Saint Matthew Island Blue King Crab Stock Assessment 2018

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Executive Summary

1. **Stock**: Blue king crab, *Paralithodes platypus*, Saint Matthew Island (SMBKC), Alaska.
2. **Catches**: Peak historical harvest was 4288 t (9.454 million pounds) in 1983/84[1]. The fishery was closed for 10 years after the stock was declared overfished in 1999. Fishing resumed in 2009/10 with a fishery-reported retained catch of 209 t (0.461 million pounds), less than half the 529.3 t (1.167 million pound) TAC. Following three more years of modest harvests supported by a fishery catch per unit effort (CPUE) of around 10 crab per pot lift, the fishery was again closed in 2013/14 due to declining trawl-survey estimates of abundance and concerns about the health of the stock. The directed fishery resumed again in 2014/15 with a TAC of 300 t (0.655 million pounds), but the fishery performance was relatively poor with a retained catch of 140 t (0.309 million pounds). The retained catch in 2015/16 was even lower at 48 t (0.105 million pounds) and the fishery has remained closed since 2016/17.
3. **Stock biomass**: The 1975-2018 NMFS trawl survey mean biomass is 5,664 t with the 2018 value being the 5th lowest (1,731 t; the third lowest since 2000). This biomass of $\geq$ 90 mm carapace length (CL) male crab is about 31% of the long term mean at 3.814 million lbs with a CV of 28%. The most recent 3-year average of the NMFS survey is 41% of the mean value, further indicating a decline in biomass compared to the survey estimates in 2010 and 2011 that were over 6 times the current average. The ADFG pot survey was again conducted in this region and the relative biomass in this index was the lowest in the time series (12% of the mean from the 11 surveys conducted since 1995). The assessment model estimates dampen the interannual variability observed in the survey biomass and suggest that the stock (in survey biomass units) is presently at about 28% of the long term model-predicted survey biomass average. The trend from these values suggests a slight decline.
4. **Recruitment**: Recruitment is based on estimated number of male crab within the 90-104 mm CL size class in each year. The 2018 trawl-survey area-swept estimate of 0.154 million male SMBKC in this size class is the third lowest in the 41 years since 1978 and follows the lowest (as observed in 2017). The recent six-year (2013 - 2018) average recruitment is only 45% of this mean. In the pot-survey, the abundance of this size group in 2017 was also the second-lowest in the time series (22% of the mean for the available pot-survey data) whereas in 2018 the value was the lowest observed at only 10% of the mean value.
5. **Management performance**: In this assessment estimated total male catch is the sum of fishery-reported retained catch, estimated male discard mortality in the directed fishery, and estimated male bycatch mortality in the groundfish fisheries. Based on the reference model for SMBKC, the estimate for mature male biomass is below the minimum stock-size threshold (MSST) in 2017/18 and is hence is in an "overfished" condition, despite fishery closures in the last two years (and hence overfishing has not occurred) (Tables 1 and 2). This state is due to observed low values in surveys. Computations which

[1]1983/84 refers to a fishing year that extends from 1 July 1983 to 30 June 1984.

indicate the relative impact of fishing (i.e., the "dynamic B_0") suggests that the current spawning stock biomass has been reduced to 60% of what it would have been in the absence of fishing.

Table 1: Status and catch specifications (1000 t) for the reference model. Notes: A - calculated from the assessment reviewed by the Crab Plan Team in September 2014, B - calculated from the assessment reviewed by the Crab Plan Team in September 2015, C - calculated from the assessment reviewed by the Crab Plan Team in September 2016, D - calculated from the assessment reviewed by the Crab Plan Team in September 2017, E - calculated from the assessment reviewed by the Crab Plan Team in September 2018.

Year	MSST	Biomass (MMB_{mating})	TAC	Retained catch	Total male catch	OFL	ABC
2013/14	1.50^A	3.01^A	0.00	0.00	0.00	0.56	0.45
2014/15	1.86^B	2.48^B	0.30	0.14	0.15	0.43	0.34
2015/16	1.84^C	2.11^C	0.19	0.05	0.05	0.28	0.22
2016/17	1.93^D	2.12^D	0.00	0.00	0.05	0.28	0.22
2017/18	1.85^E	1.29^E	0.00	0.00	0.05	0.28	0.22
2018/19		1.31^E				0.04	0.03

Table 2: Status and catch specifications (million pounds) for the reference model.

Year	MSST	Biomass (MMB_{mating})	TAC	Retained catch	Total male catch	OFL	ABC
2013/14	3.4^A	6.64^A	0.000	0.000	0.0006	1.24	0.99
2014/15	4.1^B	5.47^B	0.655	0.309	0.329	0.94	0.75
2015/16	4.1^C	4.65^C	0.419	0.110	0.110	0.62	0.49
2016/17	4.3^D	4.68^D	0.410	0.000	0.000	0.62	0.49
2017/18	4.1^E	2.85^E	0.41	0.000	0.000	0.62	0.49
2018/19		2.89^E				0.08	0.07

6. **Basis for the OFL**: Estimated mature-male biomass (MMB) on 15 February is used as the measure of biomass for this Tier 4 stock, with males measuring 105 mm CL or more considered mature. The B_{MSY} proxy is obtained by averaging estimated MMB over a specific reference period, and current CPT/SSC guidance recommends using the full assessment time frame as the default reference period (Table 3).

Table 3: Basis for the OFL (1000 t) from the reference model.

Year	Tier	B_{MSY}	Biomass (MMB_{mating})	B/B_{MSY}	F_{OFL}	γ	Basis for B_{MSY}	Natural mortality
2013/14	4b	3.06	3.01	0.98	0.18	1	1978-2013	0.18
2014/15	4b	3.28	2.71	0.82	0.14	1	1978-2014	0.18
2015/16	4b	3.71	2.45	0.66	0.11	1	1978-2015	0.18
2016/17	4b	3.67	2.23	0.61	0.09	1	1978-2016	0.18
2017/18	4b	3.86	2.05	0.53	0.09	1	1978-2016	0.18
2018/19	4b	3.7	1.31	0.35	0.09	1	1978-2018	0.18

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. 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 2010-2017 groundfish and fixed gear bycatch estimates based on NMFS Alaska Regional Office (AKRO) data. The directed fishery has been closed since 2016/17 so fishery data in recent years is unavailable.

Changes in Assessment Methodology

This assessment uses the General model for Alasks crab stocks (Gmacs) framework. The model is configured to track three stages of length categories and was first presented in May 2011 by Bill Gaeuman and accepted by the CPT in May 2012. A difference from the original approach and that used here is that natural and fishing mortality are continuous within 5 discrete seasons (using the appropriate catch equation rather than assuming an applied pulse removal). Season length in Gmacs is controlled by changing the proportion of natural mortality that is applied each season. Diagnostic output includes estimates of the "dynamic B_0" which simply computes the ratio of the spawning biomass as estimated relative to the spawning biomass that would have occurred had there been no historical fishing mortality. Details of this implementation and other model details are provided in Appendix A.

Changes in Assessment Results

Both surveys indicate a decline over the past few years. The "reference" model is that which was selected for use in 2017. The addition of new data introduced this year area are presented sequentially. Two alternative models are presented for sensitivity. One involves a re-analysis of the NMFS trawl survey data using a spatio-temporal Delta-GLMM approach (VAST model, Thorson and Barnett 2017) and the other configuration (named "Fit survey") simply adds emphasis on the design-based survey data (assumes a lower input variance). The VAST model suggests a modest increase from the 2017 survey estimate. However, the model tends to moderate the noise in the survey observations and declines

B. Responses to SSC and CPT Comments

CPT and SSC Comments on Assessments in General

Comment: *Regarding general code development, the SSC and CPT 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 blue king crab is a lithodid crab, *Paralithodes platypus* (Brant 1850).

Distribution

Blue king crab are sporadically distributed throughout the North Pacific Ocean from Hokkaido, Japan, to southeastern Alaska (Figure 1). In the eastern Bering Sea small populations are distributed around St. Matthew Island, the Pribilof Islands, St. Lawrence Island, and Nunivak Island. Isolated populations also exist in some other cold water areas of the Gulf of Alaska (NPFMC 1998). The St. Matthew Island Section for blue king crab is within Area Q2 (Figure 2), which is the Northern District of the Bering Sea king crab registration area and includes the waters north of Cape Newenham (58°39' N. lat.) and south of Cape Romanzof (61°49' N. lat.).

Stock Structure

The Alaska Department of Fish and Game (ADF&G) Gene Conservation Laboratory division, has detected regional population differences between blue king crab collected from St. Matthew Island and the Pribilof Islands[2]. NMFS tag-return data from studies on blue king crab in the Pribilof Islands and St. Matthew Island support the idea that legal-sized males do not migrate between the two areas (Otto and Cummiskey 1990). St. Matthew Island blue king crab tend to be smaller than their Pribilof conspecifics, and the two stocks are managed separately.

Life History

Like the red king crab, *Paralithodes camtshaticus*, the blue king crab is considered a shallow water species by comparison with other lithodids such as golden king crab, *Lithodes aequispinus*, and the scarlet king crab, *Lithodes couesi* (Donaldson and Byersdorfer 2005). Adult male blue king crab are found at an average depth of 70 m (NPFMC 1998). The reproductive cycle appears to be annual for the first two reproductive cycles and biennial thereafter (Jensen and Armstrong 1989) and mature crab seasonally migrate inshore where they molt and mate. Unlike red king crab, juvenile blue king crab do not form pods, but instead rely on cryptic coloration for protection from predators and require suitable habitat such as cobble and shell hash. Somerton and MacIntosh (1983) estimated SMBKC male size at sexual maturity to be 77 mm carapace length (CL). Paul et al. (1991) found that spermatophores were present in the vas deferens of 50% of the St. Matthew Island blue king crab males examined with sizes of 40-49 mm CL and in 100% of the males at least 100 mm CL. Spermataphore diameter also increased with increasing CL with an asymptote at ~ 100 mm CL. They noted, however, that although spermataphore presence indicates physiological sexual maturity, it may not be an indicator of functional sexual maturity. For purposes of management of the St. Matthew Island blue king crab fishery, the State of Alaska uses 105 mm CL to define the lower size bound of functionally mature males (Pengilly and Schmidt 1995). Otto and Cummiskey (1990) report an average growth increment of 14.1 mm CL for adult SMBKC males.

Management History

The SMBKC fishery developed subsequent to baseline ecological studies associated with oil exploration (Otto 1990). Ten U.S. vessels harvested 545 t (1.202 million pounds) in 1977, and harvests peaked in 1983 when 164 vessels landed 4288 t (9.454 million pounds) (Fitch et al. 2012; Table 7).

[2] NOAA grant Bering Sea Crab Research II, NA16FN2621, 1997.

The fishing seasons were generally short, often lasting only a few days. The fishery was declared overfished and closed in 1999 when the stock biomass estimate was below the minimum stock-size threshold (MSST) of 4,990 t (11.0 million pounds) as defined by the Fishery Management Plan (FMP) for the Bering Sea/Aleutian Islands King and Tanner crabs (NPFMC 1999). Zheng and Kruse (2002) hypothesized a high level of SMBKC natural mortality from 1998 to 1999 as an explanation for the low catch per unit effort (CPUE) in the 1998/99 commercial fishery and the low numbers across all male crab size groups caught in the annual NMFS eastern Bering Sea trawl survey from 1999 to 2005 (see survey data in next section). In November 2000, Amendment 15 to the FMP for Bering Sea/Aleutian Islands king and Tanner crabs was approved to implement a rebuilding plan for the SMBKC stock (NPFMC 2000). The rebuilding plan included a State of Alaska regulatory harvest strategy (5 AAC 34.917), area closures, and gear modifications. In addition, commercial crab fisheries near St. Matthew Island were scheduled in fall and early winter to reduce the potential for bycatch mortality of vulnerable molting and mating crab.

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 (460,859 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 5), 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[3]. 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. NMFS observer data suggest that variable but mostly limited SMBKC bycatch has also occurred in the eastern Bering Sea groundfish fisheries (Table 6).

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 3.

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

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 7); results from the annual NMFS eastern Bering Sea trawl survey (1978-2018; Table 8); results from the ADF&G SMBKC pot survey (every third year during 1995-2013, then 2015-2018; Table 9); mean somatic mass given length category by year (Table 10); 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 5); and NMFS groundfish-observer bycatch biomass estimates (1992/93-2016/17; Table 6).

Figure 4 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 5). Crab-observer sampling protocols are detailed in the crab-observer training manual (ADF&G 2013). Groundfish SMBKC bycatch data come from 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.

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 (Zheng et al. 1997). 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 5.5in 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 just three stages (male size classes) determined 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 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 also evaluated the impact 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 by $\lambda^{\text{NMFS}} = 2$ and the ADF&G pot survey is up-weighted by $\lambda^{\text{ADFG}} = 2$.

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 6 and 7 with recruitment and spawning biomass shown in Figures 8 and 9, 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" spatio-temporal index and the reference case show different time-series of data and a different model fit (Figure 10). The effect on spawning biomass suggests estimates were consistently higher since 1990 compared to the reference model (Figure 11).

c. Effective sample sizes and weighting factors

Observed and estimated effective sample sizes are compared in Table 11. Data weighting factors, standard deviation of normalized residuals (SDNRs), and median absolute residual (MAR) are presented in Table 16. The SDNR for the trawl survey is acceptable at 1.66 in the reference model. In 2017, Francis weighting was applied but given the relatively few size bins in this assessment, this application was suspended this year. The SDNRs for the pot surveys show much the same pattern between 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 12, 13, and 15. These parameter estimates are compared in Table 15. Negative log-likelihood values and management measures for each of the model configurations are compared in Tables 4 through 17.

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 15). Also, the residuals for recruitment in the first size group are large for these runs, presumably because higher estimates of recruits in some years are required to match the observed biomass trends.

c. Graphs of estimates.

Selectivity estimates show some variability between models (Figure 12). Estimated recruitment is variable over time for all models and in recent years is well below average (Figure 13). Estimated mature male biomass on 15 February also fluctuates considerably (Figure 14). Estimated natural mortality each year (M_t) is presented in Figure 15.

d. 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 16). All of the models fit the pot survey CPUE poorly (Figure 17. For both surveys the standardized residuals tend to have similar patterns with some improvement (generally) for the VAST model (Figures 18 and 19).

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 20, 21, and 22) for all scenarios. Representative residual plots of the composition data fits are generally poor (Figures 23 and 24). 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 configuration fits the the NMFS survey biomass and ADF&G pot survey CPUE data better but still has a similar residual pattern (Figures 16 and 17). It is worth noting that that this scenario (included for exploratory purposes) resulted in worse SDNR and MAR values for the two abundance indices.

e. Retrospective and historical analyses

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

f. Uncertainty and sensitivity analyses.

Estimated standard deviations of parameters and selected management measures for the models are summarized in Tables 12, 13, and 14 (and compiled together in Table 15. Probabilities for mature male biomass and OFL in 2017 are presented in Section F.

g. Comparison of alternative model scenarios.

The estimates of mature male biomass (Figure 14), for the **fit surveys** sensitivity stands out as being quite different from the other models due to a low value for pot survey catchability being estimated (which tends to scale the population). This 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 survey and the pot survey abundance indices (it upweights the pot survey more than the trawl survey) and represents a model run that places greater trust in the abundance indices, particularly the pot survey, than other data sources.

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 model using the "VAST" time series 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 (2013 SAFE), 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 1978- 2018, 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 4. ABC is taken as 80% of the OFL.

Table 4: Comparisons of management measures for the model scenarios. Biomass and OFL are in tons.

Component	Reference	VAST	Fit surveys
MMB_{2018}	1309.025	2257.996	4038.448
B_{MSY}	3698.941	4240.714	9161.159
F_{OFL}	0.043	0.075	0.059
OFL_{2018}	38.464	117.589	191.950
ABC_{2018}	30.771	94.072	153.560

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 4).

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 quite pessimistic and given the abundance relative to the proxy B_{MSY}, further reductions from fishing should be avoided. The NMFS survey results in 2018 noted much warmer conditions 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 60% of what it would have been in the absence of fishing (Figure 25) . 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

We thank the Crab Plan Team and AFSC staff for reviewing an earlier draft of this report and Andre Punt for his input into refinements to the Gmacs model code.

K. References

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Tables

Table 5: 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 6: Groundfish SMBKC male bycatch biomass (t) estimates. Trawl includes pelagic trawl and non-pelagic trawl types. Source: J. Zheng, ADF&G, and author estimates based on data from R. Foy, NMFS. Estimates used after 2008/09 are from NMFS Alaska Regional Office.

Year	Trawl bycatch	Fixed gear bycatch
1978	0.000	0.000
1979	0.000	0.000
1980	0.000	0.000
1981	0.000	0.000
1982	0.000	0.000
1983	0.000	0.000
1984	0.000	0.000
1985	0.000	0.000
1986	0.000	0.000
1987	0.000	0.000
1988	0.000	0.000
1989	0.000	0.000
1990	0.000	0.000
1991	3.538	0.045
1992	1.996	2.268
1993	1.542	0.500
1994	0.318	0.091
1995	0.635	0.136
1996	0.500	0.045
1997	0.500	0.181
1998	0.500	0.907
1999	0.500	1.361
2000	0.500	0.500
2001	0.500	0.862
2002	0.726	0.408
2003	0.998	1.134
2004	0.091	0.635
2005	0.500	0.590
2006	2.812	1.451
2007	0.045	69.717
2008	0.272	6.622
2009	0.638	7.522
2010	0.360	9.564
2011	0.170	0.796
2012	0.011	0.739
2013	0.163	0.341
2014	0.010	0.490
2015	0.010	0.711
2016	0.229	1.633
2017	0.052	6.032

Table 7: 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				

Table 8: 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		
Year	Stage-1 (90-104 mm)	Stage-2 (105-119 mm)	Stage-3 (120+ mm)	Total	CV	Total (90+ mm CL)	CV	Number 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 9: 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 10: Mean weight (kg) by stage in used in all of the models (provided as a vector of weights at length each year to Gmacs).

Year	Stage-1	Stage-2	Stage-3
1978	0.7	1.2	1.9
1979	0.7	1.2	1.7
1980	0.7	1.2	1.9
1981	0.7	1.2	1.9
1982	0.7	1.2	1.9
1983	0.7	1.2	2.1
1984	0.7	1.2	1.9
1985	0.7	1.2	2.1
1986	0.7	1.2	1.9
1987	0.7	1.2	1.9
1988	0.7	1.2	1.9
1989	0.7	1.2	2.0
1990	0.7	1.2	1.9
1991	0.7	1.2	2.0
1992	0.7	1.2	1.9
1993	0.7	1.2	2.0
1994	0.7	1.2	1.9
1995	0.7	1.2	2.0
1996	0.7	1.2	2.0
1997	0.7	1.2	2.1
1998	0.7	1.2	2.0
1999	0.7	1.2	1.9
2000	0.7	1.2	1.9
2001	0.7	1.2	1.9
2002	0.7	1.2	1.9
2003	0.7	1.2	1.9
2004	0.7	1.2	1.9
2005	0.7	1.2	1.9
2006	0.7	1.2	1.9
2007	0.7	1.2	1.9
2008	0.7	1.2	1.9
2009	0.7	1.2	1.9
2010	0.7	1.2	1.8
2011	0.7	1.2	1.8
2012	0.7	1.2	1.8
2013	0.7	1.2	1.9
2014	0.7	1.2	1.9
2015	0.7	1.2	1.9
2016	0.7	1.2	1.9
2017	0.7	1.2	1.9
2018	0.7	1.2	1.9

Table 11: 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

Table 12: Model parameter estimates, selected derived quantities, and their standard deviations (SD) for the reference model.

Parameter	Estimate	SD
Natural mortality deviation in 1998/99 (δ^M_{1998})	1.622	0.127
$\log(\bar{R})$	13.915	0.060
$\log(n^0_1)$	14.932	0.171
$\log(n^0_2)$	14.551	0.202
$\log(n^0_3)$	14.366	0.206
q_{pot}	3.535	0.265
$\log(\bar{F}^{\mathrm{df}})$	-2.166	0.055
$\log(\bar{F}^{\mathrm{tb}})$	-9.330	0.081
$\log(\bar{F}^{\mathrm{fb}})$	-8.245	0.081
log Stage-1 directed pot selectivity 1978-2008	-0.638	0.173
log Stage-2 directed pot selectivity 1978-2008	-0.321	0.126
log Stage-1 directed pot selectivity 2009-2017	-0.000	0.002
log Stage-2 directed pot selectivity 2009-2017	-0.000	0.001
log Stage-1 NMFS trawl selectivity	-0.258	0.064
log Stage-2 NMFS trawl selectivity	-0.000	0.002
log Stage-1 ADF&G pot selectivity	-0.792	0.124
log Stage-2 ADF&G pot selectivity	-0.003	0.024
F_{OFL}	0.043	0.007
OFL	38.464	10.360

Table 13: Model parameter estimates, selected derived quantities, and their standard deviations (SD) for the VAST model.

Parameter	Estimate	SD
Natural mortality deviation in 1998/99 (δ^M_{1998})	1.708	0.107
$\log(\bar{R})$	14.118	0.055
$\log(n^0_1)$	14.952	0.167
$\log(n^0_2)$	14.558	0.191
$\log(n^0_3)$	14.369	0.198
q_{pot}	2.483	0.155
$\log(\bar{F}^{\mathrm{df}})$	-2.280	0.044
$\log(\bar{F}^{\mathrm{tb}})$	-9.628	0.074
$\log(\bar{F}^{\mathrm{fb}})$	-8.556	0.074
log Stage-1 directed pot selectivity 1978-2008	-0.750	0.171
log Stage-2 directed pot selectivity 1978-2008	-0.356	0.123
log Stage-1 directed pot selectivity 2009-2017	-0.001	0.101
log Stage-2 directed pot selectivity 2009-2017	-0.000	0.000
log Stage-1 NMFS trawl selectivity	-0.264	0.065
log Stage-2 NMFS trawl selectivity	-0.015	0.020
log Stage-1 ADF&G pot selectivity	-0.582	0.116
log Stage-2 ADF&G pot selectivity	-0.010	0.022
F_{OFL}	0.075	0.008
OFL	117.590	22.383

Table 14: Model parameter estimates, selected derived quantities, and their standard deviations (SD) for the "Fit survey" model.

Parameter	Estimate	SD
Natural mortality deviation in 1998/99 (δ^M_{1998})	2.014	0.072
$\log(\bar{R})$	14.544	0.048
$\log(n^0_1)$	15.358	0.199
$\log(n^0_2)$	15.184	0.208
$\log(n^0_3)$	14.989	0.207
q_{pot}	1.051	0.041
$\log(\bar{F}^{\mathrm{df}})$	-3.158	0.031
$\log(\bar{F}^{\mathrm{tb}})$	-10.364	0.066
$\log(\bar{F}^{\mathrm{fb}})$	-9.278	0.066
log Stage-1 directed pot selectivity 1978-2008	-0.323	0.177
log Stage-2 directed pot selectivity 1978-2008	-0.058	0.145
log Stage-1 directed pot selectivity 2009-2017	-0.000	0.000
log Stage-2 directed pot selectivity 2009-2017	-0.000	0.000
log Stage-1 NMFS trawl selectivity	-0.000	0.001
log Stage-2 NMFS trawl selectivity	-0.000	0.000
log Stage-1 ADF&G pot selectivity	-0.000	0.000
log Stage-2 ADF&G pot selectivity	-0.000	0.000
F_{OFL}	0.059	0.003
OFL	191.950	19.291

Table 15: Comparisons of parameter estimates for the model scenarios.

