Trial runs of Gulf of Alaska Pacific ocean perch using AMAK

James Ianelli[1]
[1]NOAA, jim.ianelli@noaa.gov

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Executive Summary

1. **Stock**: Pacific ocean perch, *Sebastes alutus*, Gulf of Alaska.
2. **Catches**: Peak historical catch was
3. **Stock biomass**: The NMFS trawl survey mean biomass is
4. **Recruitment**: Recruitment is based on
5. **Management performance**: In this assessment estimated total catch

A. Summary of Major Changes

Changes in Management of the Fishery

There are no new changes in management of the fishery.

Changes to the Input Data

Data used in this assessment have been updated to include the most recently available fishery and survey numbers.

Changes in Assessment Methodology

This assessment uses the AMAK (Assessment model for Alaska) framework. The model is configured to track ages over time and uses both age and length composition data.

Changes in Assessment Results

B. Responses to SSC and CPT Comments

GOA Plan Team and SSC Comments on Assessments in General

Comment: *Regarding general code development, the SSC and PT outstanding requests continue to be as follows:*

1. *add the ability to conduct retrospective analyses*

   Progress was limited in implementing this feature.

2. *add ability to estimate bycatch fishing mortality rates when observer data are missing but effort data is available*

   This was completed.

3. *Continued exploration of data weighting (Francis and other approaches) and evaluation of models with and without the 1998 natural mortality spike. The authors are encouraged to bring other models forward for CPT and SSC consideration*

   We continued to include an alternative time series estimated from the NMFS trawl survey using the VAST spatiotemporal Delta GLMM model and continued with the iterative re-weighting for composition data.

C. Introduction

Scientific Name

The Pacific ocean perch is a rockfish species, *Sebastes alutus*.

Distribution

Pacific ocean perch are broadly distributed throughout the North Pacific Ocean from Hokkaido, Japan, to northern California (Figure). In the Gulf of Alaska…

Stock Structure

The regional population differences in POP…

Life History

Like other rockfish species…

Management History

The fishing seasons …

NMFS declared the stock rebuilt on 21 September 2009, and the fishery was reopened after a 10-year closure on 15 October 2009 with a TAC of 529 t (1.167 million pounds), closing again by regulation on 1 February 2010. Seven participating vessels landed a catch of 209 t (0.461 million pounds) with a reported effort of 10,697 pot lifts and an estimated CPUE of 9.9 retained individual crab per pot lift. The fishery remained open the next three years with modest harvests and similar CPUE, but large declines in the NMFS trawl-survey estimate of stock abundance raised concerns about the health of the stock. This prompted ADF&G to close the fishery again for the 2013/14 season. The fishery was reopened for the 2014/15 season with a low TAC of 297 t (0.655 million pounds) and in 2015/16 the TAC was further reduced to 186 t (0.411 million pounds) then completely closed during the 2016/17 season.

Although historical observer data are limited due to low sampling effort, bycatch of female and sublegal male crab from the directed blue king crab fishery off St. Matthew Island was relatively high historically, with estimated total bycatch in terms of number of crab captured sometimes more than twice as high as the catch of legal crab (Moore et al. 2000; ADF&G Crab Observer Database). Pot-lift sampling by ADF&G crab observers (Gaeuman 2013; ADF&G Crab Observer Database) indicates similar bycatch rates of discarded male crab since the reopening of the fishery (Table 1), with total male discard mortality in the 2012/13 directed fishery estimated at about 12% (88 t or 0.193 million pounds) of the reported retained catch weight, assuming 20% handling mortality.

These data suggest a reduction in the bycatch of females, which may be attributable to the later timing of the contemporary fishery and the more offshore distribution of fishery effort since reopening in 2009/10[1]. Some bycatch of discarded blue king crab has also been observed historically in the eastern Bering Sea snow crab fishery, but in recent years it has generally been negligible. The St. Matthew Island golden king crab fishery, the third commercial crab fishery to have taken place in the area, typically occurred in areas with depths exceeding blue king crab distribution. The NMFS observer data suggest that variable, but mostly limited, SMBKC bycatch has also occurred in the eastern Bering Sea groundfish fisheries (Table **??**).

D. Data

Summary of New Information

Data used in this assessment were updated to include the most recently available fishery and survey numbers. This assessment makes use of two new survey data points including the 2018 NMFS trawl-survey estimate of abudance, and the 2018 ADF&G pot survey CPUE. Both of these surveys have associated size compositon data. The assessment also uses updated 1993-2016 groundfish and fixed gear bycatch estimates based on AKRO data. The fishery was closed in 2016/17 so no directed fishery catch data were available. The data used in each of the new models is shown in Figure **??**.

Major Data Sources

Major data sources used in this assessment include annual directed-fishery retained-catch statistics from fish tickets (1978/79-1998/99, 2009/10-2012/13, and 2014/15-2015/16; Table 2); results from the annual NMFS eastern Bering Sea trawl survey (1978-2018; Table 3); results from the ADF&G SMBKC pot survey (every third year during 1995-2013, then 2015-2018; Table 4); mean somatic mass given length category by year (Table **??**); size-frequency information from ADF&G crab-observer pot-lift sampling (1990/91-1998/99, 2009/10-2012/13, and 2014/15-2016/17; Table 1); and the NMFS groundfish-observer bycatch biomass estimates (1992/93-2016/17; Table **??**).

