Appendix A

Pribilof Islands Golden King Crab Tier 4 Calculations

Benjamin Daly[a] and Tyler Jackson[b]
Alaska Department of Fish and Game
Division of Commercial Fisheries
351 Research Ct.
Kodiak, AK 99615, USA
Phone: [a] (907) 486-1865, [b] (907) 486-1861

The PIGKC stock is currently managed as Tier 5, but we present Tier 4 calculations here. While fishery catch data are available, the OFL calculation presented here uses only NMFS-AFSC eastern Bering Sea continental slope bottom trawl survey data.

Data

Survey biomass estimates and length composition

The NMFS-AFSC conducted an eastern Bering Sea continental slope bottom trawl survey on a biennial schedule during 2002–2016 (2006, 2014, 2018, and 2020 surveys cancelled), and are the sole data source for estimating mature male biomass (MMB) for Pribilof Islands golden king crab (PIGKC, *Lithodes aequispinus*). Results of the 2002–2016 surveys showed that a majority of golden king crab on the eastern Bering Sea continental slope occurred in the 200–400 m and 400–600 m depth ranges (Hoff and Britt 2003, 2005, 2009, 2011; Hoff 2013, 2016). Biomass, number, and density (in number per area and in weight per area) of golden king crab on the eastern Bering Sea continental slope are higher in the southern areas than in the northern areas, with highest abundance in survey subarea 2 (Pengilly and Daly 2017). For the purpose of this document, we focus on survey subareas 2, 3, and 4 as they generally conform to the ADF&G Pribilof District Management Area (PDMA, Figs. 1-3, ADF&G 2017). Length composition data are available for 2008-2016 surveys but not the 2002 and 2004 surveys (Fig. 4). For the 2008-2016 surveys, we applied length-weight regression to size composition data to estimate the weight of each crab measured. MMB was calculated using a maturity size cut-off of 107 mm CL (Somerton and Otto 1986). An area-swept estimate of biomass and of the variance of the biomass estimate was computed for each stratum within a survey subarea and summed over strata within the subarea to obtain area-swept estimates of biomass within a subarea and of the variance of that biomass estimate; estimates of the biomass and associated variances within subareas were summed over subareas to obtain biomass estimates in aggregates of subareas and of the variances of those estimates.

Total catch, bycatch, discards, and retained catch size composition data

- The 1981/82–1983/84, 1984–2019 time series of retained catch (number and weight of crab, including deadloss), effort (vessels and pot lifts), average weight of landed crab, average carapace length of landed crab, and CPUE (number of landed crab captured per pot lift) are available, but not used in the OFL calculation presented here.
- The 1993–2019 time series of weight of retained catch and estimated weight of discarded catch and estimated weight of fishery mortality of Pribilof golden king crab during the directed fishery and all other crab fisheries are available, but not used in the OFL calculation presented here.
- The groundfish fishery discarded catch data (grouped into crab fishery years from 1991/92–2008/09, and by calendar years from 2009–2019) are available, but not used in the OFL calculation presented here.
- Retained catch size composition data is available for 2001-2019, but not used in the OFL calculation presented here.

Growth per molt

The authors are not aware of data on growth per molt collected from golden king crab in the Pribilof District. Growth per molt of juvenile golden king crab, 2–35 mm CL, collected from Prince William Sound have been observed in a laboratory setting and equations describing the increase in CL and intermolt period were estimated from those observations (Paul and Paul 2001a); those results are not provided here. Growth per molt has also been estimated from golden king crab with CL ≥90 mm that were tagged in the Aleutian Islands and recovered during subsequent commercial fisheries (Watson et al. 2002); those results are not presented here because growth-per-molt information does not enter into the OFL calculation presented here.

Weight-at length (by sex)

Parameters (A and B) used for estimating weight (g) from carapace length (CL, mm) of male and female golden king crab according to the equation, Weight = $A*CL^B$ (from Table 3-5, NPFMC 2007) are: A = 0.0002988 and B = 3.135 for males and A = 0.0014240 and B = 2.781 for females.

Natural mortality rate

The default natural mortality rate assumed for king crab species by NPFMC (2007) is M=0.18.

