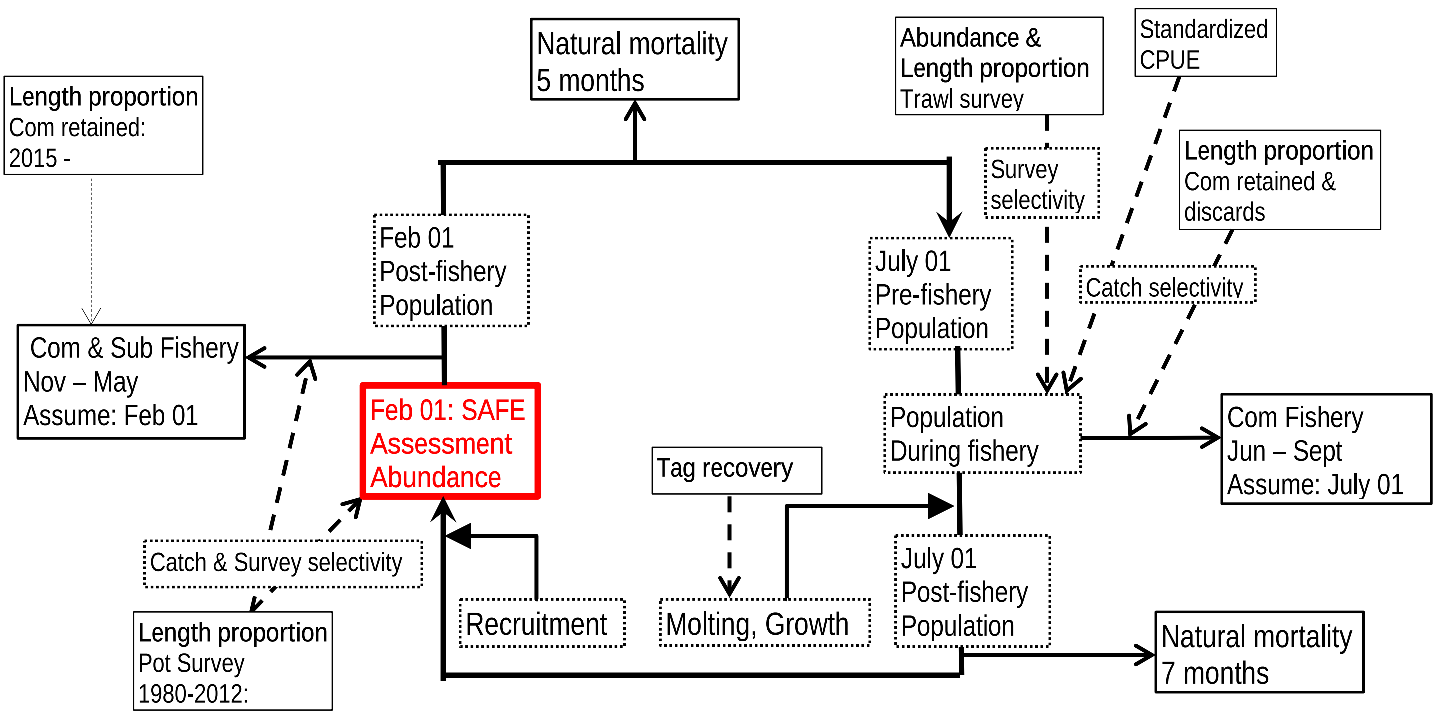
Appendix A. Description of the Norton Sound Red King Crab Model

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.**
- **All winter fishery harvest occurs on February 1st**
- **Molting and recruitment occur on July 1st**
- **Initial Population Date: February 1st 1976**

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

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

for model estimated parameters a_l.

