P_{i,l,y}\ln(\hat{P}_{i,l,y}+\kappa) - \sum_{l=1}^{l=n} P_{i,l,y}\ln(P_{i,l,y}+\kappa)\right] \\
&-\sum_{y=1}^{y=n_i}\frac{[\ln(q\cdot\hat{B}_{i,y}) - \ln(B_{i,y})]^2}{2\cdot ln(CV_{i,y}^2+1)} \\
&-\sum_{y=1}^{y=n_i}\left[\frac{\ln\left[\ln(CV_y^2+1)+w_t\right]}{2} + \frac{[\ln(\hat{f}_y+\kappa) - \ln(f_y+\kappa)]^2}{2\cdot\left[\ln(CV_y^2+1)+w_t\right]}\right] \\
&-\sum_{t=1}\frac{\tau_t^2}{2\cdot SDR^2} \\
&+W\sum_{s=1}^{s=2}\sum_{y=1}^{y=3}\sum_{l'=1}^{l'=n} K_{l',y,s}\left[\sum_{l=1}^{l=n} P_{l',l,y}\ln(\hat{P}_{l',l,y,s}+\kappa) - \sum_{l=1}^{l=n} P_{l',l,t}\ln(P_{l',l,y,s}+\kappa)\right]
\end{aligned} \qquad (32)$$

where

i: length/shell compositions of:

1 triennial summer trawl survey,
2 annual winter pot survey,
3 summer commercial fishery retained,
4 summer commercial observer discards or total catch,
5 winter commercial fishery retained.

$K_{i,y}$: the effective sample size of length/shell compositions for data set i in year y,
$P_{i,l,y}$: observed and estimated length compositions for data set i, length class l, and year y.
κ : a constant equal to 0.0001,
CV: coefficient of variation for the survey abundance,
$B_{j,y}$: observed and estimated annual total abundances for data set i and year y,
F_y: observed and estimated summer fishery CPUE,
w^2_t: extra variance factor,
SDR: Standard deviation of recruitment = 0.5,
$K_{l',y}$: sample size of length class l' released and recovered after y-th in year,
$P_{l',l,y,s}$: observed and estimated proportion of tagged crab released at length l' and recaptured at length l, after y-th year by commercial fishery pot selectivity s,
W: weighting for the tagging survey likelihood = 0.5

b. Software used: AD Model Builder (Fournier et al. 2012).

d. Out of model parameter estimation framework:

i. Parameters Estimated Independently

M: Natural mortality

Natural mortality (M = 0.18) was based on an assumed maximum age, t_{max}, and the 1% rule (Zheng 2005):

$$M = -\ln(p)/t_{\max},$$

where p is the proportion of animals that reach the maximum age and is assumed to be 0.01 for the 1% rule (Shepherd and Breen 1992, Clarke et al. 2003). The maximum age of 25, which was used to estimate M for U.S. federal overfishing limits for red king crab stocks results in an estimated M of 0.18. Among the 199 recovered crabs from the tagging returns during 1991-2007 in Norton Sound, the longest time at liberty was 6 years and 4 months from a crab tagged at 85 mm CL. The crab was below the mature size and was likely less than 6 years old when tagged. Therefore, the maximum age from tagging data is about 12, which does not support the maximum age of 25 chosen by the CPT.

Proportion of Legal-sized crab

Proportions of legal males (CW > 4.75 inches) by length group were estimated from the ADF&G trawl data 1996-2021.

e. Definition of model outputs.

i. Mature male biomass (MMB) is on **February 1st** and is consisting of the biomass of male crab in length classes 4 to 8

$$MMB = \sum_{l=4} (N_{w,l,} + O_{w,l,}) wm_l$$

wm_l: mean weight of each length class.

ii. Projected legal male biomass subject to winter and summer fishery OFL was calculated as winter biomass times summer commercial pot selectivity times proportion of legal crab. Though fishery size selectivity differs between winter and summer commercial, both fisheries were assumed to have the same selectivity because winter fishery is very small compared to summer fishery.

$$B_w = \sum_{l} (N_{w,l,} + O_{w,l,}) S_{s,l} S_{r,l} wm_l$$

iii. Recruitment: the number of males in length classes 1, 2, and 3.

f. OFL

The Norton Sound red king crab fishery consists of two distinct fisheries: winter and summer. The two fisheries are discontinuous with 5 months between the two fisheries during which natural mortalities occur. To incorporate this, the CPT in 2016 recommended the following formula:

$$OFL = \text{Winter harvest (Hw)} + \text{ Summer harvest (Hs)} \tag{1}$$

And

$$p = \frac{Hw}{OFL} \tag{2}$$

Where p is a specific proportion of winter crab harvest to total (winter + summer) harvest

At given fishery mortality (F_{OFL}), Winter harvest is a fishing mortality

$$Hw = (1 - e^{-x \cdot F})B_w \tag{3}$$

$$Hs = (1 - e^{-(1-x) \cdot F})B_s \tag{4}$$

where B_s is a summer crab biomass after winter fishery and x ($0 \leq x \leq 1$) is a fraction that satisfies equation (2).

Since B_s is a summer crab biomass after winter fishery and 5 months of natural morality, ($e^{-0.42M}$)

$$\begin{aligned} B_s &= (B_w - Hw)e^{-0.42M} \\ &= (B_w - (1 - e^{-x \cdot F})B_w)e^{-0.42M} \\ &= B_w e^{-x \cdot F - 0.42M} \end{aligned} \tag{5}$$

Substituting m for $0.42M$, summer harvest is

$$\begin{aligned} Hs &= (1 - e^{-(1-x) \cdot F})B_s \\ &= (1 - e^{-(1-x) \cdot F})B_w e^{-x \cdot F - m} = (e^{-(x \cdot F + m)} - e^{-(F+m)})B_w \end{aligned} \tag{6}$$

Thus, OFL is

$$\begin{aligned} OFL = Hw + Hs &= (1 - e^{-xF})B_w + (e^{-(x \cdot F + m)} - e^{-(F+m)})B_w \\ &= (1 - e^{-xF} + e^{-(xF+m) \cdot} - e^{-(F+m) \cdot})B_w \\ &= [1 - e^{-(F+m) \cdot} - (1 - e^{-m \cdot})e^{-xF \cdot}]B_w \end{aligned} \tag{7}$$

Combining equations (2) and (7),

$$p = \frac{Hw}{OFL} = \frac{(1-e^{-xF})B_w}{[1-e^{-(F+m)\cdot} - (1-e^{-m\cdot})e^{-xF\cdot}]B_w} \tag{8}$$

Solving equation (8) for x

$$(1-e^{-xF}) = p[1-e^{-(F+m)\cdot} - (1-e^{-m\cdot})e^{-xF\cdot}] \tag{9}$$

$$e^{-xF} - p(1-e^{-m\cdot})e^{-xF\cdot} = 1 - p[1-e^{-(F+m)\cdot}]$$

$$[1-p(1-e^{-m\cdot})]e^{-xF\cdot} = 1 - p[1-e^{-(F+m)\cdot}]$$

$$e^{-xF\cdot} = \frac{1-p[1-e^{-(F+m)\cdot}]}{1-p(1-e^{-m\cdot})}$$

Combining equations (7) and (9), and substituting back,

revised retained OFL is

$$OFL = B_w\left(1-e^{-(F_{OFL}+0,42M)} - (1-e^{-0.42M})\left(\frac{1-p(1-e^{-(F_{OFL}+0.42M)})}{1-p(1-e^{-0.42M})}\right)\right)$$

