Aleutian Islands Golden King Crab (*Lithodes aequispinus*) Model-Based Stock Assessment in Spring 2017

Draft report for the May 2017 Crab Plan Team Meeting

Prepared by:

M.S.M. Siddeek[1,] J. Zheng[1], C. Siddon[1], and B. Daly[2]

[1]Alaska Department of Fish and Game, Division of Commercial Fisheries, P.O. Box 115526, Juneau, Alaska 99811
[2]Alaska Department of Fish and Game, Division of Commercial Fisheries, 351 Research Ct., Kodiak, Alaska 99615

Executive Summary

1. *Stock*

   Golden king crab, *Lithodes aequispinus*, Aleutian Islands, east of 174° W longitude (EAG) and west of 174° W longitude (WAG).

2. *Catches*

   The Aleutian Islands golden king crab commercial fishery developed in the early 1980s; the harvest peaked in 1986/87 at 5.900 and 8.800 million pounds, respectively, for EAG and WAG. Catches have been steady since 1996/97 following implementation of total allowable catches (TACs) of 3.000 (EAG) and 2.700 (WAG) million pounds. The TACs were increased to 3.150 and 2.835 million pounds for the two respective regions for the 2008/09 fishing year following an Alaska Board of Fisheries (BOF) decision. These levels were below the limit TACs determined under Tier 5 criteria (considering 1991–1995 mean catch as the limit catch) under the most recent crab management plan. The TACs were further increased by another BOF decision to 3.310 million pounds for EAG and 2.980 million pounds for WAG beginning with the 2012/13 fishing year. The fishery has harvested close to TAC levels since 1996/97. Catch rates (crab / pot-pull) increased in both EAG and WAG fisheries in the mid-2000s. However, in recent years WAG catch rates have declined. The below par fishery performance in WAG lead to reduction in TAC to 2.235 million pounds for the 2016/17 fishing season.

3. *Stock biomass*

   Estimated mature male biomass (MMB) for EAG under all scenarios decreased from high levels during the 1990s of the directed fishery, then systematically increased during the 2000s and 2010s. Estimated MMB for WAG decreased during the late 1980s and 1990s, systematically increased during the 2000s, and decreased during last few years since 2009. The low levels of MMB for EAG were observed in 1995–1997 and in 1990s for WAG. Stock trends reflected the fishery standardized CPUE trends in both regions.

4. Recruitment

The numbers of recruits to the model size groups under all scenarios have fluctuated in both EAG and WAG. For EAG, the model recruitment was high in 1987, 1988, 2008, and 2011 to 2014; and lowest in 1986. An increasing trend in recruitment was observed since the early-1990s in EAG. The model recruitment for WAG was high in 1985 and 1986, and lowest in 2011. After 1985 and 1986 peaks, the recruitment trend was low.

5. Management performance

The model was accepted at the September 2016 CPT and October 2016 SSC meetings for OFL determination for the 2017/18 fishery cycle. In addition, the CPT in January 2017 and SSC in February 2017 recommended using the Tier 3 method to compute OFL and ABC. Since it has not yet been used for making any management decision, past management performance by this model outcome cannot be assessed. However, we provide the management performance (status and catch specifications) tables with the Tier 3 assessment results for scenario 9 for individual regions (EAG and WAG) and the entire Aleutian Islands (AI). The AI results can be compared with the prior years' performance under Tier 5 assessment procedure (Pengilly 2016):

Status and catch specifications (1000 t) of EAG golden king crab

Fishing Year	**MSST**	**Biomass (MMB)**	**TAC[a]**	**Retained Catch**	**Total Catch**	**OFL**	ABC (0.75*OFL)	ABC (0.8*OFL)
2016/17	N/A	N/A	1.501	Fishing[b]	Fishing[b]			
2017/18[c]	3.524	9.306				4.486	3.365	3.589

a. Total allowable catch, established in lb. and converted to t.
b. Fishing in progress
c. Tier 3 assessment scenario 9 results

Status and catch specifications (million lb) of EAG golden king crab

Fishing Year	**MSST**	**Biomass (MMB)**	**TAC[a]**	**Retained Catch**	**Total Catch**	**OFL**	**ABC (0.75*OFL)**	**ABC (0.8*OFL)**
2016/17	N/A	N/A	3.310	Fishing[b]	Fishing[b]			
2017/18[c]	7.769	20.515				9.890	7.417	7.912

a. Total allowable catch
b. Fishing in progress
c. Tier 3 assessment scenario 9 results

Status and catch specifications (1000 t) of WAG golden king crab

Fishing Year	**MSST**	**Biomass (MMB)**	**TAC[a]**	**Retained Catch**	**Total Catch**	**OFL**	**ABC (0.75*OFL)**	**ABC (0.8*OFL)**
2016/17	N/A	N/A	1.014	Fishing[b]	Fishing[b]			
2017/18[c]	2.520	4.927				1.532	1.149	1.226

a. Total allowable catch, established in lb. and converted to t.
b. Fishing in progress
c. Tier 3 assessment scenario 9 results

Status and catch specifications (million lb) of WAG golden king crab

Fishing Year	MSST	Biomass (MMB)	TAC[a]	Retained Catch	Total Catch	OFL	ABC (0.75*OFL)	ABC (0.8*OFL)
2016/17	N/A	N/A	2.235	Fishing[b]	Fishing[b]			
2017/18[c]	5.555	10.863				3.378	2.534	2.702

a. Total allowable catch
b. Fishing in progress
c. Tier 3 assessment scenario 9 results

During the May 2017 meeting, the CPT noted that a single OFL and ABC are defined for AIGKC. However, separate models are available by area. The CPT considered two ways for computing an OFL for AIGKC.

Approach 1: Apply the OFL control rule by area and sum the OFLs by area.

Approach 2: Determine stock status for the stock by adding the estimates of current MMB and B_{MSY} by area. This stock status is then used to determine the ratio of F_{OFL} to $F_{35\%}$ by area, which is then used to calculate the OFLs by area which are then added together to calculate an OFL for the entire stock.

The CPT preferred the 2nd approach because it relies on a single stock status determination. In contrast, use of the 1st approach would lead to the EAG area being in Tier 3a and the WAG area being in Tier 3b, which would not lead to a unique Tier level. We computed the status and catch specifications following the two approaches:

Status and catch specifications (1000 t) of Aleutian Islands golden king crab

Year	MSST	Biomass (MMB)	TAC	Retained Catch[a]	Total Catch[a]	OFL	ABC[e]
2013/14	N/A	N/A	2.853	2.894	3.192	5.69	5.12
2014/15	N/A	N/A	2.853	2.771	3.079	5.69	4.26
2015/16	N/A	N/A	2.853	2,729	3,073	5.69	4.26
2016/17	N/A	N/A	2.515	Fishing[b]	Fishing[b]	5.69	4.26
2017/18[c]	6.044	14.233				6.018	4.815
2017/18[d]	6.044	14.205				6.048	4.838

a. Total retained catch plus estimated bycatch mortality of discarded bycatch during crab fisheries and groundfish fisheries.
b. Fishing in progress
c. Approach 1 above
d. Approach 2 above
e. The last two ABC estimates are based on 20% buffer whereas the other estimates are based on 25% buffer

Status and catch specifications (million lb) of Aleutian Islands golden king crab

Year	MSST	Biomass (MMB)	TAC	Retained Catch	Total Catch[a]	OFL	ABC[e]
2013/14	N/A	N/A	6.290	6.38	7.04	12.54	11.28
2014/15	N/A	N/A	6.290	6.11	6.79	12.53	9.40
2015/16	N/A	N/A	6.290	6.016	6.775	12.53	9.40
2016/17	N/A	N/A	5.545	Fishing[b]	Fishing[b]	12.53	9.40
2017/18[c]	13.325	31.378				13.268	10.614
2017/18[d]	13.325	31.315				13.333	10.666

a. Total retained catch plus estimated bycatch mortality of discarded bycatch during crab fisheries and groundfish fisheries.
b. Fishing in progress
c. Approach 1 above
d. Approach 2 above
e. The last two ABC estimates are based on 20% buffer whereas the other estimates are based on 25% buffer

6. Basis for the OFL

We provide the OFL estimates under the Tier 3 approach for EAG, WAG, and the two regions pooled together (i.e., for the entire Aleutian Islands, AI), respectively. The length-based model developed for the Tier 3 analysis estimated MMB on February 15 each year for the period 1986 through 2016 and projected to February 15, 2017 for OFL and ABC determination. The Tier 3 approach uses the mean number of recruits for the period 1987 – 2012 for OFL and ABC calculation.

Total OFL and ABC estimates are provided for seven scenarios (1, 2, 3, 4, 9, 10, and 11) for EAG, WAG, and AI, respectively in the following six tables. Following the May 2017 CPT suggestion, we also considered a separate scenario 9** for WAG to calculate the OFL and ABC for the entire Aleutian Islands under approach 2. We treat scenario 1 as the base scenario for EAG and WAG. **We recommend the OFL and ABC estimates for scenario 9 (knife-edge selectivity). Since the OFL and ABC have been set for the entire AI under Tier 5 procedure, we suggest implementing the combined OFL and ABC for AI.**

EAG (Tier 3):

Biomass, total OFL, and ABC for the next fishing season in million pounds. Current MMB = MMB on 15 Feb. 2017.