Analytic Approach

History of Modeling Approaches

The PIGKC stock assessment has followed the Tier 5 methodology since 2012, but interest in a Tier 4 method using a random effect model and NMFS-AFSC EBS slope survey data has received growing interest. In 2017, total biomass and mature male biomass were estimated by a random effects method with the inclusion of the 2016 survey data. At that time, the CPT recommended to use the Tier 5 assessment until the model was further explored and/or additional survey data was available. Here, we further explore the utility of the random effects model, though there has been no additional fishery-independent data since the 2017 assessment.

Random effects model

The program “Survey Average Random Effects” was used to estimate biomass from the area-swept MMB (males ≥107 mm) estimates in surveyed years and to project biomass estimates for unsurveyed years into 2022 via a state-space random walk plus noise model. The state-space random walk plus noise is formulated as a random effect model, where process errors are considered “random effects” drawn from an underlying normal distribution with μ=0 and estimated σ^2 (σ_λ^2), and integrated out of the likelihood. The method was developed by the NPFMC groundfish plan team's survey averaging working group as a smoothing technique similar to the Kalman Filter, but which provides more flexibility with non-linear processes and non-normal error structures (Spencer et al. 2015).

Model scenarios

We applied the random effects model to six iterations of the EBS slope survey MMB timeseries, which varied by 1) the number of MMB input years, 2) the spatial area extent, and 3) level of stratification (Table 1). Size composition data is only available for 2008, 2010, 2012, and 2016 survey, thus MMB area-swept estimates are only available for those years. However, we calculated the ratio of MMB to total biomass for the 2008, 2010, 2012, 2016 surveys (Table 2) and applied the average ratio to the 2002 and 2004 survey total biomass and variance to approximate MMB for 2002 and 2004 surveys. The Pribilof District Management Area (PDMA) boundaries do not align with those of the EBS slope survey subareas. All of survey subareas 2 and 3, nearly all of subarea 4, and portions of subareas 1 and 5 are encompassed by the PDMA. While most of the survey biomass occurs in subareas 2-4, some GKC occur in subareas 1 and 5. For some iterations, we included portions of these subareas when calculating MMB estimates. Finally, since survey stations towed in a given season are selected from a pool of available stations via a sampling design stratified by subarea and depth range, we included MMB timeseries where MMB was calculated using average survey MMB densities within strata within subareas, and strata within the survey area (i.e., similar depth strata were combined among subareas, and subareas were neglected) (Table 3). Model scenarios were as follows:

1. **2020a**: MMB and variance in MMB 2008-2016 computed among strata within subareas 2-4, summed within subareas, and then across subareas
2. **2020b**: MMB and variance in MMB 2008-2016 computed among strata within the survey area bounded by the Pribilof Islands district and summed across strata
3. **2020c**: MMB density and variance in MMB 2008-2016 density computed among strata within subareas 2-4 and summed across strata
4. **2020d**: The same as 2020a, but included MMB estimates for 2002 and 2004 (computed using the mean ratio of MMB:total biomass from 2008-2016)
5. **2020e**: The same as 2020b, but included MMB estimates for 2002 and 2004 (computed using the mean ratio of MMB:total biomass from 2008-2016)
6. **2020f**: The same as 2020c, but included MMB estimates for 2002 and 2004 (computed using the mean ratio of MMB:total biomass from 2008-2016)

Table 1. Model scenarios, where calculation of MMB inputs varied with changes to survey input years, the spatial extent of the stock, and levels of stratification (i.e., depth stratum, subareas). PDMA refers to the Pribilof District Management Area.

Model	Survey Years	Survey Area	Stratification Levels
2020a	2008 - 2016	Subareas 2 - 4	2
2020b	2008 - 2016	PDMA	1
2020c	2008 - 2016	Subareas 2 - 4	1
2020d	2002 - 2016	Subareas 2 - 4	2
2020e	2002 - 2016	PDMA	1
2020f	2002 - 2016	Subareas 2 - 4	1

Table 2. MMB:total biomass ratios used to estimate 2002 and 2004 MMB by model scenario. Ratios are different among scenarios, depending on the biomass calculation used (i.e., spatial area extent and stratification levels).

Survey year	**2020d**	**2020e**	**2020f**
2008	0.56	0.57	0.57
2010	0.33	0.39	0.40
2012	0.30	0.30	0.30
2016	0.50	0.49	0.49
Mean	0.42	0.44	0.44
SD	0.13	0.12	0.12

Table 3. Area of each stratum within subareas. For stratification, stratum area is computed as the sum of stratum areas among similar depths within the appropriate survey area.

