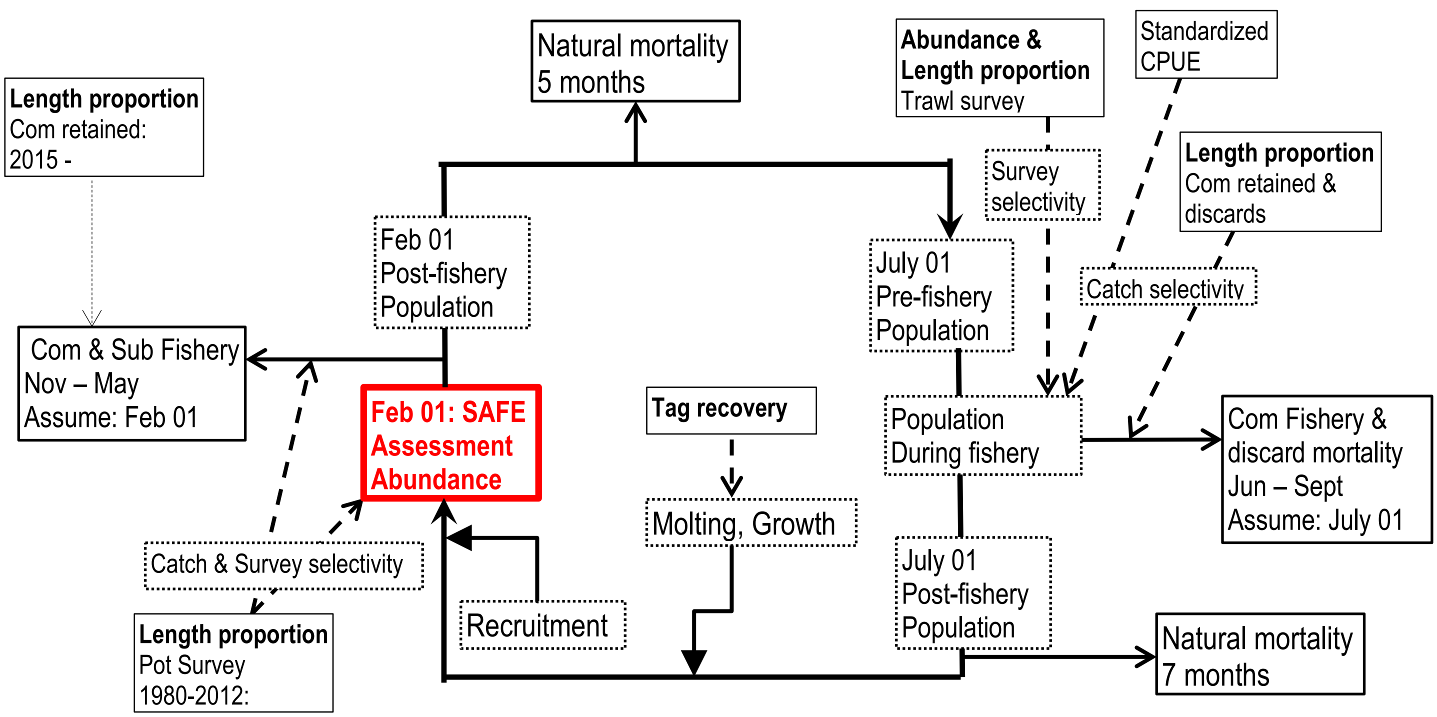
Appendix A. Description of the Norton Sound Red King Crab Model

a. Model description.

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

Norton Sound Red King Crab Modeling Scheme



Timeline of calendar events and crab modeling events:

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

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

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

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

$$N_{l,1} = p_l e^{\log\_N_{76}} \tag{1}$$

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

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

for model estimated parameters a_l.

Crab abundance on July 1st

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

$$\begin{aligned} N_{s,l,t} &= (N_{w,l,t} - C_{w,t}P_{w,n,l,t} - C_{p,t}P_{p,n,l,t} - D_{w,n,l,t} - D_{p,n,l,t})e^{-0.42M_l} \\ O_{s,l,t} &= (O_{w,l,t} - C_{w,t-1}P_{w,o,l,t} - C_{p,t}P_{p,o,l,t} - D_{w,o,l,t} - D_{p,o,l,t})e^{-0.42M_l} \end{aligned} \tag{3}$$

where

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

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

$$\begin{array}{c}
\text{1976-2007} \\
P_{w,n,l,t} = N_{w,l,t} S_{w,l} P_{lg,l} / \sum_{l=1} [(N_{w,l,t} + O_{w,l,t}) S_{w,l} P_{lg,l}] \\
P_{w,o,l,t} = O_{w,l,t} S_{w,l} P_{lg,l} / \sum_{l=1} [(N_{w,l,t} + O_{w,l,t}) S_{w,l} P_{lg,l}] \\
\text{2008-present} \\
P_{cw,n,l,t} = N_{w,l,t} S_{w,l} S_{wr,l} / \sum_{l} [(N_{w,l,t} + O_{w,l,t}) S_{w,l} S_{wr,l}] \\
P_{cw,o,l,t} = O_{w,l,t} S_{w,l} S_{wr,l} / \sum_{l} [(N_{w,l,t} + O_{w,l,t}) S_{w,l} S_{wr,l}]
\end{array} \tag{4}$$

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

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

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

$$\begin{array}{c}
P_{p,n,l,t} = N_{w,l,t} S_{w,l} / \sum_{l=3} [(N_{w,l,t} + O_{w,l,t}) S_{w,l}] \\
P_{p,o,l,t} = O_{w,l,t} S_{w,l} / \sum_{l=3} [(N_{w,l,t} + O_{w,l,t}) S_{w,l}]
\end{array} \tag{5}$$

Crab abundance on Feb 1st

Between July 01 to Feb 01 of the next year, following events occur: (1) summery fishery, (2) summer fishery discards mortality, (3) molting and recruitment, and (4) natural mortality between the two periods. Those are formulated as follows:

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

$$N_{w,l,t} = \sum_{l'=1}^{l'=l} G_{l',l}[(N_{s,l',t-1} + O_{s,l',t-1})e^{-y_c M_l} - C_{s,t}(P_{s,n,l',t-1} + P_{s,o,l',t-1}) - D_{l',t-1}]\, m_{l'} e^{-(0.58-y_c)M_l} + R_{l,t-1} \tag{6}$$

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

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

where

$G_{l',l}$: a growth matrix representing the expected proportion of crabs growing from length class l' to length class l
$C_{s,t}$: total summer catch in year t
$P_{s,n,l,t-1}$, $P_{s,o,l,t-1}$: proportion of summer catch for newshell and oldshell crabs of length class l in year $t-1$,
$D_{l,t-1}$: summer discard mortality of length class l in year $t-1$,
m_l : molting probability of length class l,
y_c : the time in year from July 1 to the mid-point of the summer fishery,
0.58: Proportion of the year from July 1st to Feb 1st is 7 months is 0.58 year,
$R_{l,t-1}$: recruitment into length class l in year $t-1$.

Discards

Discards are crabs that were caught by fisheries but were not retained, which consists of summer commercial, winter commercial and winter subsistence.

Summer and winter commercial discards

In summer ($D_{l,t}$) and winter ($D_{w,n,l,t}$, $D_{w,o,l,t}$) commercial fisheries, sublegal males (<4.75 inch CW and <5.0 inch CW since 2005) are discarded. Those discarded crabs are subject to handling mortality. The number of discards was not directly observed, and thus was estimated from the model as: Observed Catch x (estimated abundance of crab that are not caught by commercial pot)/(estimated abundance of crab that are caught by commercial pot)

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

$$D_{l,t} = C_{s,t} \frac{(N_{s,l,t} + O_{s,l,t}) S_{s,l} (1 - S_{r,l})}{\sum_{l} (N_{s,l,t} + O_{s,l,t}) S_{s,l} S_{r,l}} hm_s \tag{8}$$

$$D_{w,n,l,t} = C_{w,t} \frac{N_{w,l,t} S_{w,l} (1 - S_{wr,l})}{\sum_{l} (N_{w,l,t} + O_{w,l,t}) S_{w,l} S_{wr,l}} hm_w \tag{9}$$

$$D_{w,o,l,t} = C_{w,t} \frac{O_{w,l,t} S_{w,l} (1 - S_{wr,l})}{\sum_{l} (N_{w,l,t} + O_{w,l,t}) S_{w,l} S_{wr,l}} hm_w \tag{10}$$

where

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

Winter subsistence Discards

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

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

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

$C_{d,t}$: Winter subsistence discards catch,

Recruitment

Recruitment of year t, R_t, is a stochastic process around the geometric mean, R_0:

$$R_t = R_0 e^{\tau_t}, \tau_t \sim N(0, \sigma_R^2) \tag{13}$$

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

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

$$R_{r,t} = p_r\, R_t \tag{14}$$

where r takes multinomial distribution, same as the equation (2)

Molting Probability

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

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

Trawl net, summer commercial pot,

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

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

Winter pot selectivity

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

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

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

Growth transition matrix

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

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

Where

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

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

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

Observation model

Summer trawl survey abundance

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

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

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

Winter pot survey CPUE (**depleted**)

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

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

Summer commercial CPUE

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

$$\hat{f}_t = q_i(A_t - 0.5C_t) \tag{21}$$

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

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

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

Summer pot survey abundance (**depleted**)
Abundance of t-th year pot survey was estimated as

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

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

Summer commercial retained catch

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

$$\begin{aligned} \hat{P}_{s,n,l,t} &= N_{s,l,t} S_{s,l} S_{r,l} / A_t \\ \hat{P}_{s,o,l,t} &= O_{s,l,t} S_{s,l} S_{r,l} / A_t \end{aligned} \tag{24}$$

Summer commercial fishery discards (1977-1995)

Length/shell compositions of observer discards were modeled as

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

Summer commercial fishery total catch (2012-present)

Length/shell compositions of observer discards were modeled as

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

Summer trawl survey

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

$$\hat{P}_{st,n,l,t} = \frac{[N_{s,l,t}\, e^{-y_c M_l} - C_{s,t}\, P_{c,t}\, \hat{P}_{s,n,l',t}] e^{-(y_{st} - y_c) M_l} S_{st,l}}{\sum_l [(N_{s,l,t} + O_{s,l,t}) e^{-y_c M_l} - C_{s,t} P_{c,t} (\hat{P}_{s,n,l',t} + \hat{P}_{s,o,l',t})] e^{-(y_{st} - y_c) M_l} S_{st,l}}$$
$$\hat{P}_{st,o,l,t} = \frac{[O_{s,l,t}\, e^{-y_c M_l} - C_{s,t}\, \hat{P}_{s,o,l',t}\, P_{c,t}] e^{-(y_{st} - y_c) M_l} S_{st,l}}{\sum_l [(N_{s,l,t} + O_{s,l,t}) e^{-y_c M_l} - C_{s,t} P_{c,t} (\hat{P}_{s,n,l,t} + \hat{P}_{s,o,l,t})] e^{-(y_{st} - y_c) M_l} S_{st,l}} \tag{27}$$

Winter pot survey

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

$$\hat{P}_{sw,n,l,t} = N_{w,l,t} S_{w,l} / \sum_l [(N_{w,l,t} + O_{w,l,t}) S_{w,l}]$$
$$\hat{P}_{sw,o,l,t} = O_{w,l,t} S_{w,l} / \sum_l [(N_{w,l,t} + O_{w,l,t}) S_{w,l}] \tag{28}$$

Winter commercial retained

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

$$\hat{P}_{cw,n,l,t} = N_{w,l,t} S_{w,l} S_{wr,l} / \sum_l [(N_{w,l,t} + O_{w,l,t}) S_{w,l} S_{wr,l}]$$
$$\hat{P}_{cw,o,l,t} = O_{w,l,t} S_{w,l} S_{wr,l} / \sum_l [(N_{w,l,t} + O_{w,l,t}) S_{w,l} S_{wr,l}] \tag{29}$$

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

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

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

Estimates of tag recovery

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

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

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

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

c. Likelihood components.

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

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

where

i: length/shell compositions of :

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

$K_{i,t}$: the effective sample size of length/shell compositions for data set *i* in year *t,*
$P_{i,l,t}$: observed and estimated length compositions for data set *i*, length class *l*, and year *t.*
κ: a constant equal to 0.0001,
CV : coefficient of variation for the survey abundance,
$B_{j,t}$: observed and estimated annual total abundances for data set *i* and year *t,*
f_t : observed and estimated summer fishing CPUE,
$w^2{}_t$: extra variance factor,
SDR : Standard deviation of recruitment = 0.5,
$K_{l',t}$: sample size of length class *l'* released and recovered after *t-th* in year,
$P_{l',l,t,s}$: observed and estimated proportion of tagged crab released at length *l'* and recaptured at length *l*, after *t-th* year by commercial fishy pot selectivity *s*,
W: weighting for the tagging survey likelihood = 0.5

It is generally believed that total annual commercial crab catches in Alaska are fairly accurately reported. Thus, total annual catch was assumed known and accurate

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

d. Out of model parameter estimation framework:

i. Parameters Estimated Independently

M: Natural mortality

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

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

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

Proportion of Legal sized crab

Proportions of legal males (CW > 4.75 inches) by length group were estimated from the ADF&G trawl data 1996-2019 (Table 11).

ii. Parameters Estimated Conditionally

Estimated parameters are listed in Table 10. Selectivity and molting probabilities based on these estimated parameters are summarized in Tables 11.

A likelihood approach was used to estimate parameters

e. Definition of model outputs.

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

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

wm_l: mean weight of each length class.

ii. Projected legal male biomass subject to winter and summer fishery OFL was calculated as winter biomass times summer commercial pot selectivity times proportion of legal crab.

Though fishery size selectivity differs between winter and summer commercial, both fisheries were assumed to have the same selectivity because winter fishery is very small compared to summer fishery.

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

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

f. OFL

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

$$OFL_r = \text{Winter harvest (Hw)} + \text{Summer harvest (Hs)} \quad (1)$$

And

$$p = \frac{Hw}{OFL_r} \quad (2)$$

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

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

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

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

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

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

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

Substituting *0.42M* to *m*, summer harvest is

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

Thus, OFL is

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

Combining (2) and (7),

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

Solving (8) for x

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

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

revised retained OFL is

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

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

$$Fw = (1 - e^{-x\cdot F}) = 1 - \frac{1 - p[1 - e^{-(F+m)\cdot}]}{1 - p(1 - e^{-m\cdot})} = \frac{1 - p(1 - e^{-m\cdot}) - 1 + p[1 - e^{-(F+m)\cdot}]}{1 - p(1 - e^{-m\cdot})} \tag{10}$$
$$= \frac{p(e^{-m\cdot} - e^{-(F+m)\cdot})}{1 - p(1 - e^{-m\cdot})} = \frac{p(1 - e^{-F\cdot})e^{-0.42M\cdot}}{1 - p(1 - e^{-0.42M\cdot})}$$

Summer fishery harvest rate (Fs) is

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

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

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

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

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

Appendix B

Norton Sound Red King Crab CPUE Standardization

Note: This is an update of model by G. Bishop (SAFE 2013).

Methods

Data Source & Cleaning

Commercial fishery harvest data were obtained from ADF&G fish ticket database, which included: Landing Date, Fish Ticket Number, Vessel Number, Permit Fishery ID, Statistical Area(s) fished, Effort, and Number and Pounds of Crab harvested (Table A2-1,2,3, Figure A2-1). Fish ticket database may have multiple entries of identical Fish Ticket Number, Vessel Number, Permit Fishery ID, and Statistical Area. In those cases, at least one Effort data are missing or zero with the Number and Pounds of Crab harvested. These entries indicate that crab were either retained from the commercial fishery (i.e., not sold), or dead loss.

Following data cleaning and combining methods were conducted.

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

Data cleaning and censoring.