Scenario	Tier	$B_{35\%}$	Current MMB	MMB/ $B_{35\%}$	F_{OFL}	Recruitment Years to define $B_{35\%}$	$F_{35\%}$	OFL	ABC (P*=0.49)	ABC (0.75*OFL)	ABC (0.8*OFL)
1	3a	14.177	18.820	1.33	0.64	1987–2012	0.64	8.787	8.753	6.591	7.030
2	3a	14.309	19.050	1.33	0.63	1987–2012	0.63	8.873	8.837	6.654	7.098
3	3a	14.818	20.203	1.36	0.61	1987–2012	0.61	9.641	9.601	7.231	7.713
4	3a	13.791	17.987	1.30	0.66	1987–2012	0.66	8.301	8.268	6.226	6.641
9	3a	15.539	20.515	1.32	0.75	1987–2012	0.75	9.890	9.852	7.417	7.912
10	3a	14.265	18.840	1.32	0.62	1987–2012	0.62	8.556	8.523	6.417	6.845
11	3a	15.577	20.507	1.32	0.73	1987–2012	0.73	9.672	9.635	7.254	7.738

Biomass in 1000 t; total OFL and ABC for the next fishing season in t.

Scenario	Tier	$B_{35\%}$	Current MMB	MMB/ $B_{35\%}$	F_{OFL}	Recruitment Years to Define $B_{35\%}$	$F_{35\%}$	OFL	ABC (P*=0.49)	ABC (0.75*OFL)	ABC (0.8*OFL)
1	3a	6.430	8.536	1.33	0.64	1987–2012	0.64	3,985.959	3,970.495	2,989.469	3,188.767
2	3a	6.491	8.641	1.33	0.63	1987–2012	0.63	4,024.578	4,008.452	3,018.433	3,219.662
3	3a	6.721	9.164	1.36	0.61	1987–2012	0.61	4,373.272	4,355.014	3,279.954	3,498.617
4	3a	6.256	8.159	1.30	0.66	1987–2012	0.66	3,765.375	3,750.119	2,824.031	3,012.300
9	3a	7.048	9.306	1.32	0.75	1987–2012	0.75	4,486.052	4,468.684	3,364.539	3,588.842
10	3a	6.471	8.546	1.32	0.62	1987–2012	0.62	3,880.873	3,865.821	2,910.655	3,104.698
11	3a	7.066	9.302	1.32	0.73	1987–2012	0.73	4,387.350	4,370.392	3,290.512	3,509.880

WAG (Tier 3):

Biomass, total OFL, and ABC for the next fishing season in million pounds. Current MMB= MMB on 15 Feb. 2017.

Scenario	Tier	$B_{35\%}$	Current MMB	MMB/ $B_{35\%}$	F_{OFL}	Recruitment Years to Define $B_{35\%}$	$F_{35\%}$	OFL	ABC (P*=0.49)	ABC (0.75*OFL)	ABC (0.8*OFL)
1	3b	10.214	9.671	0.95	0.54	1987–2012	0.57	2.862	2.842	2.146	2.289
2	3b	10.099	9.535	0.94	0.54	1987–2012	0.58	2.767	2.747	2.075	2.213
3	3b	10.226	9.680	0.95	0.54	1987–2012	0.57	2.861	2.840	2.145	2.288
4	3b	9.866	9.031	0.92	0.49	1987–2012	0.54	2.445	2.427	1.834	1.956
9	3b	11.111	10.863	0.98	0.66	1987–2012	0.68	3.378	3.355	2.534	2.702
9**	3a	9.937	10.800	1.09	0.68	1993–1997	0.68	3.443	3.428	2.582	2.754
10	3b	10.049	9.704	0.97	0.59	1987–2012	0.61	3.115	3.093	2.336	2.492
11	3b	11.025	10.928	0.99	0.71	1987–2012	0.72	3.616	3.591	2.712	2.893

Biomass in 1000 t; total OFL and ABC for the next fishing season in t.

Scenario	Tier	$B_{35\%}$	Current MMB	MMB / $B_{35\%}$	F_{OFL}	Recruitment Years to Define $B_{35\%}$	$F_{35\%}$	OFL	ABC (P*=0.49)	ABC (0.75*OFL)	ABC (0.8*OFL)
1	3b	4.633	4.387	0.95	0.54	1987–2012	0.57	1,298.130	1,288.987	973.598	1,038.504
2	3b	4.581	4.325	0.94	0.54	1987–2012	0.58	1,254.898	1,245.940	941.173	1,003.918
3	3b	4.638	4.391	0.95	0.54	1987–2012	0.57	1,297.539	1,288.389	973.155	1,038.032
4	3b	4.475	4.097	0.92	0.49	1987–2012	0.54	1,108.982	1,100.974	831.737	887.186
9	3b	5.040	4.927	0.98	0.66	1987–2012	0.68	1,532.280	1,521.602	1,149.210	1,225.824
9**	3a	4.507	4.899	1.09	0.68	1993–1997	0.68	1,561.668	1,554.794	1,171.251	1,249.334
10	3b	4.558	4.402	0.97	0.59	1987–2012	0.61	1,412.980	1,402.879	1,059.735	1,130.384
11	3b	5.001	4.957	0.99	0.71	1987–2012	0.72	1,640.212	1,628.919	1,230.159	1,312.169

Aleutian Islands (AI)
Total OFL and ABC for the next fishing season in million pounds.

Scenario	OFL	ABC (P*=0.49)	ABC (0.75*OFL)	ABC (0.8*OFL)
1	11.649	11.595	8.737	9.319
2	11.64	11.584	8.729	9.311
3	12.502	12.441	9.376	10.001
4	10.746	10.695	8.06	8.597
9	13.268	13.207	9.951	10.614
9**	13.333	13.280	9.999	10.666
10	11.671	11.616	8.753	9.337
11	13.288	13.226	9.966	10.631

Aleutian Islands (AI)
Total OFL and ABC for the next fishing season in t.

Scenario	OFL	ABC (P*=0.49)	ABC (0.75*OFL)	ABC (0.8*OFL)
1	5,284.089	5,259.482	3,963.067	4,227.271
2	5,279.476	5,254.392	3,959.606	4,223.580
3	5,670.811	5,643.403	4,253.109	4,536.649
4	4,874.357	4,851.093	3,655.768	3,899.486
9	6,018.330	5,990.286	4,513.749	4,814.666
9**	6,047.720	6,023.478	4,535.790	4,838.176
10	5,293.853	5,268.700	3,970.390	4,235.082
11	6,027.562	5,999.311	4,520.671	4,822.049

7. *Probability density functions of OFL*

Assuming a lognormal distribution of total OFL, we determined the cumulative distributions of OFL and selected the median as the OFL.

8. *The basis for the ABC recommendation*

An x% buffer on the OFL; i.e., ABC = (1.0 - x/100)*OFL. We considered x = 20% and 25%. The CPT preferred 20%.

See also the section G on ABC

9. *A summary of results of any rebuilding analysis:*

Not applicable.

A. Summary of Major Changes

1. *Changes (if any) to management of the fishery*

   Propose changes to OFL and ABC under model based Tier 3 assessment.

2. *Changes to input data*

   (a) Retained catch (1981/82–2015/16), total catch (1990/91–2015/16), and groundfish bycatch (1989/90–2015/16) biomass and size compositions were the same as in the September 2016 and January 2017 assessment.

   (b) Fish ticket retained CPUE were standardized by the GLM with the lognormal link function for the 1985/86–1998/98 period, which was the same as in the September 2016 and January 2017 assessment.

   (c) For scenario 3, observer pot sample legal size crab CPUE data were extended back to 1991/92 and standardized by the generalized linear model (GLM) with the negative binomial link function, separately for 1991/92–2004/05 and 2005/06–2015/16 periods.

   (d) Male maturity proportions by size classes were added.

3. *Changes to assessment methodology*

   (a) The same model has been improved:

   (b) The ADMB cumulative gamma function was used instead of numerical approximation for recruit distribution estimation.

   (c) We removed the Tier 4 OFL fishing mortality penalty from the set of likelihood functions.

   (d) The equilibrium initial population and Tier 3 B_{MSY} reference point estimation procedures used the mean number of recruits for 1987–2012.

(e) Francis re-weighting method was used to updating the input effective sample sizes for length composition data for all scenarios (Siddeek et al. 2016c, *in press* 2017).

(a) Changes to assessment results

Not applicable because the model has not been used previously.

B. Response to September 2016 CPT comments

Comment 1: The CPT recommended bringing likelihood profile on *M*, mean MMB, and MMB depletion to the May 2017 CPT meeting.

Response:
We have provided *M* profiles in Figures 4 to 6, mean MMB profile in Figure 7 and MMB depletion profile in Figure 8. The penalty functions for mean MMB and MMB depletion profile analysis are defined in Equations A.33 and A.34 respectively in Appendix A.
We used finer incremental steps in the *M* profile calculation.

Comment 2: Tables 1 (EAG) and 15 (WAG) should be modified to provide the retained catch, pot bycatch breakdown by males and females (make clear if mortality applied) and trawl bycatch followed by total catch.