Figure maps stations from which SMBKC trawl-survey and pot-survey data were obtained. Further information concerning the NMFS trawl survey as it relates to commercial crab species is available in Daly et al. (2014); see Gish et al. (2012) for a description of ADF&G SMBKC pot-survey methods. It should be noted that the two surveys cover different geographic regions and that each has in some years encountered proportionally large numbers of male blue king crab in areas not covered by the other survey (Figure). Crab-observer sampling protocols are detailed in the crab-observer training manual (ADF&G 2013). Groundfish SMBKC bycatch data come from the NMFS Regional office and have been compiled to coincide with the SMBKC management area.

Other Data Sources

The growth transition matrix used is based on Otto and Cummiskey (1990), as in the past. Other relevant data sources, including assumed population and fishery parameters, are presented in Appendix A, which also provides a detailed description of the model configuration used for this assessment.

[1]D. Pengilly, ADF&G, pers. comm.

E. Analytic Approach

History of Modeling Approaches for this Stock

A four-stage catch-survey-analysis (CSA) assessment model was used before 2011 to estimate abundance and biomass and prescribe fishery quotas for the SMBKC stock. The four-stage CSA is similar to a full length-based analysis, the major difference being coarser length groups, which are more suited to a small stock with consistently low survey catches. In this approach, the abundance of male crab with a CL $\geq$ 90 mm is modeled in terms of four crab stages: stage 1: 90-104 mm CL; stage 2: 105-119 mm CL; stage 3: newshell 120-133 mm CL; and stage 4: oldshell $\geq$ 120 mm CL and newshell $\geq$ 134 mm CL. Motivation for these stage definitions comes from the fact that for management of the SMBKC stock, male crab measuring $\geq$ 105 mm CL are considered mature, whereas 120 mm CL is considered a proxy for the legal size of 5.5 in carapace width, including spines. Additional motivation for these stage definitions comes from an estimated average growth increment of about 14 mm per molt for SMBKC (Otto and Cummiskey 1990).

Concerns about the pre-2011 assessment model led to the CPT and SSC recommendations that included development of an alternative model with provisional assessment based on survey biomass or some other index of abundance. An alternative 3-stage model was proposed to the CPT in May 2011, but a survey-based approach was requested for the Fall 2011 assessment. In May 2012 the CPT approved a slightly revised and better documented version of the alternative model for assessment. Subsequently, the model developed and used since 2012 was a variant of the previous four-stage SMBKC CSA model and similar in complexity to that described by Collie et al. (2005). Like the earlier model, it considered only male crab $\geq$ 90 mm in CL, but combined stages 3 and 4 of the earlier model, resulting in three stages (male size classes) defined by CL measurements of (1) 90-104 mm, (2) 105-119 mm, and (3) 120 mm+ (i.e., 120 mm and above). This consolidation was driven by concern about the accuracy and consistency of shell-condition information, which had been used in distinguishing stages 3 and 4 of the earlier model.

In 2016 the accepted SMBKC assessment model made use of the modeling framework Gmacs (Webber et al. 2016). In that assessment, an effort was made to match the 2015 SMBKC stock assessment model to bridge a framework which provided greater flexibility and opportunity to evaluate model assumptions more fully.

Assessment Methodology

This assessment model again uses the modeling framework Gmacs and is detailed in Appendix A.

Model Selection and Evaluation

Five models were presented in the previous assessment. This year, four models are presented with the reference model being the same configuration as approved last year (Ianelli et al. 2017), two sensitivities are considered, one with a different treatment of NMFS bottom trawl survey (BTS) data using a geo-spatial model (VAST; Thorson and Barnett 2017; Appendix C). A second sensitivity was constructed which weights the survey data more heavily. In addition to these sensitivities, we evaluated the impacts of adding new data to the reference model. In summary, the following lists the models presented and the naming convention used:

1. **2017 Model**: the 2017 recommended model without any new data
2. **BTS**: adds in the 2018 bottom trawl survey (BTS) data
3. **BTS and pot**: as with previous but including the 2018 ADFG pot survey data (Model 16.0 or "reference case")
4. **VAST**: applies a geo-spatial delta-GLMM model (Thorson and Barnett 2017) to the BTS data which provides a different BTS index. See appendix B for details and diagnostics. This is a preliminary examination as more work is needed to ensure options for the BTS CPUE data were specified appropriately.

5. **Fit survey**: an exploratory scenario that's the same as the reference model except the NMFS trawl survey is up-weighted
6. by $\lambda^{\text{NMFS}} =$ and the ADF&G pot survey is up-weighted by $\lambda^{\text{ADFG}} =$.

Note that SSC convention would label these (item 3 above) as model 16.0 (the model first developed in that year). Since only a few models are presented here, for simplicity we labeled model 16.0 as "reference" and for the others, we used the simple naming convention presented above.