Parameter	Ref	VAST	FitSurvey
$\log(\bar{F}^{\mathrm{df}})$	-2.166	-2.280	-3.158
$\log(\bar{F}^{\mathrm{fb}})$	-8.245	-8.556	-9.278
$\log(\bar{F}^{\mathrm{tb}})$	-9.330	-9.628	-10.364
$\log(\bar{R})$	13.915	14.118	14.544
$\log(n^0_1)$	14.932	14.952	15.358
$\log(n^0_2)$	14.551	14.558	15.184
$\log(n^0_3)$	14.366	14.369	14.989
F_{OFL}	0.043	0.075	0.059
q_{pot}	3.535	2.483	1.051
log Stage-1 ADF&G pot selectivity	-0.792	-0.582	-0.000
log Stage-1 directed pot selectivity 1978-2008	-0.638	-0.750	-0.323
log Stage-1 directed pot selectivity 2009-2017	-0.000	-0.001	-0.000
log Stage-1 NMFS trawl selectivity	-0.258	-0.264	-0.000
log Stage-2 ADF&G pot selectivity	-0.003	-0.010	-0.000
log Stage-2 directed pot selectivity 1978-2008	-0.321	-0.356	-0.058
log Stage-2 directed pot selectivity 2009-2017	-0.000	-0.000	-0.000
log Stage-2 NMFS trawl selectivity	-0.000	-0.015	-0.000
Natural mortality deviation in 1998/99 (δ^M_{1998})	1.622	1.708	2.014
OFL	38.464	117.590	191.950

Table 16: Comparisons of data weights, Francis LF weights (i.e. the new weights that should be applied to the LFs), SDNR and MAR (standard deviation of normalized residuals and median absolute residual) values for the model scenarios.

Component	Reference	VAST	Fit surveys
NMFS trawl survey weight	1.00	1.00	2.00
ADF&G pot survey weight	1.00	1.00	2.00
Directed pot LF weight	1.00	1.00	1.00
NMFS trawl survey LF weight	1.00	1.00	1.00
ADF&G pot survey LF weight	1.00	1.00	1.00
Fancis weight for directed pot LF	1.47	1.43	1.15
Francis weight for NMFS trawl survey LF	0.42	0.38	0.30
Francis weight for ADF&G pot survey LF	1.01	0.88	0.18
SDNR NMFS trawl survey	1.66	1.97	2.66
SDNR ADF&G pot survey	4.51	4.82	7.83
SDNR directed pot LF	0.90	0.93	1.19
SDNR NMFS trawl survey LF	1.35	1.44	1.93
SDNR ADF&G pot survey LF	1.02	1.08	2.35
MAR NMFS trawl survey	1.21	1.10	1.99
MAR ADF&G pot survey	2.81	2.74	4.75
MAR directed pot LF	0.70	0.64	0.68
MAR NMFS trawl survey LF	0.54	0.67	1.06
MAR ADF&G pot survey LF	0.70	0.97	2.03

Table 17: Comparisons of negative log-likelihood values for the selected model scenarios. It is important to note that comparisons among models may be limited since the assumed variances are modified (e.g., **Fit surveys** model).

Component	Reference	VAST	Fit surveys
Pot Retained Catch	-73.35	-72.70	-68.87
Pot Discarded Catch	33.61	16.32	112.35
Trawl bycatch Discarded Catch	-7.43	-7.36	-7.43
Fixed bycatch Discarded Catch	-7.41	-7.33	-7.40
NMFS Trawl Survey	12.32	9.05	80.05
ADF&G Pot Survey CPUE	92.53	110.62	317.70
Directed Pot LF	-5.07	-3.89	24.31
NMFS Trawl LF	26.33	40.25	121.33
ADF&G Pot LF	-2.78	-0.48	47.58
Recruitment deviations	57.16	55.13	60.17
F penalty	9.66	9.66	9.66
M penalty	6.47	6.47	6.48
Prior	12.66	12.66	13.61
Total	154.70	168.40	709.54
Total estimated parameters	142.00	142.00	142.00

Table 18: Population abundances ($\boldsymbol{n}$) by crab stage in numbers of crab at the time of the survey and mature male biomass (MMB) in tons on 15 February for the **model configuration used in 2017**.

Year	n_1	n_2	n_3	MMB	CV MMB
1978	3023781	2049075	1702338	4768	0.170
1979	4243623	2395504	2377772	6646	0.119
1980	3602053	3203035	3555172	10372	0.083
1981	1357467	3105955	4901100	10757	0.065
1982	1475563	1798956	4913154	7752	0.076
1983	773712	1433358	3526836	4848	0.102
1984	665874	913703	2117136	3416	0.121
1985	941768	680553	1585505	3136	0.135
1986	1400419	760107	1389117	3070	0.129
1987	1353705	1046932	1491960	3577	0.118
1988	1238729	1115338	1711452	3874	0.113
1989	2797116	1072696	1873823	4383	0.108
1990	1754660	1943624	2164515	5438	0.088
1991	1821352	1639841	2626200	5454	0.089
1992	1949025	1576546	2579597	5600	0.081
1993	2189645	1628140	2673947	5817	0.075
1994	1535697	1782114	2728665	5547	0.072
1995	1805851	1461927	2624902	5457	0.074
1996	1607645	1509341	2540504	5289	0.077
1997	905249	1412491	2479049	4703	0.096
1998	678831	981495	2076444	3286	0.108
1999	400143	330674	800288	1868	0.103
2000	443486	336548	873018	2011	0.088
2001	410226	363174	941043	2168	0.081
2002	145725	353078	1008033	2282	0.077
2003	333277	199574	1033616	2156	0.078
2004	235025	255197	995281	2148	0.078
2005	512012	217920	982315	2082	0.078
2006	768757	362826	979052	2237	0.081
2007	525023	556119	1073083	2602	0.083
2008	942465	476388	1211965	2800	0.070
2009	740685	692255	1341278	2896	0.069
2010	721575	649030	1447778	2574	0.075
2011	589723	623688	1340120	2146	0.094
2012	338049	541129	1101914	1752	0.121
2013	443928	370924	889881	1986	0.113
2014	349998	374790	972470	1979	0.118
2015	342929	322745	974238	1969	0.119
2016	468871	301480	987479	2084	0.119
2017	289905	365759	1020732	2215	0.121
2018	667955	285723	1064712	2207	0.124

Table 19: Population abundances ($\boldsymbol{n}$) by crab stage in numbers of crab at the time of the survey (1 July, season 1) and mature male biomass (MMB) in tons on 15 February for the reference model.

Year	n_1	n_2	n_3	MMB	CV MMB
1978	3055234	2086108	1734507	4866	0.168
1979	4257442	2425626	2423713	6757	0.118
1980	3598122	3220853	3609886	10496	0.083
1981	1393219	3109621	4955215	10850	0.064
1982	1478218	1820475	4958541	7843	0.075
1983	780696	1441989	3567176	4896	0.102
1984	662579	920526	2138027	3447	0.121
1985	941431	680941	1599201	3151	0.136
1986	1398365	760044	1395461	3077	0.131
1987	1375810	1045746	1494783	3575	0.120
1988	1249940	1127499	1712417	3883	0.115
1989	2871869	1083089	1878810	4399	0.110
1990	1772504	1989518	2178735	5506	0.088
1991	1855773	1665166	2658312	5523	0.088
1992	1967394	1604535	2613415	5680	0.080
1993	2233267	1647885	2711451	5893	0.074
1994	1552353	1813449	2765581	5626	0.070
1995	1772244	1481762	2661725	5530	0.074
1996	1640690	1496832	2568650	5305	0.077
1997	911676	1427124	2489066	4708	0.096
1998	664027	989997	2079572	3217	0.109
1999	386325	338975	804976	1886	0.102
2000	444883	331450	879792	2018	0.086
2001	409179	362279	944263	2173	0.079
2002	143080	352188	1010174	2285	0.075
2003	337248	197779	1034707	2156	0.076
2004	214735	256857	995667	2151	0.076
2005	524236	206948	981535	2068	0.076
2006	772777	366135	974037	2232	0.076
2007	386826	559490	1070944	2601	0.075
2008	886023	399837	1198460	2689	0.064
2009	566036	634887	1285999	2731	0.058
2010	513068	530956	1352570	2266	0.067
2011	391462	466386	1169874	1652	0.088
2012	206041	376581	842952	1112	0.133
2013	268807	241573	562999	1264	0.123
2014	171187	232582	617641	1200	0.133
2015	185938	174176	586573	1144	0.135
2016	304931	163212	573050	1197	0.132
2017	189110	227051	589688	1294	0.128
2018	135140	182181	623814	1309	0.128

Table 20: Population abundances ($\boldsymbol{n}$) by crab stage in numbers of crab at the time of the survey (1 July, season 1) and mature male biomass (MMB) in tons on 15 February for the model that uses the VAST BTS index.

Year	n_1	n_2	n_3	MMB	CV MMB
1978	3115589	2101690	1739151	4886	0.152
1979	4245149	2465063	2438549	6827	0.102
1980	3495583	3226925	3640655	10562	0.071
1981	1400316	3053397	4974270	10826	0.055
1982	1403527	1805901	4948868	7803	0.065
1983	768712	1394751	3542238	4788	0.088
1984	644044	898093	2091002	3323	0.105
1985	884197	662990	1541757	3010	0.117
1986	1156489	721595	1332084	2913	0.114
1987	1361692	895651	1399045	3225	0.111
1988	1268964	1069802	1556458	3531	0.109
1989	2952458	1074794	1720430	4081	0.107
1990	1926237	2032541	2049636	5323	0.081
1991	2010839	1766715	2588514	5504	0.081
1992	2271322	1726149	2620661	5837	0.074
1993	2524916	1860671	2810045	6329	0.068
1994	1797600	2049489	2984629	6296	0.064
1995	1981816	1699175	2984717	6407	0.064
1996	2171903	1687825	2969005	6282	0.066
1997	1287692	1792037	2968533	6095	0.076
1998	861162	1324336	2700596	4499	0.079
1999	482750	410980	1048751	2423	0.094
2000	569663	410052	1128931	2573	0.076
2001	518006	459164	1203922	2768	0.068
2002	158654	446063	1286310	2907	0.063
2003	467661	237700	1314172	2724	0.064
2004	227302	344128	1261691	2747	0.064
2005	884111	242979	1248943	2608	0.064
2006	1038396	582426	1249969	2992	0.066
2007	563303	781930	1435907	3533	0.062
2008	1235648	573282	1631919	3695	0.054
2009	855319	890854	1768939	3850	0.055
2010	713124	779941	1912604	3463	0.065
2011	551612	662414	1782194	2888	0.080
2012	364563	532437	1464980	2306	0.107
2013	412392	383213	1169945	2500	0.105
2014	336213	361024	1209753	2374	0.109
2015	301365	310420	1161469	2274	0.113
2016	379614	273872	1133038	2315	0.105
2017	264416	306139	1120348	2326	0.100
2018	189768	251211	1114103	2258	0.099

Table 21: Population abundances ($\boldsymbol{n}$) by crab) stage in numbers of crab at the time of the survey (1 July, season 1) and mature male biomass (MMB) in tons on 15 February for the **fit surveys** model.

Year	n_1	n_2	n_3	MMB
1978	4677797	3931215	3233480	9847.621
1979	5679580	3957870	4761422	12429.887
1980	4358175	4535723	6470984	17440.543
1981	1550583	3976517	8080689	17667.453
1982	1771589	2196807	8020714	14103.998
1983	1110443	1733193	6327543	10774.815
1984	927307	1204239	4596325	8346.268
1985	1186602	925224	3815633	8001.730
1986	1650986	980157	3392512	7101.786
1987	2226342	1262092	3297483	7230.783
1988	2382673	1682172	3408749	7607.552
1989	6435258	1910040	3683373	8854.045
1990	3174076	4286999	4442908	12246.472
1991	3423526	3221651	5841869	13342.566
1992	3587881	3010182	6204095	14023.149
1993	4268479	3033588	6573651	15008.615
1994	3342537	3428049	6882154	15134.784
1995	2525485	3032932	7080947	15892.025
1996	4861574	2438146	7111327	15060.520
1997	3292361	3567980	7064527	16409.957
1998	1540701	3050706	7203276	12728.373
1999	1039257	585643	2182516	4739.948
2000	1819898	783942	2217206	5029.007
2001	1681408	1292948	2420978	5984.209
2002	358473	1382745	2834538	6858.585
2003	472151	661228	3098790	6537.758
2004	212213	486929	2966306	6094.289
2005	1357220	281699	2743319	5445.624
2006	2380434	863978	2562915	5763.848
2007	1840517	1637276	2802824	7056.285
2008	1319399	1580307	3328015	8001.663
2009	1402575	1271943	3701339	7635.693
2010	1274346	1217025	3770188	7008.231
2011	743295	1125918	3604064	6443.673
2012	503022	794749	3232990	5529.164
2013	527615	548703	2786488	5561.484
2014	546449	481256	2654458	5030.626
2015	450669	469626	2448183	4644.903
2016	587170	411375	2302053	4548.767
2017	248210	469551	2185962	4402.360
2018	112647	296202	2085007	4038.448

Figures

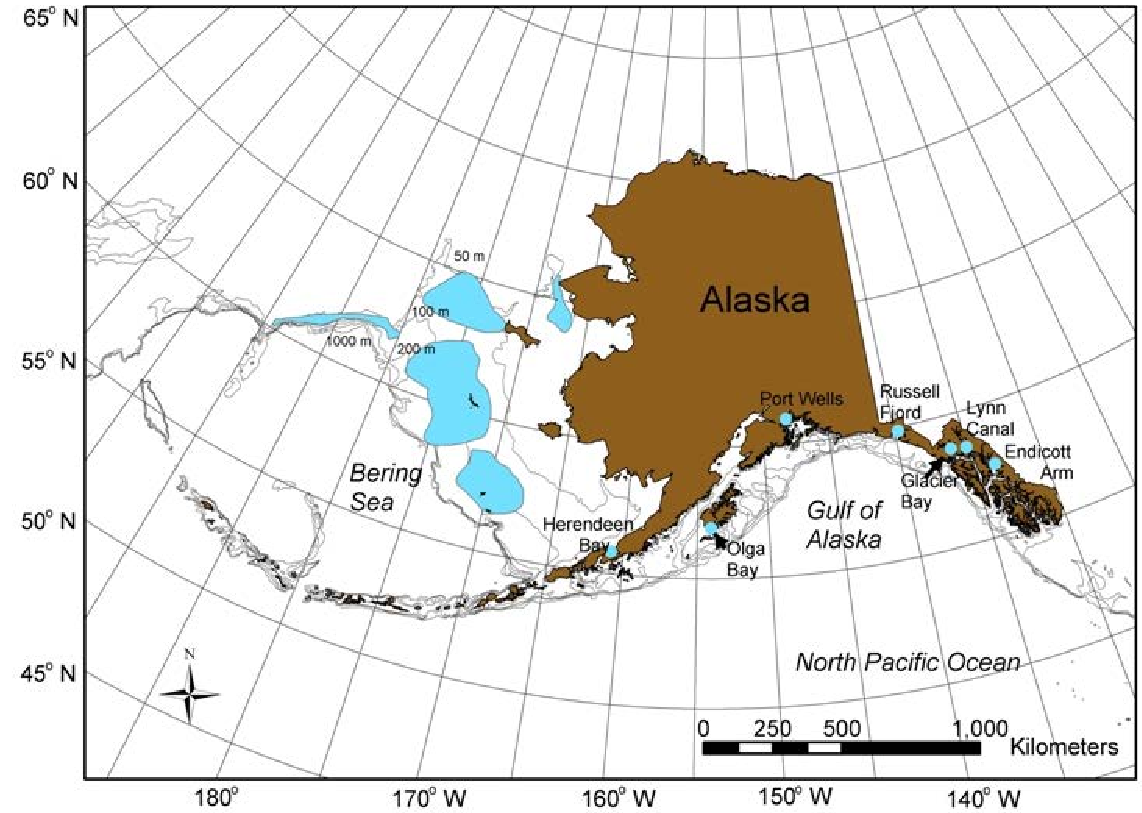

Figure 1: Distribution of blue king crab (*Paralithodes platypus*) in the Gulf of Alaska, Bering Sea, and Aleutian Islands waters (shown in blue).

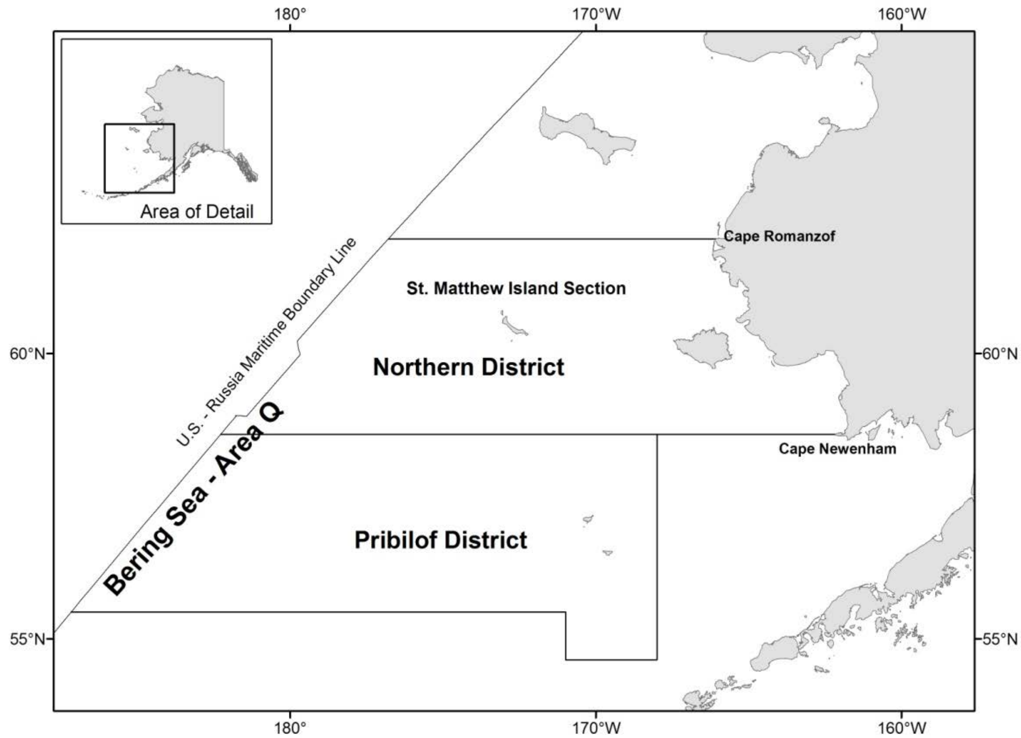

Figure 2: King crab Registration Area Q (Bering Sea).

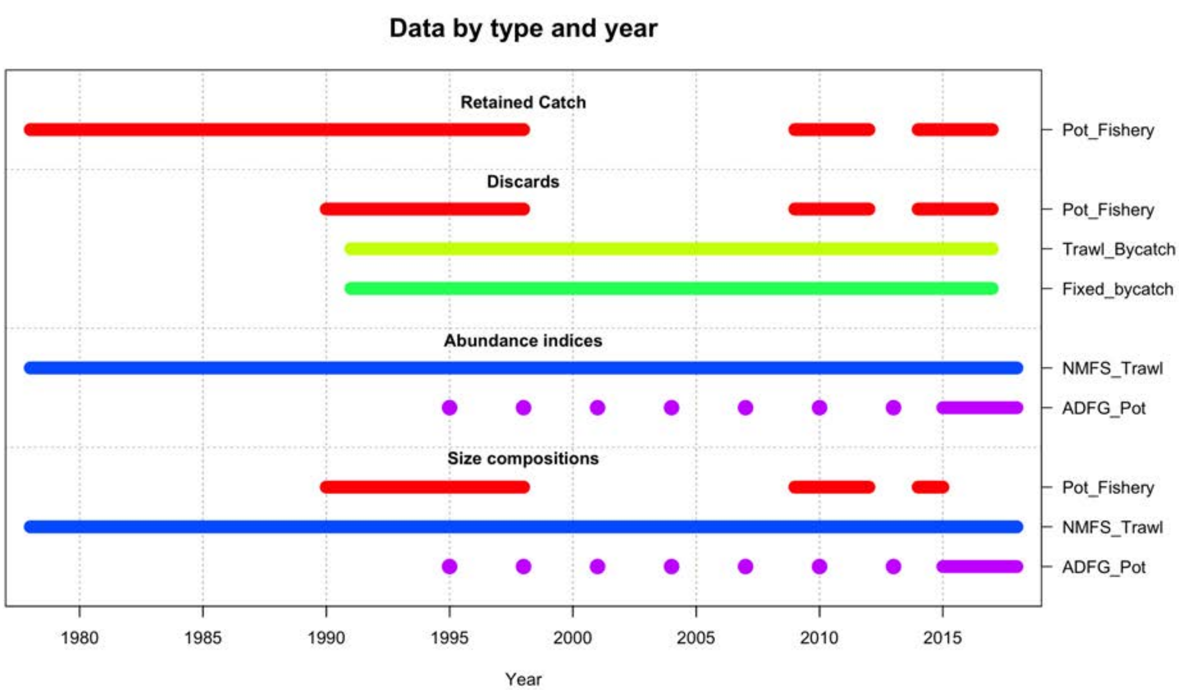

Figure 3: Data extent for the SMBKC assessment (with the 2017 Pot survey included).

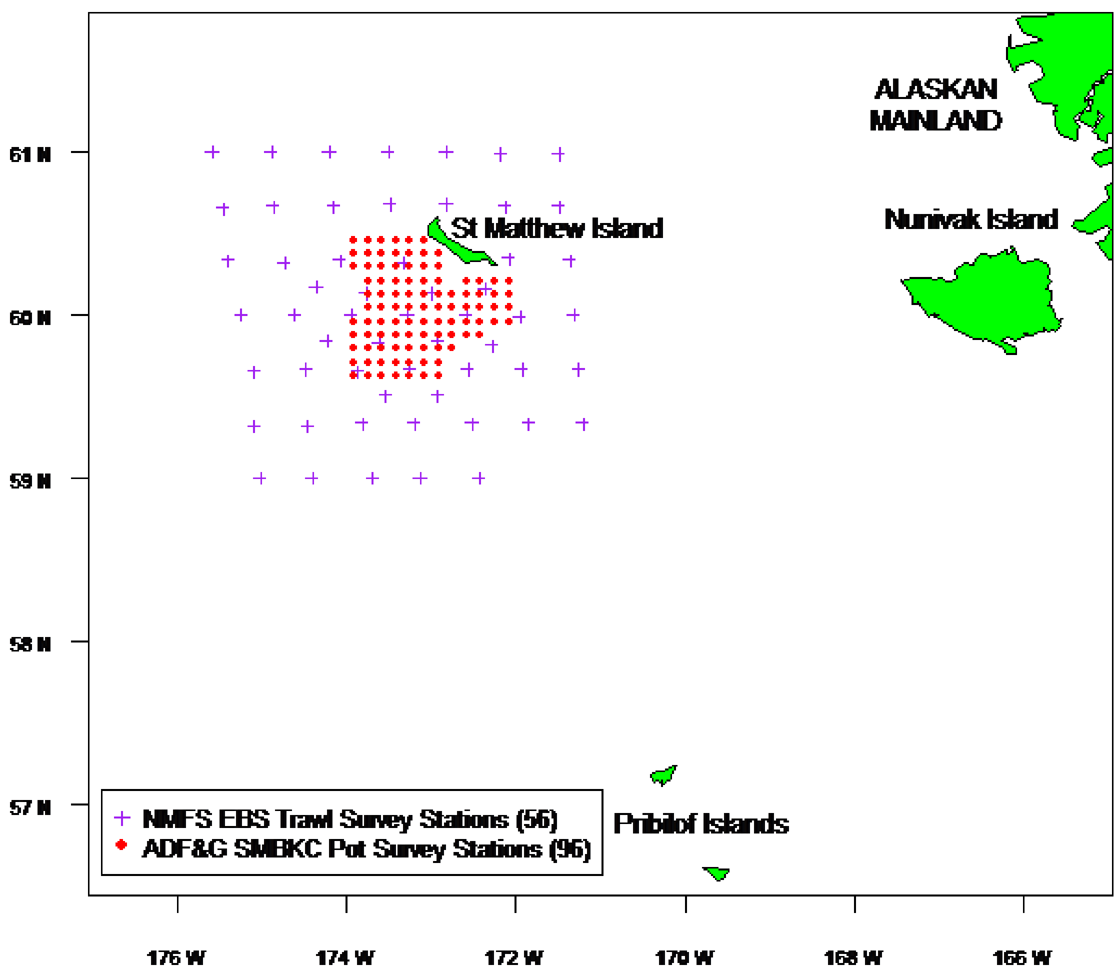

Figure 4: Trawl and pot-survey stations used in the SMBKC stock assessment.