Norton Sound commercial red king crab fishery can be largely divided into three periods: large vessel operation (1977-1993), small vessel superexclusive (1994-2007), and small vessel superexclusive and high grading (2008-2919). Pre-superexclusive fishery consists of a few large boats, occurring in west of

167 longitude, and few deliveries, while post superexclusive fishery consists of many small boats of local fishermen, occurring east of 167 longitude and near shore, and delivering frequently (Figure 1B). Post-superexclusive period can further divided into pre (1994-2007) and post (2008-2020) highgrading periods. The majority of commercially caught red king crab are sold to Norton Sound Economic Development Corporation (NSEDC). Since mid-2000s NSEDC preferred carapase width (CW) of 5 inch or greater as marketable that was greater than legal sized crab of CW 4.75 inch or larger. This preference became more explicit since 2008 and later. For the purpose of modeling, 2008 was chosen as high-grading periods.

The data were censored in

During 1977-93 period, vessels of 1 year of operation and/or 1 delivery per year harvested 20-90% of crab (Table A2-5, Figure A2-2). For instance, all vessels did only 1 delivery in 1989, and in 1988 64% of crab were harvested by 1 vessel that did only 1 delivery. On the other hand, during the 1993-2017 period of post super-exclusive fishery status, the majority of commercial crab fishery and harvest was done by vessels with more than 5 years of operations and more than 5 deliveries per year. For 1977 – 1993, censoring was made for vessels of more than 2 years of operations. Increasing deliveries to more than one would result in no estimates for some years. For 1994 – 2018, censoring was made for vessels of more than 5 years of operations and 5 deliveries per year.

Analyses

A GLM was constructed as

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

Where YR: Year, PD: Fishery periods (1977-1993, 1994-2007,2008-2019), VSL: Vessel, MSA: Statistical Area, WOY: Week of Year, and PF: Permit vs open fishery (Table 1). All variables were treated as categorical. Inclusion of interaction terms was not considered because they were absent (SAFE 2013).

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

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

The data were separated into three periods 1977-1993, 1994-2004, and 2005-2020.

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

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

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

Permit fishery	Type	Description	Years
K09Q	Open access	KING CRAB , POT GEAR VESSEL UNDER 60', BERING SEA	1994–2002
K09Z	Open access	KING CRAB , POT GEAR VESSEL UNDER 60', NORTON SOUND	1992–2017
K09ZE	CDQ	KING CRAB , POT GEAR VESSEL UNDER 60', NORTON SOUND CDQ, NSEDC	2000–2017
K09ZF	CDQ	KING CRAB , POT GEAR VESSEL UNDER 60', NORTON SOUND CDQ, YDFDA	2002–2004
K91Q	Open access	KING CRAB , POT GEAR VESSEL 60' OR OVER, BERING SEA	1978–1989
K91Z	Open access	KING CRAB , POT GEAR VESSEL 60' OR OVER, NORTON SOUND	1982–1994

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

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

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

Periods: 1977-1993

Var	Df	Deviance	Resid DF	Resid Dev	AIC
YR	15	405.92	613	588.31	
VSL	46	176.38	567	411.93	
WOY	9	30.25	558	381.68	
MSA	3	10.07	555	371.61	
MOY	2	6.33	553	365.28	
					1597.2

Periods: 1994-2007

Var	Df	Deviance	Resid DF	Resid Dev	AIC
YR	13	396.63	2371	1462.9	
VSL	43	267.56	2328	1195.4	
WOY	15	71.08	2313	1124.3	
MSA	3	24.54	2310	1099.7	
					5074.1

Var	Df	Deviance	Resid DF	Resid Dev	AIC
YR	11	463.2	3341	2002.8	
VSL	41	340.16	3300	1662.7	
WOY	13	63.91	3287	1598.8	
MSA	3	37.13	3284	1561.6	
MOY	3	4.11	3281	1557.5	
					7090.5

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

Year	Standardized		Arithmetic
	CPUE	SE	CPUE
1977	3.61	0.30	2.77
1978	3.30	0.18	5.84
1979	1.92	0.19	2.21
1980	2.64	0.21	2.18
1981	0.84	0.14	0.85
1982	0.16	0.21	0.32
1983	0.69	0.21	0.77
1984	0.96	0.21	1.05
1985	0.50	0.16	0.69
1986	1.24	0.41	2.18
1987	0.55	0.35	0.69
1988	1.43	0.39	2.32
1989	1.56	0.34	1.13
1990	1.33	0.46	1.25
1991			
1992	0.28	0.30	0.31
1993	0.66	0.11	1.10
1994	0.97	0.06	0.65
1995	0.52	0.05	0.41
1996	0.63	0.08	0.51
1997	1.01	0.10	0.82
1998	0.85	0.13	0.51
1999	0.62	0.13	0.47
2000	1.59	0.07	1.29
2001	0.90	0.06	0.61
2002	1.66	0.07	0.95
2003	1.23	0.05	0.82
2004	1.95	0.06	1.29
2005	1.16	0.05	1.22
2006	1.35	0.05	1.29
2007	1.04	0.05	0.97
2008	1.35	0.05	1.31
2009	0.91	0.04	0.95
2010	1.26	0.04	1.20
2011	1.50	0.05	1.55
2012	1.32	0.04	1.42
2013	0.69	0.04	0.78
2014	1.10	0.04	1.14
2015	1.38	0.05	1.38
2016	1.17	0.05	1.43
2017	0.97	0.05	1.17
2018	0.61	0.05	0.74
2019	0.28	0.06	0.34

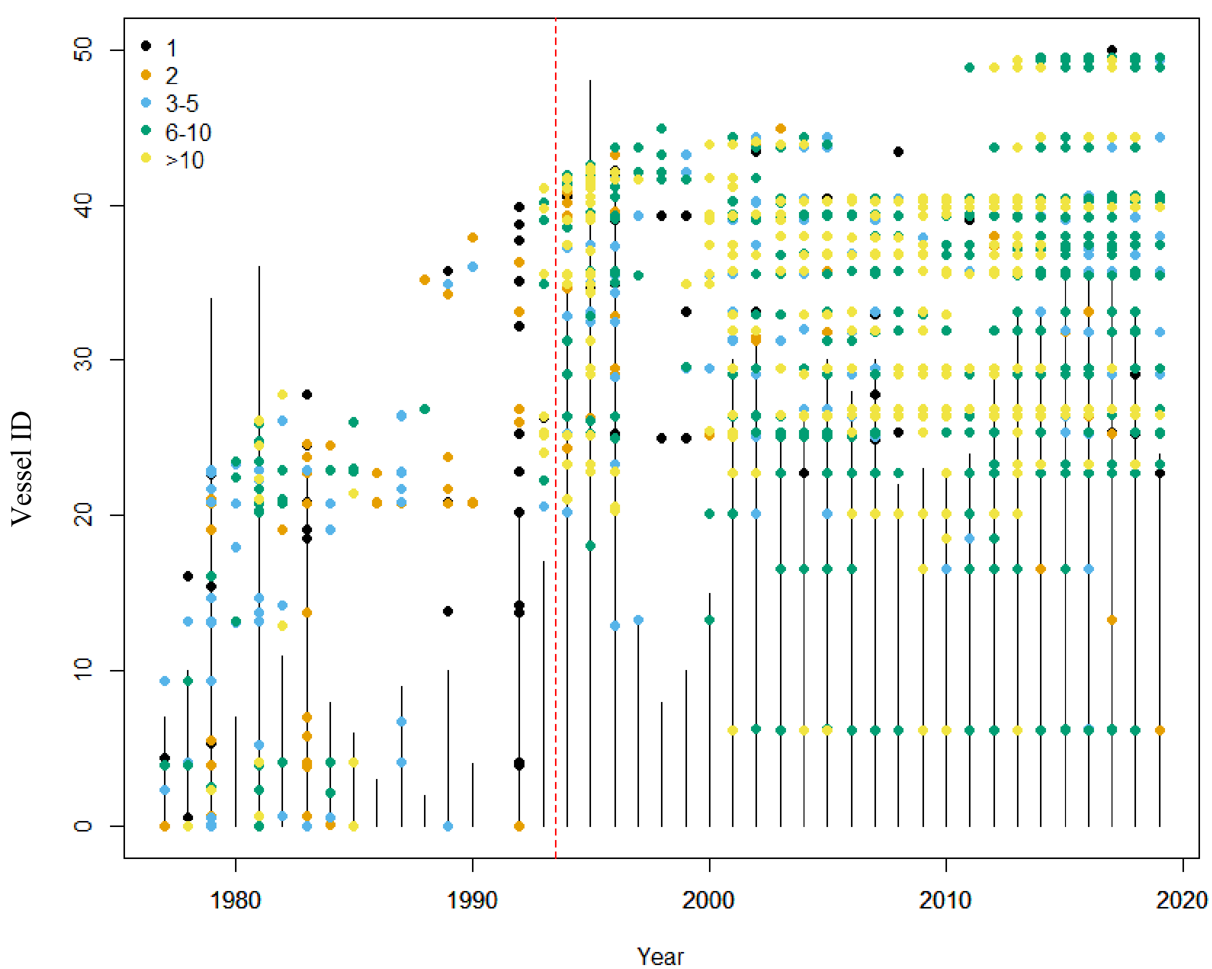


Figure B1. Number of fishing vessel (Vertical line) and distribution of unique vessel (dots) operated by year. Dot colors indicate the number of deliveries for each year by each vessel. Red vertical line indicates a break between pre (1977-1993) and post(1994-2019) Super exclusive fishery. No fishery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

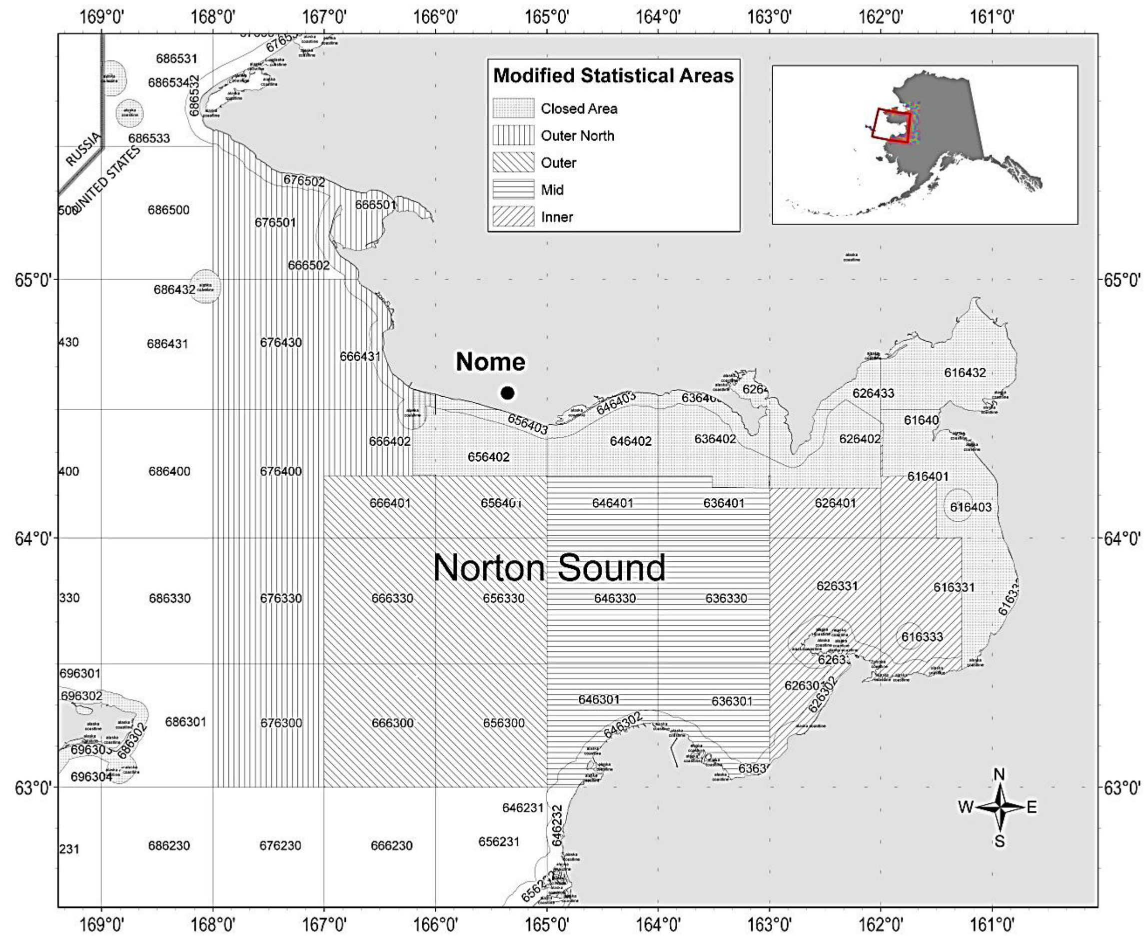


Figure A2-1. Closed area and statistical area boundaries used for reporting commercial harvest information for red king crab in Registration Area Q, Northern District, Norton Sound Section and boundaries of the new *Modified Statistical Areas* used in this analysis.

Appendix C

Norton Sound Red King Crab Summer Commercial Fishery Discard Estimation

Formal methodologies have not been established for estimating Red King Crab discards by Norton Sounds Summer commercial fishery from observer data. Here, I describe a few methods and discuss pros and cons of each method.

Data source and description of survey protocols

Norton Sound Summer Commercial fishery observer survey started in 2009 as a potential feasibility project, and formal data collection started since 2012. The observer survey in Norton Sound is voluntary. Due to small boat size, the boat that can take a fishery observer is limited. Fishery observer often work as a crew member. During the fishery, an observe inspect every pots. All lengths/shell condition/sex of red king crab in the pots were measured, and the fisherman sorts out discards that are noted. **Observed discarded crab are deemed accurate.** However, it is uncertain whether fishing behaviors of the volunteer fishermen are the same as other unobserved fishermen. Observed fishermen tend to have large boat and catcher and sellers. Here are possible concerns:

1. The observed fishermen may go to better fishing grounds with more legal crab and less sub-legals: **higher legal retain CPUE and lower discards CPUE than unobserved (lower discards proportion)**
2. The observed fishermen may not mind sorting out crab and may choose areas: **higher legal retain CPUE and higher discards CPUE than unobserved (higher discards proportion)**
3. The observed fishermen may keep more legal crab that are not accepted by NSEDC: **lower discard CPUE than unobserved (lower discard proportion)**

Data Source & Cleaning

From 2012 to 2018, crab catches of 3-4 volunteer crab fishing vessels were observed. Annual observed pots ranged 69 to 199 and total observed crab ranging from 2200 to 5300 (Table 1). All observed data were combined.

Estimation Methods

Two methods were considered: CPUE and Proportion methods. CPUE method expands observed CPUE (Observed number of crab)/(observed pots) to all fisheries pot lifts, whereas proportional method expands observed proportion of discards to retained: (observed number of discards)/(observed number of retained) to all fisheries retained catch.

CPUE has two methods: LNR and Subtraction. LNR simply expands CPUE of discards, whereas Subtraction expands CPUE of total catch and subtract total retained catch.

LNR method

LNR method simply expands CPUE of discards to total pot lifts

$$CPUE_{obs} = \frac{(N_{obs,sub} + N_{obs,ld})}{P_{obs}}$$

Where $N_{obs,\ sub}$ and $N_{obs,\ ld}$ are observed number of sublegal and legal crab discarded, and P_{obs} is the number of pot-lifts by the observed fishermen during the observed period.

$$D_{LNR} = CPUE_{obs} \cdot P_{FT.total}$$

Where $P_{FT.total}$, is total number of pot lifts of all fishermen recorded in fish tickets.