Response:
We included Table 1a that lists the retained catch, bycatch (males and females lumped together), groundfish discard catch (males and females lumped together), and the total catch with details of what rates of mortality were applied during the 1990/91–2015/16 period for the entire Aleutian Islands. Crab fishery bycatch data were recorded since 1990 after introduction of observer sampling. We will delineate the data by EAG and WAG in the near future.

Comment 3: The plots showing estimated selectivity curves should include both the estimates for pre- and post-rationalization periods.

Response:
We provided this separation in Figure 13 for EAG and Figure 32 for WAG.

Comment 4. Continue the development of a spatial model that could be used to explore the implications of changed in fishing locations

Response:
Appendix F provides a preliminary analysis to exploring the potential impact of area shrinkage on the fishery and the stock dynamics.

Response to January 2017 CPT comments

Comment 1. While the CPT accepts the approach of using a combined EAG/WAG model to estimate natural mortality, the team would also like to see evidence that tests have been done to show that the combined model gives precisely the same results as the two individual models, since only the individual models have undergone technical review. The assessment author should confirm that the combined profile (without the prior) has a minimum at 0.225 yr^{-1} because the step size for M was fairly small.

Response:
We have provided *M* profiles in Figures 4 (scenario 0a considered *M* penalty for *M* estimation), 5 (scenario 0b disregarded *M* penalty for *M* estimation), and 6 (scenario 1b disregarded *M* penalty for *M* estimation using separate EAG and WAG data sets). It appears that all results were close. The 95% confidence intervals under lognormal distribution assumption (formulas are given in Table 49) indicated highly overlapping intervals, Sc0a: 0.2143–0.2310, Sc0b: 0.2157–0.2329, EAG Sc1b: 0.2107–0.2313, and WAG Sc1b: 0.2155–0.2472. We opted to use the *M* estimation from combined data that disregarded the *M* penalty for most of the scenarios.

Comment 2. The likelihood profiles by data components for natural mortality showed that the WAG CPUE had a different profile than other data components, showing a strong improvement in fit at lower values of natural mortality. It would be good to confirm that this is correct.

Response: With the improvement of the model, the total likelihood fits for EAG and WAG attained minimum around 0.224 yr^{-1}. The CPUE likelihood patterns for EAG and WAG behaved similarly although they did not attain the minima at the total likelihood minimum value.

Comment 3. What the CPT actually wanted was to evaluate use of the retained catch CPUE time series for the period 1985–1998. Model scenario 4, which did include retained catch CPUE, suggested that it provided useful information in the early years of the fishery, and the CPT recommends that it be included in the base model for May. Examination of diagnostics for the observer CPUE data indicated there was justification for starting the observer CPUE time series in 1995, since the earlier data in 1991–1994 was based on fewer boats and different gear than was used subsequently. In addition, only the catcher-processor vessels carried observers prior to 1995.

Response:

(a) We considered the 1995/96–2015/16 observer CPUE time series in the base and most other scenarios.

(b) However, as per CPT suggestion, we considered one scenario (scenario 3) that included observer CPUE index from 1991–1994.

Comment 4. The CPT recommends that CVs for the recruitment estimates be examined and that only those recruitment estimates that are informed by data (i.e., recruit CVs less than sigma R) be used to obtain mean recruitment to initialize the model.

Response: We examined the recruit standard deviation pattern (Figure 9) and selected the time period 1987–2012 based on recruit standard deviation values < 70% sigma R for mean number of recruits estimation to determining equilibrium abundance and B_{MSY} reference points for EAG and WAG.

Comment 5. The CPT recommends that dome-shaped selectivity models not be carried forward for the May meeting.

Response: Done.

Comment 6. The CPT agrees with the author's recommendation that the Francis method be adopted as the preferred approach for selecting weights for length-composition data for AIGKC.

Response: We used Francis re-weighting method for selecting weights for length composition data for all scenarios (Appendix D).

Comment 7. The CPT recommends that the changes in the spatial pattern of fishing be evaluated further for the May CPT meeting based on plots by year (or blocks of years).

Response: Appendix F provides the spatial pattern of observer sample, effort , catch, and productivity in core and non-core areas by year during 1990–2015. The core and non-core fishing areas were defined based on finer scaling of observer sampling locations (please see Appendix F for details). We also estimated CPUE indices, catch, fishing mortality and MMB trends using core data and compared those with the estimates from the full data set models.

.

Comment 8. An F35% calculation requires vectors for maturity, selectivity, and natural mortality—all of which are available for AIGKC. Therefore the CPT recommends that AIGKC be placed in Tier 3. If the SSC agrees with this recommendation in February, there would be no need to develop OFL/ABC tables for Tier 4 in the May assessment document.

Response: We followed the Tier 3 approach.

Comment 9. The CPT recommends that these maturity data be re-evaluated for the May CPT meeting to determine whether a maturity curve can be estimated reliably.

Response: We used the maturity proportions by size estimated from1991 ADFG pot survey maturity data in the model. It appears that a reliable maturity curve can be fitted. The maturity analysis is detailed in Appendix C.

Comment 10. The CPT also discussed whether the primary abundance index for AIGKC as calculated from fishery data should be considered in recommending a Tier level. The CPT regards this as an important factor in assessment uncertainty, but recommends that this be considered when recommending a buffer for the ABC, not in determining the Tier level.

Response: Because of uncertainty in fisheries data, we provided the 20% and 25% buffer options for ABC calculation. The CPT in May 2017 selected the 20% buffer.

Comment 11. CPT would prefer to see similar runs grouped together for May, as it is hard to compare 15 model runs on one graph (for example, Figure 29 on p. 95).

Response: As per CPT suggestion we grouped the similar featured scenario plots as: Group 1: scenarios 1 (base), 2 (drop fishery CPUE index), 3 (extend observer CPUE index back to 1991/92), and 4 (three selectivity and catchability); group 2: scenarios 1, 5 (low bracketing of *M*), and 6 (high bracketing of *M*); group3: scenarios 1 and 9 (knife-edge maturity); group 4: scenarios 1, 10 (separately estimated *M* for EAG and WAG), and 11 (separately estimated *M* for EAG and WAG with knife-edge maturity).

We adopted the following color scheme for scenarios that have multiple outputs: Scenarios 1: black, 2: orange, 3: red, 4: blue, 5: violet, 6: dark green, 9: green, 10: dark red, and 11: dark blue.

Specifications of all scenarios are provided in Table T1.

Response to February 2017 SSC comments

Comment 1: The SSC recommends that, pending completion of the CPT and SSC requests, the authors bring forward a Tier 3 analysis for AIGKC for consideration at the May CPT and June SSC meetings.

Response: We did only Tier 3 analysis in this cycle.

Comment 2: The SSC strongly encourages future efforts to develop a fishery-independent survey for this resource, in addition to continuing efforts to better understand the CPUE data through investigation of the annual spatial distribution of the fishery and changes in individual vessel participation.

Response:

(a) We are making every effort to expand the fishery independent survey currently being conducted in the EAG area.

(b) Please see our response to January 2017 CPT comment 7.

Comment 3: The SSC generally supports the CPT recommendations, but recommends a slightly revised approach to the treatment of natural mortality. The SSC requests that the author prepares a likelihood profile using a finer resolution (smaller step-size). The SSC requests that the author makes a run using both EAG and WAG data sets combined that includes a prior on natural mortality (0.18) with a CV of 50%.

When the final preferred model has been developed, the SSC requests one additional run that does not use this prior on natural mortality in order to evaluate its effect.

Response:

(a) We considered two options: 1. including the *M* prior (Equation A.32 in Appendix A) and 2. Not including the *M* prior. The results appear not significantly different. Improvement of the model may have produced consistent outcome, which is encouraging (Figures 4 to 6). So, we opted to using the *M* estimate obtained without the *M* prior in all scenarios.

(b) We used the finer resolution (smaller step-size of 0.025) to calculate the profiles.

Comment 4: Finally, the author to perform jitter runs to avoid unexpected model behavior.

Response: We conducted 100 jitter runs following stock synthesis procedure for scenarios 1 and 9 for EAG and WAG, respectively. The convergence did not deviate from the original optimized positions for most runs, thus supporting global convergence (Appendix E).

Comment 5: The SSC notes that the tuning of input-to-effective sample sizes for the McAllister-Ianelli method appears to have been conducted at the level of individual year's observations. This is not consistent with general practice, or the conclusions from the 2015 CAPAM workshop, which recommended tuning the input values to the Harmonic mean effective sample size for all years by fishery or fleet. SSC supports the CPT recommendation to use the Francis method for future analyses.

Response: Our last assessment report on this topic was not clear to you. We apologize for that. Indeed, we used the harmonic mean as a single multiplier for the time series of input effective sample sizes under McAllister and Ianelli (1997) method. Anyway, in the current analysis, we used only the Francis method of iterated weighting of effective sample sizes for all scenarios including the *M* estimation scenarios (Appendix D). So, the confusion on using McAllister and Ianelli method does not arise now.