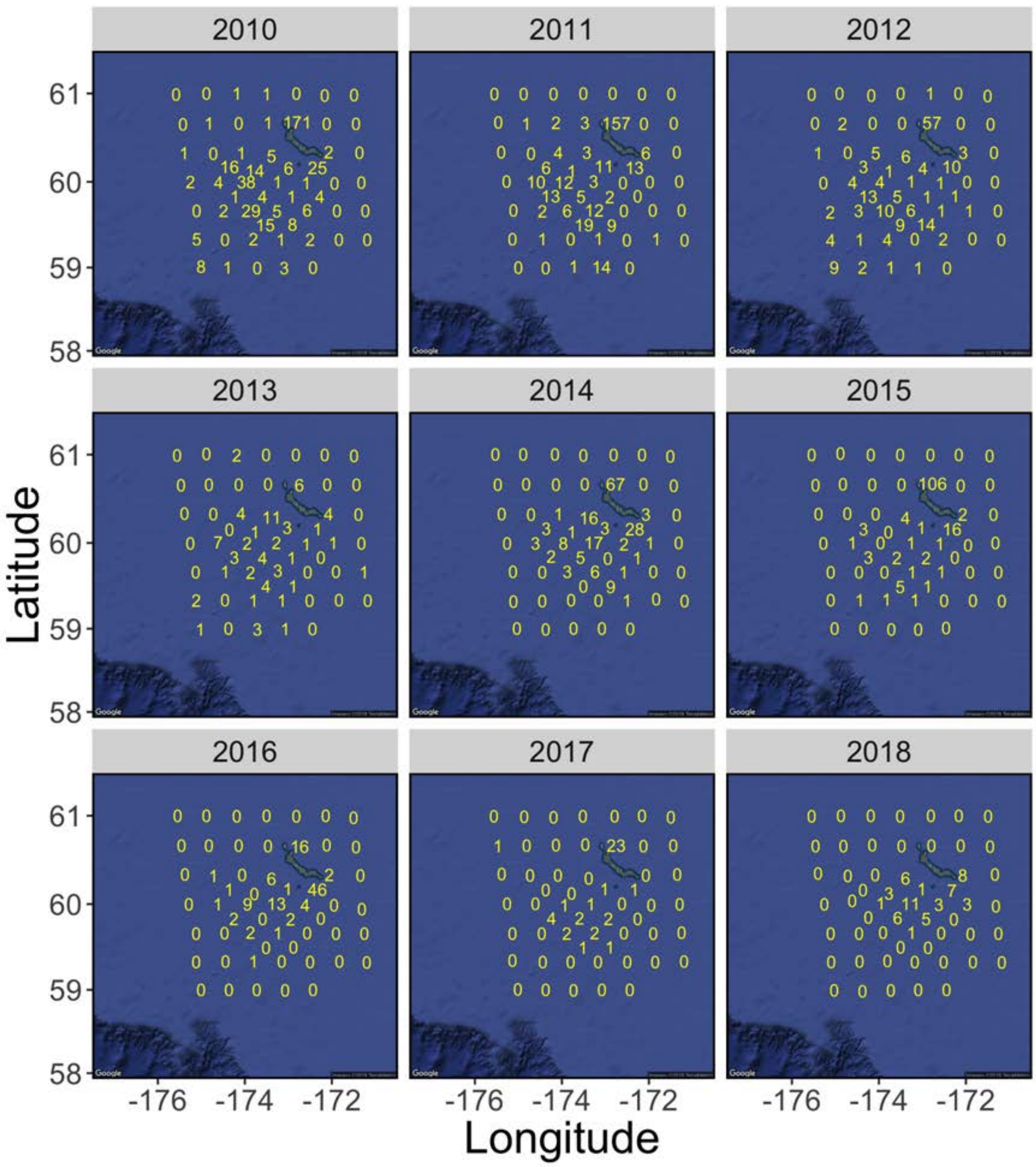

Figure 5: Catches (in numbers) of male blue king crab measuring 90 mm CL from the 2012-2017 NMFS trawl-survey at the 56 stations used to assess the SMBKC stock. Note that the area north of St. Matthew Island, which often shows large catches of crab at station R-24 is not covered in the ADF&G pot-survey data used in the assessment.

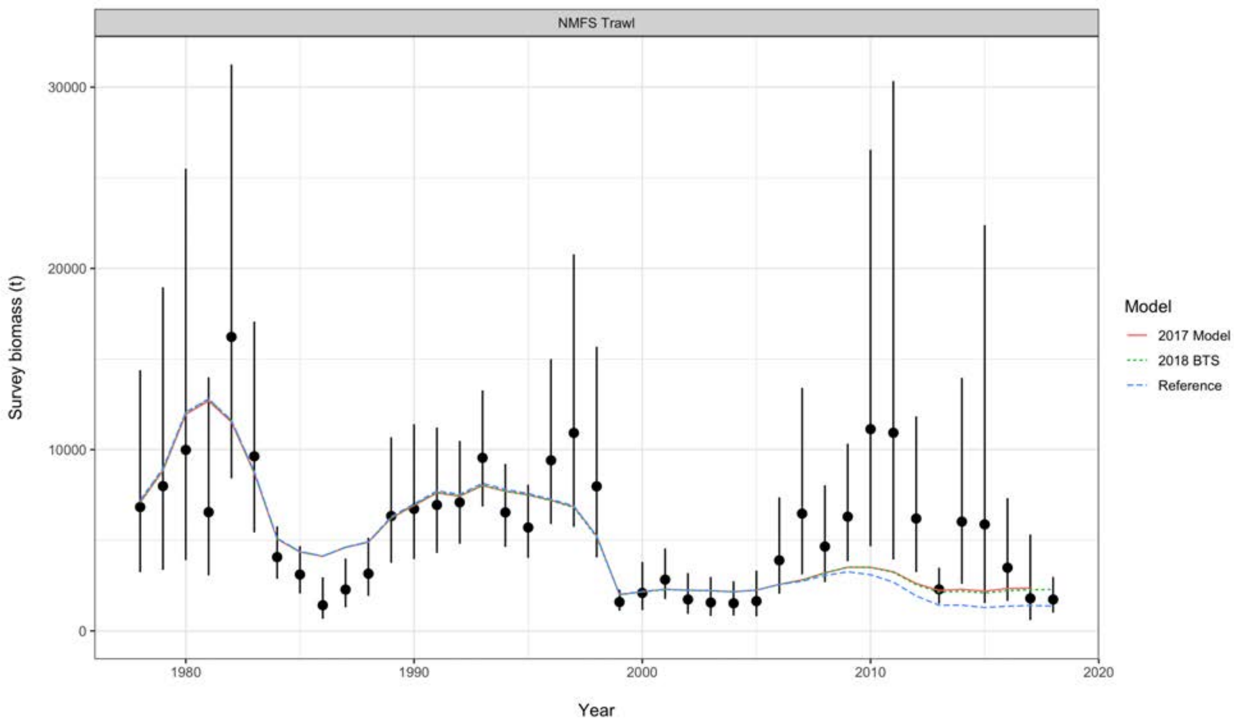

Figure 6: Fits to NMFS area-swept trawl estimates of total (>90mm) male survey biomass with the addition of new data (the Reference Model is with all new data while 2018 BTS is just with the 2018 NMFS trawl survey data added). Error bars are plus and minus 2 standard deviations.

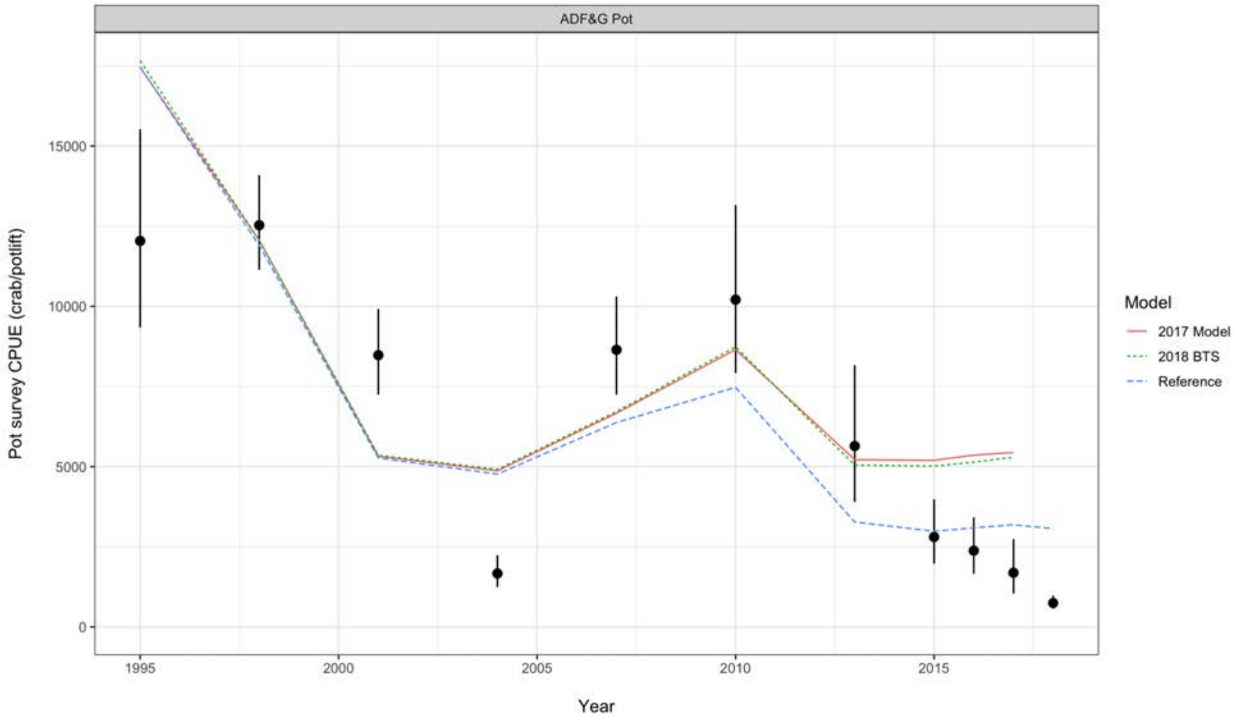

Figure 7: Comparisons of fits to CPUE from the ADF&G pot surveys with the addition of new data (note that for the 2018 BTS model the prediction for the 2018 pot survey year is ommitted from plotting routine). Error bars are plus and minus 2 standard deviations.

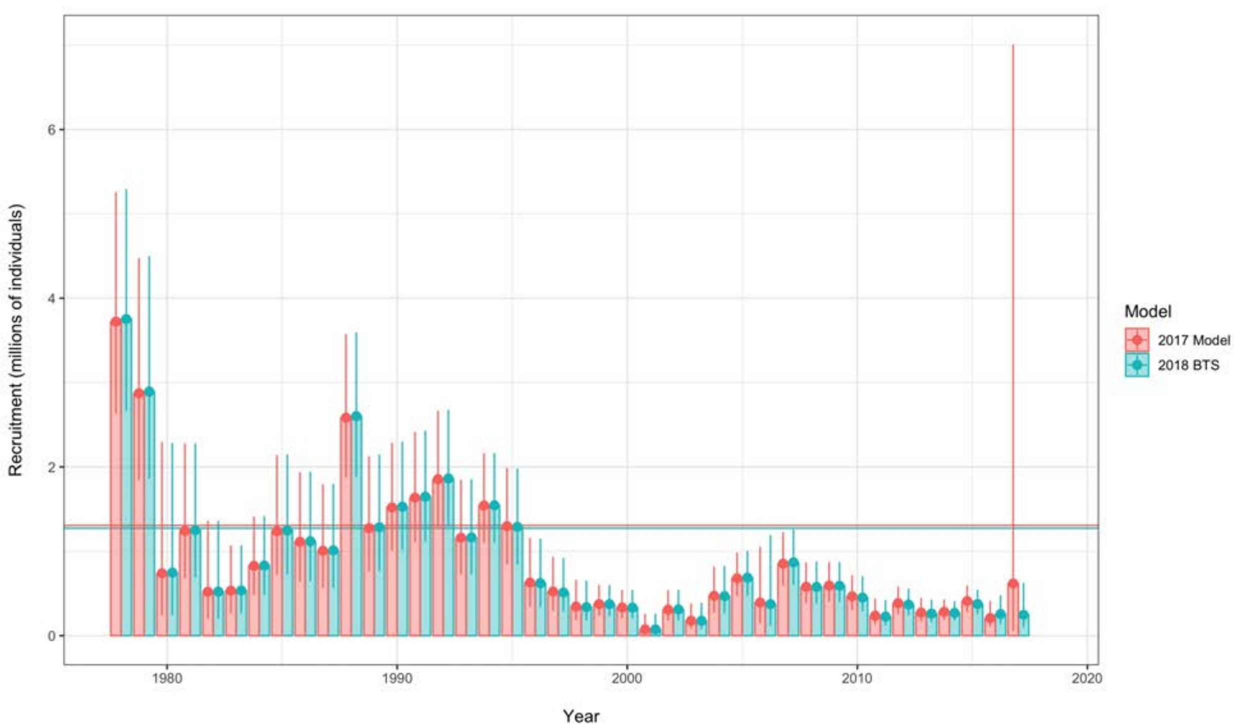

Figure 8: Sensitivity of new data in 2018 on estimated recruitment ; 1978-2018.

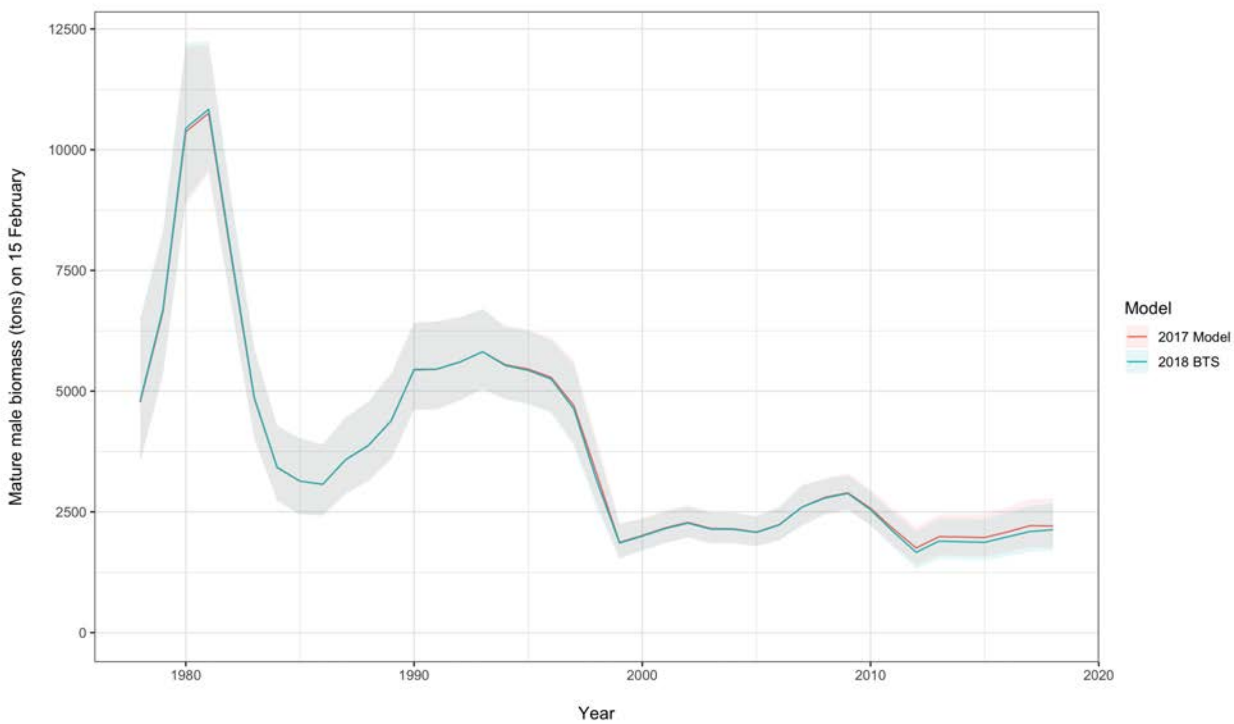

Figure 9: Sensitivity of new data in 2018 on estimated mature male biomass (MMB); 1978-2018.

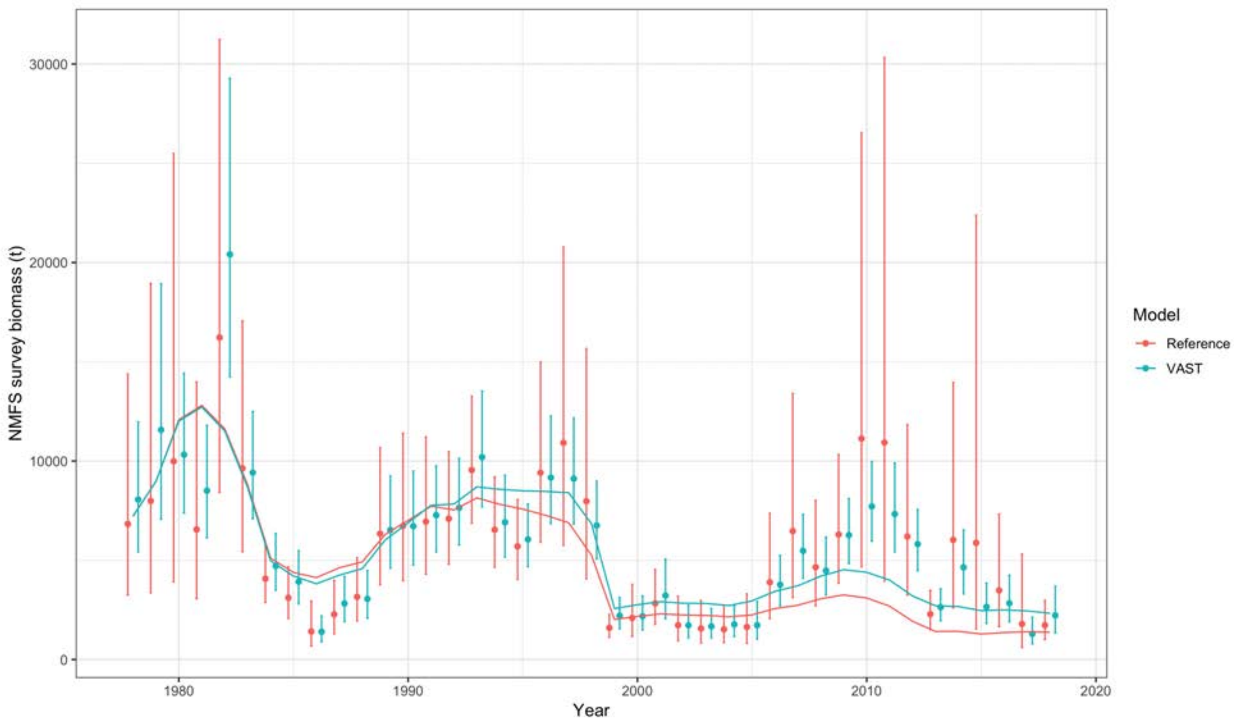

Figure 10: Comparisons of fits to area-swept estimates of total (>90mm) male survey biomass (t) for the standard design-based estimate and for estimates derived from the VAST spatio-temporal model of Thorson and Barnett (2017). Error bars are plus and minus 2 standard deviations.

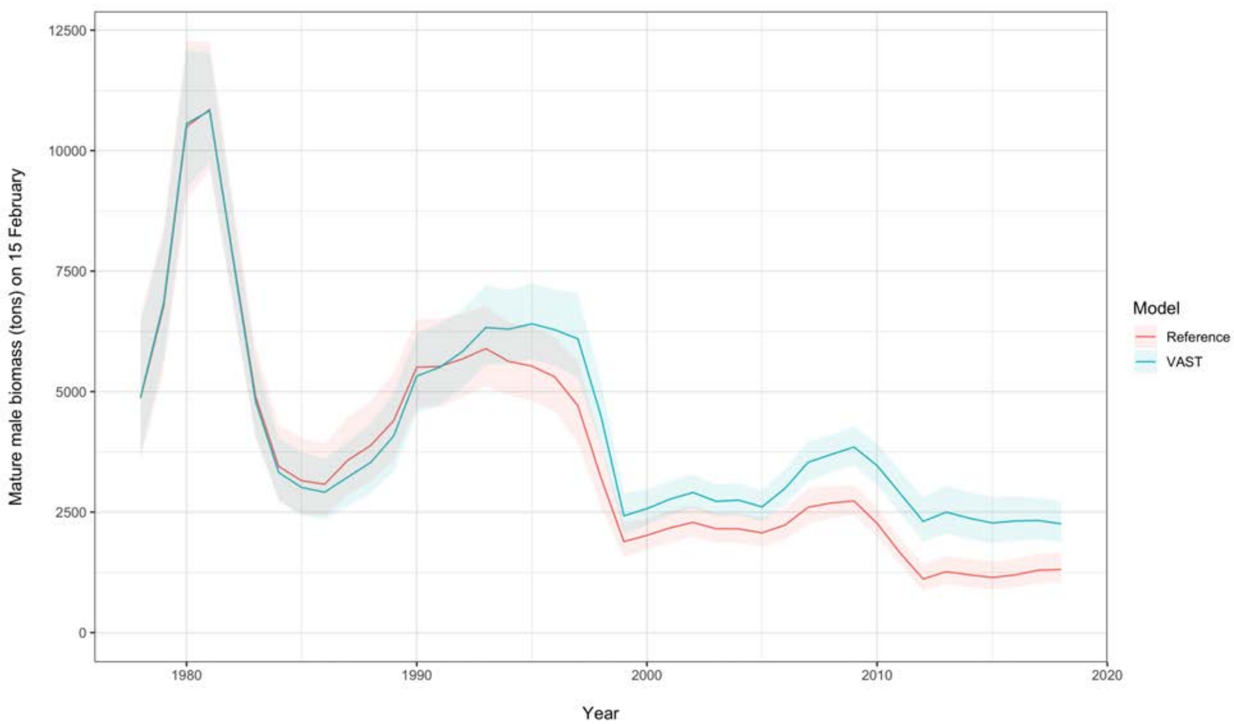

Figure 11: Sensitivity of new data in 2018 on estimated mature male biomass (MMB); 1978-2018 comparing the reference model with that fitted to the VAST BTS estimates.