Observer bias corrected LNR method adds correction to CPUE of the observed fishermen by multiplying the CPUE ratio between observed fishermen ($CPUE_{FT.obs}$) and unobserved fishermen ($CPUE_{FT.unobs}$) derived from fish tickets.

$$CPUE_{FT.obs} = \frac{(N_{FT.obs})}{P_{FT.obs}} \qquad CPUE_{FT.unobs} = \frac{(N_{FT.unobs})}{P_{FT.unobs}}$$

Where $N_{FT.obs}$ and $N_{FT.unobs}$ are total number of crab delivered (thorough out season) by observed and unobserved fishermen, and $P_{FT.obs}$ and $P_{FT.unobs}$ total number of pot lifts by observed and unobserved fishermen.

Norton Sound red king crab CPUE standardization

$$D_{LNR2} = \left(\frac{CPUE_{FT.unobs}}{CPUE_{FT.obs}} \right) \cdot D_{LNR}$$

Subtraction method

Subtraction method expands total catch CPUE and subtracts total retained catch

$$CPUE_{T.obs} = \frac{(N_{obs})}{P_{obs}}$$

Where N_{obs} is a total number of crab caught by the observed fishermen during the observed period.

$$D_{Sub} = CPUE_{T.obs} \cdot P_{FT.total} - N_{FT.total}$$

Where $N_{FT.total}$ is the total number of retained crab during the season.

Bias corrected Subtraction method is simply bias corrected total catch minus retained catch

$$D_{Sub2} = \left(\frac{CPUE_{FT.unobs}}{CPUE_{FT.obs}} \right) CPUE_{T.obs} P_{FT.total} - N_{FT.total}$$

Finally, the proportion method that expands ratio of discards to retained.

$$D_{prop} = \frac{(N_{obs,sub} + N_{obs,ld})}{N_{obs,lr}} N_{FT.total}$$

Where $N_{obs.lr}$ is observed number of retained legal crab by observed fishermen during the observed periods.

In an assessment model, total number of crab discarded by summer commercial fishery is modeled as

$$D_{l,t} = \frac{\widehat{N}_{F.D}}{\widehat{N}_{F.R}} N_{FT.total}$$

where $N_{F.R}$ and $N_{F.D}$ are model estimated number of crab retained and discarded, which is essentially the same ss proportional method.

Results

While general annual discard trends were similar among the 3 methods, the number of discards differed (Table 2). Overall, the Subtraction method estimated the highest and the Proportional method estimated the lowest. Bias correction method (LNR2, Sub2) reduced discard estimates during 2013-2017 (Table 3).

Discussion

The CPUE method assumes that observed CPUE would represent total CPUE or that there is no difference in **CPUE** between observed and unobserved fishermen. Difference between LNR and Subtraction method is that LNR method assumes that **observed discards are accurate** whereas subtraction method assumes that **observed discards are biased but observed total catches are accurate.** On the other hand, the proportional method assumes that observed discard proportions would represent total proportion or that **every fisherman has a similar crab composition**.

In Norton Sound observer survey, discarded crab are more likely accurate because separation of retained vs discards are often done in cooperation with the fishermen. However, fishermen and timing of observation are limited to convenience of volunteer fishermen who have larger boats (so that observer can be on board) and are also high catchers. They would be more efficient in catching legal crab with fewer discards than those with small boats. They would also take observers when they expect higher catch. In fact, season total retained legal crab CPUE by observed fishermen were generally higher than other unobserved fishermen (Table 2). Furthermore, their CPUE was generally higher during the periods when observers were on board. Observed fishermen appeared to go different fishing area from those of all fishermen (Table 4). Those suggest that subtraction method would probably overestimate discards. Direction of bias for LNR and proportional methods are difficult to evaluate. If the observed fishermen tend to better avoid catching sublegal crab (e.g., lower sublegal proportion), the proportional method would underestimate discard catch. But, as they have higher catch CPUE, their discard catch CPUE could still be higher than those of unobserved fishermen. Then, discard catch estimate by LNR method could overestimate as well as underestimate.

Table 1. Observed pot lifts, catch, and total pot lifts and catch from 2012 to 2018

	Observer Survey					Fish Tickets	
	Pot lifts	Sublegal	Legal retained	Legal discards		pot lifts	Retained
Year	P_{obs}	$N_{obs.sub}$	$N_{obs.lr}$	$N_{obs.ld}$	Female	$P_{FT.total}$	$N_{FT.total}$
2012	78	898	1055	177	152	10041	161113

2013	199	2775	2166	258	123	15058	130603
2014	147	1504	1838	341	104	10127	129656
2015	69	969	1676	577	224	8356	144224
2016	67	264	1700	169	878	8,009	138997
2017	110	432	2174	122	373	9440	135322
2018	78	547	1096	10	574	8797	89613
2019	28	123	142	1	89	5436	24913

Table 2. Retained Crab CPUE between observed (CPUE.ob) during the observer survey, and season total CPUE between observed and unobserved fishermen derived from fish ticket data.

Year	CPUEobs	$CPUE_{FT.obs}$	$CPUE_{FT.unobs}$
2012	13.53	16.05	16.57
2013	10.88	8.67	7.47
2014	12.50	12.80	11.87
2015	24.29	17.26	15.62
2016	25.37	17.36	15.30
2017	19.76	14.33	13.33
2018	14.05	10.19	10.09
2019	5.07	4.58	4.56

Table 3. The number of discarded crab estimated by 5 methods and model.

Year	LNR	LNR2	Sub	Sub2	Prop	Model
2012	138386	150043	113084	136182	164167	94564
2013	229502	173750	262797	167229	182880	120486
2014	127104	104697	124070	79340	130150	147066
2015	187223	135910	245965	139023	133037	88430
2016	51760	32965	115976	23394	35403	50228
2017	47543	34870	98790	36384	34484	46441
2018	62820	60714	96816	90566	45542	45848
2019	24074	23362	26729	24203	21755	28887

Table 4. Average legal crab proportion caught by 2012-2018 trawl survey and Summer commercial harvest proportion in major fishing stat area

	Catch proportion	
STAT Area	All fishermen	Observed Fishermen
666401	15%	7%
656401	21%	18%
646401	19%	46%
636401	33%	19%
626401	15%	2%

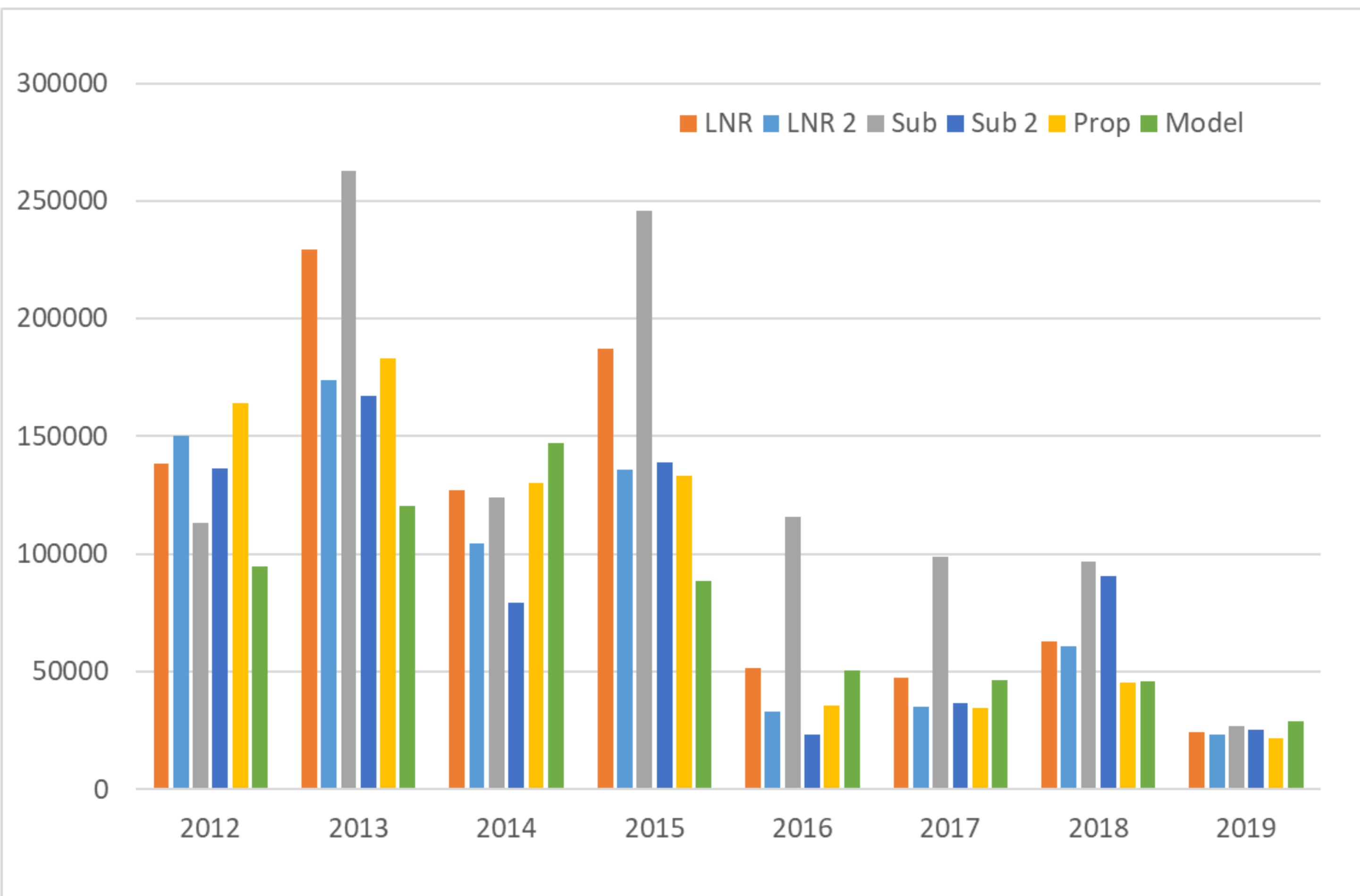


Figure 1. The number of discarded crab estimated by 3 methods.

Appendix D

VAST model estimation of Norton Sound Red King Crab abundance and distribution.

Here I present several VAST model results of Norton Sound Red King Crab abundance and distribution.

Dataset:

Trawl survey data of all years (NOAA: 1976-1991, ADFG: 1996-2020, NOAA NBS: 2010-2018) were combined as follows:

Year	Agent	Latitude	Longitude	Swept_km	Swept_NM	ADFG_tier	CPT_STD	Totalmale	Female	Juvenile
1976	NOAA	64	-164.6	0.053627	0.015635	c	S	9	1	0
1976	NOAA	64.3	-165.083	0.050804	0.014812	c	S	93	2	0
1976	NOAA	64.35	-165.417	0.047982	0.013989	c	S	20	1	0
1976	NOAA	64.33333	-166.15	0.042337	0.012343	c	S	1	0	0
1976	NOAA	64.18333	-166.15	0.045159	0.013166	c	S	25	0	0
1976	NOAA	64.03333	-166.167	0.050804	0.014812	c	S	12	0	0
1976	NOAA	64	-165.65	0.045159	0.013166	c	S	25	0	0
1976	NOAA	63.85	-165.667	0.045159	0.013166	t1	S	17	0	0
1976	NOAA	63.85	-166.067	0.047982	0.013989	t1	S	14	0	0
1976	NOAA	63.66667	-166.033	0.045159	0.013166	t1	S	5	0	0
1976	NOAA	63.66667	-165.767	0.045159	0.013166	t1	S	2	0	0
1976	NOAA	63.48333	-166.017	0.045159	0.013166	O	O	4	0	0
……										
2020	ADFG	63.65017	-165.353	0.02258	0.006583	t1	S	18	3	0
2020	ADFG	63.6645	-164.967	0.02258	0.006583	t1	O	0	2	0
2020	ADFG	63.837	-164.981	0.02258	0.006583	t1	S	0	1	0
2020	ADFG	63.8315	-165.356	0.02258	0.006583	t1	S	4	0	0
2020	ADFG	64.168	-163.066	0.02258	0.006583	c	S	0	0	0
2020	ADFG	63.8355	-165.682	0.02258	0.006583	t1	S	3	0	0
2020	ADFG	64.1795	-162.71	0.02258	0.006583	c	S	0	1	0
2020	ADFG	64.18433	-162.313	0.02258	0.006583	c	S	0	0	0
2020	ADFG	64.32883	-162.295	0.02258	0.006583	c	S	0	0	1

In the above Latitude and Longitude are trawl coordinate, Totalmale is the number of male NSRKC (> 63mm) caught in the trawl.

Model setting:

Model settings were suggested by James Thorson during the VAST modeling workshop.

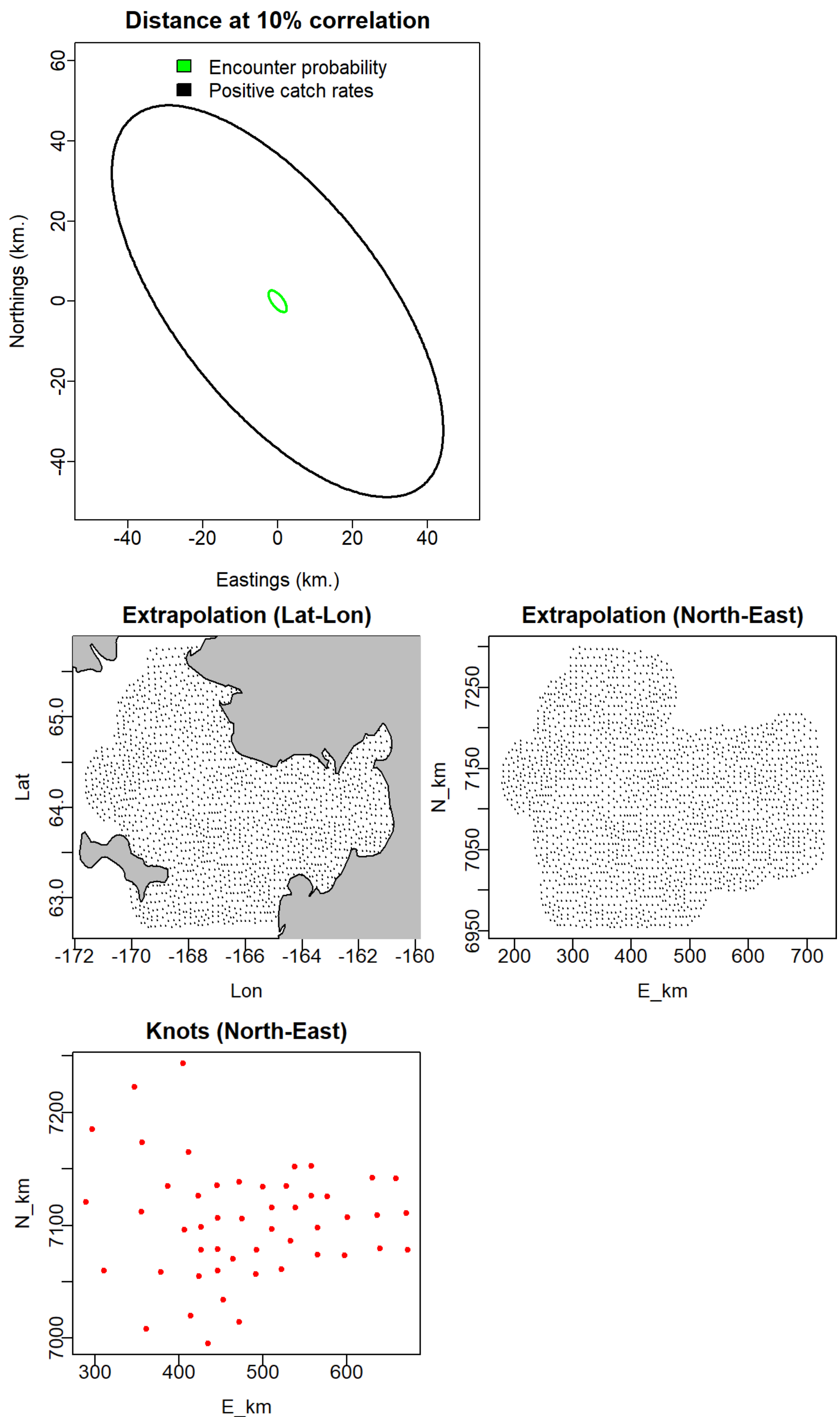
```
settings = make_settings( n_x=50, Region="Other",purpose="index2",bias.correct=FALSE,
```