Crab abundance on July 1st

Summer (01 July) crab abundance of new and oldshells consists of survivors of 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 catch ($P_{w,n,l,t}$, $P_{w,o,l,t}$) in year t were estimated as:

$$
\begin{aligned}
P_{w,n,l,t} &= N_{w,l,t} S_{w,l} P_{lg,l} / \sum_{l=1} [(N_{w,l,t} + O_{w,l,t}) S_{w,l} P_{lg,l}] \\
P_{w,o,l,t} &= O_{w,l,t} S_{w,l} P_{lg,l} / \sum_{l=1} [(N_{w,l,t} + O_{w,l,t}) S_{w,l} P_{lg,l}]
\end{aligned}
\tag{4}
$$

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

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

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

Crab abundance on Feb 1st

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

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

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

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

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,

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 length classes $S_{w,s}$ (S= l_1, l_2) 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

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 (Removed from likelihood components)
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 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:

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

Summer commercial fishery discards (1977-1995)

Length/shell compositions of observer discards were modeled as

$$\begin{aligned}\hat{P}_{b,n,l,t} &= N_{s,l,t}S_{s,l}(1-P_{lg,l}) / \sum_{l}[(N_{s,l,t}+O_{s,l,t})S_{s,l}(1-P_{lg,l})] \\ \hat{P}_{b,o,l,t} &= O_{s,l,t}S_{s,l}(1-P_{lg,l}) / \sum_{l}[(N_{s,l,t}+O_{s,l,t})S_{s,l}(1-P_{lg,l})]\end{aligned} \tag{25}$$

Summer commercial fishery total catch (2012-present)

Length/shell compositions of observer discards were modeled as

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

Summer trawl survey

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

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

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

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

Spring Pot survey 2012-2015

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

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

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

$$\hat{P}_{l',l,t,s} = \frac{S_l \cdot [X^t]_{l',l}}{\sum_{l=1}^{n} S_l \cdot [X^t]_{l',l}} \quad (30)$$

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

$$X_{l',l} = \begin{cases} m_{l'} \cdot G_{l',l} & \text{when } l' \neq l \\ m_l \cdot G_{l',l} + (1\text{-}m_i) & \text{when } l' = l \end{cases} \quad (31)$$

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

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

where

i: length/shell compositions of :

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

$K_{i,t}$: 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,
$B_{i,k,t}$: 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

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

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

d. Parameter estimation framework:

i. Parameters Estimated Independently

The following parameters were estimated independently: natural mortality (M =0.18), proportions of legal males by length group.

Natural mortality 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.

Proportions of legal males (CW > 4.75 inches) by length group were estimated from the ADF&G trawl data 1996-2011 (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. Estimate of 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 (Table 11).

ii. Projected legal male biomass for winter and summer fishery OFL was calculated as

$$Legal\_B = \sum_{l}(N_{w,l,} + O_{w,l,})S_{s,l}P_{lg,l}wm_l \text{ Baseline model}$$

$$Legal\_B = \sum_{l} (N_{w,l,} + O_{w,l,}) S_{s,l} S_{r,l} wm_l \text{ Alternative model}$$

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

iv.

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:

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

And

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

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

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

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

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 ($e^{-0.42M}$)

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

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

$$\begin{aligned} Hs &= (1 - e^{-(1-x) \cdot F}) B_s \qquad (6) \\ &= (1 - e^{-(1-x) \cdot F}) B_w e^{-x \cdot F - m} = (e^{-(x \cdot F + m)} - e^{-(F+m)}) B_w \end{aligned}$$