Results

a. Sensitivity to new data

Results for scenarios are provided with comparisons to the 2017 model and sensitivity new data are shown in Figures **??** and **??** with recruitment and spawning biomass shown in Figures **??** and **??**, respectively. The fits to survey CPUEs and spawning biomass show that the addition of new data results in more of a decline than in the 2017 assessment, especially with the addition of the pot survey.

b. Alternative NMFS bottom-trawl survey index

Results comparing model fits between the VAST model and the reference case show different time-series of data and a different model fit (Figure **??**). The effect on spawning biomass suggests estimates were consistently higher since 1990 compared to the reference model (Figure **??**).

c. Effective sample sizes and weighting factors

Observed and estimated effective sample sizes are compared in Table 5. Data weighting factors, standard deviation of normalized residuals (SDNRs), and median absolute residual (MAR) are presented in Table **??**. The SDNR for the trawl survey is acceptable at 1.66 in the reference model. Francis (2011) weighting was applied in 2017 but given the relatively few size bins in this assessment, this application was suspended this year.
The SDNRs for the pot surveys show a similar pattern in each of the scenarios, but are much higher suggesting an inconsistency between the pot survey data and the model structure and other data components. Rather than re-weighting, we chose to retain the values as specified, noting that down-weighting these data would effectively exclude the signal from this series. The MAR values for the trawl and pot surveys shows the same pattern among each of the scenarios as the SDNR. The SDNR and MAR values for the trawl survey and pot survey size compositions were relatively good, ranging from 0.54 to 0.73 for the reference case. The SDNRs for the directed pot fishery and other size compositions were similar to previous estimates.

d. Parameter estimates

Model parameter estimates for each of the Gmacs scenarios are summarized in Tables **??**, **??**, and **??**. These parameter estimates are compared in Table **??**. Negative log-likelihood values and management measures for each of the model configurations are compared in Tables **??** through **??**.

There are some differences in parameter estimates among models as reflected in the log-likelihood components and the management quantities. The parameter estimates in the "fit survey" scenario differ the most, as expected, particularly the estimate of the ADF&G pot survey catchability (q) (see Table **??**). Also, the residuals for recruitment in the first size group are large for these model runs, presumably because higher estimates of recruits in some years are required by the model to match the observed biomass trends.

Selectivity estimates show some variability between models (Figure **??**). Estimated recruitment is variable over time for all models and in recent years is well below average (Figure **??**). Estimated mature male biomass on 15 February also fluctuates considerably (Figure **??**). Estimated natural mortality each year (M_t) is presented in Figure **??**.

e. Evaluation of the fit to the data.

The model fits to total male ($\geq$ 90 mm CL) trawl survey biomass tend to miss the recent peak around 2010 and is slightly above the 2017 value for the key sensitivities (Figures **??**). All of the models fit the pot survey CPUE poorly (Figure **??**. For both surveys the standardized residuals tend to have similar patterns with some improvement (generally) for the VAST model (Figures **??** and **??**).

Fits to the size compositions for trawl survey, pot survey, and commercial observer data are reasonable but miss the largest size category in some years (Figures **??**, **??**, and **??**) for all scenarios. Representative residual plots of the composition data fits are generally poor (Figures **??** and **??**). The model fits to different types of retained and discarded catch values performed as expected given the assumed levels of uncertainty on the input data (Figure **??**).

Unsurprisingly, the **Fit surveys** model fits the the NMFS survey biomass and ADF&G pot survey CPUE data better but still has a similar residual pattern (Figures **??** and **??**). It is worth noting that that this scenario (included for exploratory purposes) resulted in worse SDNR and MAR values for the two abundance indices.

f. Retrospective and historical analyses

This is only the second year a formal assessment model developed for this stock. As such, retrospective patterns and historical analyses relative to fisheries impacts are limited.

g. Uncertainty and sensitivity analyses.

Estimated standard deviations of parameters and selected management measures for the models are summarized in Tables **??**, **??**, and **??** (compiled in Table **??**). Probabilities for mature male biomass and OFL in 2017 are presented in Section F.

h. Comparison of alternative model scenarios.

The estimates of mature male biomass (Figure **??**), for the **Fit survey** sensitivity differs from the other models due to a low value for pot survey catchability being estimated (which tends to scale the population estimate). This existng scenario results in a lower MMB from the mid-1980s through to the late-1990s, and is again lower in the most recent 5 years. This scenario upweights both the trawl and pot surveys abundance indices and represents a model run that places greater emphasis on the abundance indices.

In summary, the use of the reference model for management purposes is preferred since it provides the best fit to the data and is consistent with previous model specifications. Research on alternative model specifications (e.g., natural mortality variability) was limited this year. The VAST model may take better account of spatial processes but requires more research to ensure it has been appropriately applied and the assumptions are reasonable. Consequently, the reference model appears reasonable and appropriate for ACL and OFL determinations for this stock in 2017. Nonetheless, the **Fit surveys** model, while difficult to statistically justify, portends a more dire stock status (see below) and should highlight the caution needed in managing this resource.

F. Calculation of the OFL and ABC

The overfishing level (OFL) is the fishery-related mortality biomass associated with fishing mortality F_{OFL}. The SMBKC stock is currently managed as Tier 4, and only a Tier 4 analysis is presented here. Thus given stock estimates or suitable proxy values of B_{MSY} and F_{MSY}, along with two additional parameters α and β, F_{OFL} is determined by the control rule

$$F_{OFL} = \begin{cases} F_{MSY}, & \text{when } B/B_{MSY} > 1 \\ F_{MSY}\frac{(B/B_{MSY}-\alpha)}{(1-\alpha)}, & \text{when } \beta < B/B_{MSY} \leq 1 \end{cases} \tag{1}$$
$$F_{OFL} < F_{MSY} \text{ with directed fishery } F = 0 \text{ when } B/B_{MSY} \leq \beta$$

where B is quantified as mature-male biomass (MMB) at mating with time of mating assigned a nominal date of 15 February. Note that as B itself is a function of the fishing mortality F_{OFL} (therefore numerical approximation of F_{OFL} is required). As implemented for this assessment, all calculations proceed according to the model equations given in Appendix A. F_{OFL} is taken to be full-selection fishing mortality in the directed pot fishery and groundfish trawl and fixed-gear fishing mortalities set at their model geometric mean values over years for which there are data-based estimates of bycatch-mortality biomass.