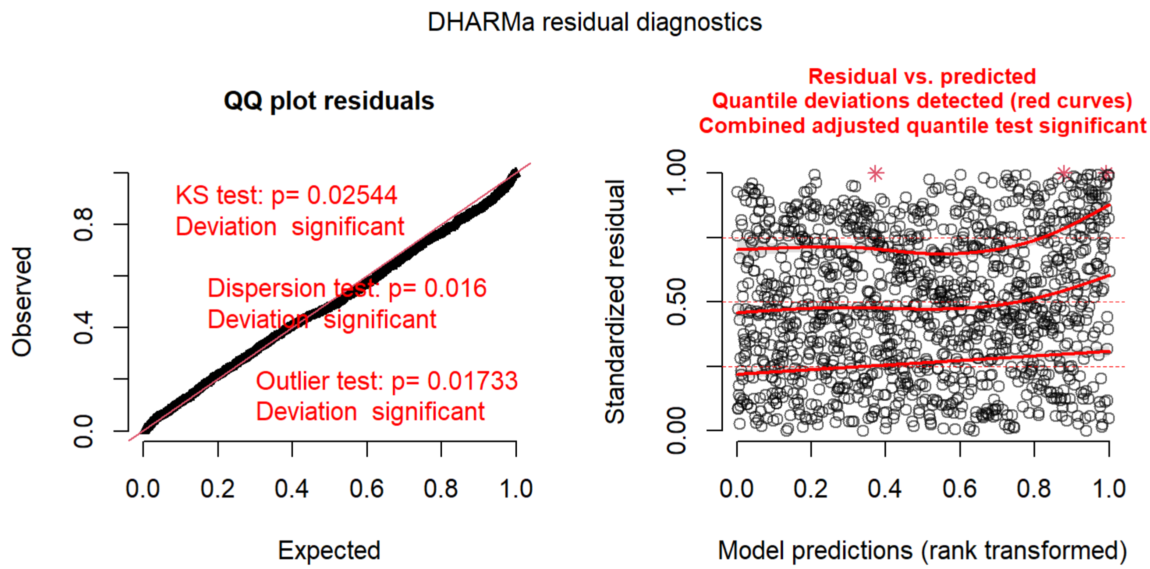
```
  FieldConfig=c("Omega1"=1, "Epsilon1"=1, "Omega2"=0, "Epsilon2"=0),
  Version="VAST_v9_2_0", use_anisotropy=TRUE)

fit = fit_model( "settings"=settings, "Lat_i"=data[,'Latitude'],
  "Lon_i"=data[,'Longitude'], "t_i"=data[,'Year'],
  "c_i"=rep(0,nrow(data)), "b_i"=data[,'Totalmale'],
  "a_i"=data[,'Swept_NM2'], "v_i"=data[,'Agent'],
  "observations_LL"=cbind("Lat"=data[,'Latitude'],"Lon"=data[,'Longitude']),
  getsd=TRUE, newtonsteps=1, grid_dim_km=c(5,5),
  maximum_distance_from_sample=50,
  knot_method="samples")
```

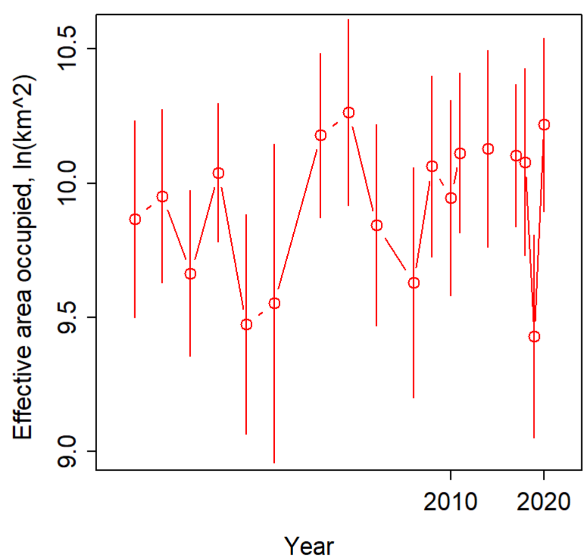
The model was ran in two data configurations: 1. All trawl survey data, 2. Trawl survey data limited to current ADFG survey stations.

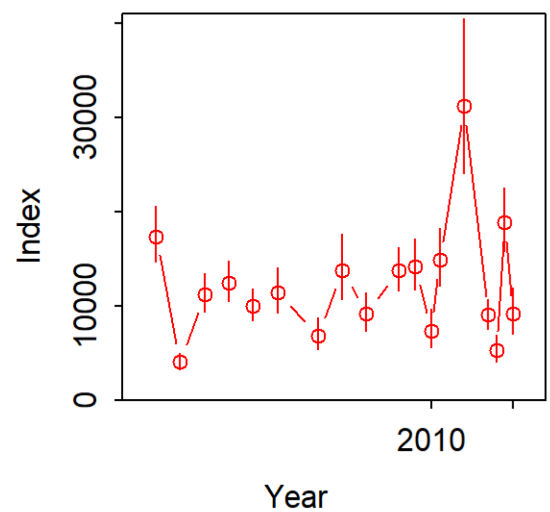
Results

1. All data

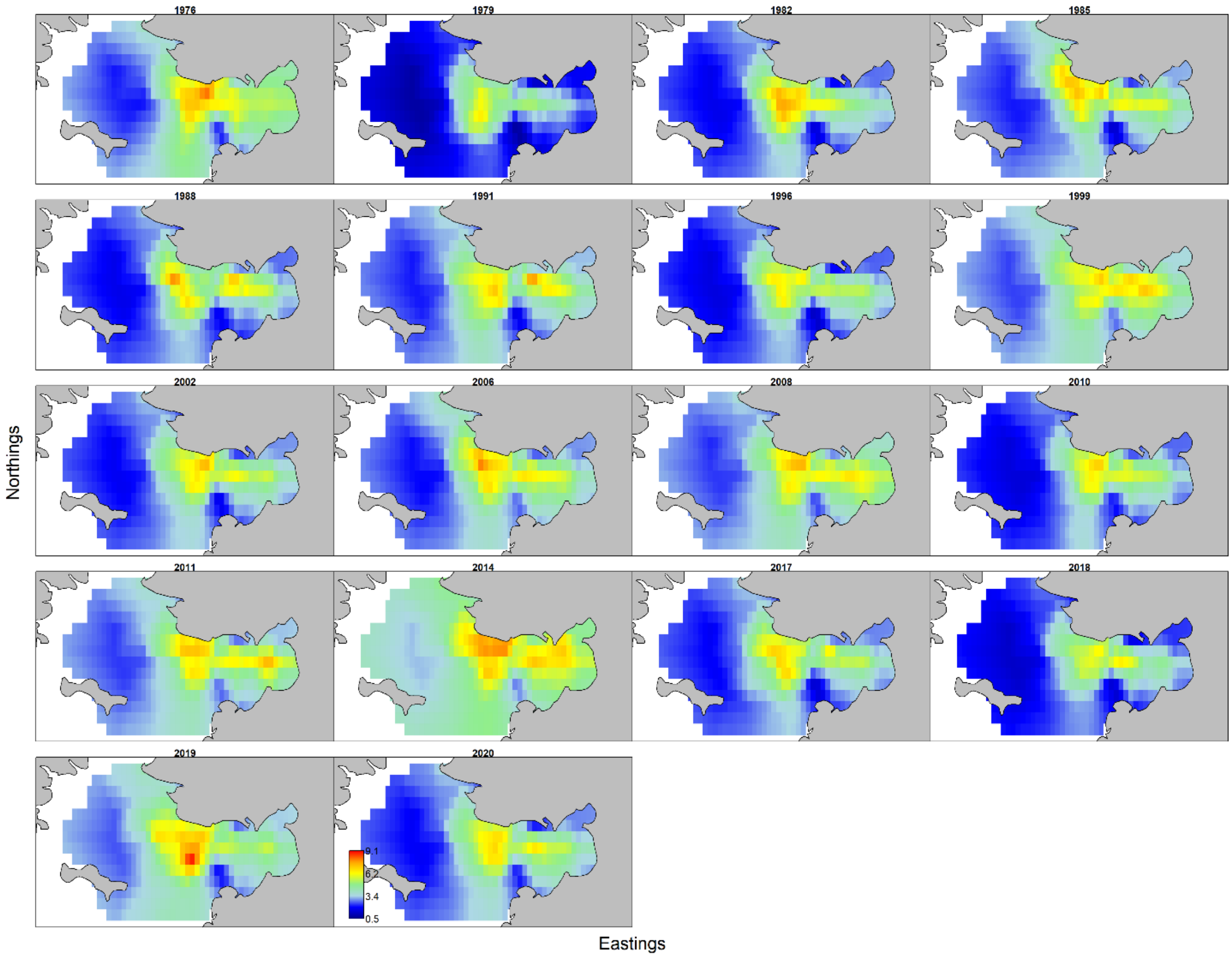

Distance at 10% correlation
Encounter probability
Positive catch rates
Northings (km.)
Eastings (km.)
-40
-20
0
20
40
60
Extrapolation (Lat-Lon)
Lat
Lon
63.0
64.0
65.0
-172
-170
-168
-166
-164
-162
-160
Extrapolation (North-East)
N_km
E_km
6950
7050
7150
7250
200
300
400
500
600
700
Knots (North-East)
N_km
E_km
7000
7100
7200
300
400
500
600


DHARMa residual diagnostics
QQ plot residuals
KS test: p= 0.02544
Deviation significant
Dispersion test: p= 0.016
Deviation significant
Outlier test: p= 0.01733
Deviation significant
Observed
Expected
Residual vs. predicted
Quantile deviations detected (red curves)
Combined adjusted quantile test significant
Standardized residual
Model predictions (rank transformed)