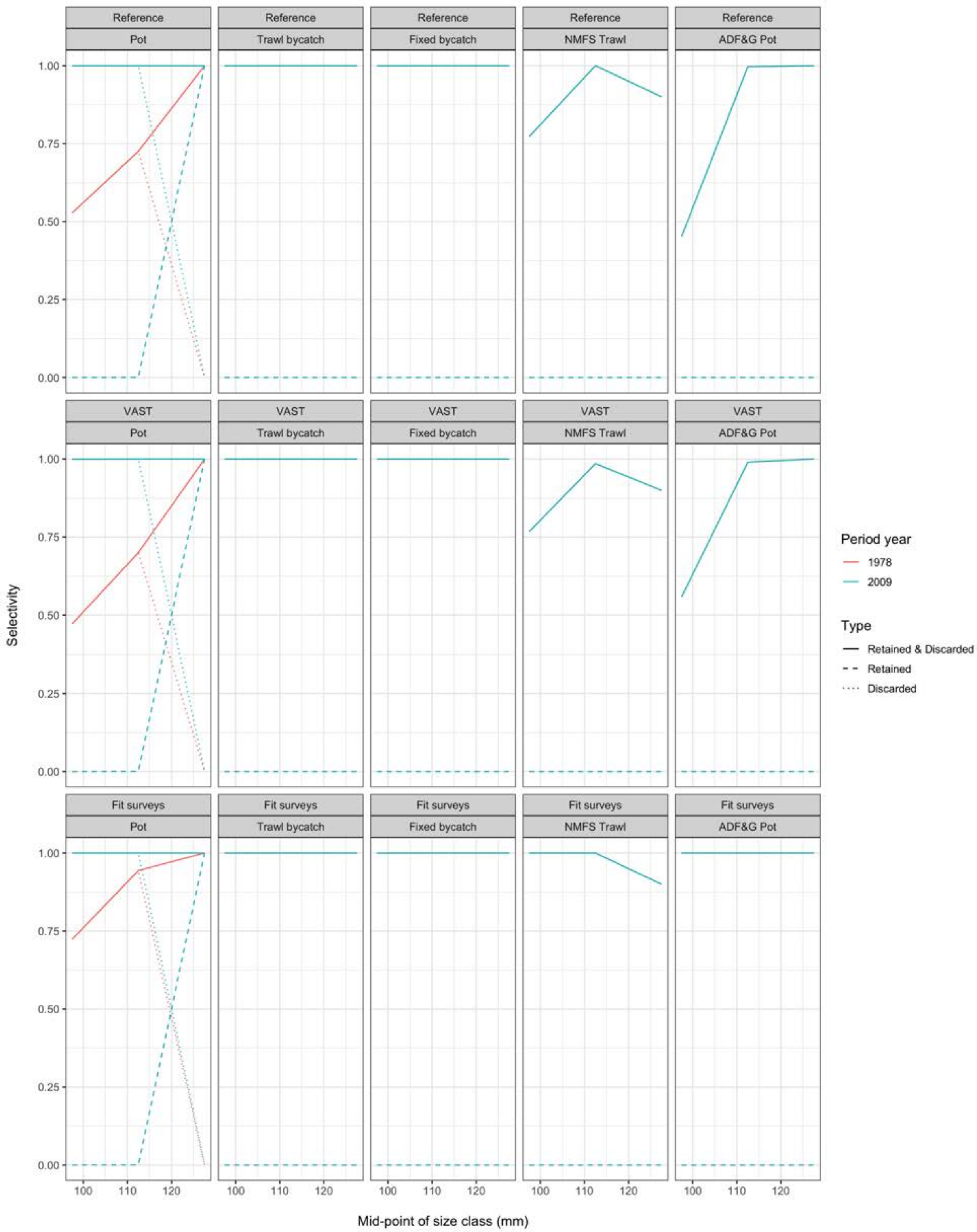

Figure 12: Comparisons of the estimated stage-1 and stage-2 selectivities for the different model scenarios (the stage-3 selectivities are all fixed at 1). Estimated selectivities are shown for the directed pot fishery, the trawl bycatch fishery, the fixed bycatch fishery, the NMFS trawl survey, and the ADF&G pot survey. Two selectivity periods are estimated in the directed pot fishery, from 1978-2008 and 2009-2017.

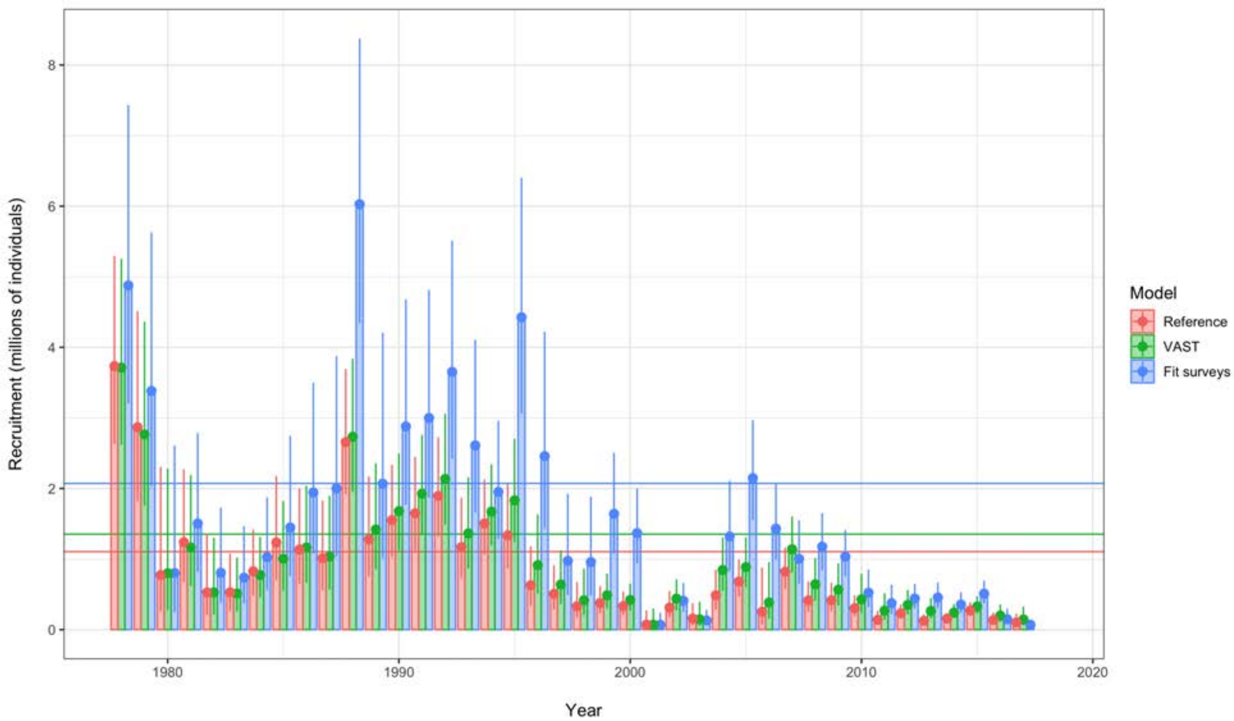

Figure 13: Estimated recruitment 1979-2017 comparing model alternatives. The solid horizontal lines in the background represent the estimate of the average recruitment parameter ($\bar{R}$) in each model scenario.

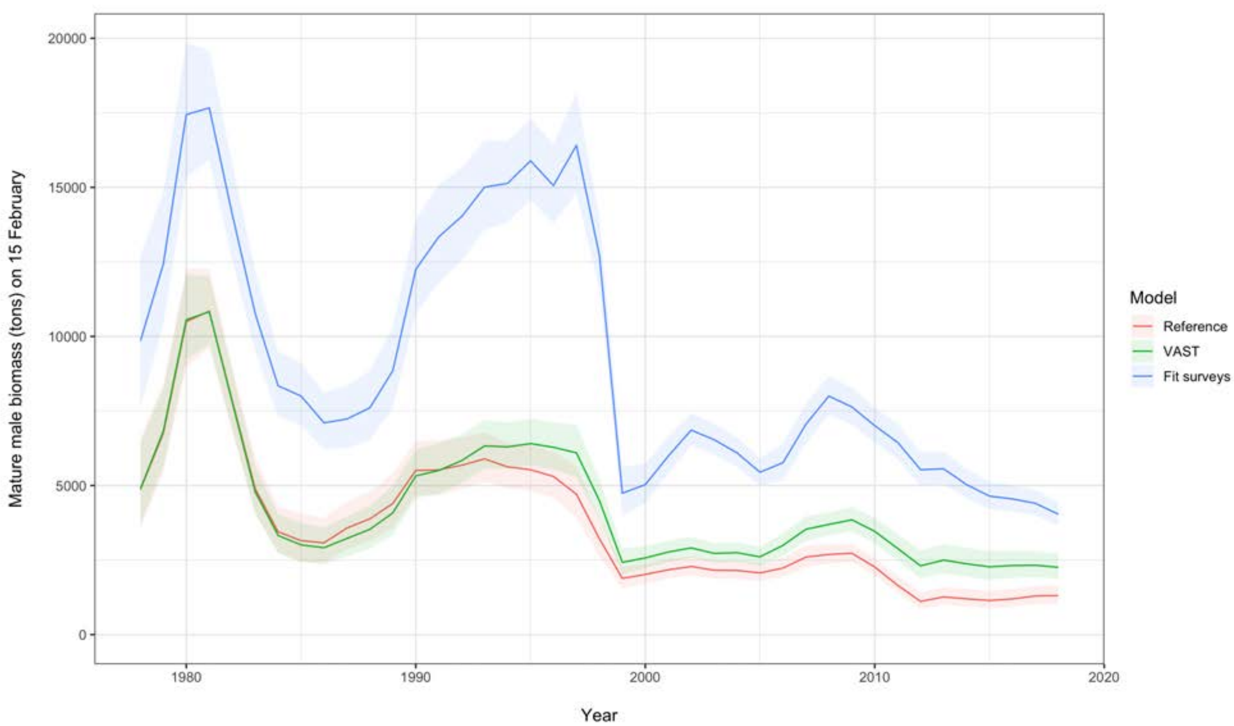

Figure 14: Comparisons of estimated mature male biomass (MMB) time series on 15 February during 1978-2018 for each of the model scenarios.

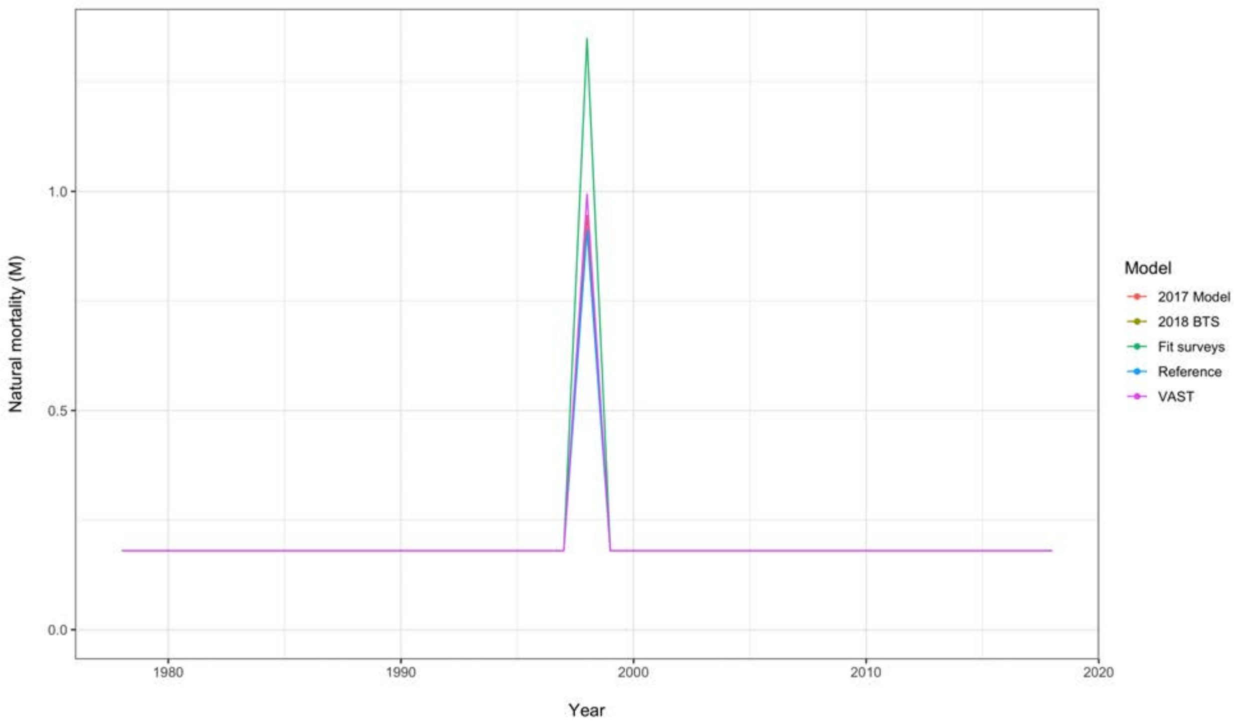

Figure 15: Time-varying natural mortality (M_t). Estimated pulse period occurs in 1998/99 (i.e. M_{1998}).

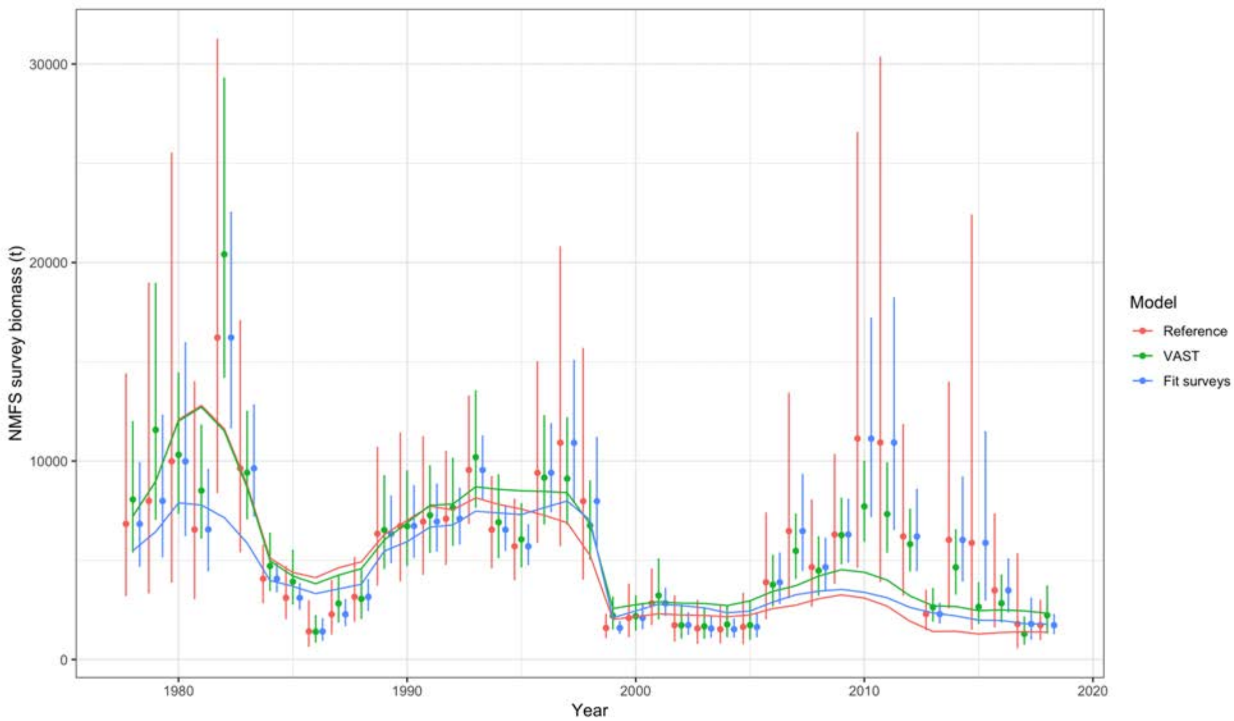

Figure 16: Comparisons of area-swept estimates of total (90+ mm CL) male survey biomass (tons) and model predictions for the model scenarios. The error bars are plus and minus 2 standard deviations.

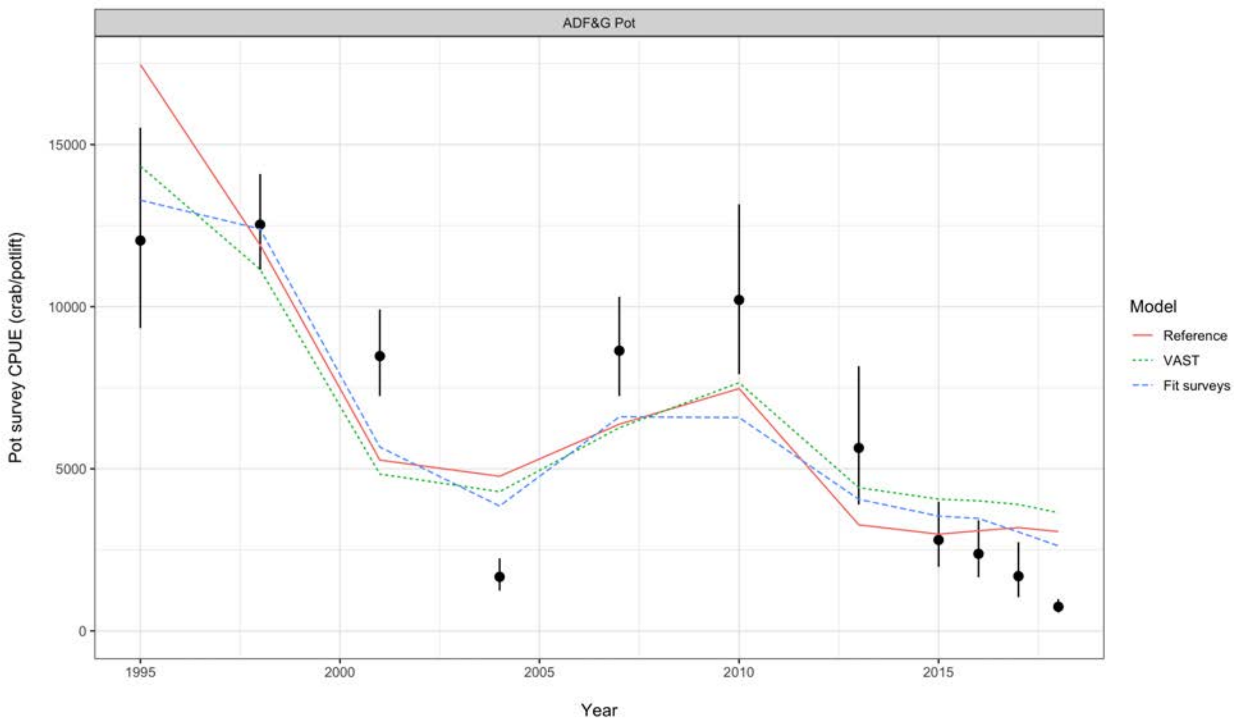

Figure 17: Comparisons of total (90+ mm CL) male pot survey CPUEs and model predictions for the model scenarios. The error bars are plus and minus 2 standard deviations.

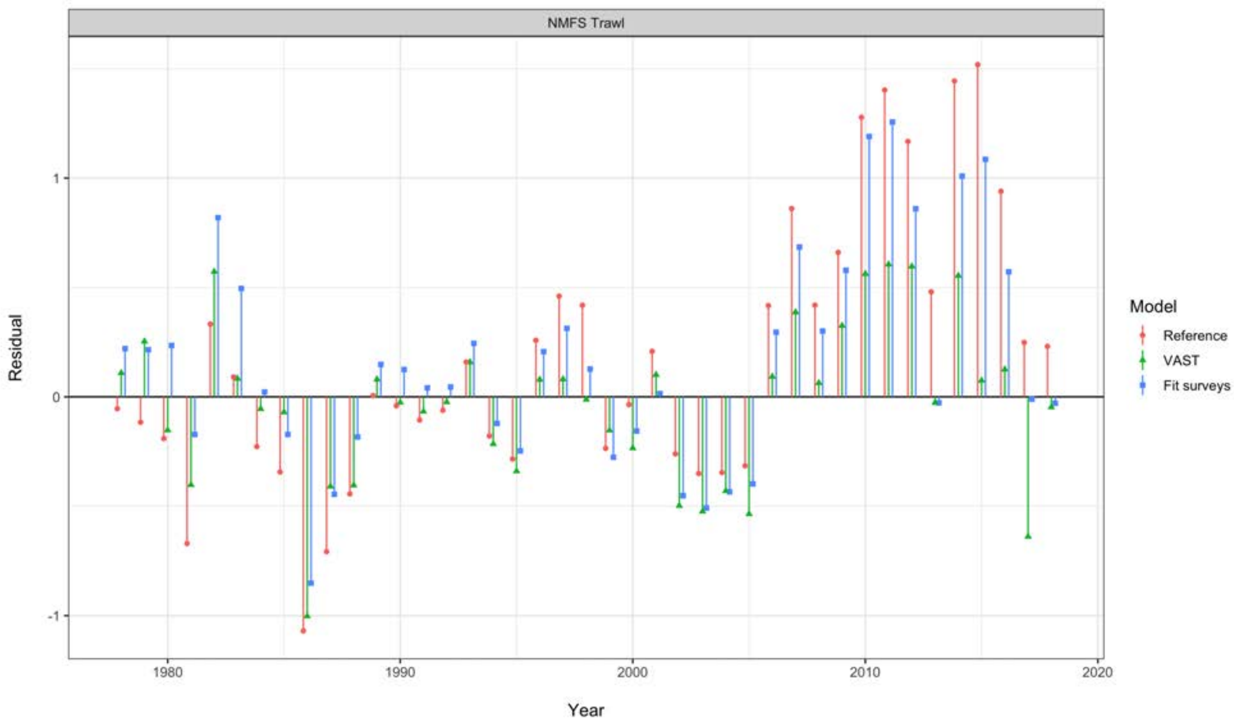

Figure 18: Standardized residuals for area-swept estimates of total male survey biomass for the model scenarios.

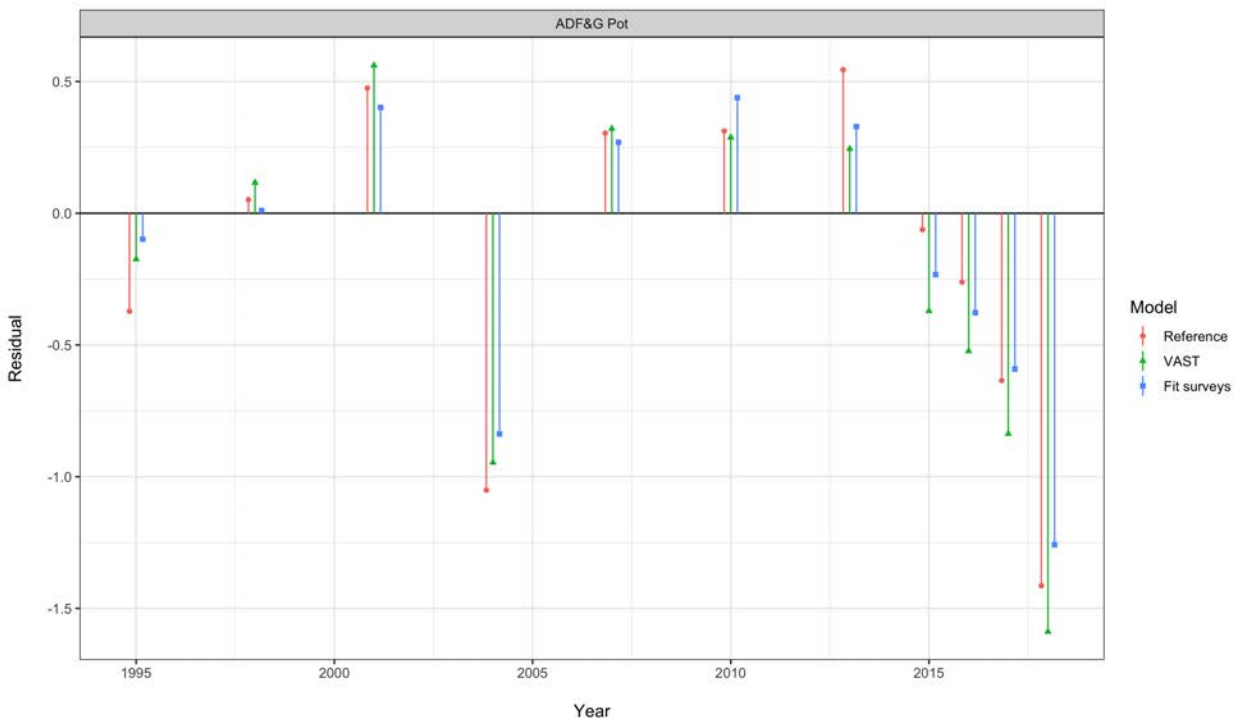

Figure 19: Standardized residuals for total male pot survey CPUEs for each of the Gmacs model scenarios.