Subarea	Stratum	Depth (m)	Stratum area (km^2)	Stratum area in PDMA (km^2)
1	1	200 - 400	4,012	88
	2	400 - 600	4,063	102
	3	600 - 800	1,742	105
	4	800 - 1,000	1,355	119
	5	1,000 - 1,200	1,107	128
2	1	200 - 400	1,158	1,158
	2	400 - 600	705	705
	3	600 - 800	591	591
	4	800 - 1,000	553	553
	5	1,000 - 1,200	536	536
3	1	200 - 400	904	904
	2	400 - 600	886	886
	3	600 - 800	910	910
	4	800 - 1,000	732	732
	5	1,000 - 1,200	676	676
4	1	200 - 400	1,236	1,094
	2	400 - 600	730	730
	3	600 - 800	694	694
	4	800 - 1,000	708	708
	5	1,000 - 1,200	662	662
5	1	200 - 400	424	167
	2	400 - 600	426	142
	3	600 - 800	432	145
	4	800 - 1,000	552	282
	5	1,000 - 1,200	570	317
6	1	200 - 400	2,596	0
	2	400 - 600	1,706	0
	3	600 - 800	917	0
	4	800 - 1,000	645	0
	5	1,000 - 1,200	496	0

Evaluation of the fit to the data

The random effects model appeared to converge for all MMB input scenarios (maximum gradient component < 0.0001) and fitted MMB and parameter estimation was primarily only sensitive to differing survey year inputs. Large CVs (> 20%) in all model iterations that used only data from 2008 – 2016 contributed to an estimated process error variance that was very small (σ_λ ~ 0.001) (Table 4), resulting in a 'flat' trend in fitted MMB (Fig. 5). When including the 2002 and 2004 MMB approximations, the model responded by capturing the relatively low survey biomass estimates in those years following a slight increasing trend (Fig. 5).

Table 4. Model parameter outputs.

Model	Joint Neg. Log Likelihood	σ_λ
2020a	0.40	0.001
2020b	1.21	0.001
2020c	1.09	0.001
2020d	2.00	0.117
2020e	2.54	0.106
2020f	2.59	0.110

Calculation of reference points

The Tier 4 OFL is calculated using the F_{OFL} control rule:

$$F_{OFL} = \begin{cases} 0 & if\ \frac{MMB}{B_{MSY}} \leq 0.25 \\ \frac{M(\frac{MMB}{B_{MSY}} - \alpha)}{1-\alpha} & if\ 0.25 < \frac{MMB}{B_{MSY}} < 1 \\ M & if\ MMB > B_{MSY} \end{cases}$$

where MMB is quantified at the mean time of mating date (15 February), B_{MSY} is defined as the average MMB for a specified period (either 2002-2016 or 2008-2016, defined in Table 1), M = 0.18 yr^{-1}, and α = 0.1. The Tier 4 OFL (Table 5) was calculated by applying a fishing mortality determined by the harvest control rule (above) to the mature male biomass at the time of fishing, which remained constant starting in 2016 (i.e., the last data input year).

Table 5. Comparisons of management quantities for the six model scenarios.

Model	B_{MSY} (t)	MMB (t)	$MMB_{projected}$	MMB / B_{MSY}	F_{OFL}	OFL (t)	OFL (lbs)
2020a	589.1	589.1	526.4	0.894	0.159	77.256	170,321
2020b	574.6	574.7	513.5	0.894	0.159	75.365	166,152
2020c	639.8	639.8	571.7	0.894	0.159	83.907	184,984
2020d	514.6	614.2	548.8	1.066	0.180	90.404	199,307
2020e	503.7	584.5	522.3	1.037	0.180	86.046	189,699
2020f	557.3	657.6	587.7	1.055	0.180	96.807	213,424

Authors recommendation
Our preferred model scenario is 2020e. While there is uncertainty in the using MMB approximations for 2002 and 2004 survey data inputs, we feel the confident the approximations capture the population trends indicated by total biomass survey estimates for these years. As such, the benefits of incorporating the additional data input years likely outweigh this added uncertainty. Further, we feel that refining the survey data inputs by the PDMA boundaries is more appropriate than using survey subareas 2-4 only, as doing so captures the full extent of this stock within the PDMA. Computing MMB and variance in MMB among stratum, within subareas for the portions of subarea 5 and 1 that are included in the PDMA is not possible due to a small number of stations within individual strata. Since subarea boundaries are likely not meaningful for PIGKC stock delineation, computing MMB estimates with stratification by depth only within the PDMA seems appropriate.