The currently recommended Tier 4 convention is to use the full assessment period, currently - , to define a B_{MSY} proxy in terms of average estimated MMB and to set $\gamma = 1.0$ with assumed stock natural mortality $M = 0.18$ yr^{-1} in setting the F_{MSY} proxy value γM. The parameters α and β are assigned their default values $\alpha = 0.10$ and $\beta = 0.25$. The F_{OFL}, OFL, ABC, and MMB in 2018 for all scenarios are summarized in Table **??**. The ABC is 80% of the OFL.

G. Rebuilding Analysis

This stock is not currently subject to a rebuilding plan. However, interpretation of the point estimate for the reference case suggests that the mature male biomass is below 50% of B_{MSY} but slightly above for the "VAST" model configuration (Table **??**).

H. Data Gaps and Research Priorities

The following topics have been listed as areas where more research on SMBKC is needed:

1. Growth increments and molting probabilities as a function of size.
2. Trawl survey catchability and selectivities.
3. Temporal changes in spatial distributions near the island.
4. Natural mortality.

I. Projections and outlook

The outlook for recruitment is pessimistic and the abundance relative to the proxy B_{MSY} is low. The NMFS survey results in 2018 noted ocean conditions warmer than normal with an absence of a "cold pool" in the region. This could have detrimental effects on the SMBKC stocks and should be carefully monitored. Relative to the impact of historical fishing, we again conducted a "dynamic-B_0" analysis. This procedure simply projects the population based on estimated recruitment but removes the effect of fishing. For the reference case, this suggests that the impact of fishing has reduced to stock to about % of what it would have been in the absence of fishing (Figure **??**) . The other non-fishing contributors to the observed depleted stock trend (ignoring stock-recruit relationship) may reflect variable survival rates due to environmental conditions and also range shifts.

J. Acknowledgements

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K. References

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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.

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

Tables

Table 1: Observed proportion of crab by size class during the ADF&G crab observer pot-lift sampling. Source: ADF&G Crab Observer Database.

Year	Total pot lifts	Pot lifts sampled	Number of crab (90 mm+ CL)	Stage 1	Stage 2	Stage 3
1990/91	26,264	10	150	0.113	0.393	0.493
1991/92	37,104	125	3,393	0.133	0.177	0.690
1992/93	56,630	71	1,606	0.191	0.268	0.542
1993/94	58,647	84	2,241	0.281	0.210	0.510
1994/95	60,860	203	4,735	0.294	0.271	0.434
1995/96	48,560	47	663	0.148	0.212	0.640
1996/97	91,085	96	489	0.160	0.223	0.618
1997/98	81,117	133	3,195	0.182	0.205	0.613
1998/99	91,826	135	1.322	0.193	0.216	0.591
1999/00 - 2008/09			FISHERY CLOSED			
2009/10	10,484	989	19,802	0.141	0.324	0.535
2010/11	29,356	2,419	45,466	0.131	0.315	0.553
2011/12	48,554	3,359	58,666	0.131	0.305	0.564
2012/13	37,065	2,841	57,298	0.141	0.318	0.541
2013/14			FISHERY CLOSED			
2014/15	10,133	895	9,906	0.094	0.228	0.679
2015/16	5,475	419	3,248	0.115	0.252	0.633
2016/17			FISHERY CLOSED			

Table 2: Fishery characteristics and update. Columns include the 1978/79 to 2015/16 directed St. Matthew Island blue king crab pot fishery. The Guideline Harvest Level (GHL) and Total Allowable Catch (TAC) are in millions of pounds. Harvest includes deadloss. Catch per unit effort (CPUE) in this table is simply the harvest number / pot lifts. The average weight is the harvest weight / harvest number in pounds. The average CL is the average of retained crab in mm from dockside sampling of delivered crab. Source: Fitch et al 2012; ADF&G Dutch Harbor staff, pers. comm. Note that management (GHL) units are in pounds, for conserving space, conversion to tons is ommitted.