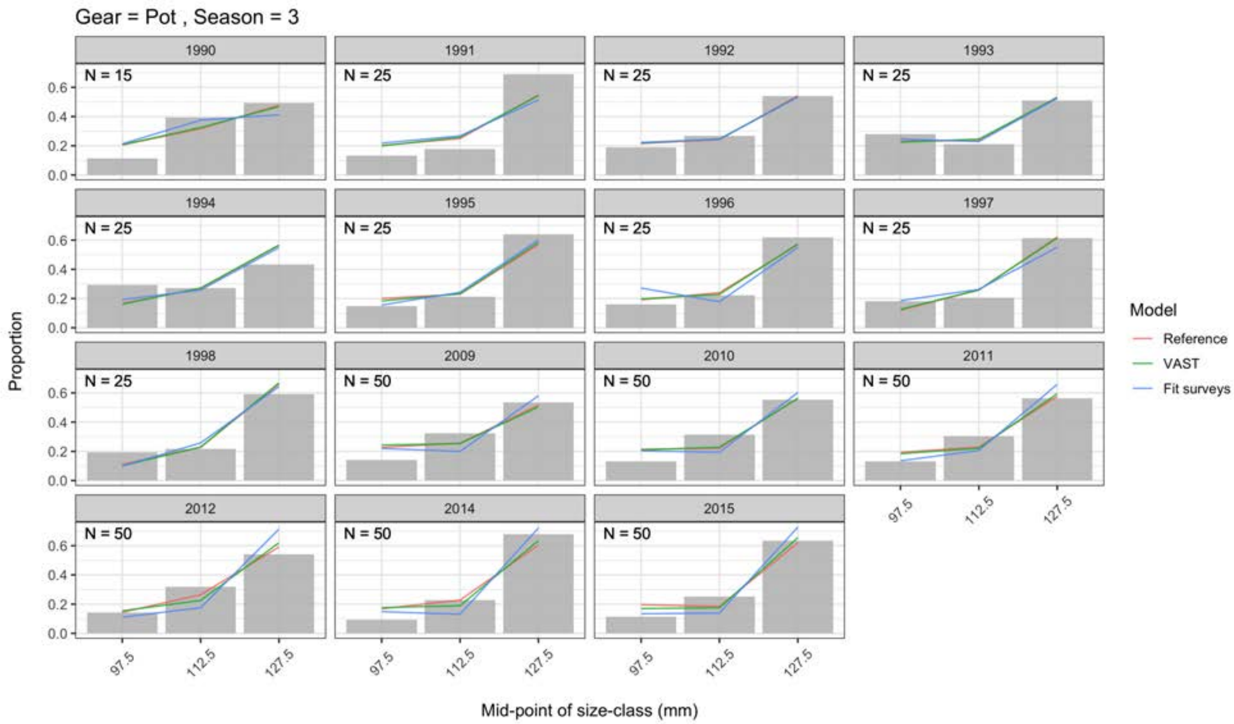

Figure 20: Observed and model estimated size-frequencies of SMBKC by year retained in the directed pot fishery for the model scenarios.

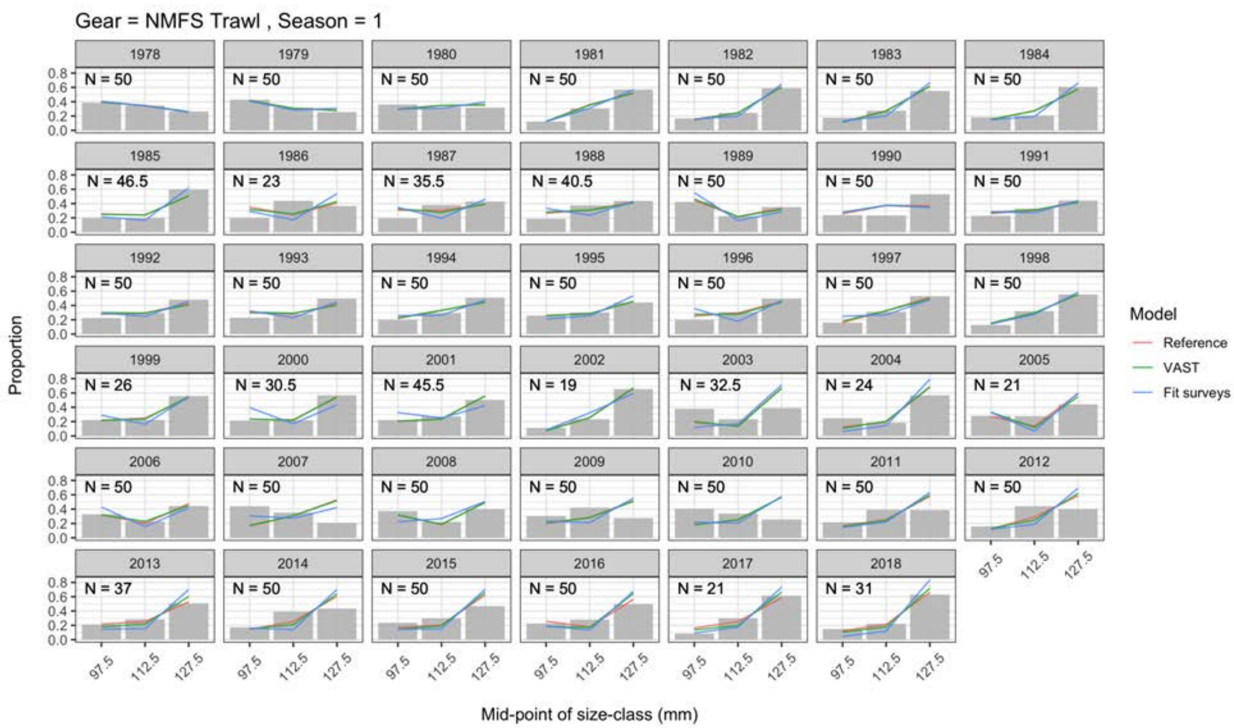

Figure 21: Observed and model estimated size-frequencies of discarded male SMBKC by year in the NMFS trawl survey for the model scenarios.

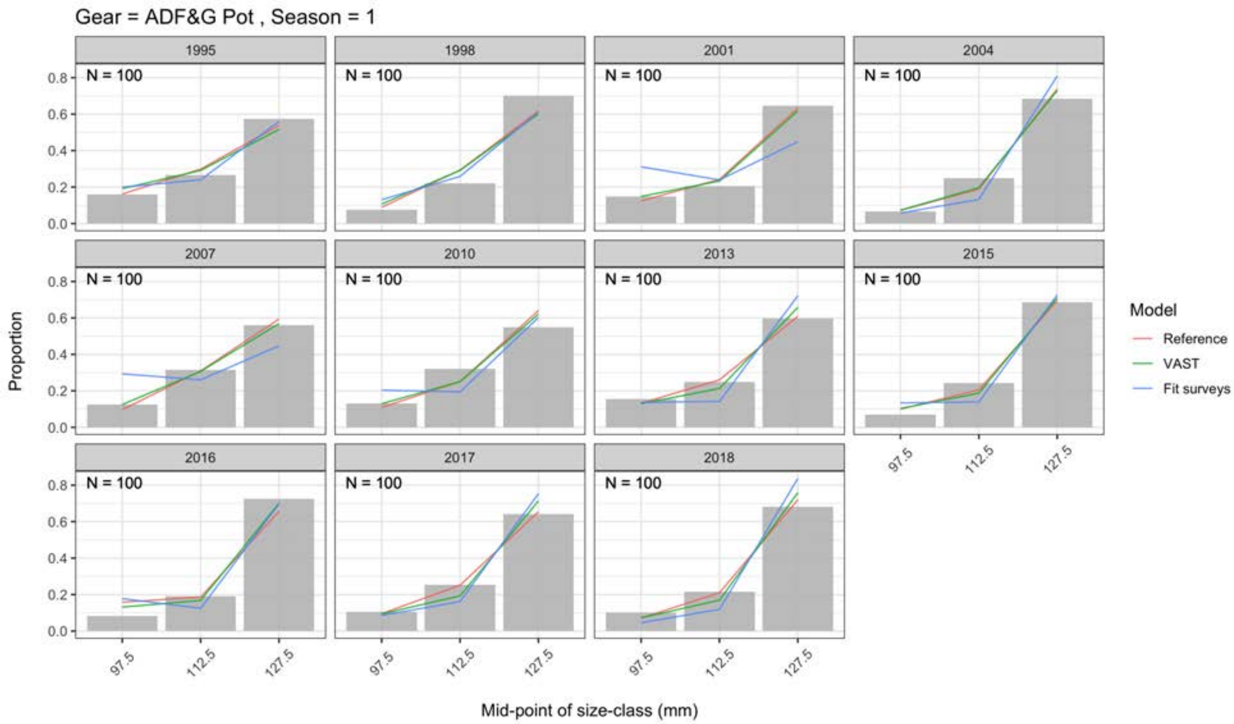

Figure 22: Observed and model estimated size-frequencies of discarded SMBKC by year in the ADF&G pot survey for the model scenarios.

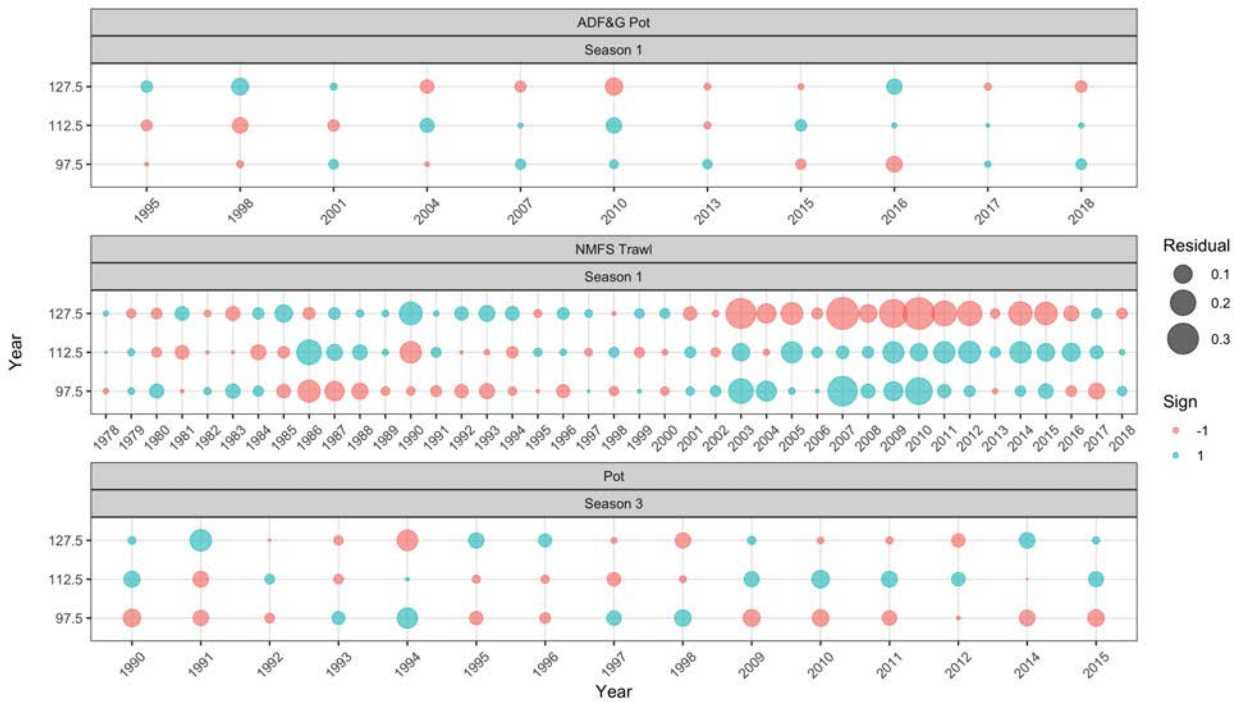

Figure 23: Bubble plots of residuals by stage and year for the directed pot fishery size composition data for SMBKC in the reference model.

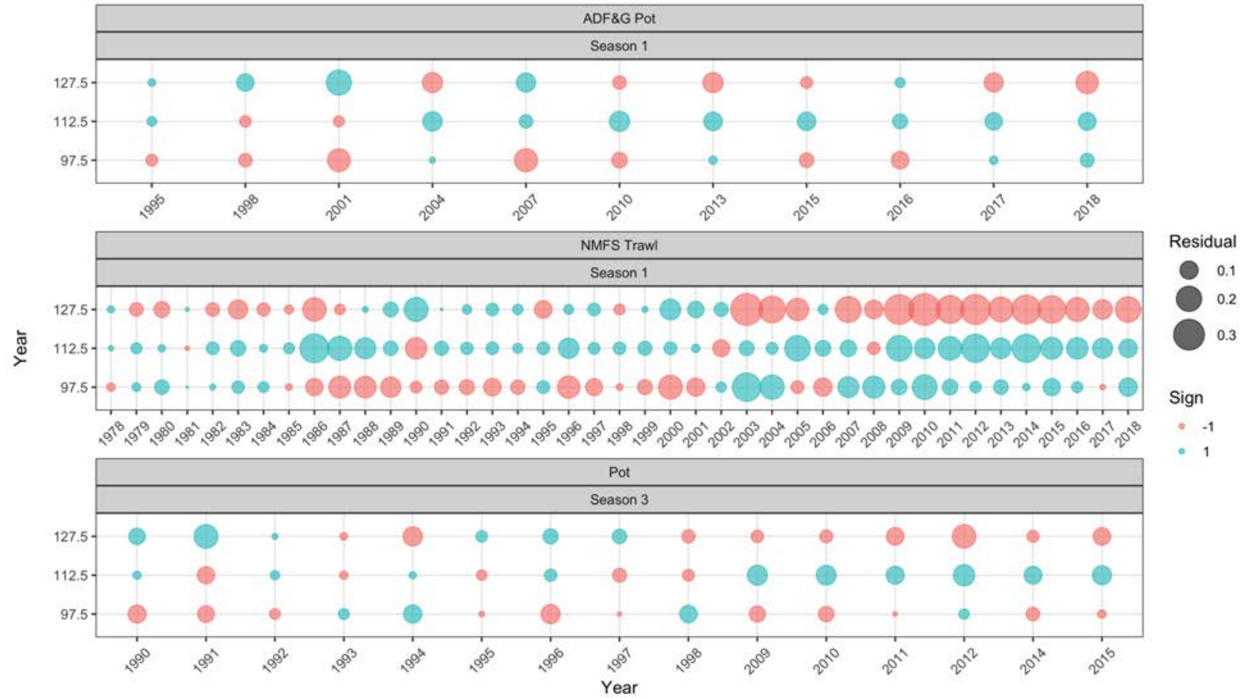

Figure 24: Bubble plots of residuals by stage and year for the ADF&G pot survey size composition data for SMBKC in the **fit surveys** model.

```
## Error in `$<-.data.frame`(`*tmp*`, "predicted", value = structure(c(436208.7633, : replacement has 13
```

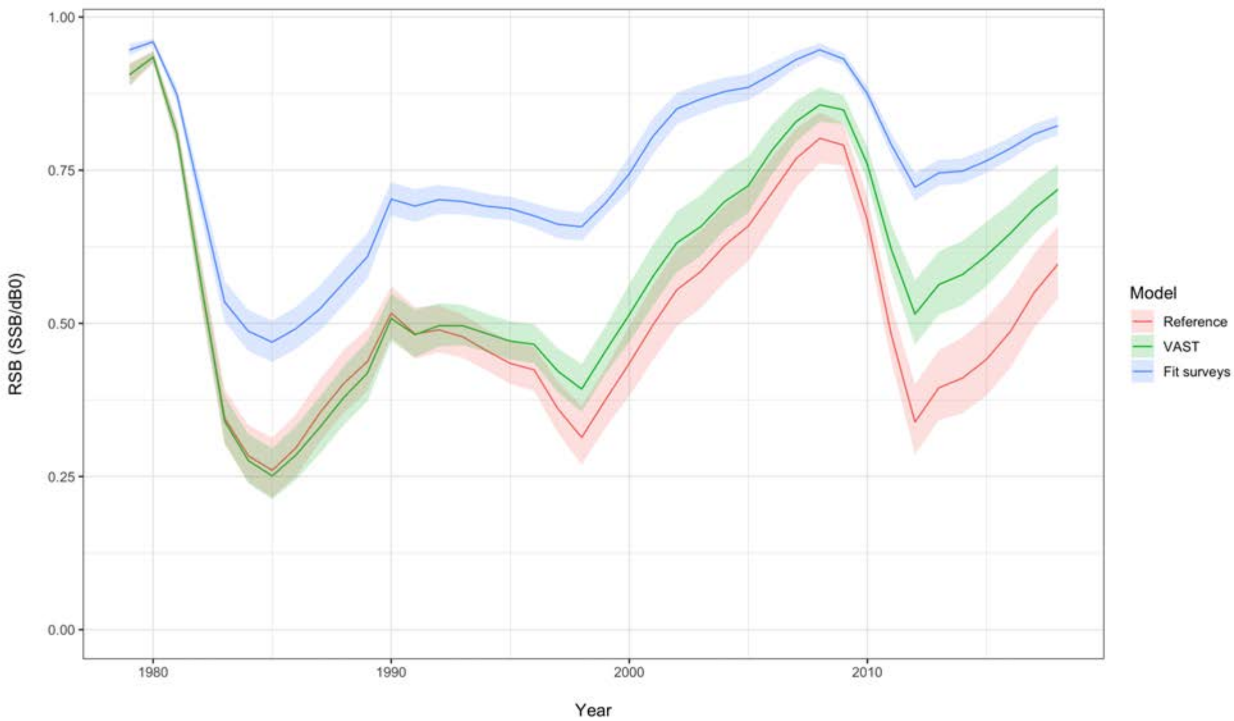

Figure 25: Comparisons of mature male biomass relative to the dynamic B_0 value, (15 February, 1978-2018) for each of the model scenarios.

Appendix A: SMBKC Model Description

1. Introduction

The Gmacs model has been specified to account only for male crab $\geq$ 90 mm in carapace length (CL). These are partitioned into three stages (size- classes) determined by CL measurements of (1) 90-104 mm, (2) 105-119 mm, and (3) 120+ mm. For management of the St. Matthew Island blue king crab (SMBKC) fishery, 120 mm CL is used as the proxy value for the legal measurement of 5.5 inch carapace width (CW), whereas 105 mm CL is the management proxy for mature-male size (5 AAC 34.917 (d)). Accordingly, within the model only stage-3 crab are retained in the directed fishery, and stage-2 and stage-3 crab together comprise the collection of mature males. Some justification for the 105 mm value is presented in Pengilly and Schmidt (1995), who used it in developing the current regulatory SMBKC harvest strategy. The term "recruit" here designates recruits to the model, i.e., annual new stage-1 crab, rather than recruits to the fishery. The following description of model structure reflects the Gmacs base model configuration.

2. Model Population Dynamics

Within the model, the beginning of the crab year is assumed contemporaneous with the NMFS trawl survey, nominally assigned a date of 1 July. Although the timing of the fishery is different each year, MMB is 15 February, which is the reference date for calculation of federal management biomass quantities. To accommodate this, each model year is split into 5 seasons (t) and a proportion of the natural mortality (τ_t), scaled relative to the portions of the year, is applied in each of these seasons where $\sum_{t=1}^{t=5} \tau_t = 1$. Each model year consists of the following processes with time-breaks denoted here by "Seasons." However, it is important to note that actual seasons are survey-to-fishery, fishery-to Feb 15, and Feb 15 to July 1. The following breakdown accounts for events and fishing mortality treatments:

1. Season 1 (survey period)
    - Beginning of the SMBKC fishing year (1 July)
    - $\tau_1 = 0$
    - Surveys
2. Season 2 (natural mortality until pulse fishery)
    - τ_2 ranges from 0.05 to 0.44 depending on the time of year the fishery begins each year (i.e., a higher value indicates the fishery begins later in the year; see Table 7)
3. Season 3 (pulse fishery)
    - $\tau_3 = 0$
    - fishing mortality applied
4. Season 4 (natural mortality until spawning)
    - $\tau_4 = 0.63 - \sum_{i=1}^{i=4} \tau_i$
    - Calculate MMB (15 February)
5. Season 5 (natural mortality and somatic growth through to June 30th)
    - $\tau_5 = 0.37$
    - Growth and molting
    - Recruitment (all to stage-1)

The proportion of natural mortality (τ_t) applied during each season in the model is provided in Table 22. The beginning of the year (1 July) to the date that MMB is measured (15 February) is 63% of the year. Therefore 63% of the natural mortality must be applied before the MMB is calculated. Because the timing of the fishery is different each year, τ_2 varies and thus τ_4 varies also.

With boldface lower-case letters indicating vector quantities we designate the vector of stage abundances during season t and year y as

$$\boldsymbol{n}_{t,y} = n_{l,t,y} = \left[n_{1,t,y}, n_{2,t,y}, n_{3,t,y}\right]^\top . \tag{2}$$

The number of new crab, or recruits, of each stage entering the model each season t and year y is represented as the vector $\boldsymbol{r}_{t,y}$. The SMBKC formulation of Gmacs specifies recruitment to stage-1 only during season $t = 5$, thus the recruitment size distribution is

$$\phi_l = \left[1, 0, 0\right]^\top , \tag{3}$$

and the recruitment is

$$\boldsymbol{r}_{t,y} = \begin{cases} 0 & \text{for} \quad t < 5 \\ \bar{R}\phi_l \delta^R_y & \text{for} \quad t = 5. \end{cases} \tag{4}$$

where $\bar{R}$ is the average annual recruitment and δ^R_y are the recruitment deviations each year y

$$\delta^R_y \sim \mathcal{N}\left(0, \sigma^2_R\right). \tag{5}$$

Using boldface upper-case letters to indicate a matrix, we describe the size transition matrix $\boldsymbol{G}$ as

$$\boldsymbol{G} = \left[\begin{array}{ccc} 1 - \pi_{12} - \pi_{13} & \pi_{12} & \pi_{13} \\ 0 & 1 - \pi_{23} & \pi_{23} \\ 0 & 0 & 1 \end{array}\right], \tag{6}$$

with π_{jk} equal to the proportion of stage-j crab that molt and grow into stage-k within a season or year.

The natural mortality each season t and year y is

$$M_{t,y} = \bar{M}\tau_t + \delta^M_y \text{ where } \delta^M_y \sim \mathcal{N}\left(0, \sigma^2_M\right) \tag{7}$$

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

$$F_{t,y} = F^{\text{df}}_{t,y} + F^{\text{tb}}_{t,y} + F^{\text{fb}}_{t,y} \tag{8}$$

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

$$\begin{aligned} F^{\text{df}}_{t,y} &= \bar{F}^{\text{df}} + \delta^{\text{df}}_{t,y} \quad \text{where} \quad \delta^{\text{df}}_{t,y} \sim \mathcal{N}\left(0, \sigma^2_{\text{df}}\right), \\ F^{\text{tb}}_{t,y} &= \bar{F}^{\text{tb}} + \delta^{\text{tb}}_{t,y} \quad \text{where} \quad \delta^{\text{df}}_{t,y} \sim \mathcal{N}\left(0, \sigma^2_{\text{tb}}\right), \\ F^{\text{fb}}_{t,y} &= \bar{F}^{\text{fb}} + \delta^{\text{fb}}_{t,y} \quad \text{where} \quad \delta^{\text{df}}_{t,y} \sim \mathcal{N}\left(0, \sigma^2_{\text{fb}}\right), \end{aligned} \tag{9}$$

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

$$\boldsymbol{Z}_{t,y} = Z_{l,t,y} = M_{t,y} + F_{t,y}. \tag{10}$$

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

$$\boldsymbol{S}_{t,y} = \left[\begin{array}{ccc} 1 - e^{-Z_{1,t,y}} & 0 & 0 \\ 0 & 1 - e^{-Z_{2,t,y}} & 0 \\ 0 & 0 & 1 - e^{-Z_{3,t,y}} \end{array}\right]. \tag{11}$$

The basic population dynamics underlying Gmacs can thus be described as

$$\begin{aligned} \boldsymbol{n}_{t+1,y} &= \boldsymbol{S}_{t,y}\boldsymbol{n}_{t,y}, & \text{if } t < 5 \\ \boldsymbol{n}_{t,y+1} &= \boldsymbol{G}\boldsymbol{S}_{t,y}\boldsymbol{n}_{t,y} + \boldsymbol{r}_{t,y} & \text{if } t = 5. \end{aligned} \tag{12}$$

3. Model Data

Data inputs used in model estimation are listed in Table 23.