Further combining equations (3) and (9), winter fishery harvest rate (Fw) is

$$Fw = (1-e^{-x\cdot F}) = 1 - \frac{1-p[1-e^{-(F+m)\cdot}]}{1-p(1-e^{-m\cdot})} = \frac{1-p(1-e^{-m\cdot}) - 1 + p[1-e^{-(F+m)\cdot}]}{1-p(1-e^{-m\cdot})} \tag{10}$$

$$= \frac{p(e^{-m\cdot} - e^{-(F+m)\cdot})}{1-p(1-e^{-m\cdot})} = \frac{p(1-e^{-F\cdot})e^{-0.42M\cdot}}{1-p(1-e^{-0.42M\cdot})}$$

Summer fishery harvest rate (Fs) is

$$Fs = (e^{-(x\cdot F+m)} - e^{-(F+m)}) = (e^{-x\cdot F} - e^{-F})e^{-m} \tag{11}$$

$$= \left(\frac{1-p[1-e^{-(F+m)\cdot}]}{1-p(1-e^{-m\cdot})} - e^{-F}\right)e^{-m}$$

$$= \left(\frac{1-p[1-e^{-(F+m)\cdot}] - e^{-F} + p(e^{-F} - e^{-(F+m\cdot)})}{1-p(1-e^{-m\cdot})}\right)e^{-m}$$

$$= \left(\frac{1-p+pe^{-(F+m)\cdot} - e^{-F} + pe^{-F} - pe^{-(F+m\cdot)}}{1-p(1-e^{-m\cdot})}\right)e^{-m}$$

$$= \frac{(1-p)(1-e^{-F})e^{-m}}{1-p(1-e^{-m\cdot})} = \frac{(1-p)(1-e^{-F})e^{-0.24M}}{1-p(1-e^{-0.24M\cdot})}$$

Appendix B

Norton Sound Red King Crab CPUE Standardization

Note: This is an update of model by G. Bishop (NPFMC 2013). Please see SAFE 2013 for more detailed descriptions.

Methods

Model

Let U_{ijk} denote the observed CPUE, U_0 the reference CPUE, P_{ij} a factor *i* at level *j*, and let X_{ij} take a value of 1 when the j^{th} level of the factor P_{ij} is present and 0 when it is not. The lognormal distribution of U_{ijk} (Quinn and Deriso 1999), can be denoted as:

$$U_{ijk} = U_0 \prod_i \prod_j P_{ij}^{X_{ij}} e^{\varepsilon_{ijk}} \qquad (1)$$

or

$$\ln(U_{ijk}) = \ln(U_0) + \sum_{i=1}^{p} \sum_{j=1}^{n_j-1} X_{ij} \ln(P_{ij}) + \varepsilon_{ijk} \ .$$

where ε_{ijk}, ~ N(0, σ^2) observation error

Substituting $\ln(U_0)$ to β_0 and $\ln(P_{ij})$ to β_{ij}, we then obtain an additive GLM lognormal error distribution of U_{ijk}:

$$\ln(U_{ijk}) = \beta_0 + \sum_{i=1}^{p} \sum_{j=1}^{n_j-1} X_{ij} \beta_{ij} + \varepsilon_{ijk} \ . \qquad (2)$$

Standardized CPUE was calculated as follows:

Norton Sound red king crab CPUE standardization

1. Divide the coefficients β_{ij} by their geometric mean $\bar{\beta}$ to obtain canonical coefficients:

$$\beta_i{}' = \frac{\beta_i}{\bar{\beta}}. \tag{3}$$

2. Exponentiate the result to obtain the arithmetic scale canonical coefficients:

$$b' = e^{\beta_i - \bar{\beta}}. \tag{4}$$

3. Subtract the year coefficient reference level to obtain standardized CPUE U_j for each year level j as:

$$U_{Yj} = e^{\beta'_{Yj} - \beta'_{Y0}}. \tag{5}$$

4. Base year CPUE index is calculated by eliminating all factors but *Year* in the GLM and following Equations (2) and (3), (4), and (5) above.

SE of the standardized CPUE is calculated as:

Standard errors of CPUE are standard errors of the Year coefficients, $\hat{\beta}_{yr}$. These are obtained from the square root of the diagonal elements of the estimated covariance matrix, cov $(\hat{\beta})$, i.e., $\sqrt{\boldsymbol{C'\emptyset C}}$.

where C = $X(X^T X)^{-1}$, C' is transpose of C; and $\emptyset$ = $\boldsymbol{\sigma^2 I_n}$
where X is the matrix of predictor variables, I_n is the identity matrix, and σ is the standard error of the GLM fit.

Data Source & Cleaning

Commercial fishery harvest data were obtained from ADF&G fish ticket database, which included: Landing Date, Fish Ticket Number, Vessel Number, Permit Fishery ID, Statistical Area(s) fished, Effort, and Number and Pounds of Crab harvested (Table B2-1,2,3, Figure B2-1). The fish ticket database may

Norton Sound red king crab CPUE standardization

have multiple entries of identical Fish Ticket Number, Vessel Number, Permit Fishery ID, and Statistical Area.

The following data cleaning and combining methods were conducted:

1. Sum crab number and efforts by Fish Ticket Number, Vessel Number, Permit Fishery ID, and Statistical Area.
2. Remove data with missing or zero values in Effort, Number of Crab, or Pounds of Crab; (these are considered true missing data).
3. Calculate CPUE as Number of Crab/Effort.

Data cleaning and censoring.

Norton Sound commercial red king crab fishery can be largely divided into three periods: large vessel operation (1977-1993), small vessel superexclusive (1994-2007), and small vessel superexclusive and high grading (2008-2019). The pre-superexclusive fishery consisted of a few large boats, fishing west of 167 longitude, and few deliveries, while the post-superexclusive fishery consists of many small boats operated by local fishermen, fishing east of 167 longitude and near shore, and delivering frequently (Figure B1). The post-superexclusive period can further be divided into pre- (1994-2007) and post (2008-2020) high grading periods. The majority of commercially caught red king crab are sold to Norton Sound Economic Development Corporation (NSEDC). Beginning in the mid-2000s NSEDC's market-preferred size of 5 inch or greater carapace width (CW) t was greater than legal-sized crab of 4.75 inch or larger CW. This preference has become more explicit since 2008. For the purpose of modeling, 2008 was chosen as the start of the high-grading period.

Censoring data

During 1977-93 period, vessels of 1 year of operation and/or 1 delivery per year harvested 20-90% of crab (Table B2-5, Figure B2-2). For instance, all vessels made only 1 delivery in 1989, and in 1988 64% of crab were harvested by 1 vessel that made only 1 delivery. On the other hand, during the 1993-2022 period of post-superexclusive fishery status, the majority of commercial crab fishery and harvest was done by vessels with more than 5 years of operations and more than 5 deliveries per year. For 1977 – 1993, censoring was made for vessels of more than 2 years of operations. Increasing deliveries to more than one would result in no estimates for some years. For 1994 – 2022, the data were censored to vessels that fished more than 5 years and delivered crab more than 5 times per year.