			Harvest					
Year	Dates	GHL/TAC	Crab	Pounds	Pot lifts	CPUE	avg wt	avg CL
1978/79	07/15 - 09/03		436,126	1,984,251	43,754	10	4.5	132.2
1979/80	07/15 - 08/24		52,966	210,819	9,877	5	4.0	128.8
1980/81	07/15 - 09/03			CONFIDENTIAL				
1981/82	07/15 - 08/21		1,045,619	4,627,761	58,550	18	4.4	NA
1982/83	08/01 - 08/16		1,935,886	8,844,789	165,618	12	4.6	135.1
1983/84	08/20 - 09/06	8.0	1,931,990	9,454,323	133,944	14	4.9	137.2
1984/85	09/01 - 09/08	2.0-4.0	841,017	3,764,592	73,320	11	4.5	135.5
1985/86	09/01 - 09/06	0.9-1.9	436,021	2,175,087	46,988	9	5.0	139.0
1986/87	09/01 - 09/06	0.2-0.5	219,548	1,003,162	22,073	10	4.6	134.3
1987/88	09/01 - 09/05	0.6-1.3	227,447	1,039,779	28,230	8	4.6	134.1
1988/89	09/01 - 09/05	0.7-1.5	280,401	1,236,462	21,678	13	4.4	133.3
1989/90	09/01 - 09/04	1.7	247,641	1,166,258	30,803	8	4.7	134.6
1990/91	09/01 - 09/07	1.9	391,405	1,725,349	26,264	15	4.4	134.3
1991/92	09/16 - 09/20	3.2	726,519	3,372,066	37,104	20	4.6	134.1
1992/93	09/04 - 09/07	3.1	545,222	2,475,916	56,630	10	4.5	134.1
1993/94	09/15 - 09/21	4.4	630,353	3,003,089	58,647	11	4.8	135.4
1994/95	09/15 - 09/22	3.0	827,015	3,764,262	60,860	14	4.9	133.3
1995/96	09/15 - 09/20	2.4	666,905	3,166,093	48,560	14	4.7	135.0
1996/97	09/15 - 09/23	4.3	660,665	3,078,959	91,085	7	4.7	134.6
1997/98	09/15 - 09/22	5.0	939,822	4,649,660	81,117	12	4.9	139.5
1998/99	09/15 - 09/26	4.0	635,370	2,968,573	91,826	7	4.7	135.8
1999/00 - 2008/09				FISHERY CLOSED				
2009/10	10/15 - 02/01	1.17	103,376	460,859	10,697	10	4.5	134.9
2010/11	10/15 - 02/01	1.60	298,669	1,263,982	29,344	10	4.2	129.3
2011/12	10/15 - 02/01	2.54	437,862	1,881,322	48,554	9	4.3	130.0
2012/13	10/15 - 02/01	1.63	379,386	1,616,054	37,065	10	4.3	129.8
2013/14				FISHERY CLOSED				
2014/15	10/15 - 02/05	0.66	69,109	308,582	10,133	7	4.5	132.3
2015/16	10/19 - 11/28	0.41	24,076	105,010	5,475	4	4.4	132.6
2016/17				FISHERY CLOSED				
2017/18				FISHERY CLOSED				

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## Error: <text>:6:37: unexpected ','
## 5:        #grep("log_fbar", x$names),
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Table 3: NMFS EBS trawl-survey area-swept estimates of male crab abundance (10^6 crab) and male (≥ 90 mm CL) biomass (10^6 lbs). Total number of captured male crab ≥ 90 mm CL is also given. Source: R. Foy, NMFS. The "+" refer to plus group.

	Abundance					Biomass		
	Stage-1	Stage-2	Stage-3			Total		Number
Year	(90-104 mm)	(105-119 mm)	(120+ mm)	Total	CV	(90+ mm CL)	CV	of crabs
1978	2.213	1.991	1.521	5.726	0.411	15.064	0.394	157
1979	3.061	2.281	1.808	7.150	0.472	17.615	0.463	178
1980	2.856	2.563	2.541	7.959	0.572	22.017	0.507	185
1981	0.483	1.213	2.263	3.960	0.368	14.443	0.402	140
1982	1.669	2.431	5.884	9.984	0.401	35.763	0.344	271
1983	1.061	1.651	3.345	6.057	0.332	21.240	0.298	231
1984	0.435	0.497	1.452	2.383	0.175	8.976	0.179	105
1985	0.379	0.376	1.117	1.872	0.216	6.858	0.210	93
1986	0.203	0.447	0.374	1.025	0.428	3.124	0.388	46
1987	0.325	0.631	0.715	1.671	0.302	5.024	0.291	71
1988	0.410	0.816	0.957	2.183	0.285	6.963	0.252	81
1989	2.169	1.154	1.786	5.109	0.314	13.974	0.271	208
1990	1.053	1.031	2.338	4.422	0.302	14.837	0.274	170
1991	1.147	1.665	2.233	5.046	0.259	15.318	0.248	197
1992	1.074	1.382	2.291	4.746	0.206	15.638	0.201	220
1993	1.521	1.828	3.276	6.626	0.185	21.051	0.169	324
1994	0.883	1.298	2.257	4.438	0.187	14.416	0.176	211
1995	1.025	1.188	1.741	3.953	0.187	12.574	0.178	178
1996	1.238	1.891	3.064	6.193	0.263	20.746	0.241	285
1997	1.165	2.228	3.789	7.182	0.367	24.084	0.337	296
1998	0.660	1.661	2.849	5.170	0.373	17.586	0.355	243
1998	0.223	0.222	0.558	1.003	0.192	3.515	0.182	52
2000	0.282	0.285	0.740	1.307	0.303	4.623	0.310	61
2001	0.419	0.502	0.938	1.859	0.243	6.242	0.245	91
2002	0.111	0.230	0.640	0.981	0.311	3.820	0.320	38
2003	0.449	0.280	0.465	1.194	0.399	3.454	0.336	65
2004	0.247	0.184	0.562	0.993	0.369	3.360	0.305	48
2005	0.319	0.310	0.501	1.130	0.403	3.620	0.371	42
2006	0.917	0.642	1.240	2.798	0.339	8.585	0.334	126
2007	2.518	2.020	1.193	5.730	0.420	14.266	0.385	250
2008	1.352	0.801	1.457	3.609	0.289	10.261	0.284	167
2009	1.573	2.161	1.410	5.144	0.263	13.892	0.256	251
2010	3.937	3.253	2.458	9.648	0.544	24.539	0.466	388
2011	1.800	3.255	3.207	8.263	0.587	24.099	0.558	318
2012	0.705	1.970	1.808	4.483	0.361	13.669	0.339	193
2013	0.335	0.452	0.807	1.593	0.215	5.043	0.217	74
2014	0.723	1.627	1.809	4.160	0.503	13.292	0.449	181
2015	0.992	1.269	1.979	4.240	0.774	12.958	0.770	153
2016	0.535	0.660	1.178	2.373	0.447	7.685	0.393	108
2017	0.091	0.323	0.663	1.077	0.657	3.955	0.600	42
2018	0.154	0.232	0.660	1.047	0.298	3.816	0.281	62