4. Model Parameters

Table 24 lists fixed (externally determined) parameters used in model computations. In all scenarios, the stage-transition matrix is

$$\boldsymbol{G} = \begin{bmatrix} 0.2 & 0.7 & 0.1 \\ 0 & 0.4 & 0.6 \\ 0 & 0 & 1 \end{bmatrix} \tag{13}$$

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

Estimated parameters are listed in Table 25 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 17). A lognormal distribution is assumed to characterize the catch data and is modelled as

$$\sigma^{\text{catch}}_{t,y} = \sqrt{\log\left(1 + \left(CV^{\text{catch}}_{t,y}\right)^2\right)} \tag{14}$$

$$\delta^{\text{catch}}_{t,y} = \mathcal{N}\left(0, \left(\sigma^{\text{catch}}_{t,y}\right)^2\right) \tag{15}$$

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

$$\sigma^{\text{I}}_{t,y} = \frac{1}{\lambda}\sqrt{\log\left(1 + \left(CV^{\text{I}}_{t,y}\right)^2\right)} \tag{16}$$

$$\delta^{\text{I}}_{t,y} = \log\left(I^{\text{obs}}/I^{\text{pred}}\right)/\sigma^{\text{I}}_{t,y} + 0.5\sigma^{\text{I}}_{t,y} \tag{17}$$

and the likelihood is

$$\sum \log\left(\delta^{\text{I}}_{t,y}\right) + \sum 0.5\left(\sigma^{\text{I}}_{t,y}\right)^2 \tag{18}$$

Gmacs 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.

Gmacs 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.

Appendix B. Data files for the reference model (16.0)

The reference model (16.0) data file

```
#==========================================================================================================
# Gmacs Main  Data  File  Version 1.1:  SM18 with all new data
# GEAR_INDEX  DESCRIPTION
#   1      : Pot fishery retained catch.
#   1      : Pot fishery with discarded catch.
#   2      : Trawl bycatch
#   3      : Fixed bycatch
#   4      : Trawl survey
#   5      : Pot survey
#==========================================================================================================
# Fisheries:  1 Pot Fishery,  2 Pot Discard,  3 Trawl by-catch, 3 Fixed by-catch
# Surveys:   4 NMFS Trawl Survey, 5 Pot Survey
#==========================================================================================================
1978  # Start year
2018  # End year
2019  # Projection year
5    # Number of seasons
5    # Number of distinct data groups (among fishing fleets and surveys)
1    # Number of sexes
1    # Number of shell condition types
1    # Number of maturity types
3    # Number of size-classes in the model
5    # Season recruitment occurs
5    # Season molting and growth occurs
4    # Season to calculate SSB
1    # Season for N output
# size_breaks (a vector giving the break points between size intervals with dimension nclass+1)
90  105  120  135
# weight-at-length input method (1 = allometry i.e. w_l = a*l^b, 2 = vector by sex, 3 = matrix by sex)
3
# weight-at-length allometry w_l = a*l^b
4.03E-07
# b (male, female)
3.141334
# Male weight-at-length
0.000748427    0.001165731    0.001930510
0.000748427    0.001165731    0.001688886
0.000748427    0.001165731    0.001922246
0.000748427    0.001165731    0.001877957
0.000748427    0.001165731    0.001938634
0.000748427    0.001165731    0.002076413
0.000748427    0.001165731    0.001899330
0.000748427    0.001165731    0.002116687
0.000748427    0.001165731    0.001938784
0.000748427    0.001165731    0.001939764
0.000748427    0.001165731    0.001871067
0.000748427    0.001165731    0.001998295
0.000748427    0.001165731    0.001870418
0.000748427    0.001165731    0.001969415
0.000748427    0.001165731    0.001926859
0.000748427    0.001165731    0.002021492
0.000748427    0.001165731    0.001931318
0.000748427    0.001165731    0.002014407
0.000748427    0.001165731    0.001977471
0.000748427    0.001165731    0.002099246
```

```
0.000748427    0.001165731    0.001982478
0.000748427    0.001165731    0.001930932
0.000748427    0.001165731    0.001930932
0.000748427    0.001165731    0.001930932
0.000748427    0.001165731    0.001930932
0.000748427    0.001165731    0.001930932
0.000748427    0.001165731    0.001930932
0.000748427    0.001165731    0.001930932
0.000748427    0.001165731    0.001930932
0.000748427    0.001165731    0.001930932
0.000748427    0.001165731    0.001930932
0.000748427    0.001165731    0.001891628
0.000748427    0.001165731    0.001795721
0.000748427    0.001165731    0.001823113
0.000748427    0.001165731    0.001807433
0.000748427    0.001165731    0.001930932
0.000748427    0.001165731    0.001894627
0.000748427    0.001165731    0.001850611
0.000748427    0.001165731    0.001930932
0.000748427    0.001165731    0.001930932
0.000748427    0.001165731    0.001930932
# Male mature weight-at-length (weight * proportion  mature)
0 0.001165732 0.001945911
# Proportion mature by sex
0 1 1
# Natural mortality per season input type (1 = vector by season, 2 = matrix by season/year)
2
# Proportion of the total natural mortality to be applied each season (each row must add to 1)
0.000   0.070   0.000   0.560   0.370
0.000   0.060   0.000   0.570   0.370
0.000   0.070   0.000   0.560   0.370
0.000   0.050   0.000   0.580   0.370
0.000   0.070   0.000   0.560   0.370
0.000   0.120   0.000   0.510   0.370
0.000   0.100   0.000   0.530   0.370
0.000   0.140   0.000   0.490   0.370
0.000   0.140   0.000   0.490   0.370
0.000   0.140   0.000   0.490   0.370
0.000   0.140   0.000   0.490   0.370
0.000   0.140   0.000   0.490   0.370
0.000   0.140   0.000   0.490   0.370
0.000   0.180   0.000   0.450   0.370
0.000   0.140   0.000   0.490   0.370
0.000   0.180   0.000   0.450   0.370
0.000   0.180   0.000   0.450   0.370
0.000   0.180   0.000   0.450   0.370
0.000   0.180   0.000   0.450   0.370
0.000   0.180   0.000   0.450   0.370
0.000   0.180   0.000   0.450   0.370
0.000   0.180   0.000   0.450   0.370
0.000   0.180   0.000   0.450   0.370
0.000   0.180   0.000   0.450   0.370
0.000   0.180   0.000   0.450   0.370
0.000   0.180   0.000   0.450   0.370
0.000   0.180   0.000   0.450   0.370
0.000   0.180   0.000   0.450   0.370
0.000   0.180   0.000   0.450   0.370
0.000   0.180   0.000   0.450   0.370
0.000   0.180   0.000   0.450   0.370
0.000   0.440   0.000   0.190   0.370
0.000   0.440   0.000   0.190   0.370
0.000   0.440   0.000   0.190   0.370
0.000   0.440   0.000   0.190   0.370
0.000   0.440   0.000   0.190   0.370
0.000   0.440   0.000   0.190   0.370
0.000   0.440   0.000   0.190   0.370
0.000   0.440   0.000   0.190   0.370
0.000   0.440   0.000   0.190   0.370
0.000   0.440   0.000   0.190   0.370
#0  0.0025  0  0.6245  0.373
# Fishing fleet names (delimited with : no spaces in names)
Pot_Fishery:Trawl_Bycatch:Fixed_bycatch
```

```
# Survey names (delimited with : no spaces in names)
NMFS_Trawl:ADFG_Pot
# Number  of  catch data  frames
4
# Number  of  rows  in  each  data  frame
29  17  27  27
##  CATCH DATA
##  Type of catch: 1 = retained, 2 = discard
##  Units of catch: 1 = biomass, 2 = numbers
##  for SMBKC Units are in number of crab for landed & 1000 kg for discards.
##  Male Retained
# year  seas   fleet  sex   obs    cv type  units mult effort  discard_mortality
1978   3     1     1     436126  0.03   1     2     1     0     0
1979   3     1     1     52966   0.03   1     2     1     0     0
1980   3     1     1     33162   0.03   1     2     1     0     0
1981   3     1     1     1045619 0.03   1     2     1     0     0
1982   3     1     1     1935886 0.03   1     2     1     0     0
1983   3     1     1     1931990 0.03   1     2     1     0     0
1984   3     1     1     841017  0.03   1     2     1     0     0
1985   3     1     1     436021  0.03   1     2     1     0     0
1986   3     1     1     219548  0.03   1     2     1     0     0
1987   3     1     1     227447  0.03   1     2     1     0     0
1988   3     1     1     280401  0.03   1     2     1     0     0
1989   3     1     1     247641  0.03   1     2     1     0     0
1990   3     1     1     391405  0.03   1     2     1     0     0
1991   3     1     1     726519  0.03   1     2     1     0     0
1992   3     1     1     545222  0.03   1     2     1     0     0
1993   3     1     1     630353  0.03   1     2     1     0     0
1994   3     1     1     827015  0.03   1     2     1     0     0
1995   3     1     1     666905  0.03   1     2     1     0     0
1996   3     1     1     660665  0.03   1     2     1     0     0
1997   3     1     1     939822  0.03   1     2     1     0     0
1998   3     1     1     635370  0.03   1     2     1     0     0
2009   3     1     1     103376  0.03   1     2     1     0     0
2010   3     1     1     298669  0.03   1     2     1     0     0
2011   3     1     1     437862  0.03   1     2     1     0     0
2012   3     1     1     379386  0.03   1     2     1     0     0
2014   3     1     1     69109   0.03   1     2     1     0     0
2015   3     1     1     24407   0.03   1     2     1     0     0
2016   3     1     1     10.000  0.03   1     2     1     0     0
2017   3     1     1     10.000  0.03   1     2     1     0     0
# Male  discards  Pot fishery
1990   3     1     1    254.9787861    0.6    2     1     1     0     0.2
1991   3     1     1    531.4483252    0.6    2     1     1     0     0.2
1992   3     1     1    1050.387026    0.6    2     1     1     0     0.2
1993   3     1     1    951.4626128    0.6    2     1     1     0     0.2
1994   3     1     1    1210.764588    0.6    2     1     1     0     0.2
1995   3     1     1    363.112032     0.6    2     1     1     0     0.2
1996   3     1     1    528.5244687    0.6    2     1     1     0     0.2
1997   3     1     1    1382.825328    0.6    2     1     1     0     0.2
1998   3     1     1    781.1032977    0.6    2     1     1     0     0.2
2009   3     1     1    123.3712279    0.2    2     1     1     0     0.2
2010   3     1     1    304.6562225    0.2    2     1     1     0     0.2
2011   3     1     1    481.3572126    0.2    2     1     1     0     0.2
2012   3     1     1    437.3360731    0.2    2     1     1     0     0.2
2014   3     1     1    45.4839749     0.2    2     1     1     0     0.2
2015   3     1     1    21.19378597    0.2    2     1     1     0     0.2
2016   3     1     1    0.021193786    0.2    2     1     1     0     0.2
2017   3     1     1    0.021193786    0.2    2     1     1     0     0.2
#   Trawl   fishery discards
1991    2   2   1   3.538   0.31    2   1   1   0   0.8
1992    2   2   1   1.996   0.31    2   1   1   0   0.8
1993    2   2   1   1.542   0.31    2   1   1   0   0.8
1994    2   2   1   0.318   0.31    2   1   1   0   0.8
1995    2   2   1   0.635   0.31    2   1   1   0   0.8
1996    2   2   1   0.500   0.31    2   1   1   0   0.8
1997    2   2   1   0.500   0.31    2   1   1   0   0.8
1998    2   2   1   0.500   0.31    2   1   1   0   0.8
1999    2   2   1   0.500   0.31    2   1   1   0   0.8
2000    2   2   1   0.500   0.31    2   1   1   0   0.8
2001    2   2   1   0.500   0.31    2   1   1   0   0.8
2002    2   2   1   0.726   0.31    2   1   1   0   0.8
```

```
2003    2   2   1   0.998   0.31    2   1   1   0   0.8
2004    2   2   1   0.091   0.31    2   1   1   0   0.8
2005    2   2   1   0.500   0.31    2   1   1   0   0.8
2006    2   2   1   2.812   0.31    2   1   1   0   0.8
2007    2   2   1   0.045   0.31    2   1   1   0   0.8
2008    2   2   1   0.272   0.31    2   1   1   0   0.8
2009    2   2   1   0.638   0.31    2   1   1   0   0.8
2010    2   2   1   0.360   0.31    2   1   1   0   0.8
2011    2   2   1   0.170   0.31    2   1   1   0   0.8
2012    2   2   1   0.011   0.31    2   1   1   0   0.8
2013    2   2   1   0.163   0.31    2   1   1   0   0.8
2014    2   2   1   0.010   0.31    2   1   1   0   0.8
2015    2   2   1   0.010   0.31    2   1   1   0   0.8
2016    2   2   1   0.229   0.31    2   1   1   0   0.8
2017    2   2   1   0.052   0.31    2   1   1   0   0.8
#   Fixed   fishery discards
1991    2   3   1   0.045   0.31    2   1   1   0   0.5
1992    2   3   1   2.268   0.31    2   1   1   0   0.5
1993    2   3   1   0.500   0.31    2   1   1   0   0.5
1994    2   3   1   0.091   0.31    2   1   1   0   0.5
1995    2   3   1   0.136   0.31    2   1   1   0   0.5
1996    2   3   1   0.045   0.31    2   1   1   0   0.5
1997    2   3   1   0.181   0.31    2   1   1   0   0.5
1998    2   3   1   0.907   0.31    2   1   1   0   0.5
1999    2   3   1   1.361   0.31    2   1   1   0   0.5
2000    2   3   1   0.500   0.31    2   1   1   0   0.5
2001    2   3   1   0.862   0.31    2   1   1   0   0.5
2002    2   3   1   0.408   0.31    2   1   1   0   0.5
2003    2   3   1   1.134   0.31    2   1   1   0   0.5
2004    2   3   1   0.635   0.31    2   1   1   0   0.5
2005    2   3   1   0.590   0.31    2   1   1   0   0.5
2006    2   3   1   1.451   0.31    2   1   1   0   0.5
2007    2   3   1   69.717  0.31    2   1   1   0   0.5
2008    2   3   1   6.622   0.31    2   1   1   0   0.5
2009    2   3   1   7.522   0.31    2   1   1   0   0.5
2010    2   3   1   9.564   0.31    2   1   1   0   0.5
2011    2   3   1   0.796   0.31    2   1   1   0   0.5
2012    2   3   1   0.739   0.31    2   1   1   0   0.5
2013    2   3   1   0.341   0.31    2   1   1   0   0.5
2014    2   3   1   0.490   0.31    2   1   1   0   0.5
2015    2   3   1   0.711   0.31    2   1   1   0   0.5
2016    2   3   1   1.633   0.31    2   1   1   0   0.5
2017    2   3   1   6.032   0.31    2   1   1   0   0.5
##  RELATIVE  ABUNDANCE DATA
##  Units of abundance: 1 = biomass, 2 = numbers
##  for SMBKC Units are in  crabs for Abundance.
##  Number  of  relative  abundance indicies
2
##  Number  of  rows  in  each  index
41  11
# Survey data (abundance indices, units are mt for trawl survey and crab/potlift for pot survey)
# Year, Seas, Fleet,  Sex,  Abundance,  CV    units
1978  1 4 1 6832.819  0.394 1
1979  1 4 1 7989.881  0.463 1
1980  1 4 1 9986.830  0.507 1
1981  1 4 1 6551.132  0.402 1
1982  1 4 1 16221.933 0.344 1
1983  1 4 1 9634.250  0.298 1
1984  1 4 1 4071.218  0.179 1
1985  1 4 1 3110.541  0.210 1
1986  1 4 1 1416.849  0.388 1
1987  1 4 1 2278.917  0.291 1
1988  1 4 1 3158.169  0.252 1
1989  1 4 1 6338.622  0.271 1
1990  1 4 1 6730.130  0.274 1
1991  1 4 1 6948.184  0.248 1
1992  1 4 1 7093.272  0.201 1
1993  1 4 1 9548.459  0.169 1
1994  1 4 1 6539.133  0.176 1
1995  1 4 1 5703.591  0.178 1
1996  1 4 1 9410.403  0.241 1
1997  1 4 1 10924.107 0.337 1
```

```
1998  1 4 1 7976.839  0.355 1
1999  1 4 1 1594.546  0.182 1
2000  1 4 1 2096.795  0.310 1
2001  1 4 1 2831.440  0.245 1
2002  1 4 1 1732.599  0.320 1
2003  1 4 1 1566.675  0.336 1
2004  1 4 1 1523.869  0.305 1
2005  1 4 1 1642.017  0.371 1
2006  1 4 1 3893.875  0.334 1
2007  1 4 1 6470.773  0.385 1
2008  1 4 1 4654.473  0.284 1
2009  1 4 1 6301.470  0.256 1
2010  1 4 1 11130.898 0.466 1
2011  1 4 1 10931.232 0.558 1
2012  1 4 1 6200.219  0.339 1
2013  1 4 1 2287.557  0.217 1
2014  1 4 1 6029.220  0.449 1
2015  1 4 1 5877.433  0.770 1
2016  1 4 1 3485.909  0.393 1
2017  1 4 1 1793.760  0.599 1
2018  1 4 1 1730.74  0.281 1
1995  1 5 1 12042.000 0.130 2
1998  1 5 1 12531.000 0.060 2
2001  1 5 1 8477.000  0.080 2
2004  1 5 1 1667.000  0.150 2
2007  1 5 1 8643.000  0.090 2
2010  1 5 1 10209.000 0.130 2
2013  1 5 1 5643.000  0.190 2
2015  1 5 1 2805.000  0.180 2
2016  1 5 1 2378.000  0.186 2
2017  1 5 1 1689.000  0.250 2
2018  1 5 1  745.000  0.140 2
##  Number  of  length  frequency matrices
3
##  Number  of  rows  in  each  matrix
15  41  11
##  Number  of  bins  in  each  matrix  (columns  of  size  data)
3  3  3
##  SIZE  COMPOSITION DATA  FOR ALL FLEETS
##  SIZE  COMP  LEGEND
##  Sex:  1 = male, 2 = female, 0 = both  sexes combined
##  Type  of  composition:  1 = retained, 2 = discard,  0 = total composition
##  Maturity  state:  1 = immature, 2 = mature, 0 = both  states  combined
##  Shell condition:  1 = new shell,  2 = old shell,  0 = both  shell types combined
##length  proportions of  pot discarded males
##Year, Seas, Fleet,  Sex,  Type, Shell,  Maturity, Nsamp,  DataVec
  1990  3 1 1 0 0 0 15  0.1133  0.3933  0.4933
  1991  3 1 1 0 0 0 25  0.1329  0.1768  0.6902
  1992  3 1 1 0 0 0 25  0.1905  0.2677  0.5417
  1993  3 1 1 0 0 0 25  0.2807  0.2097  0.5096
  1994  3 1 1 0 0 0 25  0.2942  0.2714  0.4344
  1995  3 1 1 0 0 0 25  0.1478  0.2127  0.6395
  1996  3 1 1 0 0 0 25  0.1595  0.2229  0.6176
  1997  3 1 1 0 0 0 25  0.1818  0.2053  0.6128
  1998  3 1 1 0 0 0 25  0.1927  0.2162  0.5911
  2009  3 1 1 0 0 0 50  0.1413  0.3235  0.5352
  2010  3 1 1 0 0 0 50  0.1314  0.3152  0.5534
  2011  3 1 1 0 0 0 50  0.1314  0.3051  0.5636
  2012  3 1 1 0 0 0 50  0.1417  0.3178  0.5406
  2014  3 1 1 0 0 0 50  0.0939  0.2275  0.6786
  2015  3 1 1 0 0 0 50  0.1148  0.2518  0.6333
##length  proportions of  trawl survey  males
##Year, Seas, Fleet,  Sex,  Type, Shell,  Maturity, Nsamp,  DataVec
  1978  1 4 1 0 0 0 50  0.3865  0.3478  0.2657
  1979  1 4 1 0 0 0 50  0.4281  0.3190  0.2529
  1980  1 4 1 0 0 0 50  0.3588  0.3220  0.3192
  1981  1 4 1 0 0 0 50  0.1219  0.3065  0.5716
  1982  1 4 1 0 0 0 50  0.1671  0.2435  0.5893
  1983  1 4 1 0 0 0 50  0.1752  0.2726  0.5522
  1984  1 4 1 0 0 0 50  0.1823  0.2085  0.6092
  1985  1 4 1 0 0 0 46.5 0.2023  0.2010  0.5967
  1986  1 4 1 0 0 0 23  0.1984  0.4364  0.3652
```

```
  1987  1 4 1 0 0 0 35.5 0.1944  0.3779  0.4277
  1988  1 4 1 0 0 0 40.5 0.1879  0.3737  0.4384
  1989  1 4 1 0 0 0 50  0.4246  0.2259  0.3496
  1990  1 4 1 0 0 0 50  0.2380  0.2332  0.5288
  1991  1 4 1 0 0 0 50  0.2274  0.3300  0.4426
  1992  1 4 1 0 0 0 50  0.2263  0.2911  0.4826
  1993  1 4 1 0 0 0 50  0.2296  0.2759  0.4945
  1994  1 4 1 0 0 0 50  0.1989  0.2926  0.5085
  1995  1 4 1 0 0 0 50  0.2593  0.3005  0.4403
  1996  1 4 1 0 0 0 50  0.1998  0.3054  0.4948
  1997  1 4 1 0 0 0 50  0.1622  0.3102  0.5275
  1998  1 4 1 0 0 0 50  0.1276  0.3212  0.5511
  1999  1 4 1 0 0 0 26  0.2224  0.2214  0.5562
  2000  1 4 1 0 0 0 30.5 0.2154  0.2180  0.5665
  2001  1 4 1 0 0 0 45.5 0.2253  0.2699  0.5048
  2002  1 4 1 0 0 0 19  0.1127  0.2346  0.6527
  2003  1 4 1 0 0 0 32.5 0.3762  0.2345  0.3893
  2004  1 4 1 0 0 0 24  0.2488  0.1848  0.5663
  2005  1 4 1 0 0 0 21  0.2825  0.2744  0.4431
  2006  1 4 1 0 0 0 50  0.3276  0.2293  0.4431
  2007  1 4 1 0 0 0 50  0.4394  0.3525  0.2081
  2008  1 4 1 0 0 0 50  0.3745  0.2219  0.4036
  2009  1 4 1 0 0 0 50  0.3057  0.4202  0.2741
  2010  1 4 1 0 0 0 50  0.4081  0.3371  0.2548
  2011  1 4 1 0 0 0 50  0.2179  0.3940  0.3881
  2012  1 4 1 0 0 0 50  0.1573  0.4393  0.4034
  2013  1 4 1 0 0 0 37  0.2100  0.2834  0.5065
  2014  1 4 1 0 0 0 50  0.1738  0.3912  0.4350
  2015  1 4 1 0 0 0 50  0.2340  0.2994  0.4666
  2016  1 4 1 0 0 0 50  0.2255  0.2780  0.4965
  2017  1 4 1 0 0 0 21  0.0849  0.2994  0.6157
  2018  1 4 1 0 0 0 31  0.1475  0.2219  0.6306
  ##length  proportions of  pot survey
  ##Year, Seas, Fleet,  Sex,  Type, Shell,  Maturity, Nsamp,  DataVec
  1995  1 5 1 0 0 0 100 0.1594  0.2656  0.5751
  1998  1 5 1 0 0 0 100  0.0769  0.2205  0.7026
  2001  1 5 1 0 0 0 100  0.1493  0.2049  0.6457
  2004  1 5 1 0 0 0 100  0.0672  0.2484  0.6845
  2007  1 5 1 0 0 0 100  0.1257  0.3148  0.5595
  2010  1 5 1 0 0 0 100  0.1299  0.3209  0.5492
  2013  1 5 1 0 0 0 100  0.1556  0.2477  0.5967
  2015  1 5 1 0 0 0 100  0.0706  0.2431  0.6859
  2016  1 5 1 0 0 0 100  0.0832  0.1917  0.7251
  2017  1 5 1 0 0 0 100  0.1048  0.2540  0.6412
  2018  1 5 1 0 0 0 100  0.10201    0.21611 0.68188
##  Growth data (increment)
# nobs_growth
3
# MidPoint Sex Increment CV
 97.5  1  14.1  0.2197
112.5  1  14.1  0.2197
127.5  1  14.1  0.2197
#  97.5  1 13.8 0.2197
#  112.5  1 14.1 0.2197
#  127.5  1 14.4 0.2197
# Use custom transition matrix (0=no, 1=growth matrix, 2=transition matrix, i.e. growth and molting)
0
# The custom growth matrix (if not using just fill with zeros)
# Alternative TM (loosely) based on Otto and Cummiskey (1990)
0.2  0.7  0.1
0.0  0.4  0.6
0.0  0.0  1.0
#  Use  custom  natural  mortality  (0=no,  1=yes,  by  sex  and  year)
0
0.12 0.12 0.12 0.12 0.12 0.12 0.12 0.12 0.12 0.12
0.12 0.12 0.12 0.12 0.12 0.12 0.12 0.12 0.12 0.12
0.12 0.12 0.12 0.12 0.12 0.12 0.12 0.12 0.12 0.12
0.12 0.12 0.12 0.12 0.12 0.12 0.12 0.12 0.12 0.12 0.12
## eof
9999
```