Comment 6: Recruitments that are included in the B_{MSY} calculations should have an estimated variance substantially less than sigma R, and should generally not include the terminal year's estimates (2016 in this draft analysis) unless specifically warranted by informative data. The SSC recommends the CPT and authors review the GPT guidance on making these calculations and strive for some consistency in their approach.

Response: We used a subset of recruitment estimates that excluded the terminal year's R for equilibrium abundance and B_{MSY} reference points estimation (please see our response to January 2017 CPT comment 4).

C. Introduction

1. Scientific name: Golden king crab, *Lithodes aequispinus.*
2. Distribution: In Alaska, golden king crab is distributed in the Aleutian Islands, on the continental slope of the eastern Bering Sea, and around the Gulf of Alaska to southeastern Alaska.
3. Evidence of stock structure: There is no direct evidence of separate stock structure in the Aleutian Islands. But contrast between CPUE trends suggests different factors may influence stock productivity in EAG and WAG.
4. Life history characteristics relevant to management: There is a paucity of information on golden king crab life history characteristics due in part to the deep depth distribution (~200–1000 m) and the asynchronous nature of life history events (Otto and Cummiskey 1985; Somerton and Otto 1986). The reproductive cycle is thought to last approximately 24 months and at any one time, ovigerous females can be found carrying egg clutches in highly disparate developmental states (Otto and Cummiskey 1985). Females carry large, yolk-rich, eggs, which hatch into lecithotrophic (non-feeding) larvae that are negatively phototactic (Adams and Paul 1999). Molting and mating are also asynchronous and protracted (Otto and Cummiskey 1985; Shirley and Zhou 1997) with some indications of seasonality (Hiramoto 1985). Molt increment for large males (adults) in Southeast Alaska is 16.3 mm CL per molt (Koeneman and Buchanan 1985), and was

estimated at 14.4 mm CL for legal males in the EAG (Watson et al. 2002). Annual molting probability of males decreases with increasing size, which results in a protracted inter-molt period and creates difficulty in determining annual molt probability (Watson et al. 2002). Male size-at-maturity varies among stocks (Webb 2014) and declines with increasing latitude from about 130 mm CL in the Aleutian Islands to 90 mm CL in Saint Matthew Island section (Somerton and Otto 1986). Along with a lack of annual survey data, limited stock-specific life history stock information prevents development of the standard length-based assessment model.

5. Brief summary of management history and annual ADFG harvest strategy: Since 1996, the Alaska Department of Fish and Game (ADF&G) has divided management of the Aleutian Islands golden king crab fishery at 174° W longitude (ADF&G 2002). Hereafter, the east of 174° W longitude stock segment is referred to as EAG and the west of 174° W longitude stock segment is referred to as WAG. The stocks in the two areas were managed with a constant annual guideline harvest level or total allowable (retained) catch (3.000 million pounds for EAG and 2.700 million pounds for WAG). In 2008, however, the total allowable catch was increased by the Board of Fisheries (BOF) to 3.150 and 2.830 million pounds for EAG and WAG, respectively (an approximately 5% increase in TAC). The TACs were further increased by another BOF decision to 3.310 million pounds for EAG and 2.980 million pounds for WAG beginning with the 2012/13 fishing year. The below par fishery performance in WAG in recent years lead to reduction in TAC to 2.235 million pounds for the 2016/17 fishing season.

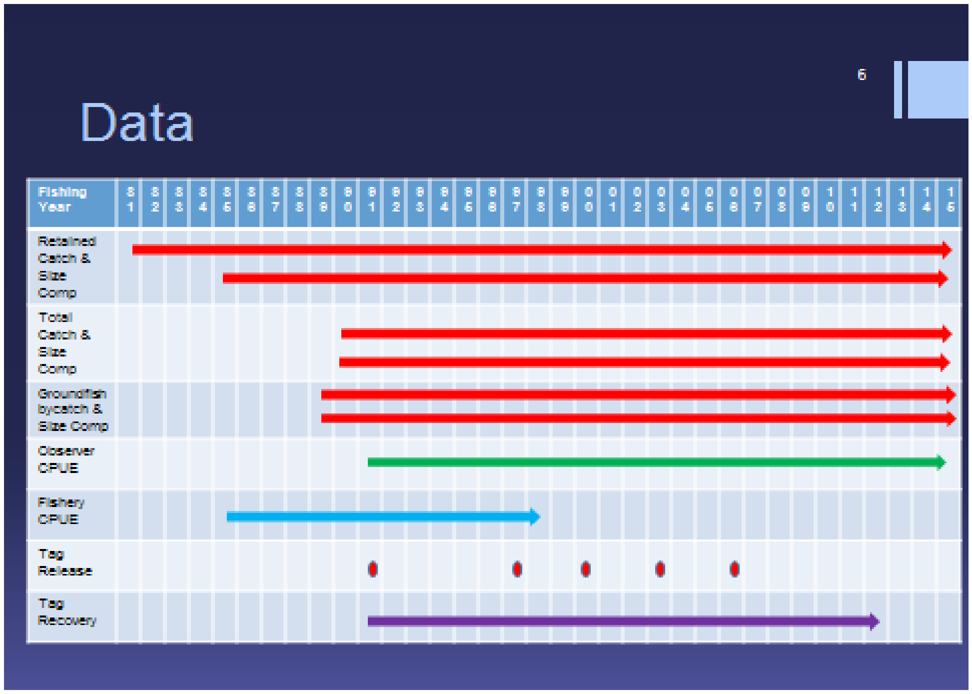
   Additional management measures include a male-only fishery and a minimum legal size limit (152.4 mm CW, or approximately 136 mm CL), which is at least one annual molt increment larger than the 50% maturity length of 120.8 mm CL for males estimated by Otto and Cummiskey (1985). We re-evaluated the male maturity size using 1991 pot survey measurements of carapace length and chela height in EAG (Appendix C). The 50% male maturity length estimates varied from 108.5 mm CL (segmented regression analysis) to 109.72 mm CL (logistic regression model fit) to 110.6 mm CL (assessment model fit). We used the maturity curve developed from the 1991 data for all scenarios except scenarios 9 and 11 in which a knife-edge 50% maturity length of 111 mm CL was used for mature male biomass (MMB) estimation. Daily catch and catch-per-unit effort (CPUE) are determined in-season to monitor fishery performance and progress towards the respective TACs. Figures 1 to 3 provide the historical time series of catches, CPUE, and the geographic distribution of catch during the recent fishing season. Increases in CPUE were observed during the late 1990s through the early 2000s, and with the implementation of crab rationalization in 2005. This is likely due to changes in gear in the late 1990s (crab fishermen, personal communication, July 1, 2008) and, after rationalization, to increased soak time (Siddeek *et al.* 2015), and decreased competition owing to the reduced number of vessels fishing. Decreased competition could allow crab vessels to target only the most productive fishing areas.

6. Summary of the history of the basis and estimates of MMB_{MSY} or proxy MMB_{MSY}: We estimated the proxy MMB_{MSY} as $B_{35\%}$ using the Tier 3 estimation procedure, which is explained in a subsequent section.

D. Data

1. Summary of new information:
    (a) Commercial fishery retained catch by size, estimated total catch by size, groundfish male discard catch by size, observer CPUE index, commercial fishery CPUE index, and tag-recapture data were updated to include 2015/16 information in September 2016 and January 2017. The details are given in the pictorial table below.
    (b) Male maturity proportion by size-class from 1991 pot survey size measurements.

2. Available catch and tagging data:



a. A time series of retained and total catch, groundfish fishery discard mortality, and pot fishery effort (Tables 1a for the entire Aleutian Islands and 1b for EAG and Table 25 for WAG). The estimation methods are described in Appendix B.

b. Time series of pot fishery and observer nominal retained and total CPUE, observer sample size, estimated observer CPUE index (Table 2 for EAG and Table 26 for WAG), and estimated commercial fishery CPUE index (Table 3 for EAG and Table 27 for WAG). The estimation methods, CPUE fits and diagnostic plots are described in Appendix B.

c. Information on length compositions (Figures 10 to 12 for length compositions for EAG; and 29 to 31 for length compositions for WAG).

d. Survey biomass estimates are not available for the area because no systematic surveys, covering the entire fishing area, have occurred.

f. Other time series data: None.

3. Length-weight relationship: $W = al^b$ where a= $3.725*10^{-4}$, b = 3.090.

4. Information on any data sources available, but excluded from the assessment: None.

E. Analytic Approach

1. *History of modeling approaches for this stock*

   A size structured assessment model based on only fisheries data has been under development for a number of years for the EAG and WAG golden king crab stocks. The model was accepted in 2016 for OFL and ABC setting for the 2017/18 season. The CPT in January and SSC in February 2017 recommended to using the Tier 3 procedure to set the OFL and ABC. They also suggested to using the maturity data to estimate MMB. We followed these suggestions in this report.

   Model Description

   a. The underlying population dynamics model is male-only and length-based (Appendix A). This model combines commercial retained catch, total catch, groundfish fishery discarded catch, standardized observer legal size catch-per-unit-effort (CPUE) indices, fishery retained catch size composition, total catch size composition, and tag recaptures by release-recapture length to estimate stock assessment parameters. The tagging data were used to calculate the size transition matrix. To estimate the male mature biomass (MMB), we used a maturity curve based on the new maturity data. To include a long time series of CPUE indices for stock abundance contrast, we also considered the 1985/86–1998/99 legal size standardized CPUE indices as a separate likelihood component in the base (scenario 1) and a number of other scenarios (see Table T1).