Table 4: Size-class and total CPUE (90+ mm CL) with estimated CV and total number of captured crab (90+ mm CL) from the 96 common stations surveyed during the ADF&G SMBKC pot surveys. Source: ADF&G.

Year	Stage-1 (90-104 mm)	Stage-2 (105-119 mm)	Stage-3 (120+ mm)	Total CPUE	CV	Number of crabs
1995	1.919	3.198	6.922	12.042	0.13	4624
1998	0.964	2.763	8.804	12.531	0.06	4812
2001	1.266	1.737	5.487	8.477	0.08	3255
2004	0.112	0.414	1.141	1.667	0.15	640
2007	1.086	2.721	4.836	8.643	0.09	3319
2010	1.326	3.276	5.607	10.209	0.13	3920
2013	0.878	1.398	3.367	5.643	0.19	2167
2015	0.198	0.682	1.924	2.805	0.18	1077
2016	0.198	0.456	1.724	2.378	0.19	777
2017	0.177	0.429	1.083	1.689	0.25	643
2018	0.076	0.161	0.508	0.745	0.14	286

Table 5: Observed and input sample sizes for observer data from the directed pot fishery, the NMFS trawl survey, and the ADF&G pot survey.

	Number measured			Input sample sizes		
Year	Observer pot	NMFS trawl	ADF&G pot	Observer pot	NMFS trawl	ADF&G pot
1978		157			50	
1979		178			50	
1980		185			50	
1981		140			50	
1982		271			50	
1983		231			50	
1984		105			50	
1985		93			46.5	
1986		46			23	
1987		71			35.5	
1988		81			40.5	
1989		208			50	
1990	150	170		15	50	
1991	3393	197		25	50	
1992	1606	220		25	50	
1993	2241	324		25	50	
1994	4735	211		25	50	
1995	663	178	4624	25	50	100
1996	489	285		25	50	
1997	3195	296		25	50	
1998	1323	243	4812	25	50	100
1999		52			26	
2000		61			30.5	
2001		91	3255		45.5	100
2002		38			19	
2003		65			32.5	
2004		48	640		24	100
2005		42			21	
2006		126			50	
2007		250	3319		50	100
2008		167			50	
2009	19802	251		50	50	
2010	45466	388	3920	50	50	100
2011	58667	318		50	50	
2012	57282	193		50	50	
2013		74	2167		37	100
2014	9906	181		50	50	
2015	3248	153	1077	50	50	100
2016		108	777		50	100
2017		42	643		21	100
2018		62	286		31	100

Figures

Distribution of blue king crab (*Paralithodes platypus*) in the Gulf of Alaska, Bering Sea, and Aleutian Islands waters (shown in blue).

King crab Registration Area Q (Bering Sea).

Trawl and pot-survey stations used in the SMBKC stock assessment.

Catches (in numbers) of male blue king crab /*ge* 90 mm CL from the 2012-2017 NMFS trawl-survey at the 56 stations used to assess the SMBKC stock. Note that the area north of St. Matthew Island, which often shows large catches of crab at station R-24 is not covered in the ADF&G pot-survey data used in the assessment.

```
## Error in .get_cpue_df(M[3:4]): could not find function ".get_cpue_df"
## Error in filter(p.df, fleet == "NMFS Trawl"): object 'p.df' not found
```

```
## Error in A[[i]]: subscript out of bounds
```

```
## Error in .get_cpue_df(M[mod_scen]): could not find function ".get_cpue_df"
## Error in filter(p.df, fleet == "NMFS Trawl"): object 'p.df' not found
```

Appendix A: Model Description

1. Introduction

The model has been specified

2. Model Population Dynamics

Within the model, the beginning of the

The natural mortality each season t and year y is

$$M_{t,y} = \bar{M}\tau_t + \delta^M_y \text{ where } \delta^M_y \sim \mathcal{N}\left(0, \sigma^2_M\right) \tag{2}$$