Norton Sound red king crab CPUE standardization

Analyses

A GLM was constructed as

$$\ln(CPUE) = YR + VSL + MSA + WOY + PF$$

Where YR: Year, VSL: Vessel, MSA: Statistical Area, WOY: Week of Year, and PF: Permit vs open fishery (Table 1). All variables were treated as categorical. Inclusion of interaction terms was not considered because they were absent (SAFE 2013).

The fishery strata (PD) consisted of the 3 periods based on changes in fishery operations, and model was run for each fishery periods.

1977-1993: Large Vessel fishery
1994-2007: Small boat fishery
2008-2022: Small boat and high-grading fishery

For selection of the best model, forward and backward stepwise selection was conducted. (R step function)

```
fit <- glm(L.CPUE.NO ~ factor(YR) + factor(VSL) + factor(WOY) +
factor(MSA) + factor(PF),data=NSdata.C)
step <- step(fit, direction='both', trace = 10)
best.glm<-glm(formula(step), data=NSdata.C)
```

Table B-1. List of variables in the fish ticket database. Variables in bold face were used for generalized linear modeling.

Variable	Description
YR	Year of commercial fishery
VSL	Unique vessel identification number
Fish Ticket Number	Unique delivery to a processor by a vessel
PF	Unique Permit Fishery categories
PD	Fishery period: 1977-1992, 1993-2004,2005-2018
Statistical Area	Unique fishery area.
MOA	Modified statistical area, combining each statistical area into 4 larger areas: Inner, Mid, Outer, Outer North
Fishing Beginning Date	Date of pots set
Landing Date	Date of crab landed to processor
WOY	Week of Landing Date **(calculated)**
Effort	The number of pot lift
Crab Numbers	Total number of crabs harvested from pots
Crab Pounds	Total pounds of crab harvested from pots
ln(CPUE)	ln(Crab Numbers/Effort) **(calculated)**

Norton Sound red king crab CPUE standardization

Table B-2. Permit fisheries, descriptions, and years with deliveries for Norton Sound summer commercial red king crab harvest data.

Permit fishery	Type	Description	Years
K09Q	Open access	KING CRAB , POT GEAR VESSEL UNDER 60', BERING SEA	1994–2002
K09Z	Open access	KING CRAB , POT GEAR VESSEL UNDER 60', NORTON SOUND	1992–2022
K09ZE	CDQ	KING CRAB , POT GEAR VESSEL UNDER 60', NORTON SOUND CDQ, NSEDC	2000–2022
K09ZF	CDQ	KING CRAB , POT GEAR VESSEL UNDER 60', NORTON SOUND CDQ, YDFDA	2002–2004
K91Q	Open access	KING CRAB , POT GEAR VESSEL 60' OR OVER, BERING SEA	1978–1989
K91Z	Open access	KING CRAB , POT GEAR VESSEL 60' OR OVER, NORTON SOUND	1982–1994

Table B-3. Modified statistical area definitions used for analysis of Norton Sound summer commercial red king crab harvest data.

Modified statistical area	Statistical areas included
Inner	616331, 616401, 626331, 626401, 626402
Mid	636330, 636401, 636402, 646301, 646330, 646401, 646402
Outer	656300, 656330, 656401, 656402, 666230, 666300, 666330, 666401
Outer North	666402, 666431, 676300, 676330 ,676400, 676430, 676501, 686330

Norton Sound red king crab CPUE standardization

Table B-4. Final generalized linear model formulae and AIC selected for Norton Sound summer commercial red king crab fishery. The dependent variable is ln(CPUE) in numbers.

Periods: 1977-1993

Var	Df	Deviance	Resid DF	Resid Dev	AIC
YR	14	269.56	377	265.4	
MSA	3	11.91	374	253.5	
MOY	2	6.134	372	247.4	
					974.01

Periods: 1994-2007

Var	Df	Deviance	Resid DF	Resid Dev	AIC
VSL	43	451.6	2401	1465.6	
YR	14	232.8	2387	1232.8	
WOY	15	72.3	2372	1160.5	
MSA	3	24.1	2369	1130.4	
					8577.0

Periods: 2008-2022

Var	Df	Deviance	Resid DF	Resid Dev	AIC
YR	12	470.3	3357	2041.5	
VSL	42	329.9	3315	1711.4	
WOY	13	65.5	3302	1645.9	
MSA	3	31.4	3299	1614.5	
MOY	3	3.2	3296	1611.3	
					7227

Norton Sound red king crab CPUE standardization

Table B-5. Standardized (censored/full data), and scaled arithmetic observed CPUE indices.

Year	St. CPUE		Arithmetic
	CPUE	CV	CPUE
1977	2.03	0.32	2.06
1978	3.87	0.16	4.31
1979	1.30	0.23	1.78
1980	1.64	0.27	1.86
1981	0.57	0.19	0.72
1982	0.25	0.15	0.30
1983	0.50	0.18	0.65
1984	1.13	0.19	0.96
1985	0.69	0.17	0.66
1986	2.24	0.47	2.01
1987	0.88	0.33	0.68
1988	2.16	0.41	1.66
1989	0.99	0.29	0.79
1990	2.03	0.32	2.06
1991			
1992	1.47	0.47	1.24
1993	0.17	0.22	0.18
1994	1.02	0.09	1.22
1995	0.43	0.17	0.79
1996	1.08	0.13	0.49
1997	1.01	0.09	0.64
1998	1.14	0.09	1.03
1999	1.30	0.13	0.74
2000	0.97	0.10	0.63
2001	2.08	0.11	1.56
2002	0.76	0.26	0.78
2003	0.76	0.10	1.23
2004	1.65	0.09	1.02
2005	1.36	0.07	1.59
2006	0.64	0.12	1.48
2007	0.93	0.10	1.62
2008	0.89	0.23	1.18
2009	1.35	0.05	1.20
2010	0.92	0.04	0.87
2011	1.35	0.04	1.11
2012	1.54	0.05	1.43
2013	1.36	0.04	1.31
2014	0.71	0.04	0.70
2015	1.08	0.04	1.03
2016	1.33	0.05	1.25
2017	1.17	0.05	1.26
2018	1.00	0.05	1.05
2019	0.58	0.05	0.71
2020			
2021			
2022	1.51	0.07	1.72