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

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

Further combining (3) and (9), Winter fishery harvest rate (Fw) i

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

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 Censoring

During 1977-92 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 – 1992, 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 1993 – 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 (1977-1992, 1993-2004,2005-2018), 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)
```

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.

Var	Df	Deviance	Resid DF	Resid Dev	AIC
YR	41	1312.43	6274	5082.7	
VSL	90	574.57	6143	3770.3	
WOY	15	82.89	6129	3195.7	
MSA	3	65.83	6125	3047.0	
PF	6	20.14	6119	3026.9	13547
+PD+MOY	3				13547.67

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

Year	Censored	
	CPUE	SE
1977	3.29	0.68
1978	4.68	0.65
1979	2.87	0.64
1980	3.07	0.65
1981	0.86	0.64
1982	0.20	0.62
1983	0.90	0.65
1984	1.59	0.65
1985	0.50	0.66
1986	1.74	0.70
1987	0.61	0.64
1988	2.36	0.86
1989	1.21	0.61
1990	1.08	0.68
1991		
1992	0.17	0.60
1993	0.90	0.35
1994	0.81	0.34
1995	0.42	0.34
1996	0.51	0.34
1997	0.84	0.35
1998	0.79	0.36
1999	0.92	0.36
2000	1.24	0.34
2001	0.64	0.34
2002	1.23	0.34
2003	0.85	0.34
2004	1.27	0.34
2005	1.19	0.34
2006	1.31	0.34
2007	1.02	0.34
2008	1.32	0.34
2009	0.84	0.34
2010	1.22	0.34
2011	1.58	0.34
2012	1.29	0.34
2013	0.67	0.33
2014	1.12	0.34
2015	1.45	0.34
2016	1.27	0.34
2017	1.10	0.34
2018	0.64	0.34

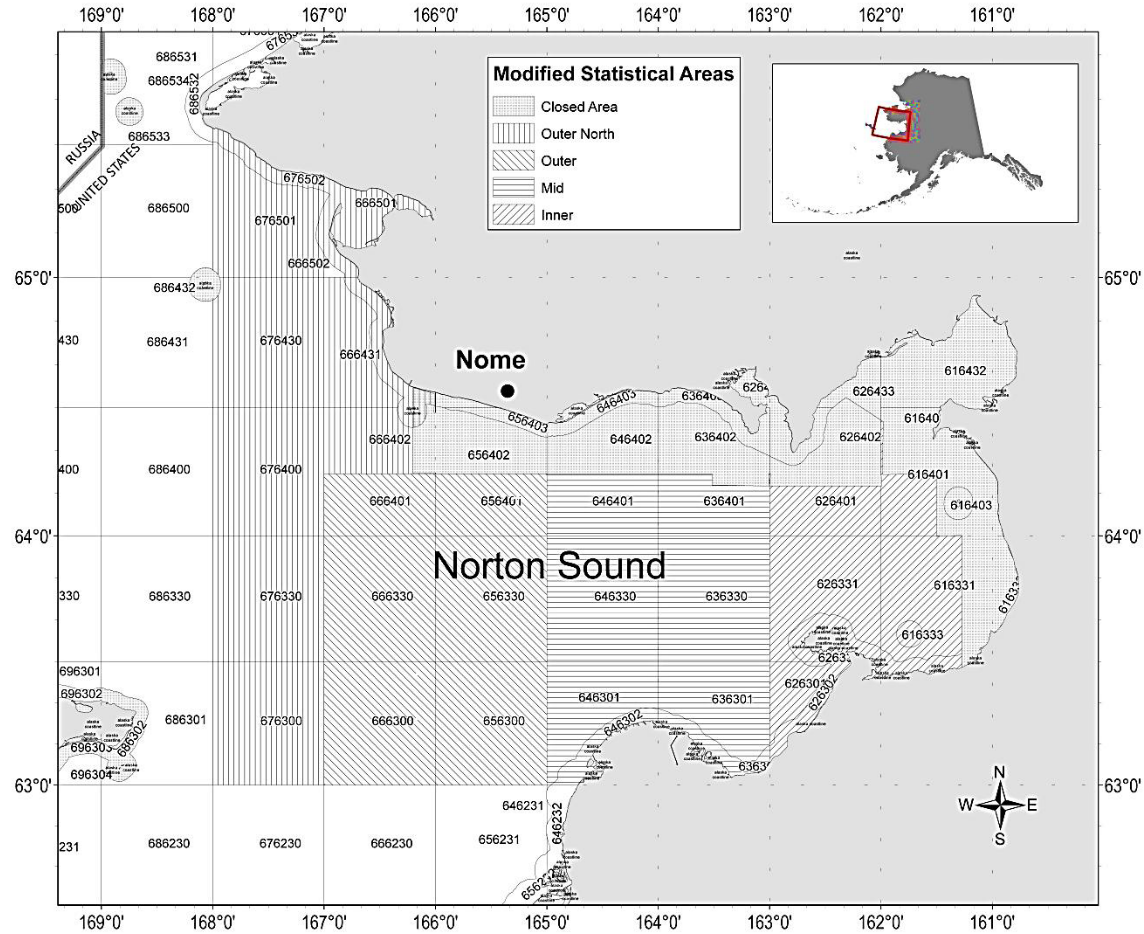


Figure A2-1. Closed area and statistical area boundaries used for reporting commercial harvest information for red king crab in Registration Area Q, Northern District, Norton Sound Section and boundaries of the new *Modified Statistical Areas* used in this analysis.

Appendix C