      There were significant changes in fishing practice due to changes in management regulations (e.g., constant TAC since 1996/97 and crab rationalization since 2005/06), pot configuration (escape web on the pot door increased to 9-inch since 1999), and improved observer recording in Aleutian Islands golden king crab fisheries since 1998. These changes prompted us to consider two sets of catchability and total selectivity parameters with only one set of retention parameters for the periods 1985/86–2004/05 and 2005/06–2015/16.

However, in order to respond to a January 2017 CPT comment, we considered three catchabilities, three sets of total selectivity, and one set of retention curves in one scenario (scenario 4).

We fitted the observer and commercial fishery CPUE indices with GLM estimated standard errors and an additional constant variance; the latter was estimated by the model fit. The assessment model predicted total and retained CPUEs. However, we compared only the predicted retained CPUE with the observer legal size crab CPUE indices in the likelihood function because observer recordings of legal size crabs are reliable.

The data series used in the current assessment for EAG ranges from 1985/86 to 2015/16 for retained catch biomass and size composition; 1995/96 to 2015/16 for standardized legal size crab observer CPUE index; 1989/90 to 2015/16 for groundfish fishery male bycatch biomass and size composition; 1985/86 to 1998/99 for standardized crab fish ticket CPUE index; 1990/91 to 2015/16 for total catch biomass and total catch length composition; 1991, 1997, 2000, 2003, and 2006 releases and up to 2012 recapture time period for tagging information, and male maturity proportion by size.

The data series used for the WAG ranges are the same as those for EAG.

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

c.–f. Details are given in Appendix A.

g. Critical assumptions and consequences of assumption failures: Because of the lack of an annual stock survey we relied heavily on standardized CPUE indices (Appendix B) and catch and size composition information to determine the stock abundance trends in both regions. We assumed that the observer and fish ticket CPUE indices are linearly related to exploitable abundance. We kept *M* constant at 0.224 yr^{-1}. The *M* value was the combined estimates for EAG and WAG. We assumed directed pot fishery discard mortality proportion at 0.20 yr^{-1}, overall groundfish fishery mortality proportion at 0.65 yr^{-1} [mean of groundfish pot fishery mortality (0.5 yr^{-1}) and groundfish trawl fishery mortality (0.8 yr^{-1})], groundfish fishery selectivity at full selection for all length classes (selectivity = 1.0). Any discard of legal size males in the directed pot fishery was not considered in this analysis. These fixed values invariably reduced the number of model parameters to be estimated and helped in convergence. We assumed different *q*'s (scaling parameter for standardized CPUE in the model, Equation A.14 in Appendix A) and logistic selectivity patterns (Equation A.9 in Appendix A) for different periods for the pot fishery. We also assumed a logistic maturity pattern in the model (Equation A.10 in Appendix A).

h. Changes to any of the above since the previous assessment: Does not apply for this assessment since the model has not been used for previous assessment.

i. Model code has been checked and validated. The code is available from the authors.

2. *Model Selection and Evaluation*

a. Description of alternative model configurations:

We considered 11 scenarios overall for EAG and WAG (Table T1). We presented OFL and ABC results for selected seven scenarios separately for EAG, WAG, and the entire AI in the executive summary tables. We considered scenario 1 as the base scenario. It considers:

i) Initial abundance by the equilibrium condition considering the mean number of recruits for 1987–2012: The equilibrium abundance was determined for 1960, projected it forward with only *M* and annual recruits until 1980, then retained catches removed during 1981–1984 and projected it to obtain the initial abundance in 1985 (see Equations A.4 and A.5 in Appendix A).

ii) Observer CPUE indices for 1995/96–2015/16.

iii) Fishery CPUE indices for 1985/86–1998/99.

iv) Initial (Stage-1) weighting of effective sample sizes: number of days for retained and total catch size compositions and number of fishing trips for groundfish discard size composition (the groundfish size composition was not used in the model fitting); and (Stage-2) iterative re-weighting of effective sample sizes by the Francis method (Appendix D).

v) Two catchability and two sets of logistic total selectivity for the periods 1985/86–2004/05 and 2005/06–2015/16, and a single set of logistic retention curve parameters.

vi) Full selectivity (selectivity =1.0) for groundfish (trawl) bycatch.

vii) Logistic maturity curve by size.

viii) Stock dynamics $M = 0.224\ yr^{-1}$, pot fishery handling mortality = $0.2\ yr^{-1}$; and mean groundfish bycatch handling mortality = $0.65\ yr^{-1}$.

ix) Size transition matrix using tagging data estimated by the normal probability function with the logistic molt probability sub-model. The tag-recaptures were treated as Bernoulli trials (i.e., Stage-1 weighting).

x) The time period, 1987/88–2012/13, was used to determine the mean number of recruits for $B_{35\%}$ (a proxy for MMB_{MSY}) estimation under Tier 3.

The salient features and variations from the base scenario of all other scenarios are listed in Table T1. The list of fixed and estimable parameters are provided in Table A1 and detail weights with coefficient of variations (CVs) assigned to each type of data are listed in Table A2 of Appendix A.

As per CPT and SSC requests, jittering of initial parameter values for scenarios 1 and 9 were done to confirm model global convergence. The results indicated that global convergence was achieved for most of the runs (Appendix E).

Table T1. Features of model scenarios. Initial condition was estimated by the equilibrium condition for all scenarios. Changes from scenario 1 specifications are highlighted by the light blue shade.

Scenario	Size-composition weighting	Catchability and logistic total selectivity sets	Maturity	CPUE data type	Treatment of *M* and Tier 3 B_{MSY} reference points	Natural mortality ($M\ yr^{-1}$)
0a	Stage-1:Number of days/trips Stage-2: Francis method	2	Logistic curve	Observer from 1995/96–2015/16 & Fish Ticket from 1985/86–1998/99	Estimate a common *M* using the combined EAG and WAG data with an *M* prior	0.223
0b	Stage-1:Number of days/trips Stage-2: Francis method	2	Logistic curve	Observer from 1995/96–2015/16 & Fish Ticket from 1985/86–1998/99	Estimate a common *M* using the combined EAG and WAG data without an *M* prior	0.224
1b	Stage-1:Number of days/trips Stage-2: Francis method	2	Logistic curve	Observer from 1995/96–2015/16 & Fish Ticket from 1985/86–1998/99	Estimate separate *M* for each area using individual EAG or WAG data without an *M* prior	EAG: 0.221 WAG: 0.231
1	Stage-1:Number of days/trips Stage-2: Francis method	2	Logistic curve	Observer from 1995/96–2015/16 & Fish Ticket from 1985/86–1998/99	Single *M* from combined EAG and WAG data; Tier 3 B_{MSY} reference points based on average recruitment from 1987–2012	0.224
2	Stage-1:Number of days/trips Stage-2: Francis method	2	Logistic curve	Omit Fish Ticket CPUE likelihood	Single *M* from combined EAG and WAG data; Tier 3 B_{MSY} reference points based on average recruitment from 1987–2012	0.224
3	Stage-1:Number of days/trips Stage-2: Francis method	2	Logistic curve	Observer CPUE from 1991/92–2015/16 & Fish Ticket	Single *M* from combined EAG and WAG data; Tier 3 B_{MSY} reference points based on average recruitment from 1987–2012	0.224

4	Stage-1:Number of days/trips Stage-2: Francis method	3	Logistic curve	Observer & Fish Ticket	Single *M* from combined EAG and WAG data; Tier 3 B_{MSY} reference points based on average recruitment from 1987–2012	0.224
5	Stage-1:Number of days/trips Stage-2: Francis method	2	Logistic curve	Observer & Fish ticket	Low bracketing value of *M*; Tier 3 B_{MSY} reference points based on average recruitment from 1987–2012	0.189
6	Stage-1:Number of days/trips Stage-2: Francis method	2	Logistic curve	Observer & Fish ticket	High bracketing value of *M*; Tier 3 B_{MSY} reference points based on average recruitment from 1987–2012	0.266
7	Stage-1:Number of days/trips Stage-2: Francis method	2	Logistic curve	Observer & Fish ticket	Single *M* from combined EAG and WAG data; Tier 3 B_{MSY} reference points based on average recruitment from 1982–2016	0.224
8	Stage-1:Number of days/trips Stage-2: Francis method	2	Logistic curve	Observer & Fish ticket	Single *M* from combined EAG and WAG data; Tier 3 B_{MSY} reference points based on average recruitment from 1996–2016	0.224
9	Stage-1:Number of days/trips Stage-2: Francis method	2	Knife-edge 111 mmCL	Observer & Fish Ticket	Single *M* from combined EAG and WAG data; Tier 3 B_{MSY} reference points based on average recruitment from 1987–2012	0.224
9**	Stage-1:Number of days/trips Stage-2: Francis method	2	Knife-edge 111 mmCL	Observer & Fish Ticket	Considered only for WAG for Approach 2 OFL and ABC calculation; Single *M* from combined EAG and WAG data; Tier 3 B_{MSY} reference points based on average recruitment from 1993–1997	0.224