Norton Sound red king crab CPUE standardization

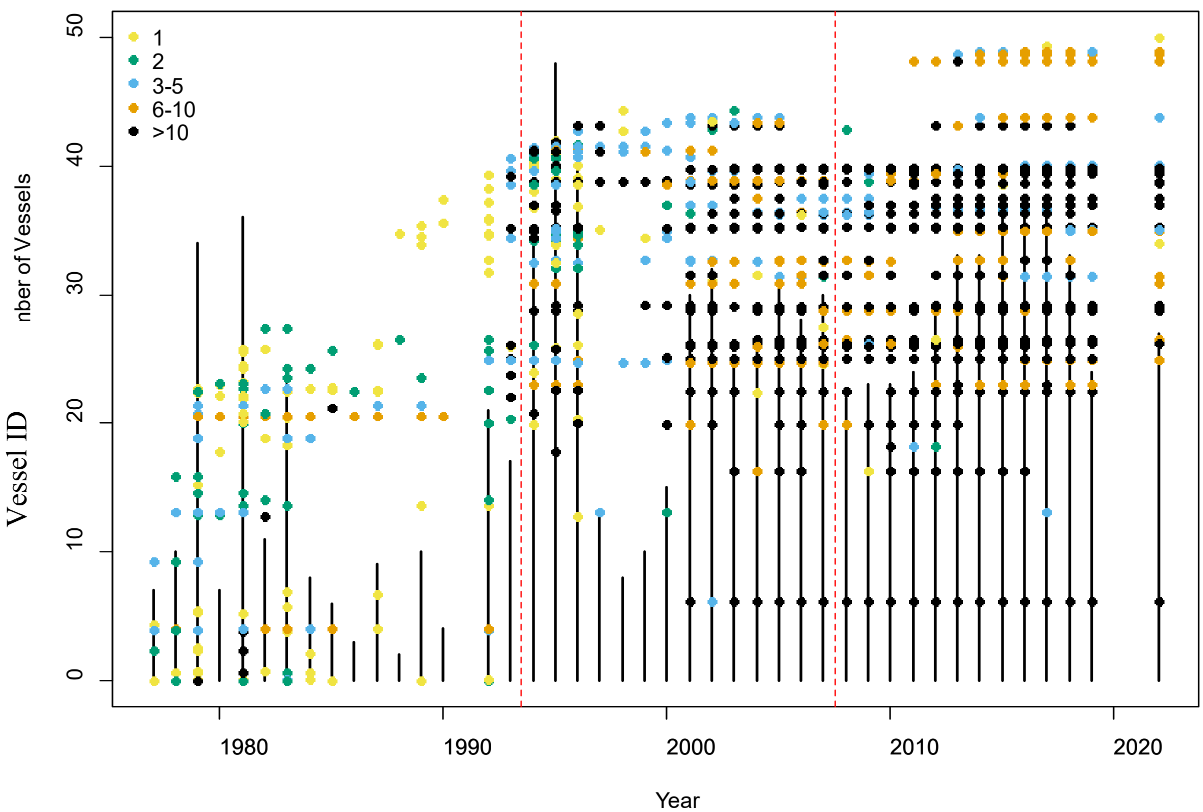


Figure B1. Number of fishing vessel (Vertical line) and distribution of unique vessel (dots) operated by year. Dot colors indicate the number of deliveries for each year by each vessel. Dashed red vertical line indicates a break between pre- (1977-1993) and post- (1994-2019) superexclusive fishery. No fishery occurred in 1993, and no fishery harvest occurred in 2020 and 2021.

Norton Sound red king crab CPUE standardization

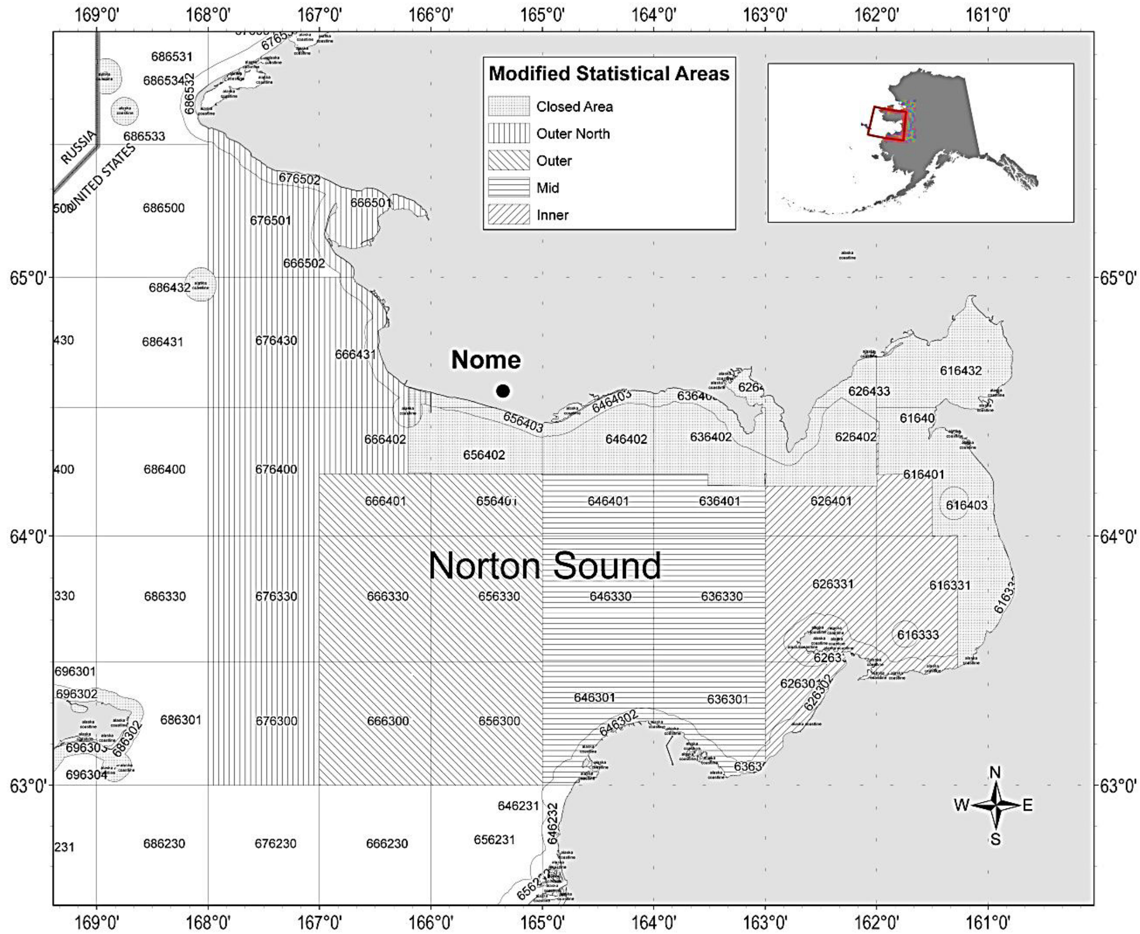


Figure A2-1. Closed area and statistical area boundaries used for reporting commercial harvest information for red king crab in Registration Area Q, Northern District, Norton Sound Section and boundaries of the new *Modified Statistical Areas* used in this analysis.

Appendix C

Norton Sound Red King Crab Summer Commercial Fishery Discard Estimation

Formal methodologies for estimating discards in the Norton Sound red king crab summer commercial fishery from observer data have not been established. Here, I describe a few methods and discuss pros and cons of each method.