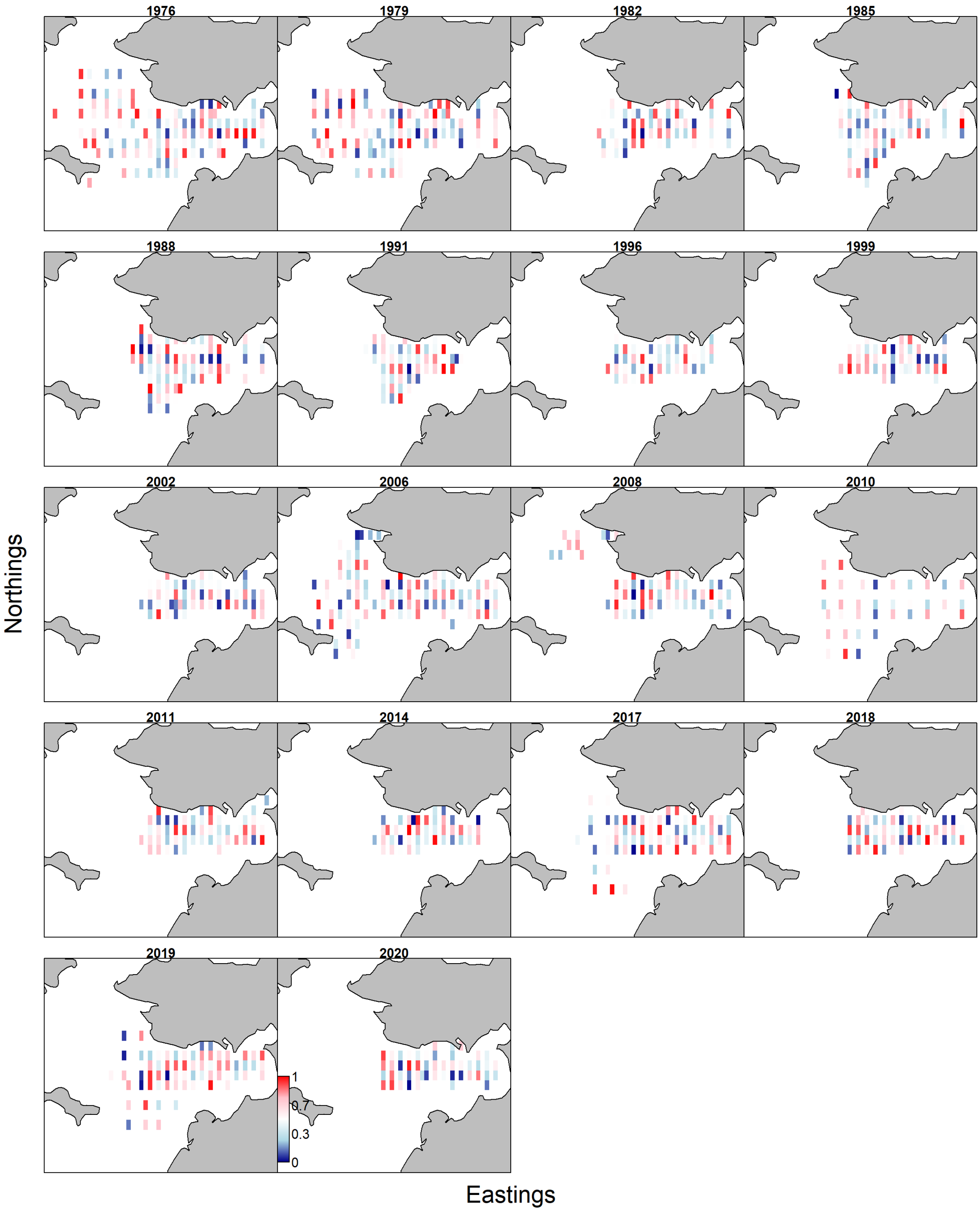

Effective area occupied, ln(km^2)
Year
2010
2020


Index
Year
2010

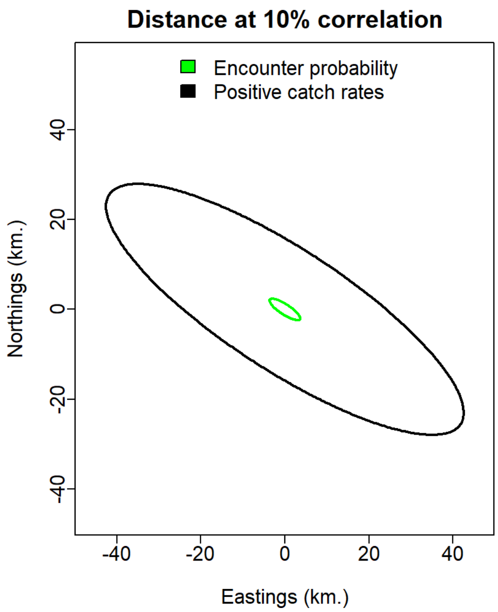
Abundance distribution

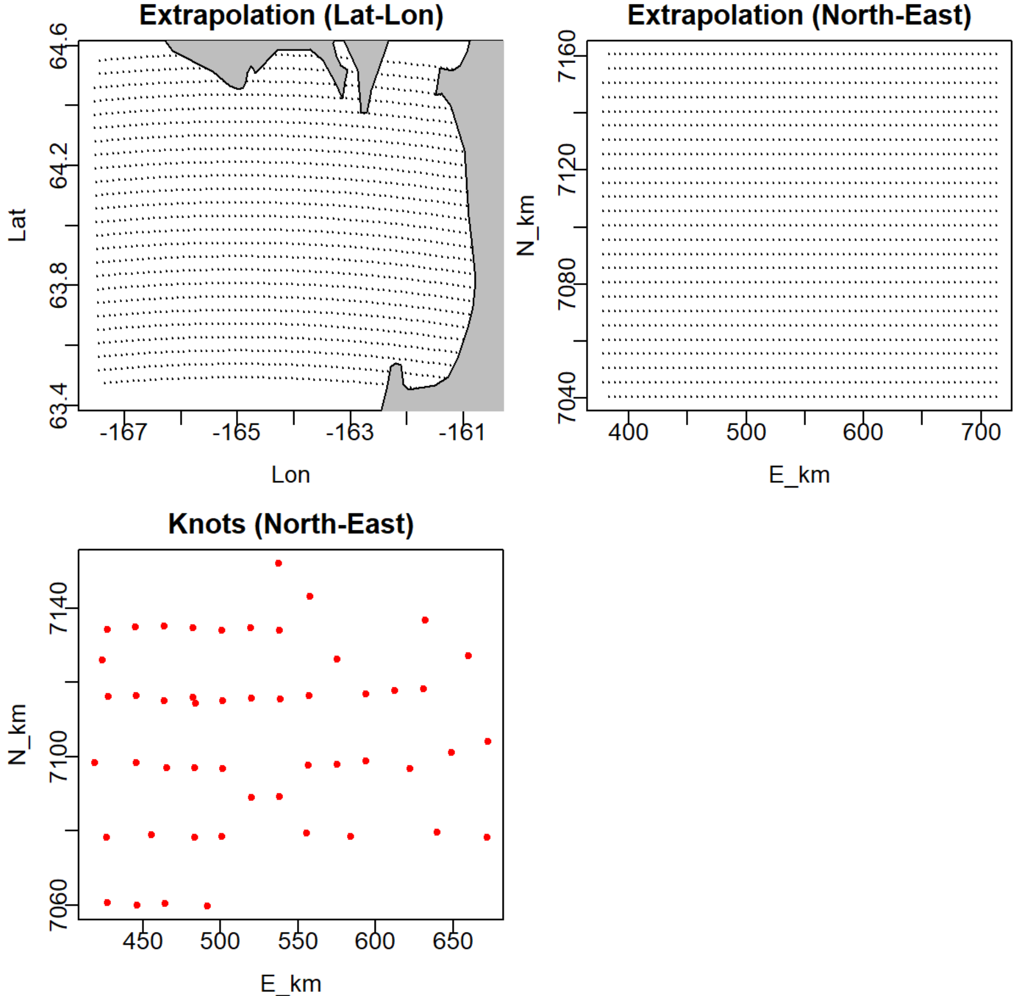


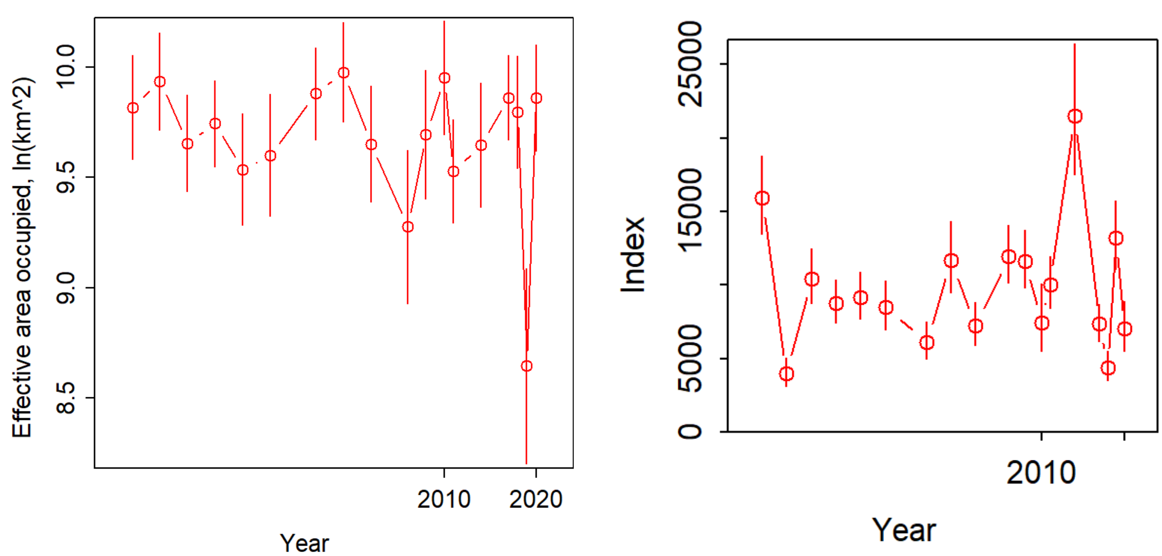
Spatial residual

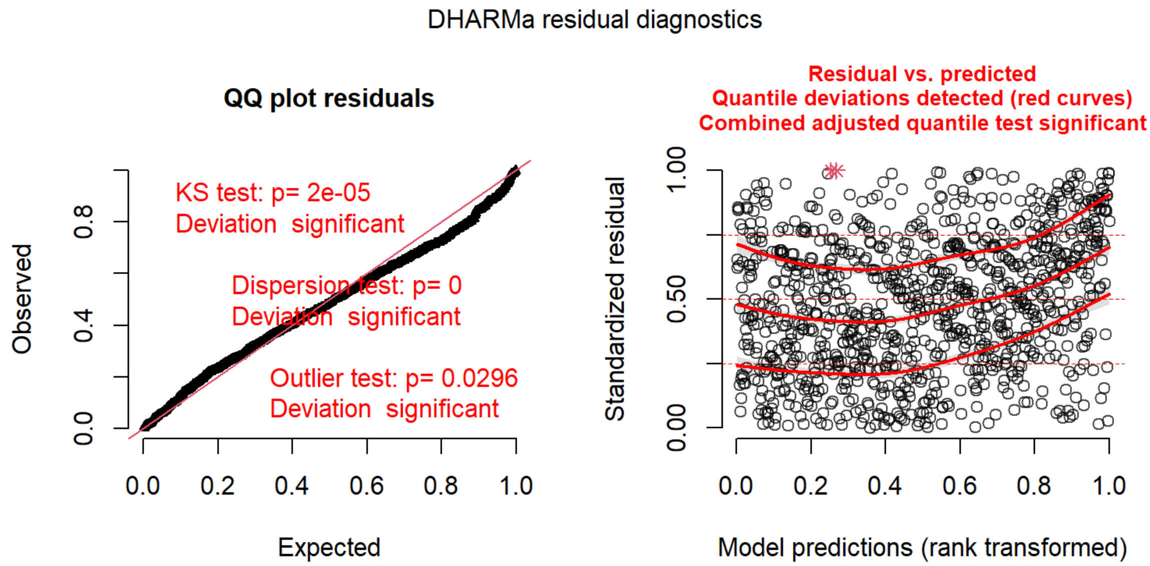


2. Limited data

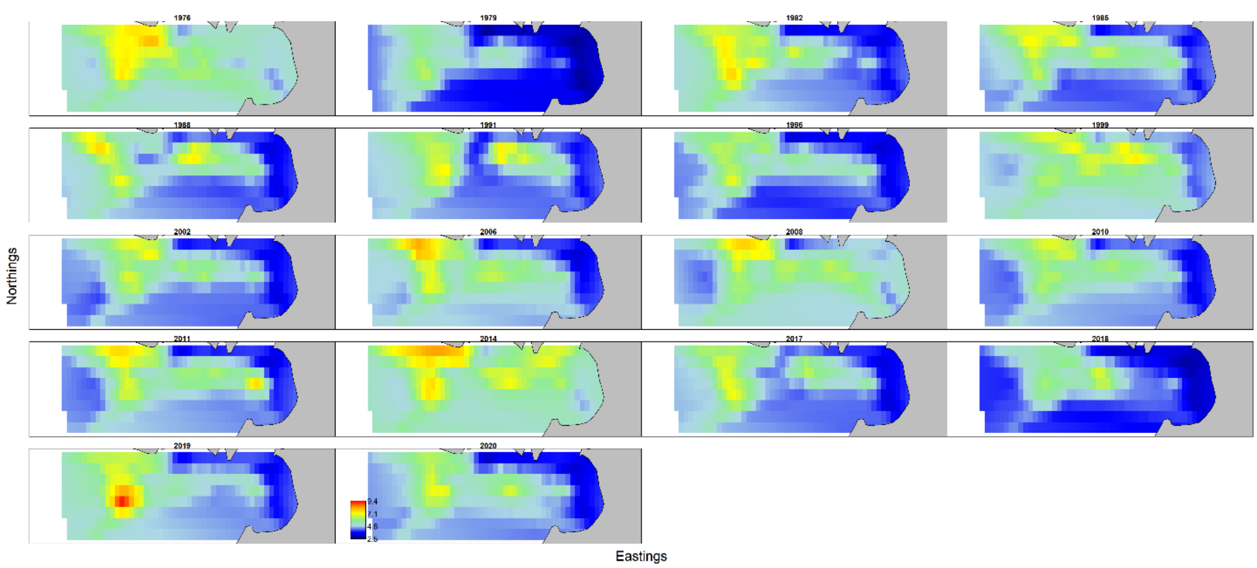



Extrapolation (Lat-Lon)
Lat
64.6
64.2
63.8
63.4
-167
-165
-163
-161
Lon
Extrapolation (North-East)
N_km
7160
7120
7080
7040
400
500
600
700
E_km
Knots (North-East)
N_km
7140
7100
7060
450
500
550
600
650
E_km

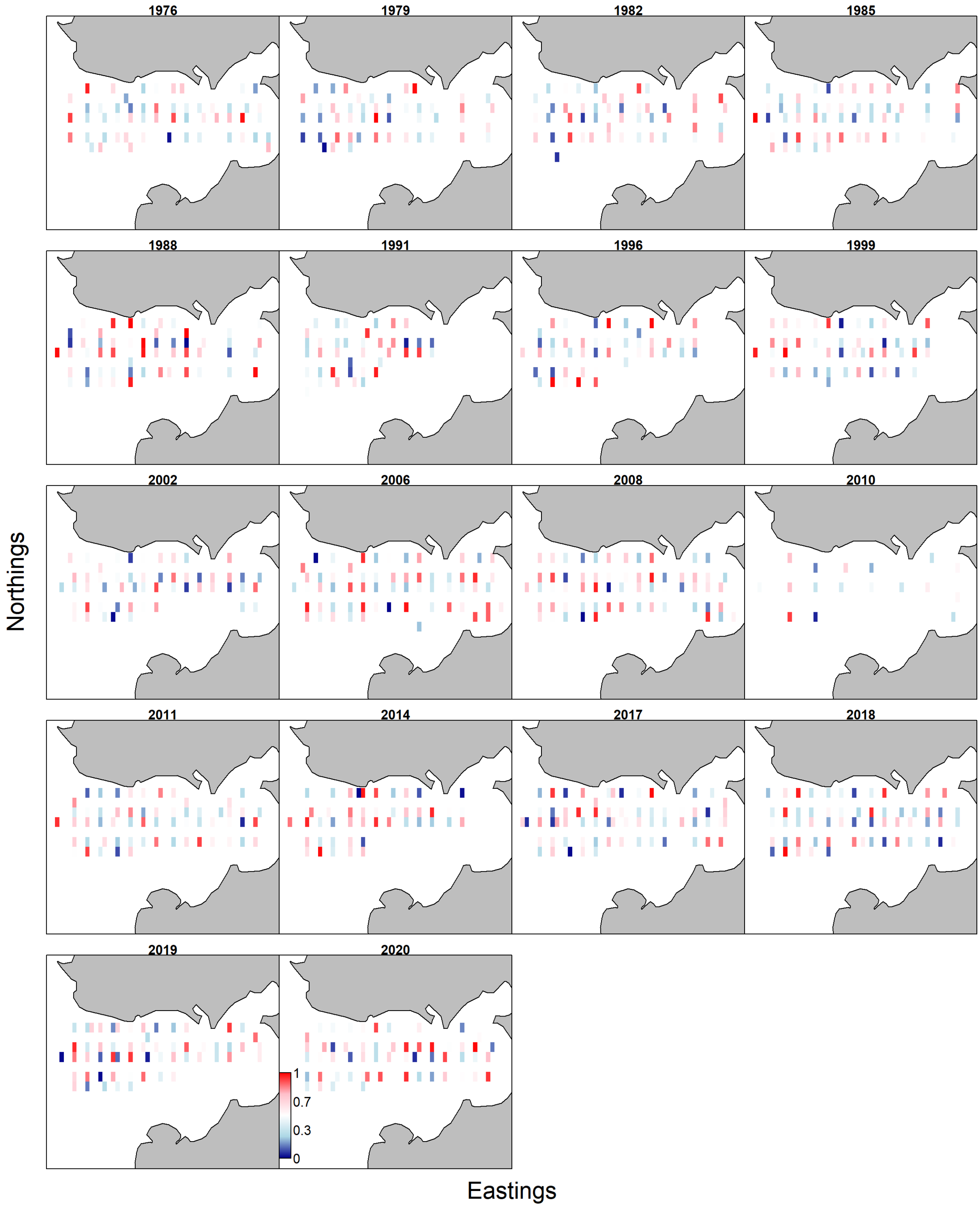

Effective area occupied, ln(km^2)
10.0
9.5
9.0
8.5
2010
2020
Year
Index
25000
15000
5000
0
2010
Year