While model estimation of MMB is a step forward in capturing population dynamics of the stock, uncertainty about future bottom trawl surveys and associated data availability is a concern. We recommend PIGKC continue to be managed as a Tier 5 stock until future surveys are solidified. The authors highlight the importance of the NMFS EBS slope bottom trawl survey, and hope that the survey is not discontinued. ADF&G is currently exploring feasibility and design of an industry-cooperative pot survey to meet data needs for PIGKC. This pot survey will be critical if the NMFS EBS slope bottom trawl survey is discontinued, but several years of data collection will be needed before data can be incorporated in model simulations.

Data gaps and research priorities
PIGKC is a data poor stock, with little information for capturing essential population dynamics including abundance and biomass. Fishery independent data are needed for estimating population abundance and biomass, spatial distribution, size at maturity, and length-weight relationships. Increased uncertainty with the future of the NMFS-AFCS biennial bottom trawl survey has elevated the need to establish an industry-cooperative survey to fill these data gaps.

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References

Hoff, G. R. 2013. Results of the 2012 eastern Bering Sea upper continental slope survey of groundfish and invertebrate resources. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-258.

Hoff, G. R. 2016. Results of the 2016 eastern Bering Sea upper continental slope survey of groundfish and invertebrate resources. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-339.

Hoff, G. R., and L. Britt. 2003. Results of the 2002 eastern Bering Sea upper continental slope survey of groundfish and invertebrate resources. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-141.

Hoff, G .R., and L. Britt. 2005. Results of the 2004 eastern Bering Sea upper continental slope survey of groundfish and invertebrate resources. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-156.

Hoff, G. R., and L. Britt. 2009. Results of the 2008 eastern Bering Sea upper continental slope survey of groundfish and invertebrate resources. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-197.

Hoff, G. R., and L. Britt. 2011. Results of the 2010 eastern Bering Sea upper continental slope survey of groundfish and invertebrate resources. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-224.

North Pacific Fishery Management Council (NPFMC). 2007. Public Review Draft: Environmental Assessment for proposed Amendment 24 to the Fishery Management Plan for Bering Sea and Aleutian Islands King and Tanner Crabs to Revise Overfishing Definitions. 14 November 2007. North Pacific Fishery Management Council, Anchorage.

Pengilly, D. and B. Daly. 2017. Updated discussion paper for May 2017 Crab Plan Team meeting: Random effects approach to modelling NMFS EBS slope survey area-swept estimates for Pribilof Islands golden king crab. Report to the North Pacific Fishery Management Council Bering Sea-Aleutian Island Crab Plan Team, 2-5 May 2017 meeting, Juneau, AK.

Spencer, P., G. Thompson, J. Ianelli, and J. Heifetz. 2015. Evaluation of statistical models for estimating abundance from a series of resource surveys. Contributed presentation in 30th Lowell Wakefield Fisheries Symposium: Tools and Strategies for Assessment and Management of Data-Limited Fish Stocks. May 12-15, 2015, Anchorage, Alaska.