Norton Sound Summer Commercial fishery observer coverage started in 2009 as a feasibility project, but formal data collection started in 2012 and terminated in 2019. **The main objective of the observer coverage was to gain information about the size composition of discarded crab, NOT to estimate total discards.** Because of this, carrying fishery observers was optional/voluntary and participation was **limited to vessels that are large enough to carry a fishery observer (a portion of the fleet are of a vessel length too small for an additional person). Thus, participating fishermen/vessels are NOT representative of the entire fleet.** The fishery observer worked as a crew member, but also recorded biological data including sex, carapace size, shell condition, etc. for all red king crab in selected pots. Fisherman sorted out discards and noted those individuals, and as such, **observed discarded crab are deemed accurate.** Because of the observer coverage is biased towards larger vessels, it is uncertain whether fishing behaviors of observed vessels are representative of unobserved vessels. Possible concerns include:

1. The participating fishermen have larger boats and are experienced. They may select better fishing grounds (e.g., higher number and proportions of legal-size crab relative to sub-legal size crabs). This leads to **higher CPUE and lower discards**.
2. The participating fisherman may allow observers when they expect higher discards. Additional free labor deckhand (i.e., observer) is always helpful. This leads to **higher discards**.
3. The participating fisherman may keep more (with catcher-seller permits) legal crab that are not accepted by NSEDC.
4. Unobserved small boat fisherman may keep more legal crab that are not accepted by NSEDC . (catcher-seller permits, personal-subsistence use).

Estimation Methods

Every discard estimation method is based on the following data (Table 1)

Observer survey data	Fish Ticket data
Sublegal crab discards (n_{sub}) and weight (w_{sub})	*NA*
Legal crab discards (n_{ld}) and weight (w_{ld})	*NA*
Legal crab retained (n_r) and weight (w_r)	Total Legal crab retained (N_R) and weight (W_R)

Norton Sound red king crab CPUE standardization

Female crab discards (n_f) and weight (w_f)	
Pot lifts (e)	Total Pot lifts (E)
Total discards ($n_d = n_{sub} + n_{ld}$) and weight ($w_d = w_{sub} + w_{ld}$)	*NA*
Total catch ($n_t = n_{sub} + n_{ld} + n_r$) and weight ($w_t = w_{sub} + w_{ld} + w_r$)	*NA*
Discards CPUE ($Cpue_d = n_d/e$) and by weight ($Cpue_d = w_d/e$)	*NA*
Total catch CPUE ($Cpue_t = n_t/e$) and by weight ($Cpue_t = w_t/e$)	*NA*
Discards/Retain ratio ($r_d = n_d/n_r$) and by weight ($r_d = w_d/n_r$)	*NA*
Discards size composition ($p_{dis,l}$)	*NA*

Note: female discards are not included because the NSRKC assessment model is male-only model.

LNR method

LNR method simply **expands observed discards CPUE (*$cpue_d$*)** to total pot lifts. This method assumes **that discarded crab are accurately accounted for** and that observed discards CPUE ($cpue_d$) is representative of all fishermen.

$$cpue_d = \frac{n_d}{e} \qquad D_{LNR} = cpue_d \cdot E \qquad (1)$$

LNR2 method

Observer bias corrected LNR method (LNR2) acknowledges that the observer discard CPUE may not be representative of all fishermen. Thus the CPUE is adjusted via taking retained CPUE by observed fishermen to all fishermen as follows:

Observed vessel retained catch $CPUE_{R,s} = \frac{N_{R.s}}{E_s}$ Entire fleet retained catch $CPUE_R = \frac{N_R}{E}$

Where $N_{R.s}$ and E_s are total number of retained crab and pot lifts of the observed fishermen from the fish ticket database, and N_R and E total number of retained crab and pot lifts by all fishermen. Then

$$D_{LNR2} = \left(\frac{CPUE_R}{CPUE_{R,s}}\right) \cdot D_{LNR} = \left(\frac{N_R}{E \cdot CPUE_{R,s}}\right) \cdot cpue_d \cdot E = \frac{cpue_d}{CPUE_{R,s}} N_R = r_{LNR2} \cdot N_R \quad (2)$$

Norton Sound red king crab CPUE standardization

Subtraction method

Subtraction method expands **total catch CPUE** and subtracts total retained catch. This method does **NOT** assume **accurate discarded crab** but assume **accurate total catch crab**

$$cpue_t = \frac{n_t}{e} \qquad D_{Sub} = cpue_t \cdot E - N_R$$

Subtraction2 method

Similar to LNR2, bias corrected Subtraction method is simply bias corrected total catch minus retained catch

$$D_{Sub2} = \left(\frac{CPUE_R}{CPUE_{R,s}}\right) \cdot cpue_t \cdot E - N_R = \left(\frac{cpue_t}{CPUE_{R,s}} - 1\right) \cdot N_R = r_{sub2} \cdot N_R \qquad (3)$$

Ratio method

The ratio method uses the identical method used in the assessment model, that multiplies the observed discards to retained catch ratio with total retained catch. This method assumes observed discards to retained ratio is accurate and representative.

$$D_{ratio} = \frac{n_d}{n_{lr}} N_R = r_d \cdot N_R \qquad (4)$$

Estimation of discard mortality biomass

One of the main objectives of estimating discard is calculating discard mortality biomass (Mb_{dis}) that is calculated as follows

$$Mb_{dis} = 0.2 \cdot D_n \cdot W_{dis} \qquad (5)$$

where, D_n is the number of discards, W_{dis} is average weight discarded crab, and 0.2 is assumed handling mortality rate.
W_{dis} is calculated as

$$W_{dis} = \sum_l p_{dis,l} \cdot wm_l \qquad (6)$$

where $p_{dis,l}$ is the proportion of discarded crab size class (l) and wm_l is average weight (lb) for each size class (Table 3).

Direct discard mortality biomass estimation method

Alternatively, the above methods can be converted directly to biomass using observed weights w_d and w_r or by using the equation (6), such that

$$w_d = n_d \sum_l p_{dis,l} \cdot wm_l \ , \ w_r = n_r \sum_l p_{r,l} \cdot wm_l \ , \ w_t = w_d + w_r,$$

$$CPUE_{R,s} = \frac{W_{R.s}}{E_s}, \qquad CPUE_R = \frac{W_R}{E}$$

Then all the above 5 methods can be converted to

LNR.lb method

$$cpue_d = \frac{w_d}{e} \qquad Mb_{LNR} = 0.2 \cdot cpue_d \cdot E$$

LNR2.lb method

$$Mb_{LNR2} = 0.2 \cdot \frac{cpue_d}{CPUE_{R,s}} W_R = 0.2 \cdot r_{LNR2} \cdot W_R$$

Sub.lb method

$$cpue_t = \frac{w_t}{e} \qquad Mb_{Sub} = 0.2 \cdot \left(cpue_t \cdot E - W_R \right)$$

Norton Sound red king crab CPUE standardization

Sub2.lb

$$Mb_{Sub2} = \left(\frac{cpue_t}{CPUE_{R,s}} - 1 \right) \cdot W_R = 0.2 \cdot r_{sub2} \cdot W_R$$

Ratio.lb

$$Mb_{ratio} = 0.2 \frac{w_d}{w_r} W_R = 0.2 \cdot r_{ratio} \cdot W_R$$

Results

Overall subtraction method appeared to give higher discard mortality than other methods. Between the number and lb methods, LNR and LNR.lb methods were identical, and discrepancies were under 5% for LNR2 and ratio methods. On the other hand, subtraction method (Sub, Sub2) had +/- 60% differences.

Discussion

As stated, the NSRKC observer survey was not designed or intended to estimate discards, and this estimation was conducted at the request of the CPT and SSC. Methods using CPUE (LNR, LNR2, Sub, Sub2) assumes that observed vessels are representative of the entire fleet. Difference between LNR and Subtraction method is that LNR method assumes that observed discards are accurate whereas subtraction method assumes that observed discards are biased but observed total catches are accurate. On the other hand, the ratio method assumes that observed discard proportions would represent total proportion or that every fisherman has a similar crab composition.