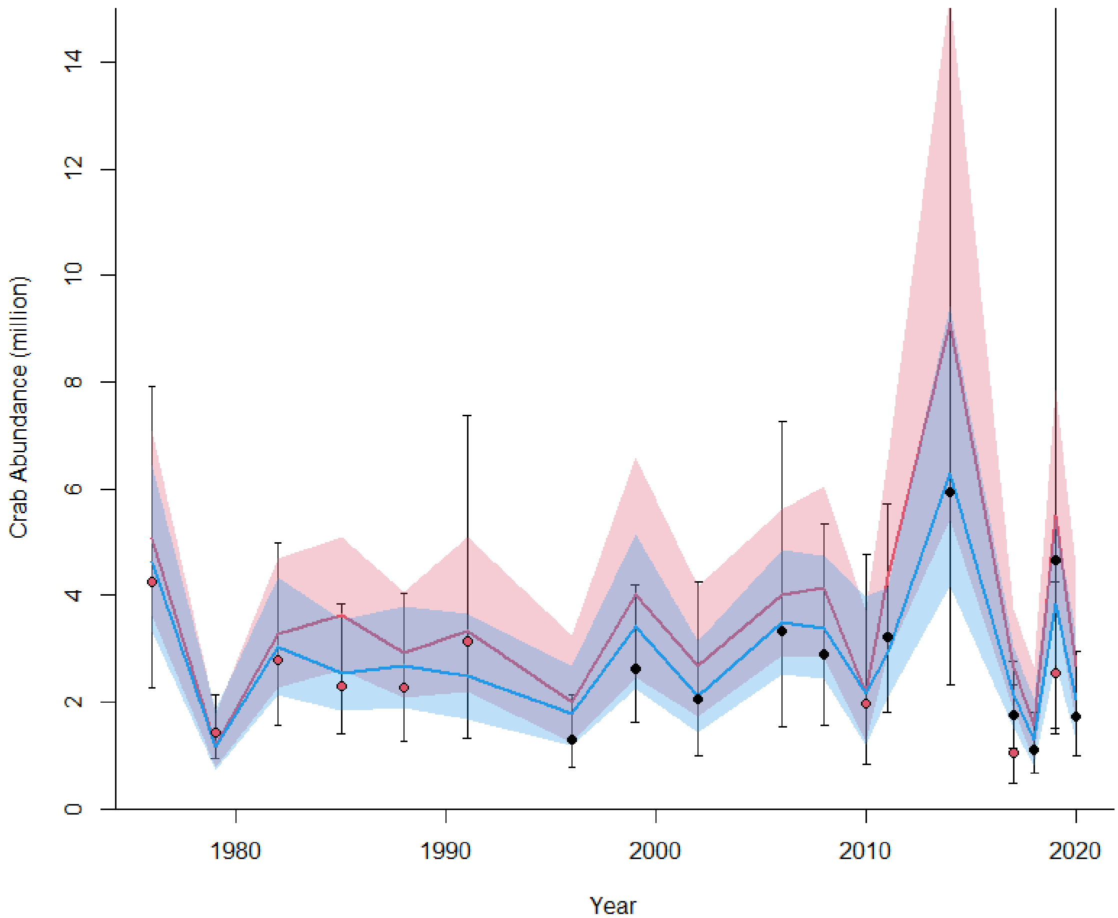
Abundance distribution



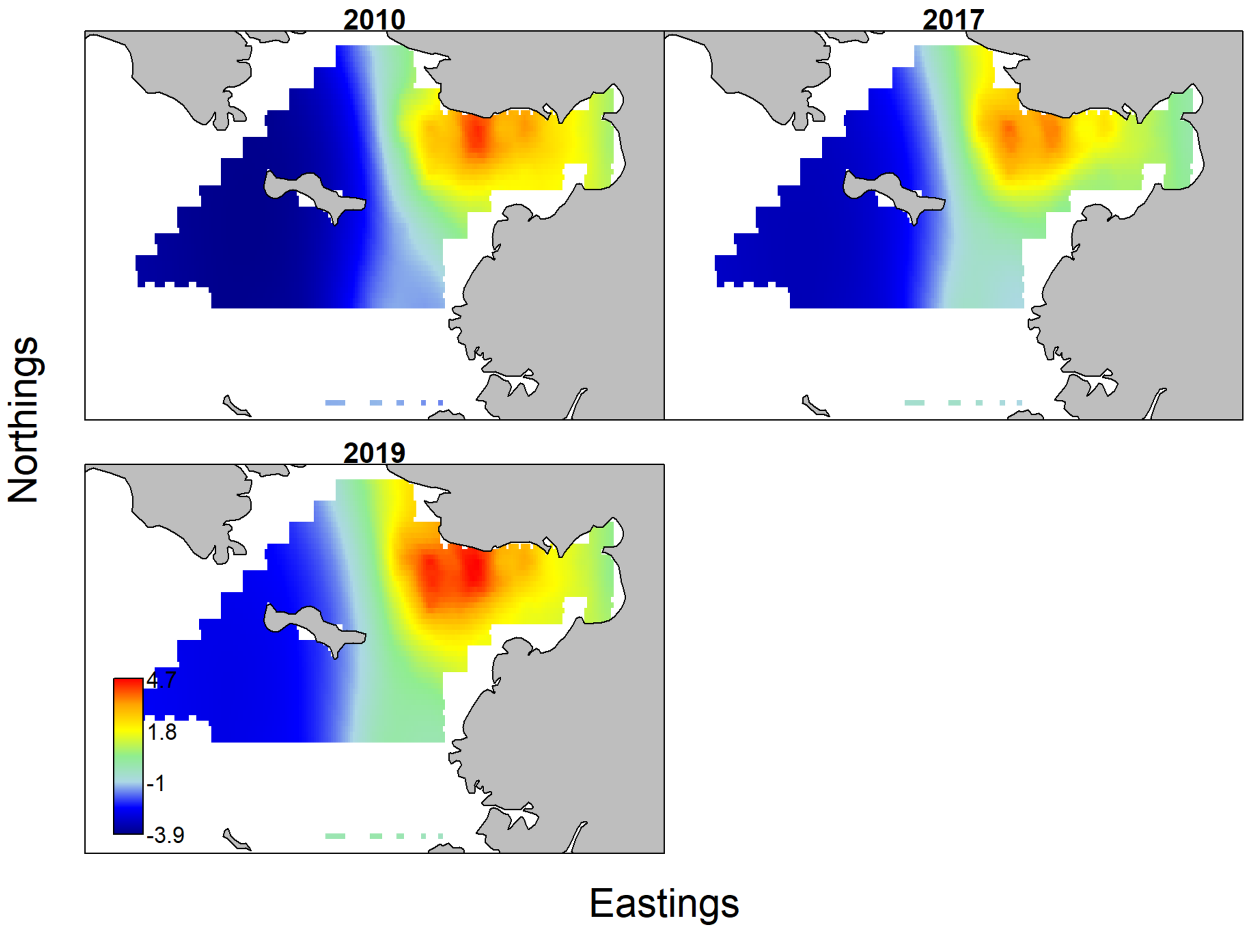
Spatial residuals



Comparison of abundance among survey (dots and line: NOAA: red, ADFG: black, 95CI), VAST estimate of all data (red) and ADFG survey stations (blue).



VAST model output of entire Q3 region by NBS survey only



Discussion

Estimates of abundance were generally similar among survey and VAST. Model estimated CI ranges were smaller than survey CI, and abundance using all data set was larger than those with limited data, which is expected. VAST estimated of NSRKC distribution differ among years and survey dataset. Running and fitting NSRKC trawl data with VAST appeared to be difficult, probably because of lack of consistent data.

Appendix E

Comparison of NSRKC Assessment model and GMACS.

Here I present GMACS model results of Norton Sound Red King Crab.

Achievements from Sept 2020 to Jan 2021.

Run GMACS with assessment model results.

Issues remained:

1. Could not match initial model size composition
2. Could not match winter pot fishery selectivity
3. Could not match retention probability
4. Structural difference not resolved: assessment model remove catch directly (i.e. Catch is not modeled), whereas gmacs estimates catch (i.e., fishing mortality estimated).

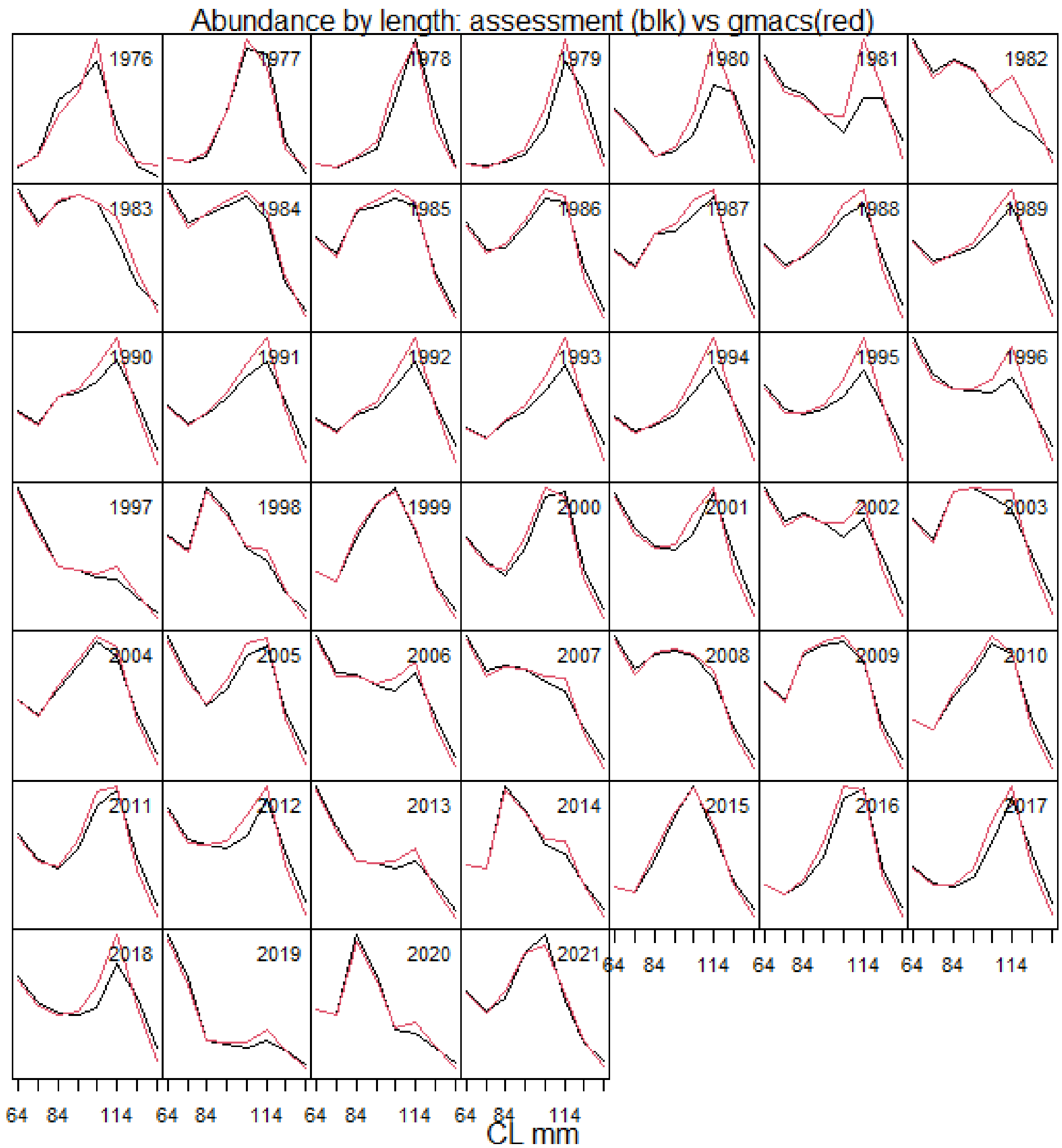


Figure 1. Male abundance between assessment model (black) and gmacs (red)

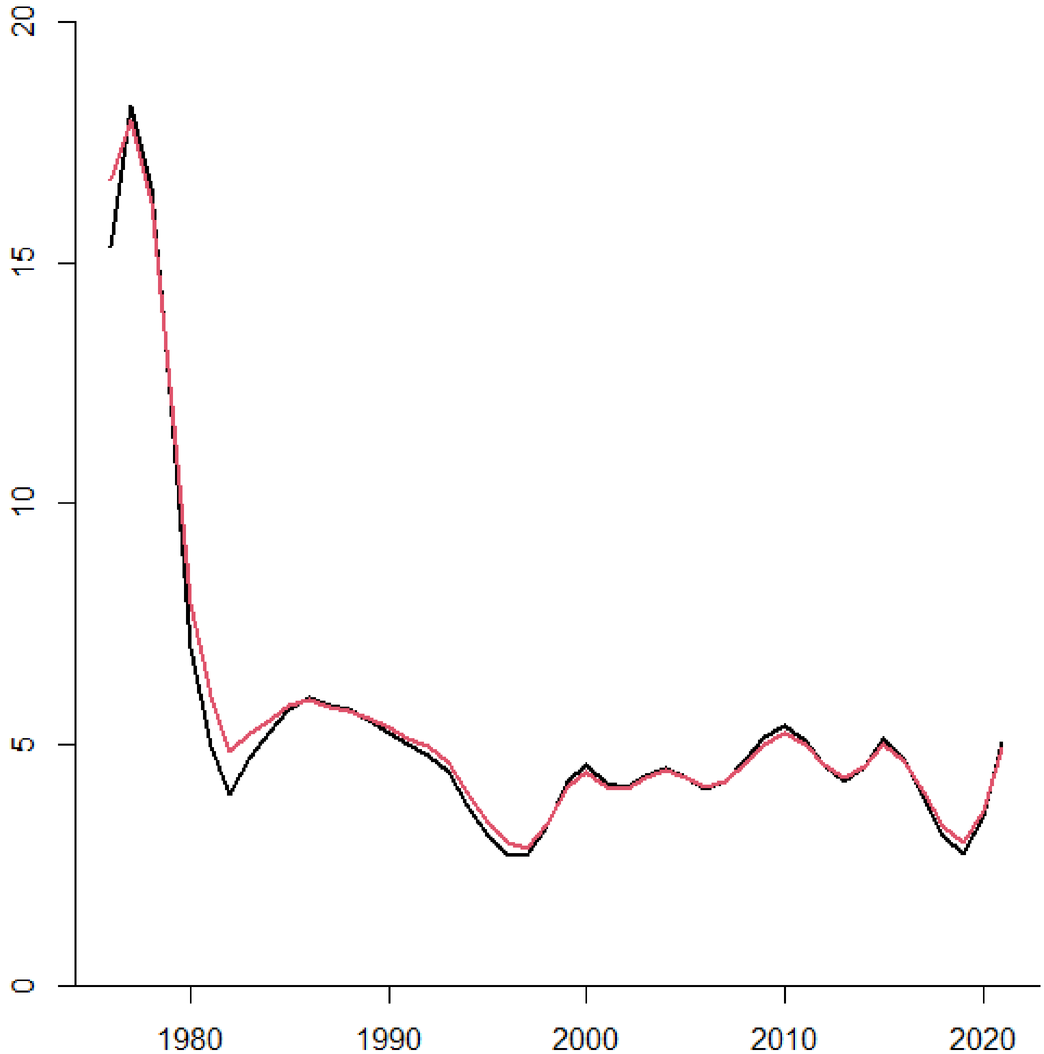


Figure 2: MMB projection between assessment model (black) and gmacs (red)

Appendix F:

Female NSRKC clutch fullness by length class.

Per request by

Table 1. The number of mature females by year, length class, and clutch fullness from trawl survey.
Note: Clutch fullness definition differ between NOAA and ADFG

			Clutch fullness						
Year	Agent	Length class	1	2	3	4	5	6	7
1976	NOAA	54-63	0	0	0	0	1	0	0
1976	NOAA	64-73	1	1	0	7	4	11	2
1976	NOAA	74-83	1	0	5	17	16	36	4
1976	NOAA	84-93	1	1	0	6	13	18	3
1976	NOAA	94-103	0	0	1	0	1	4	0
1979	NOAA	64-73	3	0	0	0	0	0	0
1979	NOAA	74-83	0	0	0	0	0	2	0
1979	NOAA	84-93	0	0	1	0	0	5	0
1979	NOAA	>94	0	0	0	0	0	1	0
1982	NOAA	54-63	0	0	0	0	0	1	0
1982	NOAA	64-73	0	1	0	1	0	15	0
1982	NOAA	74-83	0	0	0	1	0	38	0
1982	NOAA	84-93	0	0	0	1	1	25	0
1982	NOAA	94-103	0	0	0	0	0	4	0
1982	NOAA	104-113	0	0	0	0	0	1	0
1982	NOAA	114-123	0	0	0	0	0	1	0
1985	NOAA	64-73	0	0	0	0	0	6	0
1985	NOAA	74-83	0	0	0	0	0	18	0
1985	NOAA	84-93	0	0	0	0	0	14	0
1985	NOAA	94-103	0	0	0	0	0	9	0
1988	NOAA	54-63	0	0	0	1	0	0	0
1988	NOAA	64-73	1	0	0	2	4	10	0
1988	NOAA	74-83	0	1	1	0	5	37	0
1988	NOAA	84-93	0	0	1	0	1	29	0
1988	NOAA	94-103	0	0	0	0	0	4	0
1991	NOAA	74-83	0	0	1	1	0	2	0

1991	NOAA	84-93	0	0	2	1	3	7	0
1991	NOAA	94-103	0	0	0	0	0	5	0
1996	ADFG	64-73	11	0	0	1	5	1	0
1996	ADFG	74-83	9	0	1	6	8	4	0
1996	ADFG	84-93	0	0	1	1	8	4	0
1996	ADFG	94-103	0	0	0	0	3	1	0
1996	ADFG	104-113	0	0	0	0	0	1	0
1999	ADFG	64-73	1	0	0	0	3	0	0
1999	ADFG	74-83	0	0	1	0	10	1	0
1999	ADFG	84-93	1	0	0	0	9	8	0
1999	ADFG	94-103	0	0	0	0	4	4	0
1999	ADFG	104-113	0	0	0	0	0	1	0
2002	ADFG	64-73	2	0	0	4	7	4	0
2002	ADFG	74-83	3	0	1	9	26	16	0
2002	ADFG	84-93	1	0	1	4	14	15	0
2002	ADFG	94-103	0	0	0	2	4	7	0
2002	ADFG	104-113	0	0	0	1	1	5	0
2006	ADFG	64-73	1	0	1	5	3	0	0
2006	ADFG	74-83	1	0	3	9	23	3	0
2006	ADFG	84-93	0	0	0	3	15	4	0
2006	ADFG	94-103	0	0	0	1	4	1	0
2006	ADFG	104-113	0	0	0	0	2	0	0
2006	ADFG	114-123	1	0	0	0	1	0	0
2006	ADFG	124-133	0	0	0	0	2	0	0
2006	ADFG	134=143	0	0	0	0	1	0	0
2008	ADFG	54-63	0	0	0	1	0	0	0
2008	ADFG	64-73	2	0	7	2	1	0	0
2008	ADFG	74-83	0	1	1	10	12	3	0
2008	ADFG	84-93	0	0	1	7	5	3	0
2008	ADFG	94-103	0	0	0	1	0	0	0
2008	ADFG	114-123	0	0	0	1	2	0	0
2010	NOAA	64-73	0	0	0	1	0	0	0
2010	NOAA	74-83	0	0	0	6	0	1	0
2010	NOAA	84-93	0	0	0	1	0	4	0
2010	NOAA	94-103	0	0	0	3	0	1	0
2010	NOAA	104-113	0	0	0	0	0	2	0
2011	ADFG	64-73	4	0	0	6	4	0	0
2011	ADFG	74-83	1	0	1	10	9	3	0
2011	ADFG	84-93	1	0	0	0	8	5	0
2011	ADFG	94-103	0	0	1	1	4	2	0