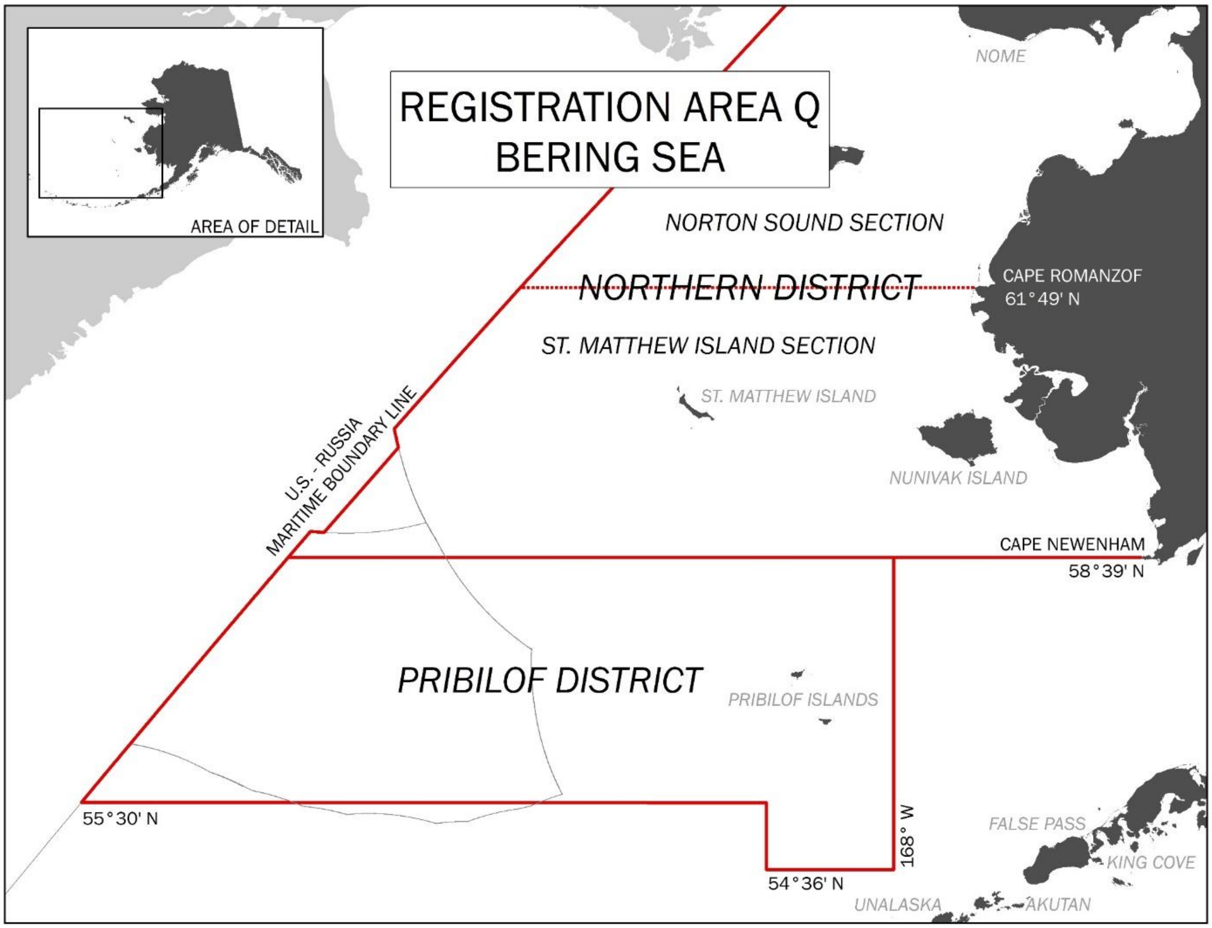

Figure 1. Bering Sea Registration Area Q, subdivided into the Northern District and Pribilof District management areas.