10	Stage-1:Number of days/trips Stage-2: Francis method	2	Logistic curve	Observer & Fish Ticket	Separate *M* from EAG and WAG data; Tier 3 B_{MSY} reference points based on average recruitment from 1987–2012	EAG: 0.221 WAG: 0.231
11	Stage-1:Number of days/trips Stage-2: Francis method	2	Knife-edge 111 mmCL	Observer & Fish Ticket	Separate *M* from EAG and WAG data; Tier 3 B_{MSY} reference points based on average recruitment from 1987–2012	EAG: 0.221 WAG: 0.231

b. Progression of results: Model was previously not used, so, not applicable.
c. Model was previously not used. So labeling the previous year approved model as model 0 is not applicable.
d. Evidence of search for balance between realistic and simpler models: Unlike annually surveyed stocks, Aleutian Islands golden king crab stock biomass is difficult to track and several biological parameters are assumed based on knowledge from red king crab (e.g., handling mortality rate of 0.2 yr^{-1}) due to a lack of species/stock specific information. We fixed a number of model parameters after initially running the model with free parameters to reduce the number of parameters to be estimated (e.g., groundfish bycatch selectivity parameters were fixed). The 11 scenarios also considered different configuration of parameters to select parsimonious models. The detailed results of the selected seven scenarios are provided in tables and figures. The total catch OFLs and the reduction in terminal (2015) MMB from the initial condition (i.e., virgin MMB in 1960) for the entire 11 scenarios for EAG and WAG are provided in Table 49. The reduction in terminal MMB from the initial condition is higher for WAG than EAG.
e. Convergence status and criteria: ADMB default convergence criteria were used.
f. Table of the sample sizes assumed for the size compositional data:

   We estimated the initial input effective sample sizes (i.e., Stage-1) either as number of fishing days for retained and total catch compositions and number of fishing trips for groundfish size composition (Note: we did not use the groundfish size composition in the model fit) for all scenarios. Then we estimated the Stage-2 effective sample sizes iteratively from Stage-1 input effective sample sizes using the Francis' (2011, 2016) mean length based method (Appendix D).

   We provide the initial input sample sizes (Stage-1) and Stage-2 effective sample sizes for scenarios 1 to 6 and 9 to 11 in Tables 4 to 12 for EAG and Tables 28 to 36 for WAG.

g. Provide the basis for data weighting, including whether the input effective sample sizes are tuned and the survey CV adjusted: Described previously (f) and details are in Appendix D.
h. Do parameter estimates make sense? The estimated parameter values are within the bounds and various plots suggest that the parameter values are reasonable for a fixed *M* value for these stocks.
i. Model selection criteria: We used a number of diagnostic criteria to select the appropriate models for our recommendation: CPUE fits, observed vs. predicted tag recapture numbers by time at large and release size, retained and total catch, and groundfish bycatch fits. Figures are provided for the preferred scenarios in the Results section.
j. Residual analysis: We illustrated residual fits by bubble plots for size composition predictions in various figures in the Results section.
k. Model evaluation: Only one model with a number of scenarios is presented and the evaluations are presented in the Results section below.

3. *Results*

1. List of effective sample sizes and weighting factors:

The Stage-1 and Stage-2 effective sample sizes are listed for various scenarios in Tables 4 to 12 for EAG and Tables 28 to 36 for WAG. The weights for different data sets are provided in Table A2 for various scenarios, respectively, for EAG and WAG (Appendix A). These weights (with the corresponding coefficient of variations) adequately fitted the length compositions and no further changes were examined.

We used weighting factors for catch biomass, recruitment deviation, pot fishery F, and groundfish fishery F. We set the retained catch biomass to a large value (500.0) because retained catches are more reliable than any other data sets. We scaled the total catch biomass in accordance with the observer annual sample sizes with a maximum of 250.0. The total catches were derived from observer nominal total CPUE and effort. In some years, observer sample sizes were low (Tables 2 and 26). We chose a small groundfish bycatch weight (0.2) based on the

September 2015 CPT suggestion to lower its weight. We used the best fit criteria to choose the lower weight for the groundfish bycatch. Groundfish bycatch of Aleutian Islands golden king crab is very low. We set the CPUE weights to 1.0 for all scenarios. We included a constant (model estimated) variance in addition to input CPUE variance for the CPUE fit. We used the Burnham et al. (1987) suggested formula for ln(CPUE) [and ln(MMB)] variance estimation (Equation A.15 of Appendix A). However, the estimated additional variance values were small for both observer and fish ticket CPUE indices for the two regions. Nevertheless, the CPUE index variances estimated from the negative binomial and lognormal GLMs were adequate to fit the model, as confirmed by the fit diagnostics (Fox and Weisberg 2011). Parameter estimates are provided in Tables 13 and 14 for EAG and 37 and 38 for WAG for a subset (nine) of scenarios. The numbers of estimable parameters are listed in Table A1 of Appendix A. The weights with the corresponding coefficient of variations specifications are detailed in Tables A2 of Appendix A for EAG and WAG.

2. Include tables showing differences in likelihood: Tables 24 and 48 list the total and component negative log likelihood values and their differences between scenarios of similar sample sizes and free parameters for EAG and WAG, respectively.
3. Tables of estimates:
    a. The parameter estimates with coefficient of variation for nine scenarios which are a subset of eleven scenarios are summarized respectively in Tables 13 and 14 for EAG and 37 and 38 for WAG. We have also provided the boundaries for parameter searches in those tables. All parameter estimates were within the bounds.
    b. All scenarios considered molt probability parameters in addition to the linear growth increment and normally distributed growth variability parameters to determine the size transition matrix.
    c. The mature male and legal male abundance time series for representative nine scenarios among the eleven scenarios are summarized in Tables 15 to

23 (scenarios 1, 2, 3, 4, 5, 6, 9, 10, and 11) for EAG and Tables 39 to 47 for WAG.

d. The recruitment estimates for those nine scenarios are summarized in Tables 15 to 23 for EAG and Tables 39 to 47 for WAG.

e. The likelihood component values and the total likelihood values for nine scenarios are summarized in Table 24 for EAG and Table 48 for WAG. Scenarios 3 (observer CPUE time series extended back to 1991/92) has the minimum among the total negative log likelihoods for models with base data and equal number of free parameters for EAG and WAG, respectively.

4. Graphs of estimates:

   a. Total selectivity and retention curves of the pre- and post-rationalization periods for nine of the eleven scenarios are illustrated in Figure 13 for EAG and Figure 32 for WAG. Total selectivity for the pre-rationalization period was used in the tagging model. The groundfish bycatch selectivity appeared flat in the preliminary analysis, indicating that all size groups were vulnerable to the gear. This is also shown in the size compositions of groundfish bycatch (Figures 12 and 31 for EAG and WAG, respectively). Thus, we set the groundfish bycatch selectivity to 1.0 for all length-classes in the subsequent analysis.

   b. The mature male biomass time series for nine (a subset of eleven) scenarios are depicted in Figures 28 and 47 for EAG and WAG, respectively. Mature male biomass tracked the CPUE trends well for all scenarios for EAG and WAG. The biomass variance was estimated using Burnham et al. (1987) suggested formula (Equation A.15 in Appendix A). We determined the mature male biomass values on 15 February each year and considered the 1986–2016 time series of recruits for estimating mean number of recruits for $B_{35\%}$ calculation under Tier 3 approach.

   c. The full selection pot fishery F over time for nine scenarios is shown in Figures 27 and 46 for EAG and WAG, respectively. The F peaked in late 1980s and early to mid-1990s and systematically declined in the EAG. On the other hand, the F peaked in late 1980s, 1990s and early 2000s, then declined in late 2000s and slightly increased since 2010 in the WAG. The increase in F in recent years may be due to a decline in abundance under constant high harvest allocation to WAG.

d. F vs. MMB: We provide these plots for scenarios 1 and 9 for EAG and WAG in Figure 48.
e. Stock-Recruitment relationship: None.
f. The temporal changes in total number of recruits to the modeled population for nine scenarios are illustrated in Figure 15 for EAG and in Figure 34 for WAG. The recruitment distribution to the model size group (101–185 mm CL) is shown in Figures 16 and 35 for EAG and WAG, respectively for the nine scenarios.