2011	ADFG	104-113	0	0	0	0	1	0	0
2014	ADFG	64-73	0	0	0	2	1	0	0
2014	ADFG	74-83	0	0	0	14	8	3	0
2014	ADFG	84-93	0	0	1	2	5	0	0
2014	ADFG	94-103	0	0	0	0	1	0	0
2017	ADFG	64-73	4	0	1	1	2	1	0
2017	ADFG	74-83	1	0	1	0	1	0	0
2017	ADFG	84-93	0	0	0	1	2	3	0
2017	ADFG	94-103	0	0	1	0	4	2	0
2017	ADFG	104-113	1	0	0	0	0	2	0
2017	NOAA	64-73	0	0	0	1	0	0	0
2017	NOAA	74-83	0	0	0	1	0	1	0
2017	NOAA	84-93	0	0	0	0	0	1	0
2017	NOAA	94-103	0	0	0	0	0	2	0
2017	NOAA	104-113	0	0	0	0	0	3	0
2017	NOAA	114-123	0	0	0	1	0	0	0
2018	ADFG	64-73	1	0	0	0	0	0	0
2018	ADFG	74-83	0	0	0	1	4	3	0
2018	ADFG	84-93	1	0	0	1	4	0	0
2018	ADFG	94-103	1	1	0	0	1	1	0
2019	ADFG	54-63	3	0	0	0	0	0	0
2019	ADFG	64-73	31	1	8	11	7	1	0
2019	ADFG	74-83	18	0	5	10	7	2	0
2019	ADFG	84-93	1	0	0	2	2	1	0
2019	ADFG	94-103	0	0	0	0	1	0	0
2019	NOAA	64-73	2	0	1	1	0	0	0
2019	NOAA	74-83	1	0	0	8	0	0	0
2019	NOAA	84-93	0	1	0	2	0	0	0
2019	NOAA	104-113	0	0	0	1	0	0	0
2020	ADFG	54-63	0	0	1	0	0	0	0
2020	ADFG	64-73	5	0	4	3	12	1	0
2020	ADFG	74-83	2	3	15	16	30	29	0
2020	ADFG	84-93	0	0	1	6	12	12	0
2020	ADFG	94-103	0	0	0	0	0	4	0

Table 2: Criteria of maturity and clutch fullness used in ADFG and NOAA trawl surveys

Maturity	
ADFG (1996 - 2002)	Immature: < 72mm CL and no egg Mature: ≥ 72mm CL or with egg
ADFG (2006 - 2020)	Immature: small abdominal flap Mature: oval-shaped abdominal flap full covered
NOAA (1976 – 1991)	Immature: NA Mature: NA
NOAA NBS (2010 – 2019)	Immature: NA Mature: NA
Clutch size	
ADFG (1996 – 2020)	1: Barren clean plepod, 2: Barren matted plepod 3: 1- 29% full, 4: 30-59% full, 5: 60-89% full, 6: 90-100% full
NOAA (1976 – 2019)	0: Immature, 1: Barren clean plepod, 2: 1- 12.5% full, 3: 12.5 - 25% full, 4: 26-50% full, 5: 51-75% full, 6: 76-100% full, 7: > 100% full, 9: No data

Appendix G

Norton Sound red king crab 2021 SAFE assessment model review by CPT (Jan & Sept 2021) and SSC (Feb & Oct 2021).

CPT: Jan 2021

Toshihide ("Hamachan") Hamazaki (ADF&G, Anchorage) presented the assessment for Norton Sound red king crab. A single model was presented at the request of the CPT from the September 2020 meeting (Model 19.0). The CPT appreciates Hamachan's responsiveness to the numerous requests made (including VAST GMACS explorations and providing pot loss data). Jen Bell (ADF&G, Nome) also presented information on the extent and future direction of research efforts aimed at understanding NSRKC population dynamics. For instance, pot loss data were presented in response to a CPT request, and Jen also described studies to understand where lost pots are moved by shifting ice. Other areas of investigation are the high abundances of male crab that track consistently from one year to the next in both surveys and harvests, infrequent but significant occurrences of barren females, and male functional maturity. Analyses of tagging data in years during which surveys were not available were particularly useful in better understanding cohort dynamics. The CPT expressed enthusiastic support for continued investigations of the research questions presented. Several members of the public also contributed to productive discussion around OFL calculations and historical perspectives.

The CPT accepted model 19.0 for use in management. Although the assessment author supported continued use of a retained catch OFL, the CPT endorsed the LNR2 method for accounting for discards to support calculation of a total catch OFL. The various methods for accounting for discards gave similar results, and the LNR2 method produced an OFL close to the median of the various methods. The author updated the relationship between carapace width and carapace length used to determine what crab are legal, but the CPT recommends that the methods be better described. The CPT recommended continuing the 30% buffer on ABC chosen by the SSC last year. The SSC justified the 30% buffer based on ten points (see table below). Some of these points are less of a concern this year, which might suggest reducing the size of the buffer would be appropriate. However, the CPT identified several new issues that should be addressed within the assessment such as fishery timing with respect to cohort progression, estimates of growth, changes in the definition of legal crab based on updated data used to translate between carapace length and width, and the way in which the OFL is calculated using 'legal' size (≥4 ¾" CW) crab, rather than a selectivity curve reflecting the 'exploited' crab (≥5" CW). The CPT considers that these points, at the very least, are a counterbalance to the issues that might be excluded from the SSC's list of concerns in the table below, which informed the CPT decision to retain the 30% buffer.

Although the assessment has used the abundance of legal male to define OFL/ABC, the CPT recommends that future assessments use standard methods with estimated selectivity and retention curves to define the OFL/ABC. Industry selection for larger than legal crab could result in higher F than F_{OFL} for retained crab and unaccounted discard for legal crab under market size. The CPT noted that the total catch OFL was very similar across all model scenarios examined.

The CPT had several requests for the author:

- Explore and document the reasons for the changes in the relationship between carapace length and carapace width. Document which data sources are excluded or included and for what reason.

- Plot the legal biomass over time using the different proportions of legal size crab to better understand the magnitude of the impact of the change.
- The OFL should be specified based on total catch including retained catch and non-surviving discard. Specifying the OFL based on legal crab would result in higher OFLs than if based on retained crab. This would then translate to higher exploitation rates on the exploitable crab than the target rates and increased discard mortality on non-preferred size crab that must be sorted through to achieve the OFL.
- Revisit growth assumptions. Growth appears to be consistently overestimated in the assessment, producing too many large crab. The CPT looks forward to seeing the results from the laboratory studies on growth for NSRKC at the next meeting.
- Revisit natural mortality assumptions. Both the assumed natural mortality for small crab and the larger natural mortality for crab greater than 123 mm CL should be better justified. The author noted that the maximum age observed in the tagging studies was 12 years, which is much lower than the assumed value of 25 years. Further, the "1% method" used by the authors to calculate a natural mortality generally provides lower estimates of M than empirical studies (see the tool at Barefoot Ecologist Toolbox for examples).
- Future figures of clutch fullness should include confidence bounds.
- Further consider which of the methods to account for discards are most appropriate for NSRKC given probable future data availability. The CPT realizes that no method will be perfect, but an imperfect consideration of discards is better than ignoring them.
- Explore having Jon Richar work on a VAST model for Norton Sound trawl surveys.

A list of SSC concerns that directed the adoption of a 30% buffer in 2020 with indications of whether the concern was still an issue and a brief explanation if it is not.

SSC Feb 2021

Martin Dorn (NOAA-AFSC) presented the 2021 assessment for NSRKC. Several members of the public also contributed testimony concerning model uncertainty, observations from the grounds, and historical perspectives in oral testimony. Public oral testimony is summarized below. There was also written testimony provided.

Wes Jones (Norton Sound Economic Development Corporation; NSEDC) testified about his concerns regarding the model and the current state of the stock. He clarified a point in the presentation, indicating that there was no market because the Alaska Board of Fisheries had closed the Norton Sound district to summer crab fishing. Mr. Jones clarified that if there were crab to buy, there may have been a market. Mr. Jones stated concerns about the low amount of NSRKC caught in the trawl survey and that the subsistence catch was the lowest on record. Current reports from this winter are revealing that the majority of the catch is sublegal, with very few crab of market size. Testimony was provided that the model has been overestimating growth, so the recruitment pulse seems to be a year ahead in the model rather than what the fishery is seeing on the grounds, and that the model is predicting a quicker recovery than reality. Therefore, a large buffer is warranted.

Charles Lean (Norton Sound Fishery Advisory Committee) testified that the current abundance indicates that the stock was still in rebuilding mode after taking large catches prior to 2018. He had concerns about the model producing too high a biomass estimate. His testimony referred to “passive management”, and that State regulations and the management strategy were being disregarded. Mr. Lean also believes that pot loss rate is severely underestimated because, at the end of the season, there is no requirement to report lost pots. He has observed that when the ice is thinner, the pots drop quicker and closer to Nome, while in years of thicker ice, they may be transported in the ice all the way to the Chukchi Sea. Since females reach sexual maturity about a year before males, there was a lull in clutch fullness because the pulse of young males was not mature yet. He noted that every time there have been clutch fullness issues, it coincided with heavy male harvest. He also described that handling mortality in the winter is much higher than the summer, so there is a need to establish two seasonal discard mortality estimates.

Scott Kent (NSEDC) described his experience as a fishery manager and developer of the harvest strategy. He noted that the harvest strategy was developed around the notion that the stock was rebuilt and that the local small boat fishery would not harm the stock. Initially, it was going to be a typical ramp harvest strategy, but there was a desire for more flexibility for managers to be able to apply a more conservative harvest rate. Mr. Kent stated that since then, the harvest rate has been set so that the GHL has been pretty close to the ABC every year. This seemed to be working early on, but now greater conservation is warranted. He suggested that the SSC should consider a larger buffer.

The SSC appreciates the NSRKC presentation and the work of the CPT and assessment authors. Responses to past SSC comments presented at the beginning of the document were thorough. The SSC also thanks the public for their useful testimony and observations from the grounds and the fishery. The NSRKC stock supports three fisheries: summer commercial, winter commercial, and subsistence. The summer commercial fishery, which accounts for most of the catch, reached a peak in the late 1970s, but catches have averaged around 10% of that peak recently. The commercial crab fisheries did not operate in 2020 and only winter subsistence catch occurred.

A single model was presented (19.0) as a viable model for setting specifications. A GMACS model was developed to mirror the existing model, but was not ready for full consideration. **The SSC supports the CPT recommendation to use Model 19.0 for specifications. Based on Model 19.0, stock biomass is above MSST so the stock is not overfished, and retained catch during 2020 did not exceed the OFL for this stock so overfishing is not occurring.** The SSC commends the state of Alaska for conducting their trawl survey during a pandemic. The 2020 survey biomass estimate was very low compared to 2019, yet the model does not follow that data point, and instead continues to predict an increase. Fishery CPUE had declined precipitously until 2019, and there is no CPUE value for 2020. Without these data, a valuable indicator of abundance and fishery performance is missing in this year's assessment. In addition, there was no NMFS 2020 trawl survey. The recommended ABC is more than double the 2020 ABC despite many indications that the stock may not be that healthy.

Some of the SSC's previous concerns were alleviated, such as the majority of the crab catch is occurring inside the survey area (>95% in nearly all years). The work on barren females was appreciated and seemed to be of lesser concern this year. The SSC thanks the authors for the information on pot loss and the potential impact of ghost fishing mortality. The information on using electronic trackers on the ice to consider where lost pots may end up was interesting and the SSC encourages further exploration. The authors report trouble with implementing the VAST model for NSRKC survey data and the CPT reported that Jon Richar's analyses suggest the NSRKC was not a very good candidate compared to other crab stocks. The successful tagging work showed fairly strong westward movement and the SSC encourages the upcoming efforts to increase tagging in 2021. The SSC notes that the tagging work might shed light on how closed the population is, and that future tagging work should include random releases to better understand whether crabs tagged offshore behave similarly to those tagged close to shore.

The most significant past CPT and SSC request was to shift to total catch harvest specifications. The author provided additional details on methodology to estimate discards in Appendix G. **The move to a total catch OFL and ABC in this assessment represents the best available science and the SSC supports this change to be consistent with other assessments and national standards for federal fisheries.** As the CPT stated, an uncertain estimate is better than ignoring discard mortality altogether. The method recommended by the CPT and the SSC produces similar OFL estimates as the other methods of estimating total catch OFL and ABC. It also included a correction factor for the observer effect. The SSC believes that this is the best method at this time, but recommends the author continue to explore ways to improve discard estimation, either through refinement of the currently selected method, or through alternative data sources. The SSC has several clarifications and requests related to this methodology described in Appendix G.

- The CPUE methods use a denominator of pot lifts. Please describe whether soak time was relatively consistent, variable, or is completely unknown.
- The information presented in the Appendix G discussion was confusing and the SSC requests some clarification on the comparison among methods.
- Also, justification for not using the model estimated discards might be helpful to provide some context.

The SSC appreciates the CPT table documenting previous concerns expressed by the SSC when adopting the 30% buffer for NSRKC in 2020/2021 and whether they still represent major concerns. As stated above, some of these issues may have lessened slightly. However, in addition to those ongoing concerns, there are now some additional considerations listed below:

1. The ADF&G survey abundance is much lower in 2020 than 2019, and the model is not fitting this new observation very well.
2. The retrospective bias was 0.18 for the 10-year peel, but the SSC is unsure how confident to be in that estimate because of the different data streams and fixed retention probabilities. The Mohn's rho of 0.26 in the recent 5-year peel presented is somewhat more substantial and is positive. In other words, the model is overestimating MMB by 26% each year on average. The overestimation of growth may be contributing to this retrospective pattern.
3. One of the selectivity parameters is on a bound, and it appears to be survey selectivity which could contribute to the poor fit to the recent ADF&G survey data point. This also raises questions about if the model has properly converged.
4. The recommended ABC is increasing when the only available 2020 survey estimate is low, and fishery CPUE has steeply declined in past years. Since there was no commercial fishery in 2020, there is no fishery CPUE estimate which increases uncertainty. The fit to recent low commercial CPUE values is poor, similar to the trawl survey. There also were no NMFS trawl survey data to evaluate.
5. While an improvement, the minimal data informing the estimate of total catch OFL further emphasizes the uncertainty in the estimation of discards.
6. The high recruitment discussed last year was supported by a high survey biomass estimate. The low biomass estimate in 2020 lowers confidence in the magnitude of this recruitment pulse. This potential large recruitment is still mostly below the preferred commercial size.

The CPT recommended continuing with the 30% buffer recommended by the SSC last year. However, for the above reasons, and previous concerns identified last year that remain unresolved, the SSC recommends increasing the buffer from 30% to 40% this year (Table 2).