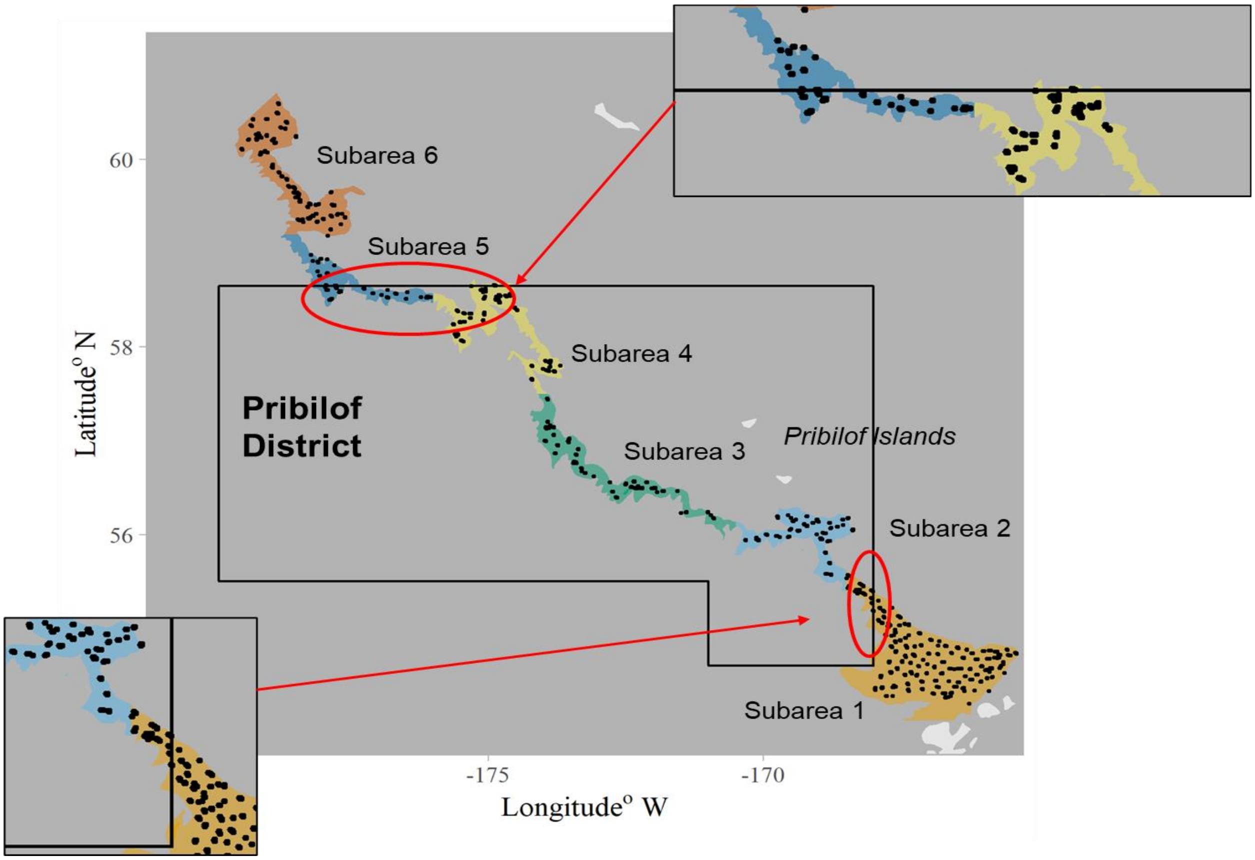

Figure 2. Map of survey subareas, with locations of all possible stations for surveys between 2002 – 2016. Portions of subareas 1 and 5 fall within the Pribilof District Management Area.