The reference model (16.0) control file

```
## ---------------------------------------------------------------------------------- ##
## LEADING PARAMETER CONTROLS                                                         ##
# Controls for leading parameter vector theta
# LEGEND FOR PRIOR:
#                  0 -> uniform #                 1 -> normal #                 2 -> lognormal
#                  3 -> beta
#                  4 -> gamma
# ntheta
  12
## ---------------------------------------------------------------------------------- ##
# ival       lb       ub       phz   prior     p1      p2        # parameter        #
  0.18      0.01       1       -4      2   0.18    0.02        # M
  14.3      -7.0      30       -2      0    -7       30        # log(R0)
  10.0      -7.0      20       -1      1   -10.0     20        # log(Rini)
  13.39     -7.0      20        1      0    -7       20        # log(Rbar)
  80.0      30.0     310       -2      1    72.5    7.25       # Recruitment size distribution expected value
  0.25       0.1       7       -4      0     0.1     9.0       # Recruitment size scale (variance component)
  0.2      -10.0     0.75      -4      0  -10.0    0.75        # log(sigma_R)
  0.75      0.20     1.00      -2      3     3.0    2.00       # steepness
  0.01      0.00     1.00      -3      3    1.01    1.01       # recruitment autocorrelation
 14.5       5.00    20.00       1      0    5.00   20.00       # logN0 vector of initial numbers at length
 14.0       5.00    20.00       1      0    5.00   20.00       # logN0 vector of initial numbers at length
 13.5       5.00    20.00       1      0    5.00   20.00       # logN0 vector of initial numbers at length
## GROWTH PARAM CONTROLS                                                              ##
## Two lines for each parameter if split sex, one line if not                         ##
## number of molt periods
1
## Year(s) molt period changes (blank if no changes)
## ---------------------------------------------------------------------------------- ##
# ival       lb       ub        phz  prior     p1      p2        # parameter        #
  14.1      10.0     30.0       -3      0     0.0   999.0       # alpha males or combined
   0.0001    0.0      0.01      -3      0     0.0   999.0       # beta males or combined
   0.45      0.01     1.0       -3      0     0.0   999.0       # gscale males or combined
 121.5      65.0    145.0       -4      0     0.0   999.0       # molt_mu males or combined
   0.060     0.0      1.0       -3      0     0.0   999.0       # molt_cv males or combined

## ---------------------------------------------------------------------------------- ##
## SELECTIVITY CONTROLS                                                               ##
##     Each gear must have a selectivity and a retention selectivity. If a uniform    ##
##     prior is selected for a parameter then the lb and ub are used (p1 and p2 are   ##
##     ignored)                                                                       ##
## LEGEND                                                                             ##
##     sel type: 0 = parametric, 1 = coefficients, 2 = logistic, 3 = logistic95,     ##
##               4 = double normal (NIY)                                              ##
##     gear index: use +ve for selectivity, -ve for retention                        ##
##     sex dep: 0 for sex-independent, 1 for sex-dependent                           ##
## ---------------------------------------------------------------------------------- ##
## ivector for number of year periods or nodes                                        ##
## POT       TBycatch FBycatch  NMFS_S   ADFG_pot
## Gear-1    Gear-2   Gear-3    Gear-4   Gear-5
   2         1        1         1        1         # Selectivity periods
   0         0        0         0        0         # sex specific selectivity
   0         3        3         0        0         # male selectivity type
## Gear-1    Gear-2   Gear-3    Gear-4   Gear-5
   1         1        1         1        1         # Retention periods
   0         0        0         0        0         # sex specific retention
   3         2        2         2        2         # male retention type
   1         0        0         0        0         # male retention flag (0 -> no, 1 -> yes)
## gear  par   sel                                            phz    start  end        ##
## index index par sex  ival  lb    ub     prior p1     p2     mirror period period     ##
# Gear-1
   1     1     1   0    0.4   0.001 1.0    0       0      1     3     1978   2008
   1     2     2   0    0.7   0.001 1.0    0       0      1     3     1978   2008
   1     3     3   0    1.0   0.001 2.0    0       0      1    -2     1978   2008
   1     1     1   0    0.4   0.001 1.0    0       0      1     3     2009   2018
   1     2     2   0    0.4   0.001 1.0    0       0      1     3     2009   2018
   1     3     3   0    1.0   0.001 2.0    0       0      1    -2     2009   2018
# Gear-2
   2     7     1   0    40     10.0  200    0      10    200    -3     1978   2018
```

```
  2    8    2   0   60     10.0  200   0     10   200   -3    1978   2018
# Gear-3
  3    9    1   0   40     10.0  200   0     10   200   -3    1978   2018
  3   10    2   0   60     10.0  200   0     10   200   -3    1978   2018
# Gear-4
  4    8    1   0   0.7    0.001 1.0   0      0     1    4    1978   2018
  4    9    2   0   0.7    0.001 1.0   0      0     1    4    1978   2018
  4   10    3   0   0.9    0.001 1.0   0      0     1   -5    1978   2018
# Gear-5
  5   11    1   0   0.4    0.001 1.0   0      0     1    4    1978   2018
  5   12    2   0   0.7    0.001 1.0   0      0     1    4    1978   2018
  5   13    3   0   1.0    0.001 2.0   0      0     1   -2    1978   2018
## Retained
# Gear-1
 -1   14    1   0  120   100   200   0     1   900   -1    1978   2018
 -1   15    2   0  123   110   200   0     1   900   -1    1978   2018
# Gear-2
 -2   16    1   0  595    1    700   0     1   900   -3    1978   2018
 -2   17    2   0   10    1    700   0     1   900   -3    1978   2018
# Gear-3
 -3   18    1   0  590    1    700   0     1   900   -3    1978   2018
 -3   19    2   0   10    1    700   0     1   900   -3    1978   2018
# Gear-4
 -4   20    1   0  580    1    700   0     1   900   -3    1978   2018
 -4   21    2   0   20    1    700   0     1   900   -3    1978   2018
# Gear-5
 -5   22    1   0  580    1    700   0     1   900   -3    1978   2018
 -5   23    2   0   20    1    700   0     1   900   -3    1978   2018

## ———————————————————————————————————————————————————————————————————————————————— ##
## PRIORS FOR CATCHABILITY
##     If a uniform prior is selected for a parameter then the lb and ub are used (p1   ##
##     and p2 are ignored). ival must be > 0                                            ##
## LEGEND                                                                               ##
##     prior: 0 = uniform, 1 = normal, 2 = lognormal, 3 = beta, 4 = gamma               ##
## ———————————————————————————————————————————————————————————————————————————————— ##
##  LAMBDA: Arbitrary relative weights for each series, 0 = do not fit.
## SURVEYS/INDICES ONLY
## ival    lb      ub    phz   prior   p1      p2    Analytic?   LAMBDA
  1.0     0.5     1.2   -4    0       0       9.0   0           1       # NMFS trawl
 0.003     0       5     3    0       0       9.0   0           1       # ADF&G pot
## ———————————————————————————————————————————————————————————————————————————————— ##

## ———————————————————————————————————————————————————————————————————————————————— ##
## ADDITIONAL CV FOR SURVEYS/INDICES                                                    ##
##     If a uniform prior is selected for a parameter then the lb and ub are used (p1   ##
##     and p2 are ignored). ival must be > 0                                            ##
## LEGEND                                                                               ##
##     prior: 0 = uniform, 1 = normal, 2 = lognormal, 3 = beta, 4 = gamma               ##
## ———————————————————————————————————————————————————————————————————————————————— ##
## ival        lb         ub        phz   prior     p1      p2
  0.0000001     0.00000001   10.0      -4    4         1.0     100   # NMFS
  0.0000001     0.00000001   10.0      -4    4         1.0     100   # ADF&G
## ———————————————————————————————————————————————————————————————————————————————— ##

## ———————————————————————————————————————————————————————————————————————————————— ##
## PENALTIES FOR AVERAGE FISHING MORTALITY RATE FOR EACH GEAR
## ———————————————————————————————————————————————————————————————————————————————— ##
## Mean_F  STD_PHZ1  STD_PHZ2     PHZ
  0.2       0.05     50.0       1   # Pot
  0.0001     0.05     50.0       1   # Trawl
  0.0001     0.05     50.0       1   # Fixed
  0.00      2.00     20.00     -1   # NMFS
  0.00      2.00     20.00     -1   # ADF&G
## ———————————————————————————————————————————————————————————————————————————————— ##

## ——————————————————————————————————————————————————————————————————————————————— ##
## OPTIONS FOR SIZE COMPOSTION DATA (COLUMN FOR EACH MATRIX)
## ———————————————————————————————————————————————————————————————————————————————— ##
## LIKELIHOOD OPTIONS
##   -1) Multinomial with estimated/fixed sample size
##   -2) Robust approximation to multinomial
```

```
##   -3) logistic normal (NIY)
##   -4) multivariate-t (NIY)
##   -5) Dirichlet
## AUTOTAIL COMPRESSION
##   pmin is the cumulative proportion used in tail compression.
## ------------------------------------------------------------------------------------ ##
#  1   1   1  # Type of likelihood
  2   2   2  # Type of likelihood
#  5   5   5   # Type of likelihood
  0   0   0   # Auto tail compression (pmin)
  1   1   1   # Initial value for effective sample size multiplier
 -4  -4  -4   # Phz for estimating effective sample size (if appl.)
  1   2   3   # Composition aggregator
  1   1   1   # LAMBDA
## ------------------------------------------------------------------------------------ ##

## ------------------------------------------------------------------------------------ ##
## TIME VARYING NATURAL MORTALIIY RATES                                                 ##
## ------------------------------------------------------------------------------------ ##
## TYPE:
##      0 = constant natural mortality
##      1 = Random walk (deviates constrained by variance in M)
##      2 = Cubic Spline (deviates constrained by nodes & node-placement)
##      3 = Blocked changes (deviates constrained by variance at specific knots)
##      4 = Time blocks
## ------------------------------------------------------------------------------------ ##
## Sex-specific? (0=no, 1=yes)
0
## Type
3
## Phase of estimation
3
## STDEV in m_dev for Random walk
10.0
## Number of nodes for cubic spline or number of step-changes for option 3
2
0 # Females (ignored if single sex...)
## Year position of the knots (vector must be equal to the number of nodes)
1998 1999
# 1976 1980 1985 1994 # Females (ignored if single sex...)
## ------------------------------------------------------------------------------------ ##

## ------------------------------------------------------------------------------------ ##
## OTHER CONTROLS
## ------------------------------------------------------------------------------------ ##
  3       # Estimated rec_dev phase
  3       # Estimated rec_ini phase
  0       # VERBOSE FLAG (0 = off, 1 = on, 2 = objective func)
  2       # Initial conditions (0 = Unfished, 1 = Steady-state fished, 2 = Free parameters)
  1978    # First year for average recruitment for Bspr calculation
  2018    # Last year for average recruitment for Bspr calculation
  0.35    # Target SPR ratio for Bmsy proxy
  1       # Gear index for SPR calculations (i.e. directed fishery)
  1       # Lambda (proportion of mature male biomass for SPR reference points)
  1       # Use empirical molt increment data (0 = FALSE, 1 = TRUE)
  0       # Stock-Recruit-Relationship (0 = None, 1 = Beverton-Holt)
## EOF
9999
```

Appendix C. Spatio-temporal analysis of NMFS bottom-trawl survey SMBKC data

Overview

This application of VAST was configured to model a subset of NMFS/AFSC bottom trawl survey data. Specifically, the station-specific CPUE (kg per hectare) for male crab great than or equal to 90mm CW were compiled from 1978-2018. Further details can be found at the GitHub repo mainpage, wiki, and glossary. The R help files, e.g., `?Data_Fn` for explanation of data inputs, or `?Param_Fn` for explanation of parameters. VAST has involved many publications for developing individual features (see references section below). What follows is intended as a step by step documentation of applying the model to these data.

Model configuration

The following loads in the main libraries.

Spatial settings

The following settings define the spatial resolution for the model, and whether to use a grid or mesh approximation as well as specific model settings.

Data preparation

Data-frame for catch-rate data

The following extracts a subset of the data file downloaded from AKFIN.

Build and run model

To estimate parameters, first create a list of data-inputs used for parameter estimation. `Data_Fn` has some simple checks for buggy inputs, but also please read the help file `?Data_Fn`.

Diagnostic plots

Convergence

Diagnostics generated during parameter estimation can confirm that parameter estimates are away from upper or lower bounds and that the final gradient for each fixed-effect is close to zero. For explanation of parameters, please see references (and specifically `Data_Fn` in R).

Encounter-probability component

One can check to ensure that observed encounter frequencies for either low or high probability samples are within the 95% predictive interval for predicted encounter probability (Figure . Diagnostics for positive-catch-rate component was evaluated using a standard Q-Q plot. Qualitatively, the fits to SMBKC are reasonable but could stand some more evaluation for improvement as only one configuration was tested here (Figures ?? and .

Pearson residuals

Spatially the residual pattern can be evaluated over time. Results for SMBKC shows that consistent positive or negative residuals accross or within years is limited for the encounter probability component of the model and for the positive catch rate component (Figures 29 and 30, respectively). Some VAST plots for visualizing results can be seen by examining the direction of faster or slower spatial decorrelation (termed "geometric anisotropy"; Figure 31).

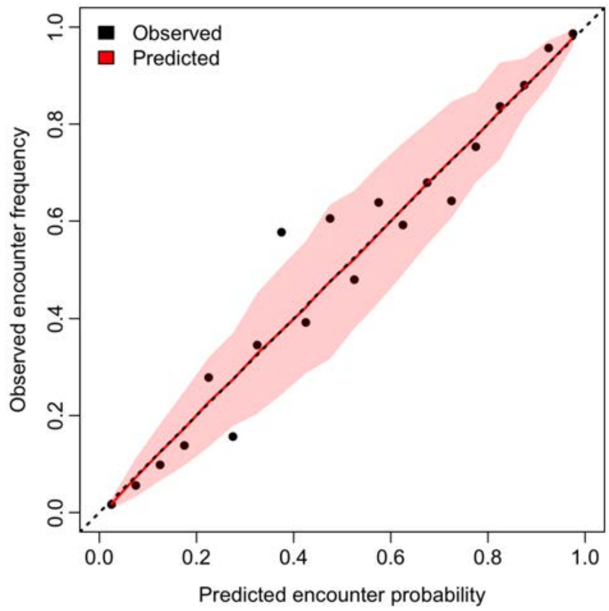

Figure 26: Observed encounter rates and predicted probabilities for SMBKC.

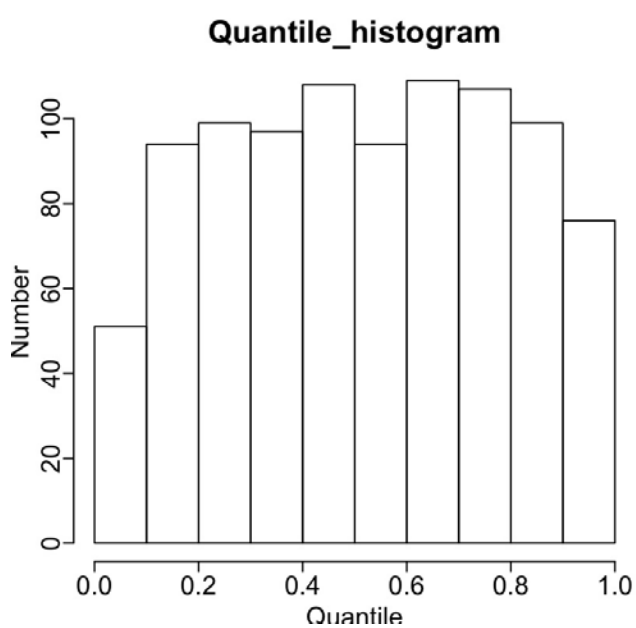

Figure 27: Plot indicating distribution of quantiles for "positive catch rate" component.

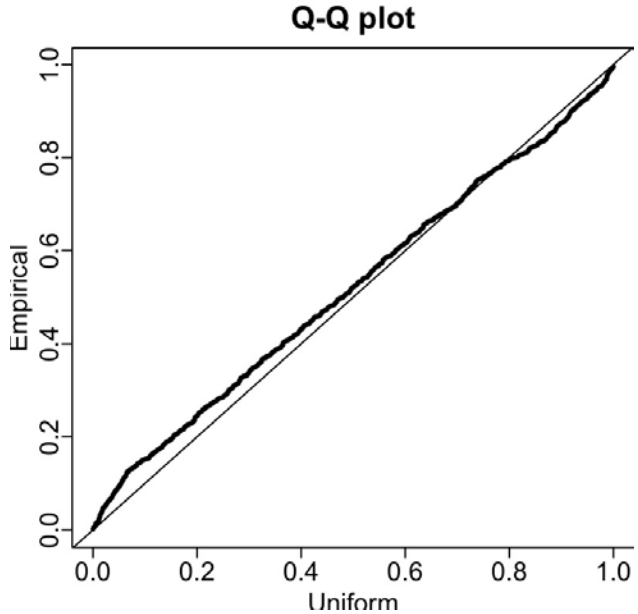

Figure 28: Quantile-quantile plot of residuals for "positive catch rate" component.

Densities and biomass estimates

Relative densities over time suggests that the biomass of males >89mm are generally concentrated within the central part of the survey region (Figure 32). For the application to SMBKC, the biomass index was scaled to have the same mean as that from the design-based estimate (5,764 t) of abundance (Table 27).

Appendix C references

Please cite 2016 (ICES J. Mar. Sci. J. Cons.) if using the package; 2016 (Glob. Ecol. Biogeogr) if exploring factor decomposition of spatio-temporal variation; 2015 (ICES J. Mar. Sci. J. Cons.) if calculating an index of abundance; 2016 (Methods Ecol. Evol.) if using the center-of-gravity metric; 2016 (Fish. Res.) if using the bias-correction feature; 2016 (Proc R Soc B) if using the effective-area-occupied metric.

Thorson, J.T., and Barnett, L.A.K. In press. Comparing estimates of abundance trends and distribution shifts using single- and multispecies models of fishes and biogenic habitat. ICES J. Mar. Sci. J. Cons

Thorson, J.T., Ianelli, J.N., Larsen, E., Ries, L., Scheuerell, M.D., Szuwalski, C., and Zipkin, E. 2016. Joint dynamic species distribution models: a tool for community ordination and spatiotemporal monitoring. Glob. Ecol. Biogeogr. 25(9): 1144-1158. doi:10.1111/geb.12464. url: http://onlinelibrary.wiley.com/doi/10.1111/geb.12464/abstract

Thorson, J.T., Shelton, A.O., Ward, E.J., Skaug, H.J., 2015. Geostatistical delta-generalized linear mixed models improve precision for estimated abundance indices for West Coast groundfishes. ICES J. Mar. Sci. J. Cons. 72(5), 1297-1310. doi:10.1093/icesjms/fsu243. URL: http://icesjms.oxfordjournals.org/content/72/5/1297

Thorson, J.T., and Kristensen, K. 2016. Implementing a generic method for bias correction in statistical models using random effects, with spatial and population dynamics examples. Fish. Res. 175: 66-74. doi:10.1016/j.fishres.2015.11.016. url: http://www.sciencedirect.com/science/article/pii/S0165783615301399

Thorson, J.T., Pinsky, M.L., Ward, E.J., 2016. Model-based inference for estimating shifts in species distribution, area occupied, and center of gravity. Methods Ecol. Evol. 7(8), 990-1008. doi:10.1111/2041-210X.12567. URL: http://onlinelibrary.wiley.com/doi/10.1111/2041-210X.12567/full

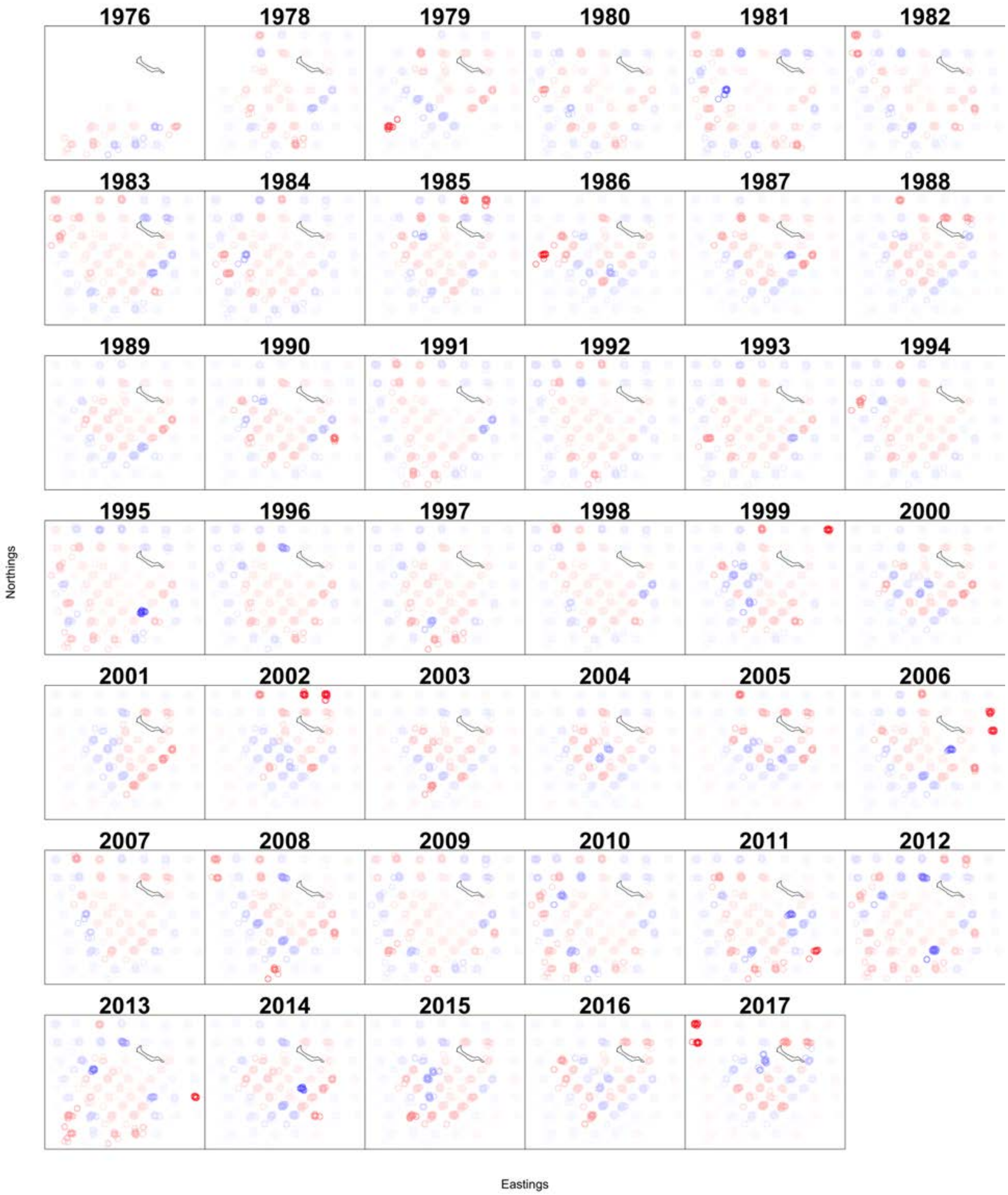

Figure 29: Pearson residuals of the encounter probability component at SMBKC stations, 1976-2018.