Fishing mortality by year y and season t is denoted $F_{t,y}$ and calculated as

$$F_{t,y} = F^{\text{df}}_{t,y} + F^{\text{tb}}_{t,y} + F^{\text{fb}}_{t,y} \tag{3}$$

where $F^{\text{df}}_{t,y}$ is the fishing mortality associated with the directed fishery, $F^{\text{tb}}_{t,y}$ is the fishing mortality associated with the trawl bycatch fishery, $F^{\text{fb}}_{t,y}$ is the fishing mortality associated with the fixed bycatch fishery. Each of these are derived as

$$\begin{aligned}
F^{\text{df}}_{t,y} &= \bar{F}^{\text{df}} + \delta^{\text{df}}_{t,y} \quad \text{where} \quad \delta^{\text{df}}_{t,y} \sim \mathcal{N}\left(0, \sigma^2_{\text{df}}\right), \\
F^{\text{tb}}_{t,y} &= \bar{F}^{\text{tb}} + \delta^{\text{tb}}_{t,y} \quad \text{where} \quad \delta^{\text{df}}_{t,y} \sim \mathcal{N}\left(0, \sigma^2_{\text{tb}}\right), \\
F^{\text{fb}}_{t,y} &= \bar{F}^{\text{fb}} + \delta^{\text{fb}}_{t,y} \quad \text{where} \quad \delta^{\text{df}}_{t,y} \sim \mathcal{N}\left(0, \sigma^2_{\text{fb}}\right),
\end{aligned} \tag{4}$$

where $\delta^{\text{df}}_{t,y}$, $\delta^{\text{tb}}_{t,y}$, and $\delta^{\text{fb}}_{t,y}$ are the fishing mortality deviations for each of the fisheries, each season t during each year y, $\bar{F}^{\text{df}}$, $\bar{F}^{\text{tb}}$, and $\bar{F}^{\text{fb}}$ are the average fishing mortalities for each fishery. The total mortality $Z_{l,t,y}$ represents the combination of natural mortality $M_{t,y}$ and fishing mortality $F_{t,y}$ during season t and year y

$$\boldsymbol{Z}_{t,y} = Z_{l,t,y} = M_{t,y} + F_{t,y}. \tag{5}$$

The survival matrix $\boldsymbol{S}_{t,y}$ during season t and year y is

$$\boldsymbol{S}_{t,y} = \left[\begin{array}{ccc} 1-e^{-Z_{1,t,y}} & 0 & 0 \\ 0 & 1-e^{-Z_{2,t,y}} & 0 \\ 0 & 0 & 1-e^{-Z_{3,t,y}} \end{array}\right]. \tag{6}$$

The basic population dynamics underlying Gmacs can thus be described as

$$\begin{aligned}
\boldsymbol{n}_{t+1,y} &= \boldsymbol{S}_{t,y}\boldsymbol{n}_{t,y}, && \text{if } t < 5 \\
\boldsymbol{n}_{t,y+1} &= \boldsymbol{G}\boldsymbol{S}_{t,y}\boldsymbol{n}_{t,y} + \boldsymbol{r}_{t,y} && \text{if } t = 5.
\end{aligned} \tag{7}$$

3. Model Data

Data inputs used in model estimation are listed in Table 6.

4. Model Parameters

Table 7 lists fixed (externally determined) parameters used in model computations. In all scenarios, the stage-transition matrix is

$$\boldsymbol{G} = \left[\begin{array}{ccc} 0.2 & 0.7 & 0.1 \\ 0 & 0.4 & 0.6 \\ 0 & 0 & 1 \end{array}\right] \tag{8}$$

Table 6: Data inputs used in model estimation.

Data	Years	Source
Directed pot-fishery retained-catch number (not biomass)	1978/79 - 1998/99 2009/10 - 2015/16	Fish tickets (fishery closed 1999/00 - 2008/09 and 2016/17)
Groundfish trawl bycatch biomass	1992/93 - 2016/17	NMFS groundfish observer program
Groundfish fixed-gear bycatch biomass	1992/93 - 2016/17	NMFS groundfish observer program
NMFS trawl-survey biomass index (area-swept estimate) and CV	1978-2018	NMFS EBS trawl survey
ADF&G pot-survey abundance index (CPUE) and CV	1995-2017	ADF&G SMBKC pot survey
NMFS trawl-survey stage proportions and total number of measured crab	1978-2018	NMFS EBS trawl survey
ADF&G pot-survey stage proportions and total number of measured crab	1995-2017	ADF&G SMBKC pot survey
Directed pot-fishery stage proportions and total number of measured crab	1990/91 - 1998/99 2009/10 - 2015/16	ADF&G crab observer program (fishery closed 1999/00 - 2008/09 and 2016/17)

Table 7: Fixed model parameters for all scenarios.

Parameter	Symbol	Value	Source/rationale
Trawl-survey catchability	q	1.0	Default
Natural mortality	M	0.18 yr^{-1}	NPFMC (2007)
Size transition matrix	$\boldsymbol{G}$	Equation 8	Otto and Cummiskey (1990)
Stage-1 and stage-2 mean weights	w_1, w_2	0.7, 1.2 kg	Length-weight equation (B. Foy, NMFS) applied to stage midpoints
Stage-3 mean weight	$w_{3,y}$	Depends on year Table **??**	Fishery reported average retained weight from fish tickets, or its average, and mean weights of legal males
Recruitment SD	σ_R	1.2	High value
Natural mortality SD	σ_M	10.0	High value (basically free parameter)
Directed fishery handling mortality		0.2	2010 Crab SAFE
Groundfish trawl handling mortality		0.8	2010 Crab SAFE
Groundfish fixed-gear handling mortality		0.5	2010 Crab SAFE

which is the combination of the growth matrix and molting probabilities.