Overall, there has been a great deal of work that has been done for this stock and the SSC recognizes the effort by the assessment authors to address some long-standing and complex issues associated with this assessment. The SSC supports the CPT's list of suggestions and looks forward to considering a GMACS version of the model next year.

Beyond the concerns listed above, the SSC encourages continued progress on the following priorities:

General:

- Investigations into size at maturity for this stock, referencing that of other red king crab stocks if useful.
- The inclusion of local, traditional and subsistence knowledge (LKTKS) information in the assessment, an effort the SSC understands cannot be fully pursued until appropriate protocols are developed and pandemic conditions ease. This particular issue is also discussed further in the SSC comments on the progress report from the LKTKS Taskforce (Agenda Item D-2).
- Reporting on pot loss, especially in regard to potential pot losses at the end of the season as noted in public testimony.
- Continue exploration of data-weighting assumptions. Provide clarification and justification for the current data weighting scheme utilized in the model.

Assessment document:

- The authors' responses to CPT and SSC comments could be reorganized by topic, as opposed to review body, to reduce redundancy and clarify the authors' responses.
- In the Analytic approach, more descriptive text should be included in the sections describing the model and its assumptions, to reduce referring to Appendix A.
- Furthermore, a thorough description of the model selection and evaluation criteria, and most particularly, the results of the author's recommended models (and the base model, if they differ) is a basic requirement for a complete assessment document. A list of figures and tables is not an acceptable description of results.
- Finally, the figures should be reviewed with respect to the caption descriptions and legends. There were some inaccuracies or conflicting statements found.
- Please explain how the SD was determined for the CPUE as it is the same from 2000 - 2019. Is this a fixed SD? If so shouldn't the CV be fixed rather than the SD?

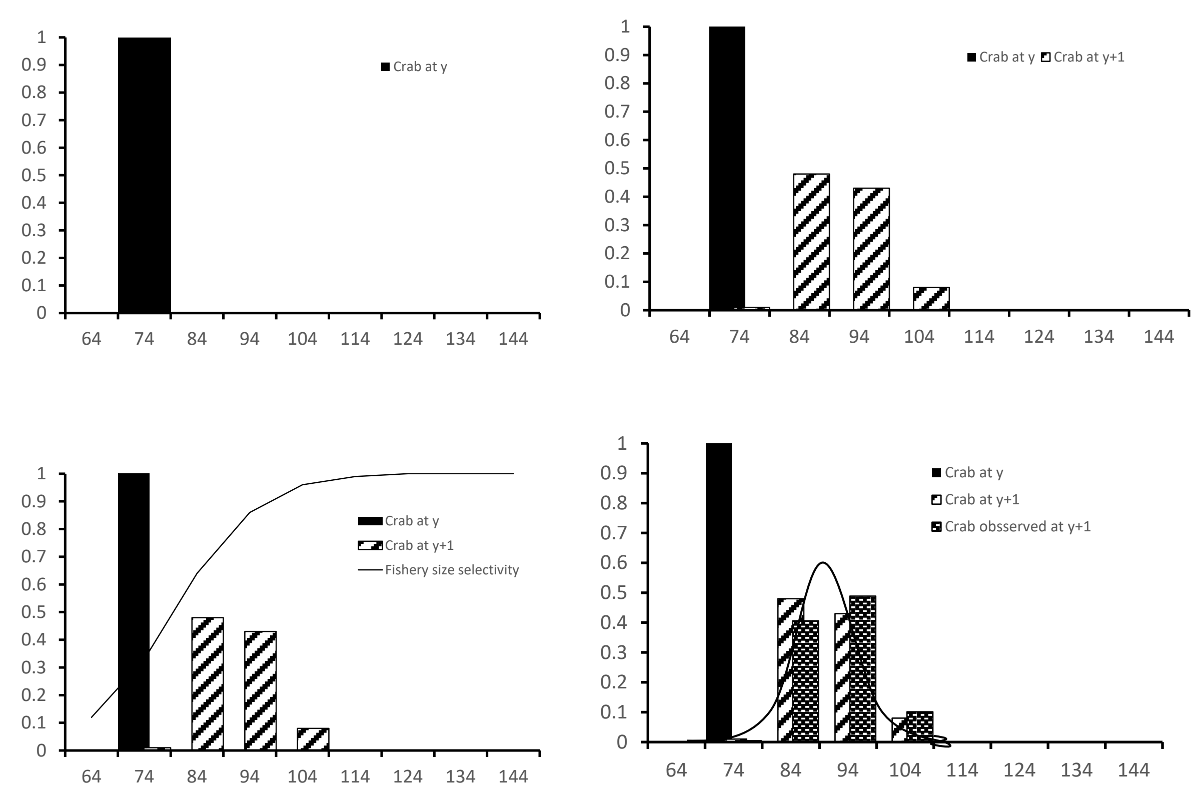
Appendix H

Norton Sound Red King Crab tag recovery data.

In the Norton Sound red king crab assessment model tag-recovery size distribution data are used to estimate size-transition matrix that is a probability distribution of each size class at year **y** to transitioning to other size classes at year **y+1**. The size transition matrix is a combined probability of 1) probability of crab did not molt and 2) conditional probability of post-molt growth given that the crab is molted.

As illustrated in Figure 1, crab of a size class tagged and released at year y will transition to multiple size classes at year y+1 (size transition probability). **The crab that remained in the same size class in year y+1 are either (1) crab did not molt, or molted but small growth.** The crabs will be captured by fishery that has size selectivity probability. Size distribution of the recovered tagged crab at year y+1 is a combination of both size transition matrix and fishery size selectivity. For estimating size transition matrix, probability of post-molt size distribution was fitted to a normal distribution and molt probability is estimated from observed proportion of new-old shell from commercial catch and trawl survey data.

Figure 1: Tag recovery process



Assembly of tag recovered data.

In Norton Sound, tag-recovery operations were conducted largely in 3 periods:1980-1985, 1986-2010, and 2012-2015. The first period was conducted as a part of mark-recapture experiment during summer commercial fishery period. The second periods were conducted as a part of winter pot survey. And the third was conducted as a part of migration study.

Table 1: NSRKC Tag-recovery data

Year		n	Tagged size (CL mm)
1980-1985	Summer Mark-Recapture	281	64-140
1986-2010	Winter Pot Survey	475	67-133
2012-2015	NPRB tagging	2170	71-145

All tagged crabs were recovered from by commercial or subsistence fisheries. The recovered crabs (if brought by a fishermen) were measured. **Shell condition (New vs Old) at the time of tagging and recovery were not always recorded, especially before 2012.** All tagged crabs were recovered from 0 to 6 years

Table 2: The number of crab recovered years at large.

Years liberty	n
0	850
1	1112
2	549
3	269
4	107
5	30
6	7

Data Cleaning and processing

The data were cleaned as follows

1. Convert each tagging and recovered length to 8 length classes

2. Remove data that were captured within a year (0 year at liberty).
   Tagging occurred in winter-summer and recovery occurred in summer. NSRKC molts in late fall, so that molting does not occur if they were recovered within the same year.

3. Separate tag recovery data pre and post 1993 to reflect changes of fishery (large boat to small boat fishery).

This was done under the assumption that fishery size selectivity curve (i.e., recapture probability) differ between the two fishery periods. However, because the assessment model estimate only 1 selectivity for summer commercial fishery, the data were later combined.

4. Remove data recovered size class was smaller than tagged size class (Table 3)
   Assumed that crab does not shrink.

5. Calculate proportion by size class (Table 4)

Table 3. The number of tagged data released and recovered after 1 year – 6 year during 1980-1992 and 1993-2019 periods. Bold numbers indicate crab with smaller recovery size (and thus removed).

Year: 1980-1992: Year at liberty 1

	64-73	74-83	84-93	94-103	104-113	114-123	124-33	> 134
64-73	0	1	1	0	0	0	0	0
74-83	0	0	0	0	0	0	0	0
84-93	0	0	0	5	10	0	0	0
94-103	0	0	0	3	31	26	2	0
104-113	0	0	0	**1**	16	34	7	0
114-123	0	0	0	0	0	16	26	5
124-133	0	0	0	0	0	0	15	10
>134	0	0	0	0	0	0	0	15

Year: 1980-1992: Year at liberty 2

	64-73	74-83	84-93	94-103	104-113	114-123	124-33	> 134
64-73	0	0	0	1	0	0	0	0
74-83	0	0	0	0	2	0	0	0
84-93	0	0	0	0	2	1	0	0
94-103	0	0	0	0	1	1	0	0
104-113	0	0	0	0	0	13	6	0
114-123	0	0	0	0	0	2	9	1
124-133	0	0	0	0	0	0	0	4
>134	0	0	0	0	0	0	0	6

Year: 1980-1992: Year at liberty 3

	64-73	74-83	84-93	94-103	104-113	114-123	124-33	> 134
64-73	0	0	0	0	0	0	0	0
74-83	0	0	0	0	0	2	0	0
84-93	0	0	0	0	0	1	0	0
94-103	0	0	0	0	1	3	1	0
104-113	0	0	0	0	0	0	3	0
114-123	0	0	0	0	0	0	1	0
124-133	0	0	0	0	0	0	0	2
>134	0	0	0	0	0	0	0	1

Year: 1980-1992: Year at liberty 4

	64-73	74-83	84-93	94-103	104-113	114-123	124-33	> 134
64-73	0	0	0	0	1	1	0	0
74-83	0	0	0	0	0	0	0	0
84-93	0	0	0	0	1	1	1	0
94-103	0	0	0	0	0	0	1	0
104-113	0	0	0	0	0	0	1	1
114-123	0	0	0	0	0	0	0	1
124-133	0	0	0	0	0	0	0	0
>134	0	0	0	0	0	0	0	0

Year: 1980-1992: Year at liberty 5

	64-73	74-83	84-93	94-103	104-113	114-123	124-33	> 134
64-73	0	0	0	0	0	0	0	0
74-83	0	0	0	0	0	2	0	0
84-93	0	0	0	0	0	0	1	0
94-103	0	0	0	0	0	0	0	1
104-113	0	0	0	0	0	0	0	0
114-123	0	0	0	0	0	0	0	0
124-133	0	0	0	0	0	0	0	0
>134	0	0	0	0	0	0	0	0

Year: 1993-2021: Year at liberty 1

	64-73	74-83	84-93	94-103	104-113	114-123	124-33	> 134
64-73	0	0	3	0	0	0	0	0
74-83	0	0	21	22	4	0	0	0
84-93	0	0	0	42	81	7	1	0
94-103	0	0	**1**	7	165	82	0	1
104-113	0	0	0	0	59	109	15	0
114-123	0	0	0	0	**4**	72	72	19
124-133	0	0	0	0	0	**7**	41	15
>134	0	0	0	0	**1**	0	0	11

Year: 1993-2021: Year at liberty 2

	64-73	74-83	84-93	94-103	104-113	114-123	124-33	> 134
64-73	0	0	1	5	4	0	0	0
74-83	0	0	0	12	94	5	0	0
84-93	0	0	0	5	34	69	3	0
94-103	0	0	0	2	33	38	19	0
104-113	0	0	0	0	7	64	18	0
114-123	0	0	0	0	**2**	9	38	6
124-133	0	0	0	0	0	**1**	9	12
>134	0	0	0	0	0	0	0	2

Year: 1993-2021: Year at liberty 3

	64-73	74-83	84-93	94-103	104-113	114-123	124-33	> 134
64-73	0	0	0	0	11	11	0	0
74-83	0	0	0	0	19	46	6	0
84-93	0	0	0	2	14	27	9	0
94-103	0	0	0	0	2	32	13	0
104-113	0	0	0	0	0	9	18	4
114-123	0	0	0	0	0	0	10	3
124-133	0	0	0	0	0	0	1	7

>134	0	0	0	0	0	0	0	0

Year: 1993-2021: Year at liberty 4

	64-73	74-83	84-93	94-103	104-113	114-123	124-33	> 134
64-73	0	0	0	0	3	5	1	0
74-83	0	0	0	0	4	17	11	1
84-93	0	0	0	0	1	9	12	2
94-103	0	0	0	0	0	3	5	1
104-113	0	0	0	0	0	3	9	1
114-123	0	0	0	0	0	0	1	4
124-133	0	0	0	0	0	0	0	1
>134	0	0	0	0	0	0	0	0

Year: 1993-2021: Year at liberty 5

	64-73	74-83	84-93	94-103	104-113	114-123	124-33	> 134
64-73	0	0	0	0	1	1	0	2
74-83	0	0	0	0	1	2	3	0
84-93	0	0	0	0	0	3	4	1
94-103	0	0	0	0	0	0	1	1
104-113	0	0	0	0	0	1	1	1
114-123	0	0	0	0	0	0	1	0
124-133	0	0	0	0	0	0	0	0
>134	0	0	0	0	0	0	0	0

Year: 1993-2021: Year at liberty 6

	64-73	74-83	84-93	94-103	104-113	114-123	124-33	> 134
64-73	0	0	0	0	1	0	1	0
74-83	0	0	0	0	0	1	2	0
84-93	0	0	0	0	0	0	0	0
94-103	0	0	0	0	0	0	0	1
104-113	0	0	0	0	0	0	0	1
114-123	0	0	0	0	0	0	0	0

124-133	0	0	0	0	0	0	0	0
>134	0	0	0	0	0	0	0	0

Table 4: Observed transition size distribution fitted by the assessment model
Year at liberty 1

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

Year at liberty 2

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

Year at liberty 3

	64-73	74-83	84-93	94-103	104-113	114-123	124-33	> 134	n
64-73	0	0	0	0	0.5	0.5	0	0	22
74-83		0	0	0	0.26	0.66	0.082	0	73
84-93			0	0.04	0.26	0.53	0.17	0	53

94-103				0	0.06	0.67	0.27	0	52
104-113					0	0.26	0.62	0.12	34
114-123						0	0.79	0.21	14
124-133							0.1	0.9	10
>134								1	1

Estimates of tag recovery

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

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

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

$$X_{l',l} = \begin{cases} m_{l'} \cdot G_{l',l} & \text{when } l' \neq l \\ m_l \cdot G_{l',l} + (1\text{-}m_i) & \text{when } l' = l \end{cases} \tag{2}$$

Where growth matrix $G_{l',l}$ (the expected proportion of crab molting from length class l' to length class l) was μ

assumed to be normally distributed:

$$G_{l',l} = \begin{cases} \dfrac{\int_{lm_l - h}^{lm_l + h} N(L \mid \mu_{l'}, \sigma^2)\, dL}{\sum_{l=1}^{n} \int_{lm_l - h}^{lm_l + h} N(L \mid \mu_{l'}, \sigma^2)\, dL} & \text{when } l \geq l' \\ 0 & \text{when } l < l' \end{cases} \tag{3}$$

Where

$$N(x \mid \mu_{l'}, \sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(L-\mu_{l'})^2}{\sigma^2} \right)$$
$$lm_l = L_1 + st \cdot l$$
$$\mu_l = L_1 + \beta_0 + \beta_1 \cdot l$$

Note

It should be noted that transition probability is based on size classes of both **molted and unmolted (without shell condition)**. Transition matrix does not include shell conditions. In the assessment model, molting probability is estimated by observed shell condition of trawl survey and commercial catch. **Individual crab growth increments was NOT calculated** in the above operation. At individual crab level, there were many crabs with growth increment of+/- 3mm that could be **umolted, molted but small growth, or measurement error**. Whether or not considering them as unmolted (i.e growth = 0) does not change size distribution unless crabs of the length are at the border between two size classes. In that case, growth increments of +/- 3mm will put the crab to adjacent class size. However, almost all of those crabs remain in the same size class, so that correction is unnecessary.

In model fitting, mean growth (μ) is should be considered as *ad hoc* mean growth mean that were conventionally estimated to fit the observed size distribution. Thus, μ does not necessarily indicate mean molting growth.