5. Evaluation of the fit to the data:
   g. Fits to catches: The fishery retained, total, and groundfish bycatch (observed vs. estimated) plots for nine scenarios are illustrated in Figures 19 and 38 for EAG and WAG, respectively. The 1981/82–1984//85 retained catch plots for nine scenarios are depicted in Figures 20 and 39 for EAG and WAG, respectively. All predicted fits were very close to observed values, especially for retained catch and groundfish bycatch mortality. However, pre 1995 total catch data did not fit well.
   h. Survey data plot: We did not consider the pot survey data for the analysis.
   i. CPUE index data: The predicted vs. input CPUE indices for nine scenarios are shown in Figure 26 for EAG and Figure 45 for WAG. All scenarios appear to fit the CPUE indices satisfactorily for EAG. However, the scenario 3 fit (extended observer CPUE indices) overestimated the CPUE trend in late years of the pre-rationalization period for EAG. The CPUE variance was estimated using Burnham et al. (1987) suggested formula (Equation A.15 in Appendix A).
   j. Tagging data: The predicted vs. observed tag recaptures by length-class for years 1 to 6 recaptures are depicted in Figure 14 for EAG and Figure 33 for WAG. The predictions appear reasonable. Note that we used the

EAG tagging information for size transition matrix estimation for both stocks (EAG and WAG). The size transition matrices estimated using EAG tagging data in the EAG and WAG models were similar.

k. Molt probability: The predicted molt probabilities vs. CL for the nine scenarios are depicted in Figures 17 and 36 for EAG and WAG, respectively. The fits appear to be satisfactory.
l. Maturity curve: The observed and predicted maturity probability vs. CL for the nine scenarios are depicted in Figures 18 and 37 for EAG and WAG, respectively. The fits appear to be satisfactory. We show the knife-edge selection curve in the same figures as well. The model estimated 50% maturity length under scenario 1 was 110.62 mm CL.
m. Fit to catch size compositions: Retained, total, and groundfish discard length compositions are shown in Figures 10 to 12 for EAG and 29 to 31 for WAG. The retained and total catch size composition fits appear satisfactory. But, the fits to groundfish bycatch size compositions are bad. Note that we did not use the groundfish size composition in any of the model scenario fits.

   We illustrate the standardized residual plots as bubble plots of size composition over time for retained catch (Figures 21, 23, 49, 51, 53, and 55 for EAG, and 40, 42, 57, 59, 61, and 63 for WAG) and for total catch (Figures 22, 24, 50, 52, 54, and 56 for EAG, and 41, 43, 58, 60, 62, and 64 for WAG) for selected scenarios (1, 9, 2, 3, 4, and 11). The retained catch bubble plots appear random for the selected scenarios.
n. Marginal distributions for the fits to the composition data: We did not provide this plot in this report.
o. Plots of implied versus input effective sample sizes and time series of implied effective sample sizes: We did not provide the plots, but provided the estimated values in Tables 4 to 12 for EAG and in Tables 28 to 36 for WAG, respectively.
p. Tables of RMSEs for the indices: We did not provide this table in this report.

q. Quantile-quantile (Q–Q) plots: We did not provide this plot for model fits in this report. However, we provided this plot for the CPUE standardization fits in Appendix B.

6. Retrospective and historical analysis: The retrospective fits for five scenarios (a subset of eleven scenarios) are shown in Figure 25 for EAG and in Figure 44 for WAG. The retrospective fits were prepared for the whole time series 1961 to 2016. The retrospective patterns did not show severe departure when five terminal year's data were removed systematically and hence the current formulation of the model appears stable. A severe drop in modeled biomass from the initial MMB occurred when the fishery time series started in 1981.
7. Uncertainty and sensitivity analysis:
   a. The main task was to determine a plausible size transition matrix to project the population over time. In a previous study, we investigated the sensitivity of the model to determining the size transition matrix by using or not using a molt probability function (Siddeek *et al*. 2016a). The model fit is better when the molt probability model is included. Therefore, we included a molt probability sub-model for the size transition matrix calculation in all scenarios.
   b. We also determined likelihood values at different *M*, mean MMB, and MMB depletion values and plotted component negative likelihood against *M*, mean MMB, and MMB depletion (Figures 4 to 8). We discussed the merit of *M* estimation within the model in the CPT and SSC comments section.
   c. Conduct 'jitter analysis': We conducted the (random) jitter analysis on scenarios 1 and 9 model fitted parameters (details in Appendix E).

F. Calculation of the OFL

Specification of the Tier level:

The Aleutian Islands golden king crab stocks are currently managed under a Tier 5 (average catch OFL) control rule. Following January 2017 CPT and February

2017 SSC recommendations we proceeded to compute OFL and ABC under Tier 3 estimation procedure.

The critical assumptions for B_{MSY} reference point estimation are:

a. Natural mortality is constant.
b. Growth transition matrix is fixed and estimated using tagging data with the molt probability sub-model.
c. Total fishery selectivity and retention curves are length dependent and the 2005/06–2015/16 period selectivity estimates are used.
d. Groundfish bycatch fishery selectivity is kept constant at 1.0 for all length groups.
e. Model estimated recruits (in millions of crab) are averaged for the time period 1987 – 2012.
f. Model estimated groundfish bycatch mortality values are averaged for the period 2005 to 2014 (10 years).
g. A size dependent maturity proportion is used for MMB estimation.

Method: We simulated the population abundance starting from the model estimated terminal year stock size by length, model estimated parameter values, a fishing mortality value (F), and adding a constant number of annual recruits. Once the stock dynamics were stabilized (we used the 99th year estimates) for an F, we calculated the MMB/R for that F. We computed the relative *MMB/R* in percentage, $\left(\frac{MMB}{R}\right)_{x\%}$ (where x% = $\frac{\frac{MMB_F}{R}}{\frac{MMB_0}{R}} \times 100$ and MMB_0/R is the virgin *MMB/R*) for different F values.

$F_{35\%}$ is the F value that produces the MMB/R value equal to 35% of MMB_0/R.

$B_{35\%}$ is estimated using the following formula:

$B_{35\%} = \left(\frac{MMB}{R}\right)_{35} \times \bar{R}$, where $\bar{R}$ is the mean number of model estimated recruits for a selected period.

F_{OFL} is determined using Equation A.31 in Appendix A. The OFL is estimated by an iterative procedure accounting for intervening total removals (see Appendix A for the formulas).

The F_{OFL} , total catch OFL, and the retained catch portion of the OFL for coming year for scenarios 1 and 9 are:

Scenario 1:

EAG: F_{OFL} = 0.64; OFL total catch = 3.986 thousand metric tons, retained catch portion of the OFL = 3.858 thousand metric tons.

WAG: F_{OFL} = 0.54; OFL total catch = 1.298 thousand metric tons; retained catch portion of the OFL = 1.213 thousand metric tons.

AI: OFL total catch = 5.284 thousand metric tons.

Scenario 9:

EAG: F_{OFL} = 0.75; OFL total catch = 4.486 thousand metric tons, retained catch portion of the OFL = 4.337 thousand metric tons.

WAG: F_{OFL} = 0.66; OFL total catch = 1.532 thousand metric tons; retained catch portion of the OFL = 1.429 thousand metric tons.

AI: OFL total catch = 6.018 thousand metric tons.

G. Calculation of the ABC

We estimated the cumulative probability distribution of OFL assuming a log normal distribution of OFL. We calculated the OFL at the 0.5 probability and the ABC at the 0.49 probability and considered an additional buffers by setting ABC =0.75*OFL and ABC =0.8*OFL. The ABC estimates with the 20% buffer for scenarios 1 and 9 are:

Scenario 1:

EAG: ABC = 3.189 thousand metric tons.

WAG: ABC = 1.039 thousand metric tons.

AI: ABC = 4.227 thousand metric tons.

Scenario 9:

EAG: ABC = 3.589 thousand metric tons.

WAG: ABC = 1.226 thousand metric tons.

AI: ABC = 4.815 thousand metric tons.

H. Rebuilding Analysis

Not applicable.

I. Data Gaps and Research Priorities

1. The recruit abundances were estimated from commercial catch sampling data. The implicit assumption in the analysis was that the estimated recruits come solely from the same exploited stock through growth and mortality. The current analysis did not consider the possibility that additional recruitment may occur through immigration from neighboring areas and possibly separate sub-stocks. Extensive tagging experiments or resource surveys are needed to investigate stock distributions.
2. We estimated M in the model. However, an independent estimate of M is needed for comparison. Tagging is one possibility.
3. An extensive tagging study will also provide independent estimates of molting probability and growth. We used the historical tagging data to determine the size transition matrix.
4. An arbitrary 20% handling mortality rate on discarded males was used, which was obtained from the red king crab literature (Kruse et al. 2000; Siddeek 2002). An experimentally-based independent estimate of handling mortality is needed for golden king crab.
5. The Aleutian king crab research foundation has recently initiated crab survey programs in the Aleutian Islands. This program needs to be strengthened and continued for golden king crab research to address some of the data gaps and establish a fishery independent data source.
6. We have been using the length-weight relationship established based on late 1990s data for golden king crab. The Aleutian king crab research foundation program can help us to update this relationship by collecting new length weight information.

7. We have recently included the male maturity data in the model. The maturity data available to us were collected in 1984 and 1991. The foundation can help us to update the maturity information by collecting new data on size, chela height, and egg and clutch conditions.

J. Acknowledgments

We thank David Barnard, Miranda Westphal, Ethan Nichols, Robert Foy, Vicki Vanek, Leland Hulbert, and Andrew Nault for preparing/providing various fisheries and biological data and plots for this assessment; We appreciate the technical and editorial help at various time from Andre Punt, Martin Dorn, William Stockhausen, Sherri Dressel, Ben Daly, Joel Webb, Hamazaki Hamachan, Karla Bush, William Bechtol, CPT and SSC members, industry personnel, and industry consultants.