Estimated parameters are listed in Table 8 and include an estimated natural mortality deviation parameter in 1998/99 (δ^M_{1998}) assuming an anomalous mortality event in that year, as hypothesized by Zheng and Kruse (2002), with natural mortality otherwise fixed at 0.18 yr^{-1}.

5. Model Objective Function and Weighting Scheme

The objective function consists of the sum of several "negative log-likelihood" terms characterizing the hypothesized error structure of the principal data inputs (Table **??**). A lognormal distribution is assumed to

Table 8: The lower bound (LB), upper bound (UB), initial value, prior, and estimation phase for each estimated model parameter.

Parameter	LB	Initial value	UB	Prior	Phase
Average recruitment $\log(\bar{R})$	-7	10.0	20	Uniform(-7,20)	1
Stage-1 initial numbers $\log(n_1^0)$	5	14.5	20	Uniform(5,20)	1
Stage-2 initial numbers $\log(n_2^0)$	5	14.0	20	Uniform(5,20)	1
Stage-3 initial numbers $\log(n_3^0)$	5	13.5	20	Uniform(5,20)	1
ADF&G pot survey catchability q	0	3.0	5	Uniform(0,5)	1
Stage-1 directed fishery selectivity 1978-2008	0	0.4	1	Uniform(0,1)	3
Stage-2 directed fishery selectivity 1978-2008	0	0.7	1	Uniform(0,1)	3
Stage-1 directed fishery selectivity 2009-2017	0	0.4	1	Uniform(0,1)	3
Stage-2 directed fishery selectivity 2009-2017	0	0.7	1	Uniform(0,1)	3
Stage-1 NMFS trawl survey selectivity	0	0.4	1	Uniform(0,1)	4
Stage-2 NMFS trawl survey selectivity	0	0.7	1	Uniform(0,1)	4
Stage-1 ADF&G pot survey selectivity	0	0.4	1	Uniform(0,1)	4
Stage-2 ADF&G pot survey selectivity	0	0.7	1	Uniform(0,1)	4
Natural mortality deviation during 1998 δ_{1998}^M	-3	0.0	3	Normal(0, σ_M^2)	4
Recruitment deviations δ_y^R	-7	0.0	7	Normal(0, σ_R^2)	3
Average directed fishery fishing mortality $\bar{F}^{\text{df}}$	-	0.2	-	-	1
Average trawl bycatch fishing mortality $\bar{F}^{\text{tb}}$	-	0.001	-	-	1
Average fixed gear bycatch fishing mortality $\bar{F}^{\text{fb}}$	-	0.001	-	-	1

characterize the catch data and is modelled as

$$\sigma_{t,y}^{\text{catch}} = \sqrt{\log\left(1 + \left(CV_{t,y}^{\text{catch}}\right)^2\right)} \tag{9}$$

$$\delta_{t,y}^{\text{catch}} = \mathcal{N}\left(0, \left(\sigma_{t,y}^{\text{catch}}\right)^2\right) \tag{10}$$

where $\delta_{t,y}^{\text{catch}}$ is the residual catch. The relative abudance data is also assumed to be lognormally distributed

$$\sigma_{t,y}^{\text{I}} = \frac{1}{\lambda}\sqrt{\log\left(1 + \left(CV_{t,y}^{\text{I}}\right)^2\right)} \tag{11}$$

$$\delta_{t,y}^{\text{I}} = \log\left(I^{\text{obs}}/I^{\text{pred}}\right)/\sigma_{t,y}^{\text{I}} + 0.5\sigma_{t,y}^{\text{I}} \tag{12}$$

and the likelihood is

$$\sum \log\left(\delta_{t,y}^{\text{I}}\right) + \sum 0.5\left(\sigma_{t,y}^{\text{I}}\right)^2 \tag{13}$$

AMAK calculates standard deviation of the normalised residual (SDNR) values and median of the absolute residual (MAR) values for all abundance indices and size compositions to help the user come up with resonable likelihood weights. For an abundance data set to be well fitted, the SDNR should not be much greater than 1 (a value much less than 1, which means that the data set is fitted better than was expected, is not a cause for concern). What is meant by “much greater than 1” depends on m (the number of years in the data set). Francis (2011) suggests upper limits of 1.54, 1.37, and 1.26 for m = 5, 10, and 20, respectively. Although an SDNR not much greater than 1 is a necessary condition for a good fit, it is not sufficient. It is important to plot the observed and expected abundances to ensure that the fit is good.

AMAK also calculates Francis weights for each of the size composition data sets supplied (Francis 2011). If the user wishes to use the Francis iterative re-weighting method, first the weights applied to the abundance indices should be adjusted by trial and error until the SDNR (and/or MAR) are adequte. Then the Francis weights supplied by Gmacs should be used as the new likelihood weights for each of the size composition data sets the next time the model is run. The user can then iteratively adjust the abudance index and size composition weights until adequate SDNR (and/or MAR) values are achieved, given the Francis weights.

6. Estimation

The model was implemented using the software AD Model Builder (Fournier et al. 2012), with parameter estimation by minimization of the model objective function using automatic differentiation. Parameter estimates and standard deviations provided in this document are AD Model Builder reported values assuming maximum likelihood theory asymptotics.