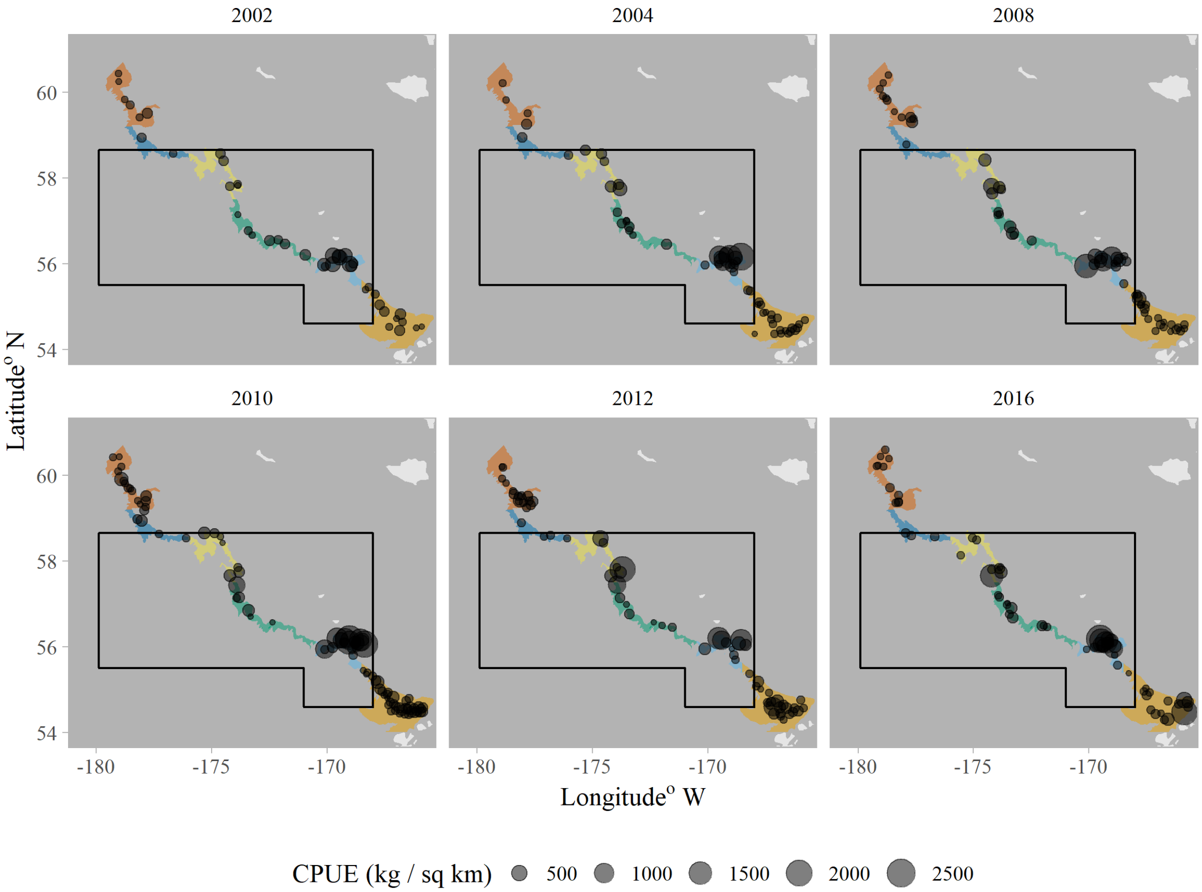

Figure 3. NMFS Eastern Bering Sea upper continental slope bottom trawl survey golden king crab CPUE (kg km^{-2}) total catch biomass for 2002-2016 surveys. Different color polygons correspond to the six different survey subareas with subarea numbering in progressing order from north to south. The black line depicts the Pribilof District Management Area boundary.