Norton Sound Red King Crab Summer Commercial fishery Discards 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 crabs 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 crabs 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 crabs that are not accepted by NSEDC: **lower discards CPUE than unobserved (lower discards 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 crabs ranging from 2200 to 5300 (Table 1). All observed data were combined.

Estimation Methods

Two methods were considered: CPUE and Proportion method. 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 crabs 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 subtract 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 crabs by observed fishermen during the observed periods.

In assessment model, total number of crabs 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 discards 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 high by discards estimates of 2013 and 2015.

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 discards proportions would represent total proportion or that **every fisherman has similar crab composition**.

In Norton Sound observer survey, discarded crabs are more likely accurate because separation of retained vs discards are often done in corporation with the fishermen. However, fishermen and timing of observation are limited to convenience of volunteer fishermen who have larger boat (so that observer can be on board) and are high also catchers. They would be more efficient in catching legal crabs 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 crabs (e.g., lower sublegal proportion), the proportional method would underestimate discard catch. But, as they have higher catch CPUE, their discards catch CPUE could still be higher than those of unobserved fishermen. Then, discards 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	
Year	Pot lifts P_{obs}	Sublegal $N_{obs.sub}$	Legal retained $N_{obs.lr}$	Legal discards $N_{obs.ld}$	Female	pot lifts $P_{FT.total}$	Retained $N_{FT.total}$