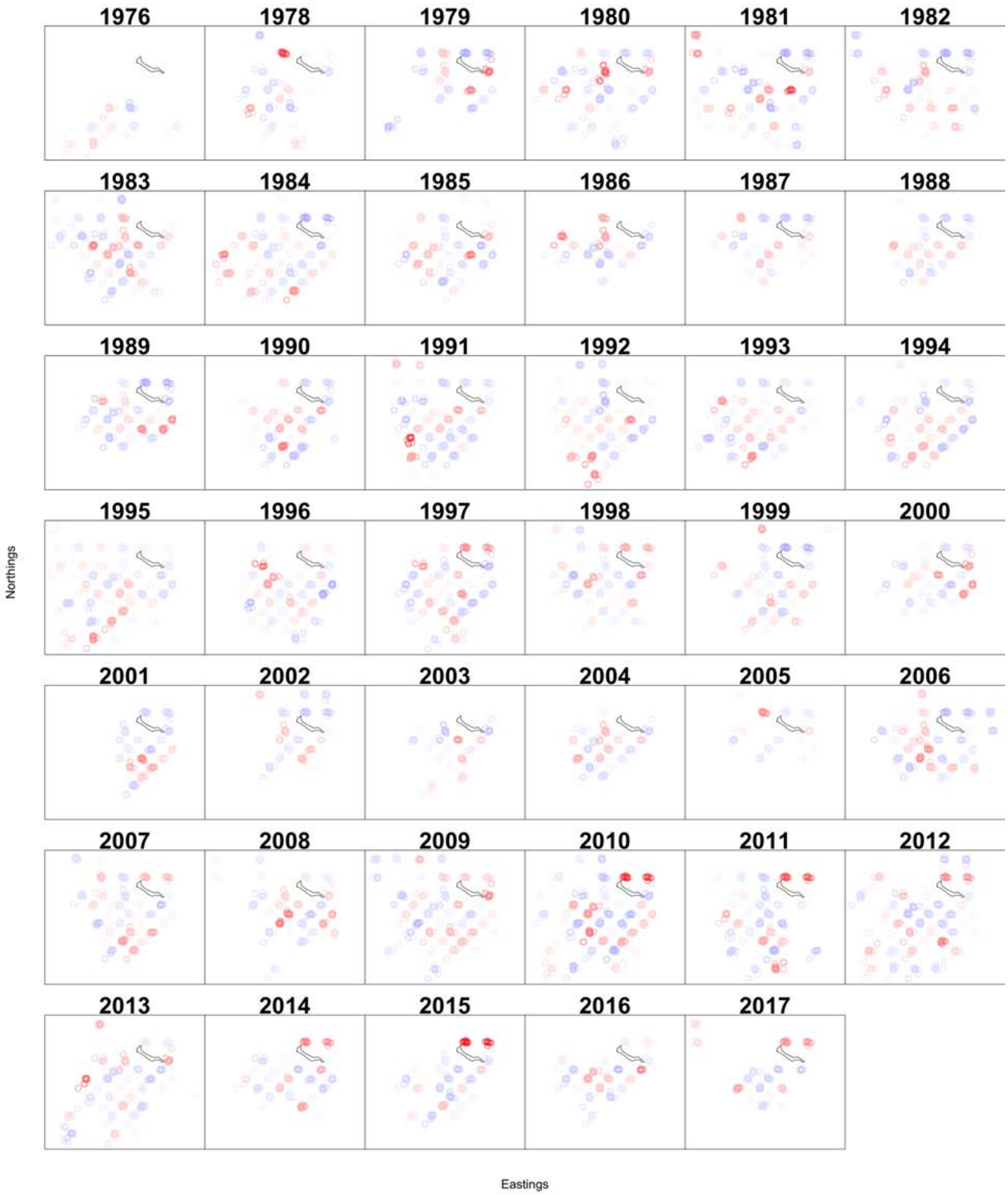

Figure 30: Pearson residuals of the positive catch rate component for SMBKC stations, 1976-2018.

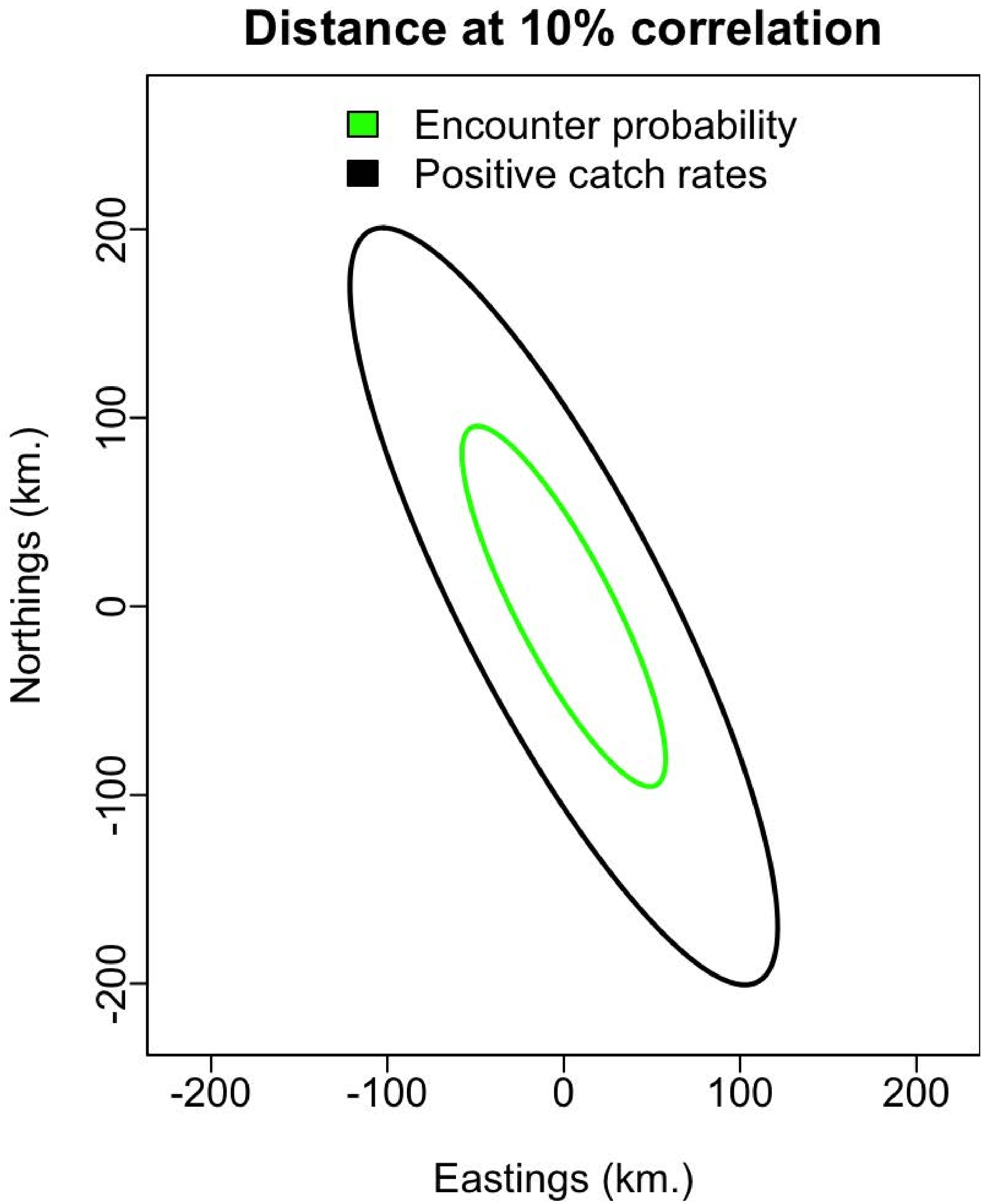

Figure 31: Directional decorrelation for SMBKC stations, 1978-2018.

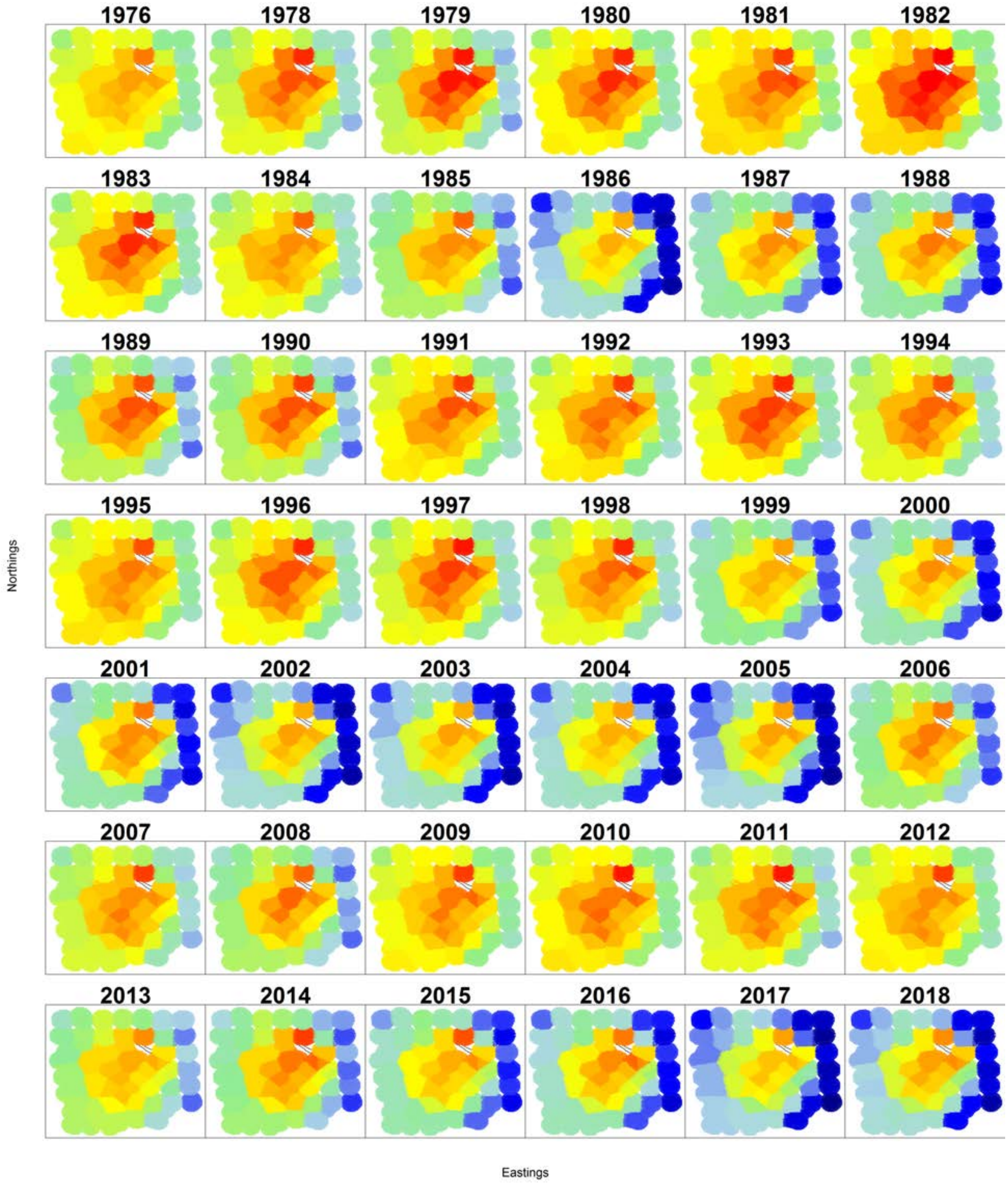

Figure 32: St. Matthews Island blue king crab (males >89mm) density maps as predicted using the VAST model approach, 1976-2018.

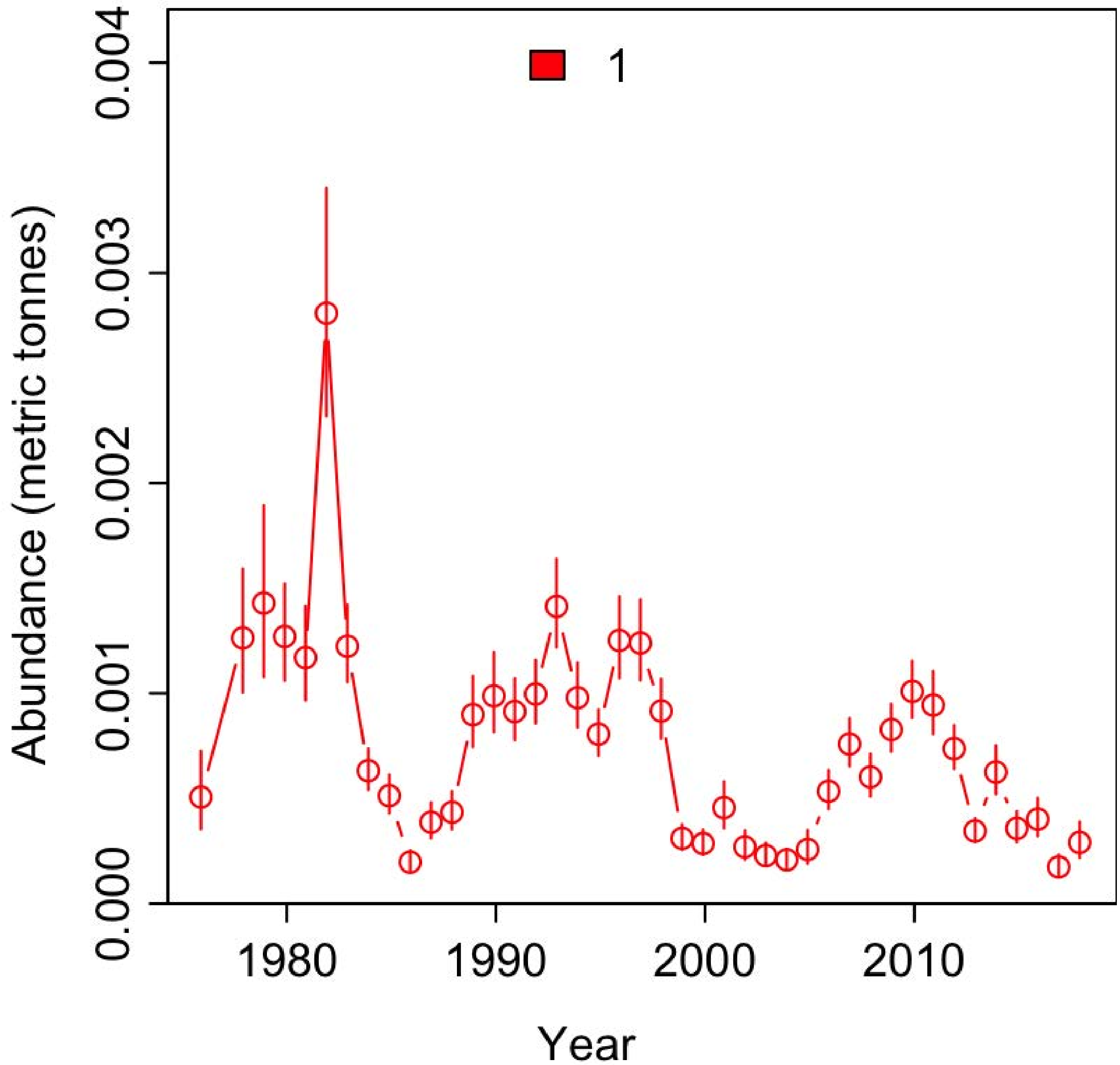

Figure 33: St. Matthews Island blue king crab (males >89mm) relative abundance as predicted using the VAST model approach.

Thorson, J.T., Rindorf, A., Gao, J., Hanselman, D.H., and Winker, H. 2016. Density-dependent changes in effective area occupied for sea-bottom-associated marine fishes. Proc R Soc B 283(1840): 20161853. doi:10.1098/rspb.2016.1853. URL: http://rspb.royalsocietypublishing.org/content/283/1840/20161853.

To see these entries in BibTeX format, use 'print(, bibtex=TRUE)', 'toBibtex(.)', or set 'options(citation.bibtex.max=999)'.

Table 22: Proportion of the natural mortality (τ_t) that is applied during each season (t) in the model.

Year	Season 1	Season 2	Season 3	Season 4	Season 5
1978	0.00	0.07	0.00	0.56	0.37
1979	0.00	0.06	0.00	0.57	0.37
1980	0.00	0.07	0.00	0.56	0.37
1981	0.00	0.05	0.00	0.58	0.37
1982	0.00	0.07	0.00	0.56	0.37
1983	0.00	0.12	0.00	0.51	0.37
1984	0.00	0.10	0.00	0.53	0.37
1985	0.00	0.14	0.00	0.49	0.37
1986	0.00	0.14	0.00	0.49	0.37
1987	0.00	0.14	0.00	0.49	0.37
1988	0.00	0.14	0.00	0.49	0.37
1989	0.00	0.14	0.00	0.49	0.37
1990	0.00	0.14	0.00	0.49	0.37
1991	0.00	0.18	0.00	0.45	0.37
1992	0.00	0.14	0.00	0.49	0.37
1993	0.00	0.18	0.00	0.45	0.37
1994	0.00	0.18	0.00	0.45	0.37
1995	0.00	0.18	0.00	0.45	0.37
1996	0.00	0.18	0.00	0.45	0.37
1997	0.00	0.18	0.00	0.45	0.37
1998	0.00	0.18	0.00	0.45	0.37
1999	0.00	0.18	0.00	0.45	0.37
2000	0.00	0.18	0.00	0.45	0.37
2001	0.00	0.18	0.00	0.45	0.37
2002	0.00	0.18	0.00	0.45	0.37
2003	0.00	0.18	0.00	0.45	0.37
2004	0.00	0.18	0.00	0.45	0.37
2005	0.00	0.18	0.00	0.45	0.37
2006	0.00	0.18	0.00	0.45	0.37
2007	0.00	0.18	0.00	0.45	0.37
2008	0.00	0.18	0.00	0.45	0.37
2009	0.00	0.44	0.00	0.19	0.37
2010	0.00	0.44	0.00	0.19	0.37
2011	0.00	0.44	0.00	0.19	0.37
2012	0.00	0.44	0.00	0.19	0.37
2013	0.00	0.44	0.00	0.19	0.37
2014	0.00	0.44	0.00	0.19	0.37
2015	0.00	0.44	0.00	0.19	0.37
2016	0.00	0.44	0.00	0.19	0.37
2017	0.00	0.44	0.00	0.19	0.37
2018	0.00	0.44	0.00	0.19	0.37

Table 23: 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 24: 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 13	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 10	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

Table 25: 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

Table 26: SMBKC parameter estimates, bounds, and final gradients as derived from the VAST modeling framework.

Param	Lower	MLE	Upper	final_gradient
ln_H_input	-50.0	-0.157	50.0	0.00001
ln_H_input	-50.0	-0.637	50.0	-0.00006
beta1_ct	-50.0	1.068	50.0	0.00001
beta1_ct	-50.0	-1.381	50.0	0.00001
beta1_ct	-50.0	-2.306	50.0	-0.00002
beta1_ct	-50.0	-0.486	50.0	0.00001
beta1_ct	-50.0	0.556	50.0	0.00001
beta1_ct	-50.0	-0.774	50.0	0.00001
beta1_ct	-50.0	-0.643	50.0	-0.00004
beta1_ct	-50.0	-0.616	50.0	0.00000
beta1_ct	-50.0	-1.786	50.0	0.00000
beta1_ct	-50.0	-3.240	50.0	-0.00000
beta1_ct	-50.0	-2.464	50.0	0.00001
beta1_ct	-50.0	-2.955	50.0	0.00002
beta1_ct	-50.0	-2.080	50.0	0.00001
beta1_ct	-50.0	-1.924	50.0	-0.00001
beta1_ct	-50.0	-0.402	50.0	-0.00002
beta1_ct	-50.0	-0.534	50.0	-0.00001
beta1_ct	-50.0	-0.867	50.0	-0.00001
beta1_ct	-50.0	-1.032	50.0	-0.00001
beta1_ct	-50.0	0.265	50.0	-0.00002
beta1_ct	-50.0	-0.869	50.0	-0.00001
beta1_ct	-50.0	-1.201	50.0	-0.00001
beta1_ct	-50.0	-1.061	50.0	-0.00004
beta1_ct	-50.0	-1.742	50.0	0.00001
beta1_ct	-50.0	-2.691	50.0	-0.00001
beta1_ct	-50.0	-3.145	50.0	-0.00001
beta1_ct	-50.0	-3.401	50.0	-0.00004
beta1_ct	-50.0	-3.412	50.0	0.00002
beta1_ct	-50.0	-3.214	50.0	0.00002
beta1_ct	-50.0	-3.797	50.0	-0.00001
beta1_ct	-50.0	-1.776	50.0	0.00000
beta1_ct	-50.0	-1.032	50.0	-0.00002
beta1_ct	-50.0	-1.630	50.0	-0.00001
beta1_ct	-50.0	0.157	50.0	0.00001
beta1_ct	-50.0	0.141	50.0	0.00001
beta1_ct	-50.0	-1.206	50.0	-0.00003
beta1_ct	-50.0	0.143	50.0	0.00001
beta1_ct	-50.0	-0.956	50.0	0.00005
beta1_ct	-50.0	-2.236	50.0	0.00001
beta1_ct	-50.0	-2.546	50.0	-0.00001
beta1_ct	-50.0	-3.100	50.0	-0.00000
beta1_ct	-50.0	-3.756	50.0	0.00002
L_omega1_z	-50.0	2.282	50.0	0.00007
L_epsilon1_z	-50.0	0.683	50.0	-0.00009
logkappa1	-4.7	-3.695	-1.9	-0.00003
beta2_ct	-50.0	-8.669	50.0	0.00004
beta2_ct	-50.0	-7.498	50.0	0.00008
beta2_ct	-50.0	-7.295	50.0	0.00011
beta2_ct	-50.0	-7.582	50.0	0.00008
beta2_ct	-50.0	-7.801	50.0	-0.00014
beta2_ct	-50.0	-6.802	50.0	0.00000
beta2_ct	-50.0	-7.813	50.0	0.00013
beta2_ct	-50.0	-8.131	50.0	-0.00000
beta2_ct	-50.0	-8.362	50.0	-0.00010
beta2_ct	-50.0	-8.978	50.0	-0.00006
beta2_ct	-50.0	-8.486	50.0	0.00001

Table 27: SMBKC male >89mm biomass (t) estimates as derived from the VAST modeling framework.

Year	Estimate	CV
1977	4149.9	0.933
1978	8257.2	0.204
1979	11852.5	0.255
1980	10570.5	0.172
1981	8714.3	0.168
1982	20910.3	0.186
1983	9646.5	0.145
1984	4824.5	0.154
1985	4017.3	0.173
1986	1435.4	0.232
1987	2894.2	0.203
1988	3131.6	0.198
1989	6685.3	0.180
1990	6882.2	0.178
1991	7448.5	0.151
1992	7835.2	0.144
1993	10445.3	0.145
1994	7084.7	0.151
1995	6202.7	0.132
1996	9390.2	0.150
1997	9335.1	0.149
1998	6917.6	0.147
1999	2260.9	0.181
2000	2237.3	0.197
2001	3305.7	0.233
2002	1767.8	0.239
2003	1714.8	0.222
2004	1812.2	0.219
2005	1773.7	0.273
2006	3862.7	0.169
2007	5607.0	0.149
2008	4587.6	0.165
2009	6419.3	0.132
2010	7902.4	0.132
2011	7510.2	0.154
2012	5958.9	0.135
2013	2702.6	0.155
2014	4759.7	0.175
2015	2719.7	0.192
2016	2905.8	0.209
2017	1325.5	0.259
2018	2281.2	0.264