Estimates of discarded crab are more likely to be accurate on the observed vessels because retained and discarded crab are distinguished in cooperation with the fishermen. However, these estimates are likely biased low relative to the entire fleet because of the fact that observer coverage is voluntary and generally limited to larger boats which are generally more efficient in catching legal crab with fewer discards than those with small boats. In addition, fisherman may volunteer for observer coverage when catches are anticipated to be high. This is generally supported by fish ticket data where total season retained catch CPUE is generally higher by observed fishermen than unobserved fishermen (Table 2a,b). and retained catch CPUE is generally higher during periods when observers are on board. When observers were on board, fishermen went to different fishing areas from the rest of the fleet including those without observers (Table 4). Because of this nonuniformity in fishing behavior, total catch and discard estimation for the entire fishery is likely inaccurate and difficult to evaluate including the directionality of the bias. In the absence of TRUE observation, relative accuracies of the estimates among the 10 methods were highly uncertain. Furthermore, in the absence of objective criteria for selecting a method for estimation, it is difficult to choose the most appropriate method for the NSRKC fishery.

Norton Sound red king crab CPUE standardization

Table 1a. Observed pot lifts, catch, and total pot lifts and catch from 2012 to 2019

	Observer Survey						
Year	Pot lifts E	Sublegal n_{sub}	Legal retained n_r	Legal discards n_{ld}	Female n_f	*Discarded lb*	*Retained lb*
2012	82	1,025	1,112	177	155	1,404	3,210
2013	190	2,647	2,109	258	120	2,648	6,172
2014	141	1,472	1,752	315	103	2,684	5,252
2015	69	969	1,676	577	224	2,635	4,495
2016	67	264	1,700	169	877	710	4,840
2017	108	432	2,174	122	373	845	6,731
2018	77	547	1,095	10	573	678	3,583
2019	28	123	142	1	89	116	432

Table 1b Fish tickets

	All fishermen			Sampled fishermen		
Year	pot lifts E	Retained N_R	Retained lb	pot lifts E_s	Retained N_{Rs}	Retained lb
2012	10,041	161,113	475,990	3,595	52,185	154,444
2013	15,058	130,603	391,863	7,545	74,466	223,725
2014	10,124	129,656	389,004	3,729	53,741	161,573
2015	8,356	144,224	4,011,112	2,323	49,986	138,936
2016	8,009	138,997	420,159	1,882	45,225	135,581
2017	9,401	135,322	411,736	2,079	37,767	116,701
2018	8,797	89,613	298,396	2,494	26,031	88,095
2019	5,436	24,913	75,023	949	4,458	13,114

Table 2a. Estimated quantity: number method

Year	$cpue_d$	$cpue_t$	$CPUE_{R,s}$	$CPUE_R$	r_{LNR2}	r_{sub2}	r_d
2012	14.66	28.22	14.52	16.05	1.01	0.94	1.08
2013	15.29	26.39	9.87	8.67	1.55	1.67	1.38
2014	12.67	25.10	14.41	12.80	0.88	0.74	1.02
2015	22.41	46.70	21.52	17.26	1.04	1.17	0.92
2016	6.46	31.84	24.03	17.36	0.27	0.32	0.25
2017	5.13	25.26	18.17	14.33	0.28	0.39	0.25
2018	7.23	21.45	10.44	10.19	0.69	1.06	0.51
2019	4.43	9.50	4.70	4.58	0.94	1.02	0.87

Norton Sound red king crab CPUE standardization

Average	11.0	26.81	14.71	12.66	0.83	0.92	0.79

Table 2b. Estimated quantities: lb method

Year	$cpue_d$	$cpue_t$	$CPUE_{R,s}$	$CPUE_R$	r_{LNR2}	r_{sub2}	r_d
2012	17.13	56.28	42.96	47.40	0.40	0.31	0.44
2013	13.94	46.42	29.65	26.02	0.47	0.57	0.43
2014	19.04	56.29	43.33	38.41	0.44	0.30	0.51
2015	38.18	103.33	59.81	48.00	0.64	0.73	0.59
2016	10.59	82.83	72.04	52.46	0.15	0.15	0.15
2017	7.82	70.15	56.13	43.62	0.14	0.25	0.13
2018	8.81	55.34	35.32	33.92	0.25	0.57	0.19
2019	4.14	19.57	13.82	13.80	0.30	0.42	0.27
Average	14.96	61.27	44.13	37.96	0.35	0.41	0.34

Table 3 discarded crab size proportions ($p_{dis,l}$) and calculated W_{dis}.

Size class	34	44	54	64	74	84	94	104	114	124	134		W_{dis}
Average weight (lb) (wm_l)	0.09	0.18	0.32	0.52	0.82	1.20	1.70	2.32	2.99	3.69	4.37		
2012	0.00	0.01	0.12	0.20	0.12	0.16	0.28	0.10	0.01	0.00	0.00		1.17
2013	0.00	0.02	0.11	0.29	0.25	0.14	0.15	0.04	0.00	0.00	0.00		0.91
2014	0.00	0.00	0.01	0.04	0.10	0.27	0.43	0.13	0.01	0.00	0.00		1.50
2015	0.00	0.00	0.00	0.02	0.08	0.18	0.47	0.21	0.03	0.01	0.00		1.70
2016	0.00	0.00	0.01	0.04	0.05	0.17	0.53	0.18	0.02	0.00	0.00		1.64
2017	0.00	0.00	0.02	0.10	0.16	0.14	0.30	0.26	0.01	0.00	0.00		1.53
2018	0.00	0.00	0.04	0.09	0.18	0.36	0.30	0.02	0.00	0.00	0.00		1.22
2019	0.02	0.05	0.18	0.24	0.10	0.12	0.27	0.02	0.00	0.00	0.00		0.93
Average	0.00	0.01	0.06	0.13	0.13	0.19	0.34	0.12	0.01	0.00	0.00		1.33

Table 4. The number of discarded crab estimated by 5 methods via **number method**.

Year	D_{LNR}	D_{LNR2}	D_{Sub}	D_{Sub2}	D_{ratio}
2012	147,186	154,492	122,239	136,303	174,153
2013	230,229	202,324	266,770	230,229	179,896
2014	128,347	114,021	124,525	128,347	132,246
2015	187,223	150,175	245,965	187,223	133,037
2016	51,760	37,382	115,976	51,760	35,403
2017	48,424	38,212	103,125	48,424	34,484
2018	63,635	62,107	99,123	63,635	45,584
2019	24,074	23,486	26,729	24,074	21,755

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Table 5a. Discard mortality (lb) by 5 methods via **number method**.