K. Literature Cited

Adams, C.F., and A.J. Paul. 1999. Phototaxis and geotaxis of light-adapted zoeae of the golden king crab *Lithodes aequispinus* (Anomura: Lithodidae) in the laboratory. Journal of Crustacean Biology. 19(1): 106-110.

ADF&G (Alaska Department of Fish and Game). 2002. Annual management report for the shellfish fisheries of the Westward Region, 2001. Alaska Department of Fish and Game, Division of Commercial Fisheries, Regional Information Report 4K02–54, Kodiak, Alaska.

Barnard, D.R., and R. Burt. 2004. Summary of the 2002 mandatory shellfish observer program database for the general and CDQ fisheries. Alaska Department of Fish and Game, Division of Commercial Fisheries, Regional Information Report 4K04–27, Kodiak, Alaska.

Barnard, D.R., R. Burt, and H. Moore. 2001. Summary of the 2000 mandatory shellfish observer program database for the open access fisheries. Alaska Department of Fish and Game, Division of Commercial Fisheries, Regional Information Report 4K01–39, Kodiak, Alaska.

Bowers, F.R., M. Schwenzfeier, S. Coleman, B.J. Failor-Rounds, K. Milani, K. Herring, M. Salmon, and M. Albert. 2008. Annual management report for the commercial and subsistence shellfish fisheries of the Aleutian Islands, Bering Sea, and the Westward Region’s shellfish observer program, 2006/07. Alaska Department of Fish and Game, Divisions of Sport Fish and Commercial Fisheries, Fishery Management Report No. 08-02, Anchorage, Alaska.

Bowers, F.R., M. Schwenzfeier, K. Herring, M. Salmon, J. Shaishnikoff, H. Fitch, J. Alas, and B. Baechler. 2011. Annual management report for the commercial and subsistence shellfish fisheries of the Aleutian Islands, Bering Sea, and the Westward Region's shellfish observer program, 2009/10. Alaska Department of Fish and Game, Divisions of Sport Fish and Commercial Fisheries, Fishery Management Report No. 11-05, Anchorage, Alaska.

Burnham, K.P., D.R. Anderson, G.C. White, C. Brownie, and K.H. Pollock. 1987. Design and analysis methods for fish survival experiments based on release-recapture. American Fisheries Society, Monograph 5, 437p.

Fournier, D.A., H.J. Skaug, J. Ancheta, J. Ianelli, A. Magnusson, M.N. Maunder, A. Nielsen, and J. Sibert. 2012. AD Model Builder: using automatic differentiation for statistical inference of highly parameterized complex nonlinear models. Optim. Methods Softw. 27:233-249.

Fox, J., and S. Weisberg. 2011. An R Companion to Applied Regression. Second edition. Sage Publications, Inc. 449 p.

Francis, R.I.C.C. 2011. Data weighting in statistical fisheries stock assessment models. Can. J. Fish. Aquat. Sci. 68: 1124–1138.

Francis, R.I.C.C. (*in press,* 2016). Revisiting data weighting in fisheries stock assessment models. Fisheries Research.

Gaeuman, W.B. 2011. Summary of the 2009/10 mandatory crab observer program database for the BSAI commercial crab fisheries. Fishery Data Series No. 11-04. Alaska Department of Fish and Game, Kodiak.

Hiramoto, K. 1985. Overview of the golden king crab, *Lithodes aequispina*, fishery and its fishery biology in the Pacific waters of Central Japan. Pages 297-315, In: Proceedings of the International King Crab Symposium. Alaska Sea Grant College Program, AK-SG-85-12, Fairbanks, Alaska.

Koeneman, T.M., and D.V. Buchanan. 1985. Growth of the golden king crab, *Lithodes aequispina*, in Southeast Alaskan waters. Pages 281-297, In: Proceedings of the International King Crab Symposium. Alaska Sea Grant College Program, AK-SG-85-12, Fairbanks, Alaska.

Kruse, G.H., L.C. Byrne, F.C. Funk, S.C. Matulich, and J. Zheng. 2000. Analysis of minimum size limit for the red king crab fishery in Bristol Bay, Alaska. N. Am. J. Fish. Manage. 20:307-319.

Maunder, M.N., and A.E. Punt. 2004. Standardizing catch and effort data: a review of recent approaches. Fisheries Research, 70: 141-159.

McAllister, M.K., and J.N. Ianelli. 1997. Bayesian stock assessment using catch-age data and the sampling/importance resampling algorithm. Can. J. Fish. Aquat. Sci. 54: 284–300.

Moore, H., L.C. Byrne, and M.C. Schwenzfeier. 2000. Summary of the 1999 mandatory shellfish observer program database for the open access fisheries. Alaska Department of Fish and Game, Division of Commercial Fisheries, Regional Information Report 4K00–50, Kodiak, Alaska.

NPFMC (North Pacific Fishery Management Council). 2007. Amendment 24 to the Fishery Management Plan for Bering Sea and Aleutian Islands king and Tanner crabs to revise overfishing definitions. North Pacific Fishery Management Council, Anchorage, Alaska.

Otto, R.S., and P.A. Cummiskey. 1985. Observations on the reproductive biology of golden king crab (*Lithodes aequispina*) in the Bering Sea and Aleutian Islands. Pages 123-135 In: Proceedings of the International King Crab Symposium. Alaska Sea Grant College Program, AK-SG-85-12, Fairbanks, Alaska.

Pengilly, D. 2016. Aleutian Islands golden king crab – 2016 Tier 5 assessment. 2016 Crab SAFE report chapter (September 2016). North Pacific Fishery Management Council, Anchorage, Alaska.

Punt, A.E. (*In press*). Some insights into data weighting in integrated stock assessments. Fisheries Research.

R Core Team. 2016. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.

Shirley, T.C., and S. Zhou. 1997. Lecithotrophic development of the golden king crab *Lithodes aequispinus* (Anomura: Lithodidae). J. Crust. Biol., 17(2):207-216.

Siddeek, M.S.M. 2002. Review of biological reference points used in Bering Sea and Aleutian Islands (king and Tanner) crab management. Alaska Department of Fish and Game, Division of Commercial Fisheries, Regional Information Report 5J02-06, Juneau, Alaska.

Siddeek, M.S.M., D.R. Barnard, L.J. Watson, and R.K. Gish. 2005. A modified catch-length analysis model for golden king crab (*Lithodes aequispinus*) stock assessment in the eastern Aleutian Islands. Pages 783-805 in Fisheries assessment and management in data limited situations, Alaska Sea Grant College Program, AK-SG-05-02, Fairbanks, Alaska.

Siddeek, M.S.M., J. Zheng, and D. Pengilly. 2015. Aleutian Islands Golden King Crab (*Lithodes aequispinus*) Model-Based Stock Assessment in Fall 2015. Draft report submitted for the September 2015 Crab Plan Team Meeting. North Pacific Fishery Management Council, Anchorage, Alaska.

Siddeek, M.S.M., J. Zheng, A.E. Punt, and Vicki Vanek. 2016a. Estimation of size-transition matrices with and without moult probability for Alaska golden king crab using tag–recapture data. Fisheries Research, 180:161-168.

Siddeek, M.S.M., Jie Zheng, and Doug Pengilly 2016b. Standardizing CPUE from the Aleutian Islands golden king crab observer data. In: T.J. Quinn II, J.L. Armstrong, M.R. Baker, J. Heifetz, and D. Witherell (eds.), Assessing and Managing Data-Limited Fish Stocks. Alaska Sea Grant, University of Alaska Fairbanks, Alaska, USA, pp. 97-116.

Siddeek, M.S.M., J. Zheng, and D. Pengilly. 2016c. Aleutian Islands Golden King Crab (*Lithodes aequispinus*) Model-Based Stock Assessment in Spring 2016. Draft report submitted for the May 2016 Crab Plan Team Meeting. North Pacific Fishery Management Council, Anchorage, Alaska.

Siddeek, M.S.M., J. Zheng, A.E. Punt, and D. Pengilly (*in press*, 2017). Effect of data weighting on the mature male biomass estimate for Alaskan golden king crab. CAPAM Data weighting Workshop, San Diego, California. Fisheries Research (2017), http://dx.doi.org/10.1016/j.fishres.2017.02.001.

Somerton, D.A., and R.S. Otto. 1986. Distribution and reproductive biology of the golden king crab, *Lithodes aequispina*, in the Eastern Bering Sea. Fishery Bulletin. 81(3): 571-584.

Starr, P.J. 2012. Standardized CPUE analysis exploration: using the rock lobster voluntary logbook and observer catch sampling programmes. New Zealand Fisheries Assessment Report 2012/34, 75 p.

Watson, L.J., D. Pengilly, and S.F. Blau. 2002. Growth and molting of golden king crabs (*Lithodes aequispinus*) in the eastern Aleutian Islands, Alaska. Pages 169-187 *in* Crabs in cold water regions: biology, management, and economics, Alaska Sea Grant College Program, AK-SG-02-01, Fairbanks, Alaska.

Webb. J. 2014. Reproductive ecology of commercially important Lithodid crabs. Pages 285-314 *in* B.G. Stevens (ed.). King Crabs of the World: Biology and Fisheries Management. CRC Press, Taylor & Francis Group, New York.