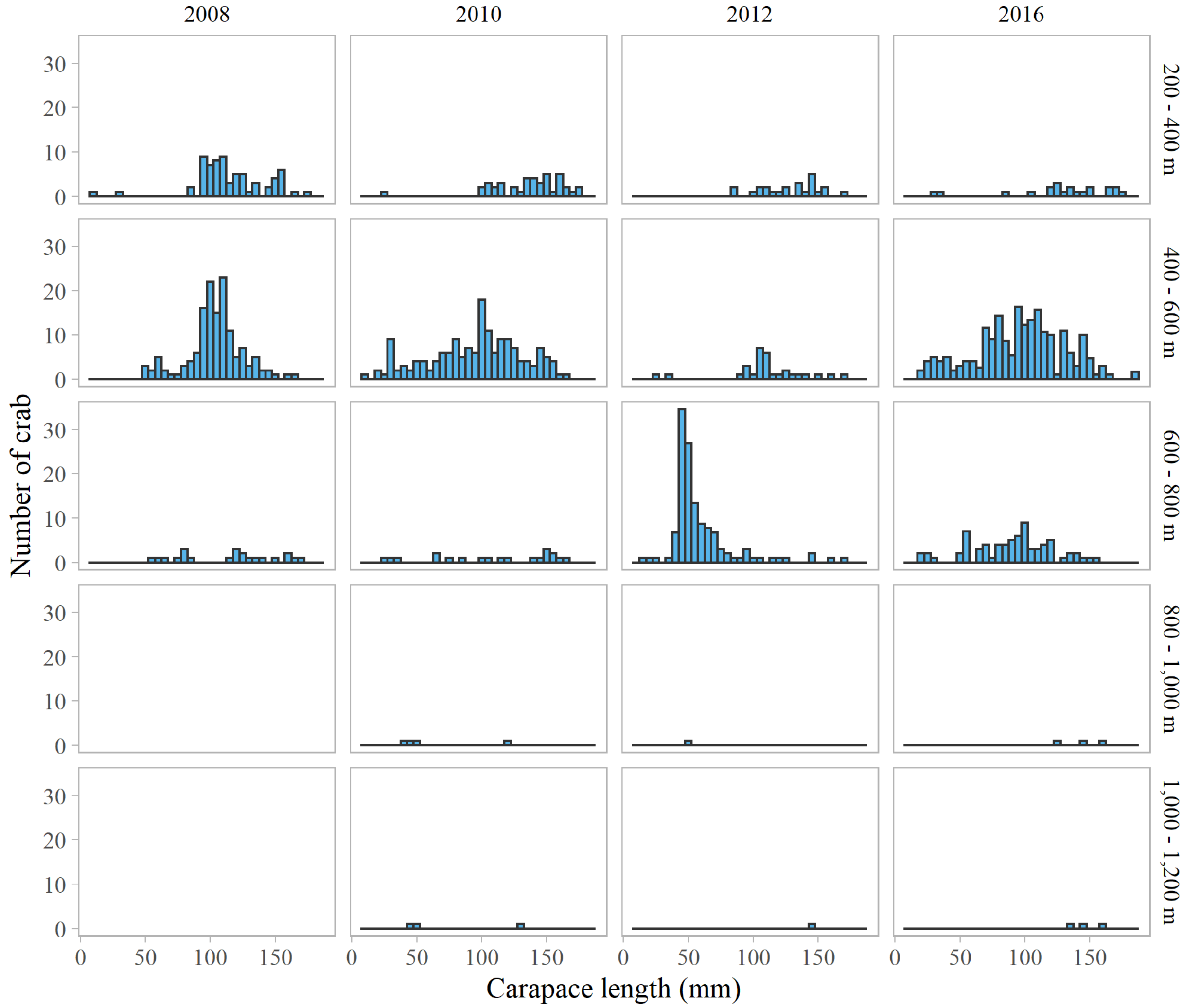

Figure 4. Size frequency of male golden king crab captured in the Pribilof District Management Area during the 2008, 2010, 2012, and 2016 NMFS Eastern Bering Sea upper continental slope bottom trawl survey.

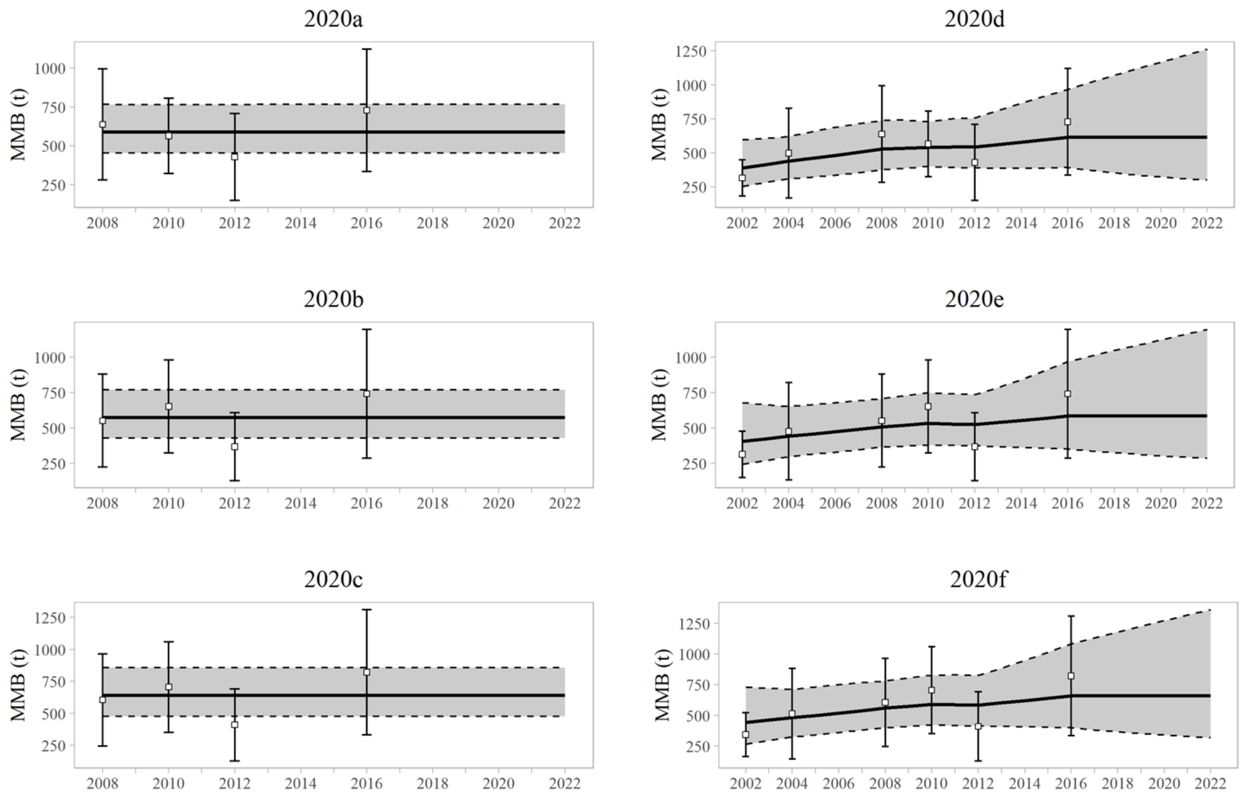

Figure 5. Model fits for PIGKC MMB, with panels referring to different model scenarios. Points correspond to the survey mature male biomass estimates ±95% CI and the black line corresponds to fitted biomass by random effects model ±95% CI (shaded area).