Year	*LNR*	*LNR2*	*Sub*	*Sub2*	*Ratio*
2012	34,395	36,102	28,565	31,851	40,696
2013	41,969	36,882	48,630	41,969	32,794
2014	38,560	34,256	37,411	38,560	39,731
2015	63,815	51,187	83,837	63,815	45,345
2016	16,968	12,255	38,020	16,968	11,606
2017	14,773	11,658	31,462	14,773	10,521
2018	15,492	15,120	24,131	15,492	11,097
2019	4,496	4,386	4,992	4,496	4,063

Table 5b. Discard mortality (lb) by 5 methods via **weight method.**

Year	*LNR.lb*	*LNR2.lb*	*Sub.lb*	*Sub2.lb*	*Ratio.lb*
2012	343,95	37,952	17,817	29,507	41,647
2013	41,969	36,833	61,419	44,313	33,624
2014	38,560	34,184	36,199	23,264	39,766
2015	63,815	51,218	92,456	58,370	47,025
2016	16,968	12,356	48,652	12,590	12,322
2017	14,773	11,479	50,099	20,564	10,338
2018	15,492	14,877	37,693	33,826	11,291
2019	4,496	4,490	6,267	6,239	4,021

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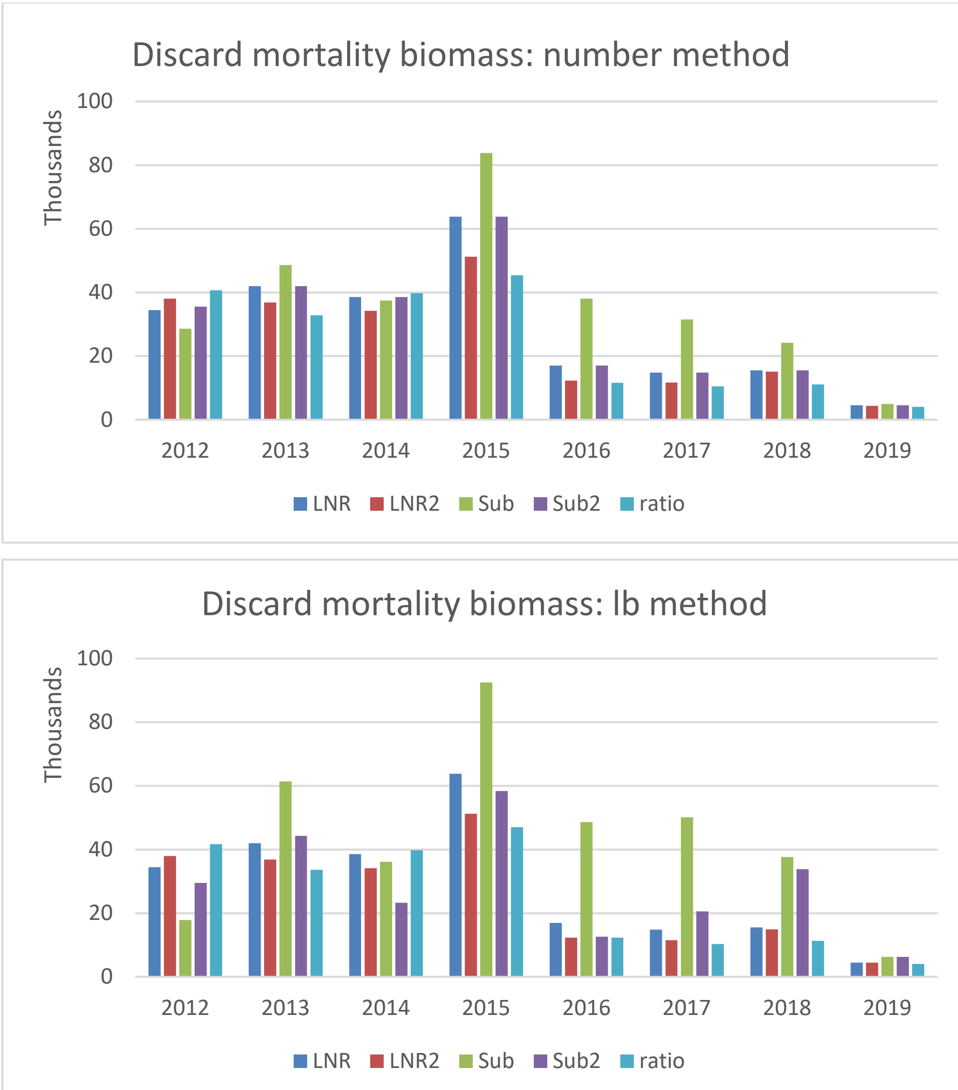

Figure 1. Discarded crab mortality biomass estimated by 5 proposed methods.

Discards Estimate without observer survey

Total catch OFL-ABC of NSRKC have been calculated since adoption of the NSRKC assessment model; however, it was not adopted because of the lack of discard estimate. Total catch OFL-ABC for NSRKC was set for the first time in 2020 based on the fact that discards could be estimated for 2012-2019, but in the same year the NSRKKC fishery observer program was terminated. This made it impossible to assess annual catch limit (ACL) overage for the NSRKC fishery. This prompted request by CPT-SSC to explore a method to estimate discards with NO DATA. Given that the NSRKC observer survey was not intended to estimate discards, developing a method is highly speculative.

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There are 3 general approaches estimating discards for future fisheries in the absence of observer data:

1. Apply averages on observed retained catch and effort
2. Predict discards from observed retained catch and effort
3. Predict discards from observed crab size composition

Approaches 1 & 2

Approach 1

1. Apply averages of $cpue_d$, $cupe_t$, r_{LNR2}, r_{sub2} and r_d of the lb method (Table 2b)
2. Calculate average discards mortality/retained weight ratio of the 2012-2019 surveys.

Table 6: discard mortality weight/retained weight ratio of the 5 estimation methods.

Year	*LNR*	*LNR2*	*Sub*	*Sub2*	*Ratio*
2012	0.072	0.080	0.037	0.062	0.087
2013	0.107	0.094	0.157	0.113	0.086
2014	0.099	0.088	0.093	0.060	0.102
2015	0.159	0.128	0.230	0.146	0.117
2016	0.040	0.029	0.116	0.030	0.029
2017	0.036	0.028	0.122	0.050	0.025
2018	0.052	0.050	0.126	0.113	0.038
2019	0.060	0.060	0.084	0.083	0.054
Average	0.078	0.070	0.121	0.082	0.067

Approach 2: Construct a linear regression of predicting $cpue_d$, $cupe_t$, $CPUE_{Rs}$, and r_c from observed $CPUE_R$.

Table 7: linear regression equation

	Regression equation	R^2
$cpue_d$	$cpue_d = 0.4037+0.3834CPUE_R$	0.22
$cpue_t$	$cpue_t = -1.5427+1.655CPUE_R$	0.74
$CPUE_{Rs}$	$CPUE_{Rs} = -6.2385+1.3271CPUE_R$	0.87
r_d	*No correlation*	

In 2022, total potlift (E) was 5154, and total number of retained crab was 125042, total weight was 317173, and $CPUE_R$ was 61.54. Applying those, estimated quantities are as follows.

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Table 8: average and predicted quantities for 2022 fishery

	Average	*Regression*
$cpue_d$	14.96	24.00
$cpue_t$	61.27	100.30
$CPUE_{Rs}$		75.43
r_{LNR2}	0.35	0.32
r_{sub2}	0.41	0.33
r_d	0.34	

Applying those to the equations, estimated discard mortality biomass (lb) of 2022 was

Table 9: The number of discards and regression method.

	LNR	*LNR2*	*Sub*	*Sub2*	*Ratio*
Regression	24,737	20,181	199,797	104,594	
Average	15,416	22,055	-272	26,041	21,355
Average lb	24,806	22,055	38,261	26,041	21,355

Approach 3: Predict discards from observed trawl survey crab size composition

Trawl survey selectivity method uses the same method for estimating discards (Appendix A, equations 8). **Trawl survey length proportion data as a proxy for true length proportions.** The model estimated trawl survey selectivity is 1.0 for all lengths. This assumes that trawl survey length composition equals NSRKC length proportion subject to fishery.

Discards length proportion $p_{dis,l}$ can be estimated by multiplying model estimated fishery selectivity (S_l) and 1- retention probability ($S_{ret,l}$)

$$p_{dis,l} = p_{twl,l} \cdot S_l \cdot \left(1 - S_{ret.l}\right)$$

Then calculate discards-retained ratio (r_{dis}) as

$$r_d = \frac{\sum_l p_{twl,l} \cdot S_l \cdot \left(1 - S_{ret,l}\right)}{\sum_l p_{twl,l} \cdot S_l \cdot S_{ret,l}}$$

The discard biomass unit (w_{dis}) is

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$$W_{dis} = \frac{\sum_{l} p_{twl,l} \cdot S_l \cdot \left(1 - S_{ret,l}\right) \cdot wm_l}{\sum_{l} p_{twl,l} \cdot S_l \cdot \left(1 - S_{ret,l}\right)}$$

During the 2012-2019 periods, trawl survey occurred in 2014, 2017, 2018, and 2019. The table below shows trawl survey length proportion, and model estimated selectivity and retention probability from the 2021 assessment model

Table 10: Table: trawl survey size composition, fishery size selectivity (S_l), retention probability (S_{ret}), and estimated discard size composition.

Size	34	44	54	64	74	84	94	104	114	124	134
Trawl											
2014	0.01	0	0.01	0.01	0.07	0.14	0.25	0.27	0.14	0.06	0.02
2017	0.11	0.02	0.01	0.06	0.12	0.11	0.06	0.09	0.13	0.23	0.07
2018	0.02	0.33	0.42	0.08	0.05	0.02	0.02	0.01	0.01	0.01	0.02
2019	0	0	0.02	0.13	0.47	0.26	0.04	0.02	0.01	0.02	0.03
2022	0.12	0.03	0.04	0.14	0.15	0.15	0.14	0.12	0.07	0.03	0.01
S_l	0	0.01	0.04	0.12	0.33	0.64	0.86	0.96	0.99	1	1
S_{ret}	0	0	0	0	0	0	0.07	0.88	1	1	1
Discard											
2014	0	0	0.00	0.00	0.07	0.26	0.58	0.09	0	0	0
2017	0	0	0.00	0.04	0.22	0.40	0.27	0.00	0	0	0
2018	0	0.04	0.22	0.13	0.22	0.17	0.21	0.02	0	0	0
2019	0	0	0.00	0.04	0.42	0.45	0.09	0.01	0	0	0
2022	0	0.00	0.01	0.06	0.17	0.32	0.39	0.05	0	0	0

Comparing the estimated with observed, the estimated r_d tend to be higher than observed, especially 2018 and 2019.

Table 11 Comparisons of parameters between trawl survey method and ratio (number) method.

	r_d	W_{dis}	Ob.r_d	Ob.W_{dis}	*Pred* Mb_{dis}	Ob. Mb_{dis}
2014	0.75	1.57	1.00	1.50	30,300	38,967
2017	0.35	1.28	0.25	1.53	12,060	11,748
2018	1.54	0.92	0.51	1.22	25,238	10,421
2019	4.70	1.05	0.87	0.93	24,842	10,852
2022	1.40	1.34			47,024	

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Comparison of methods

Putting the above methods together, 21 discard catch mortality were calculated. Total catch ranged from 0.35 to 0.39 million lb and below ABC of 0.4 million lb.

Table 12 estimates of 2022 total catch based on the 15 methods.

	2022 Total Catch (million lb)
Regression	
LNR	0.36
LNR2	0.36
Sub	0.54
Sub2	0.44
Average	
LNR	0.35
LNR2	0.36
Sub	0.34
Sub2	0.37
Ratio	0.36
Average lb	
LNR	0.36
LNR2	0.36
Sub	0.38
Sub2	0.37
Ratio	0.36
Trawl	0.39

Discussion

As presented the above, overage of ACL is highly depended on *ad hoc* estimation methods being selected. This suggests that a method has to be selected on the merit of scientific accuracy and precision before total catch is calculated. The 15 alternatives presented the above are examples and there could be alternative methods that would provide more accurate and precise estimates. Same as the discussion regarding selecting a method for estimating discards with data, objective criteria for selecting a method for estimating discards without data are not established, and thus author's recommendation is not provided.

Regardless the method being ultimately selected, a question of jurisprudence should be answered first: "should ACL overage that has significant regulatory consequences be determined by an estimate based on NO data?"

The total ABC of NSRKC is calculated as

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Total ABC = ABC_Buffer·(retained OFL + 0.2·discards OFL) = $Mb_{R,p} + Mb_{dis,p}$

Based on the preseason ABC, GHL is determined as

GHL < ABC_Buffer·(retained OFL) = $Mb_{R,p}$

Which assumes that discards morality (Mb_{dis}) would be

$$Mb_{dis} = \frac{Mb_{dis,p}}{Mb_{R,p}} \cdot Mb_R$$

And thus, the postseason total catch ($Mb_R + Mb_{dis}$) would be less than ABC unless Mb_R far exceeds GHL.

In reality; however, the projected discard mortality do not always match the observed one. During the 2012-2019 period, observed ratio of discard mortality/retained was up to 8.75 times greater than projected (Table).

Table: Projected and observed mort_lb and "observed" /predicted $mort\_lb_b$ ratio during the 2012-2019 fisheries.

	2012	2013	2014	2015	2016	2017	2018	2019
Projected	0.010	0.019	0.028	0.045	0.047	0.042	0.037	0.059
Retrospective	0.062	0.091	0.110	0.069	0.035	0.029	0.039	0.083
Observed								
Obs. LNR	0.072	0.107	0.099	0.159	0.040	0.036	0.052	0.060
Obs. LNR2	0.080	0.094	0.088	0.128	0.029	0.028	0.050	0.060
Obs. Sub	0.037	0.157	0.093	0.230	0.116	0.122	0.126	0.084
Obs. Sub2	0.062	0.113	0.060	0.146	0.030	0.050	0.113	0.083
Obs. Ratio	0.087	0.086	0.102	0.117	0.029	0.025	0.038	0.054
Ob/Project ratio								
Retrospective	6.20	4.79	3.93	1.53	0.74	0.69	1.05	1.41
LNR	7.23	5.64	3.54	3.54	0.86	0.85	1.40	1.02
LNR2	7.97	4.95	3.14	2.84	0.63	0.66	1.35	1.01
Sub	3.74	8.25	3.32	5.12	2.46	2.90	3.41	1.42
Sub2	6.20	5.95	2.14	3.23	0.64	1.19	3.06	1.41
Ratio	8.75	4.52	3.65	2.61	0.62	0.60	1.02	0.91

For 2022, projected mort_lb was 0.058 and retrospective (model 21.0) mort_lb was 0.065, which can be translated into projected and retrospective total catch of 0.36 million lb.