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.

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%

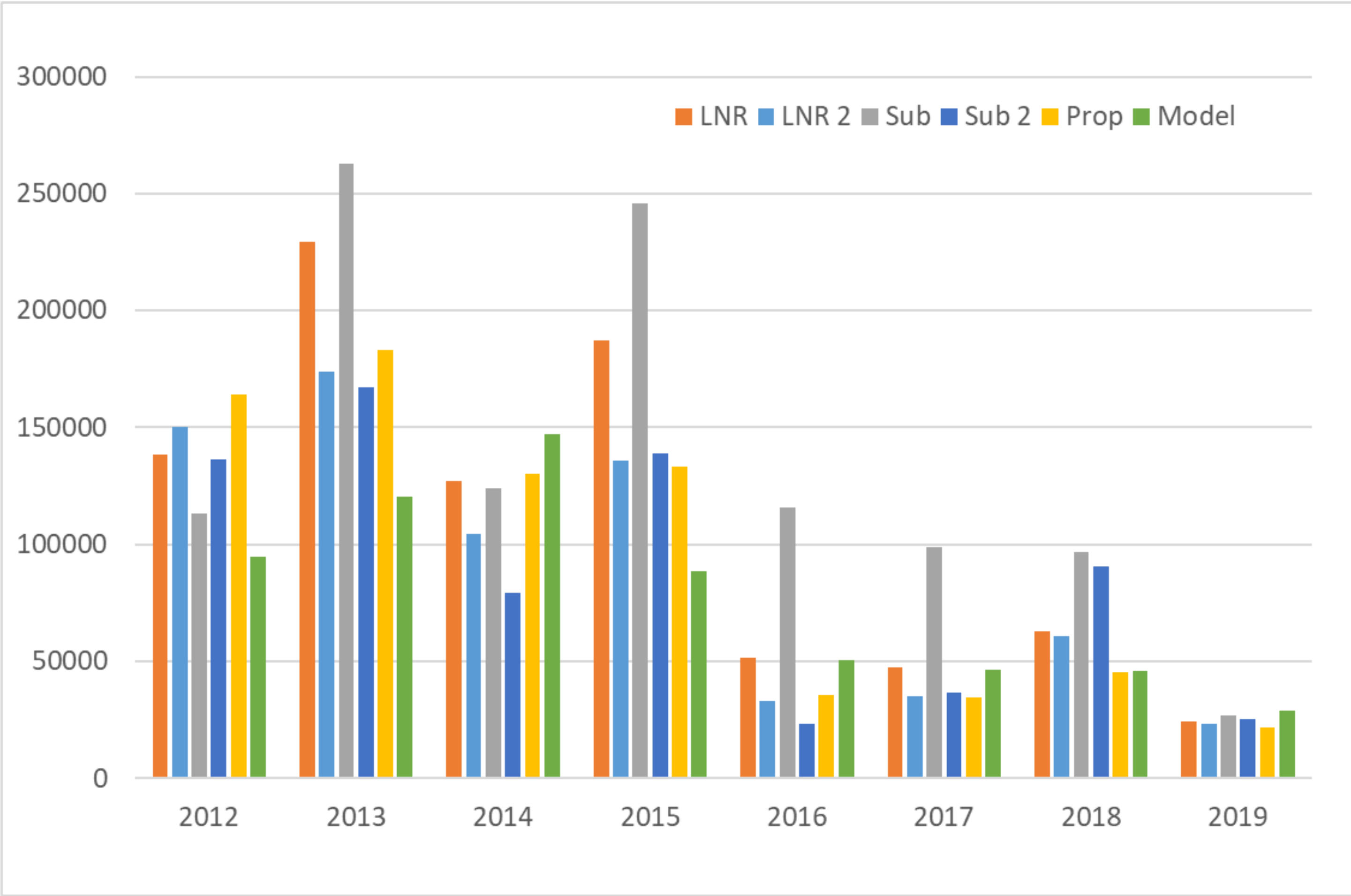


Figure 1. The number of discarded crab estimated by 3 methods.

Model 19.0

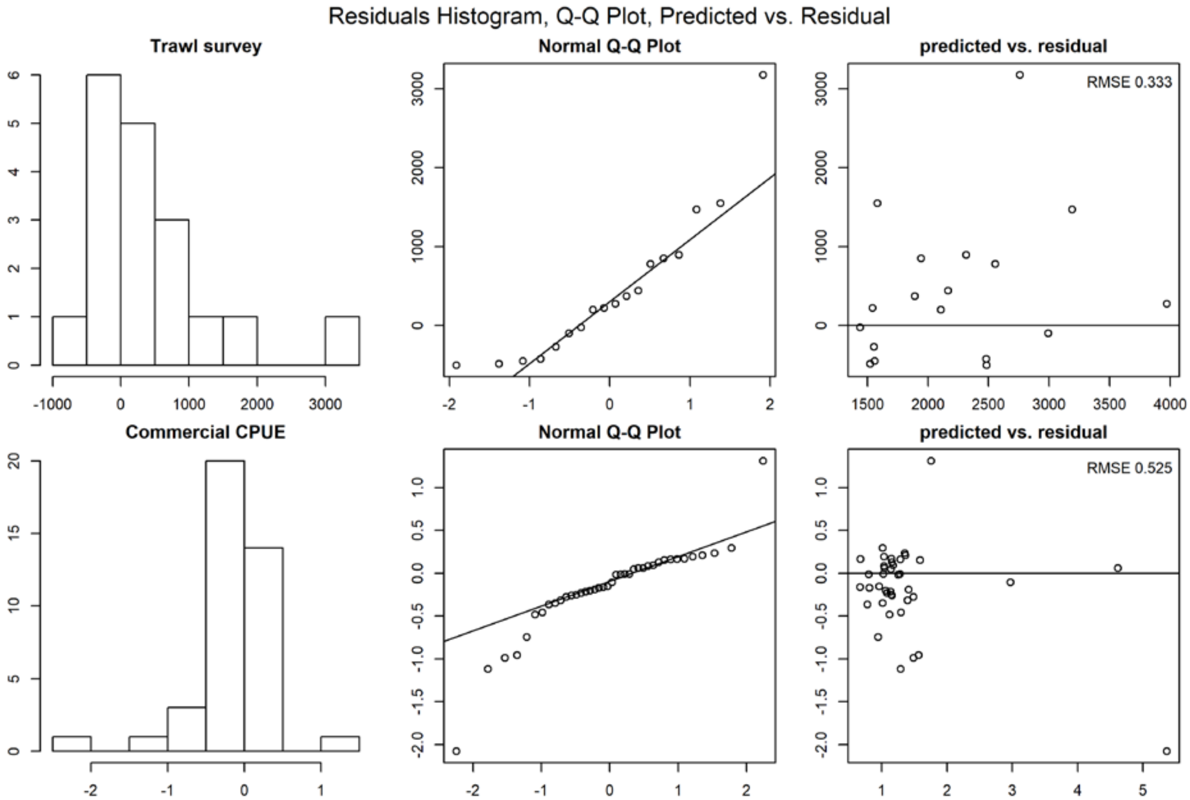


Figure D1-1. QQ plot of trawl survey and commercial CPUE.

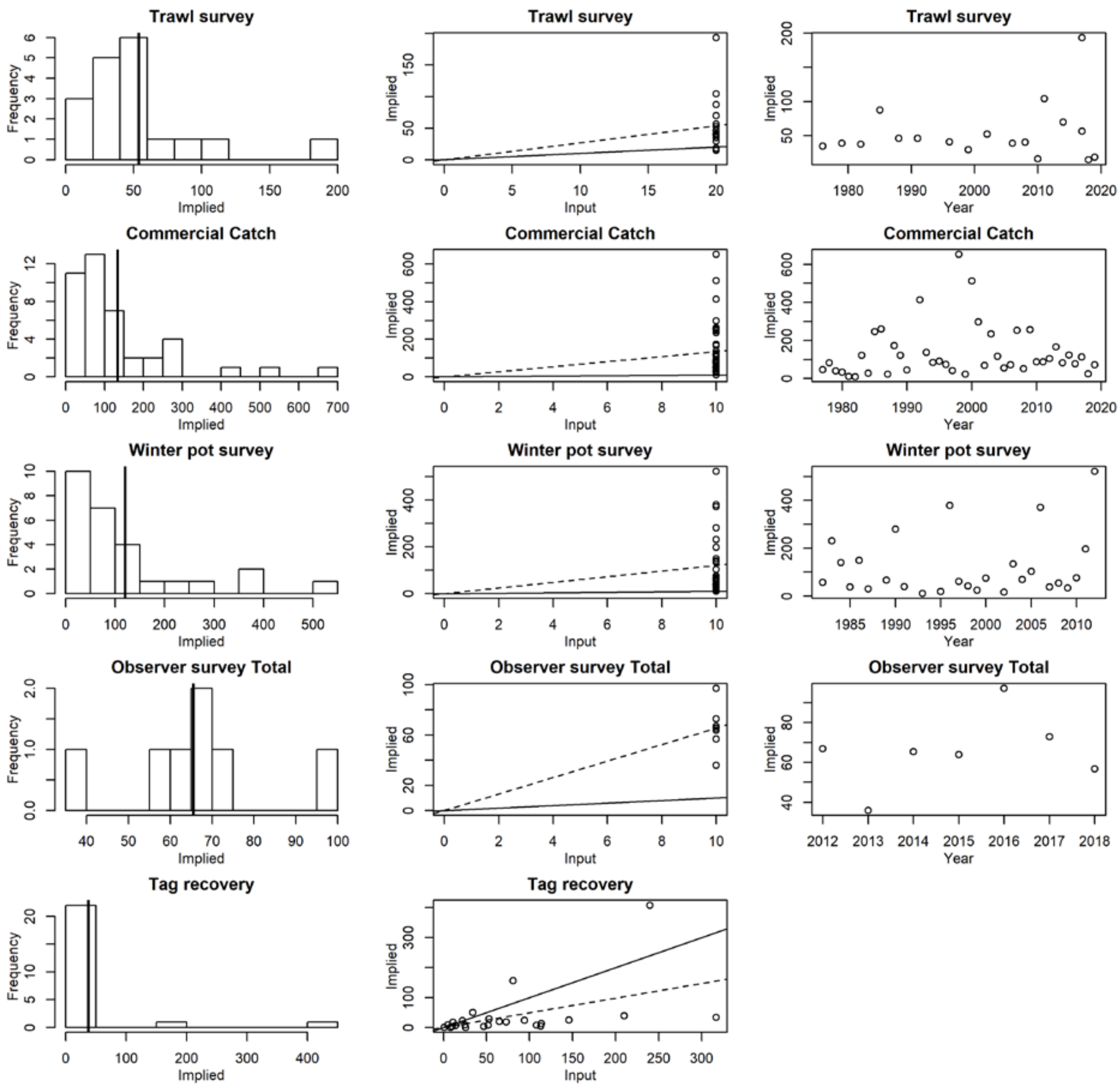


Figure D1-2: Implied effective samples. Figures in the first column show implied effective sample size (x-axis) vs. frequency (y-axis).
Vertical solid line is the mean implied effective sample size.
The second column shows input sample size (x-axis) vs. implied effective sample size (y-axis). Dashed line indicates linear regression slope, and solid line is 1:1 line. The third column show year (x-axis) vs. implied effective sample size (y-axis).

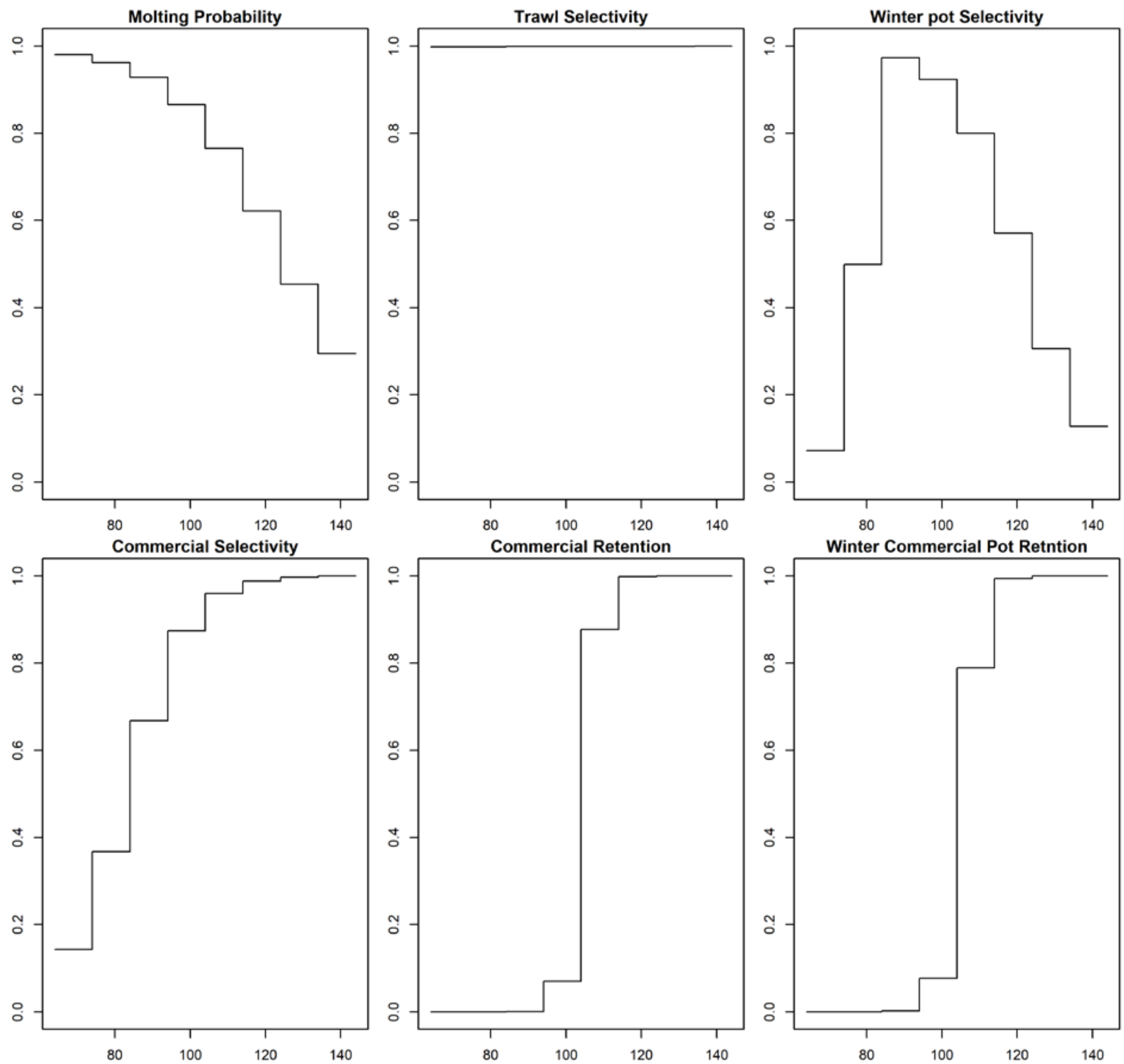


Figure D1-3. Molting probability and trawl/pot selectivity. X-axis is carapace length.

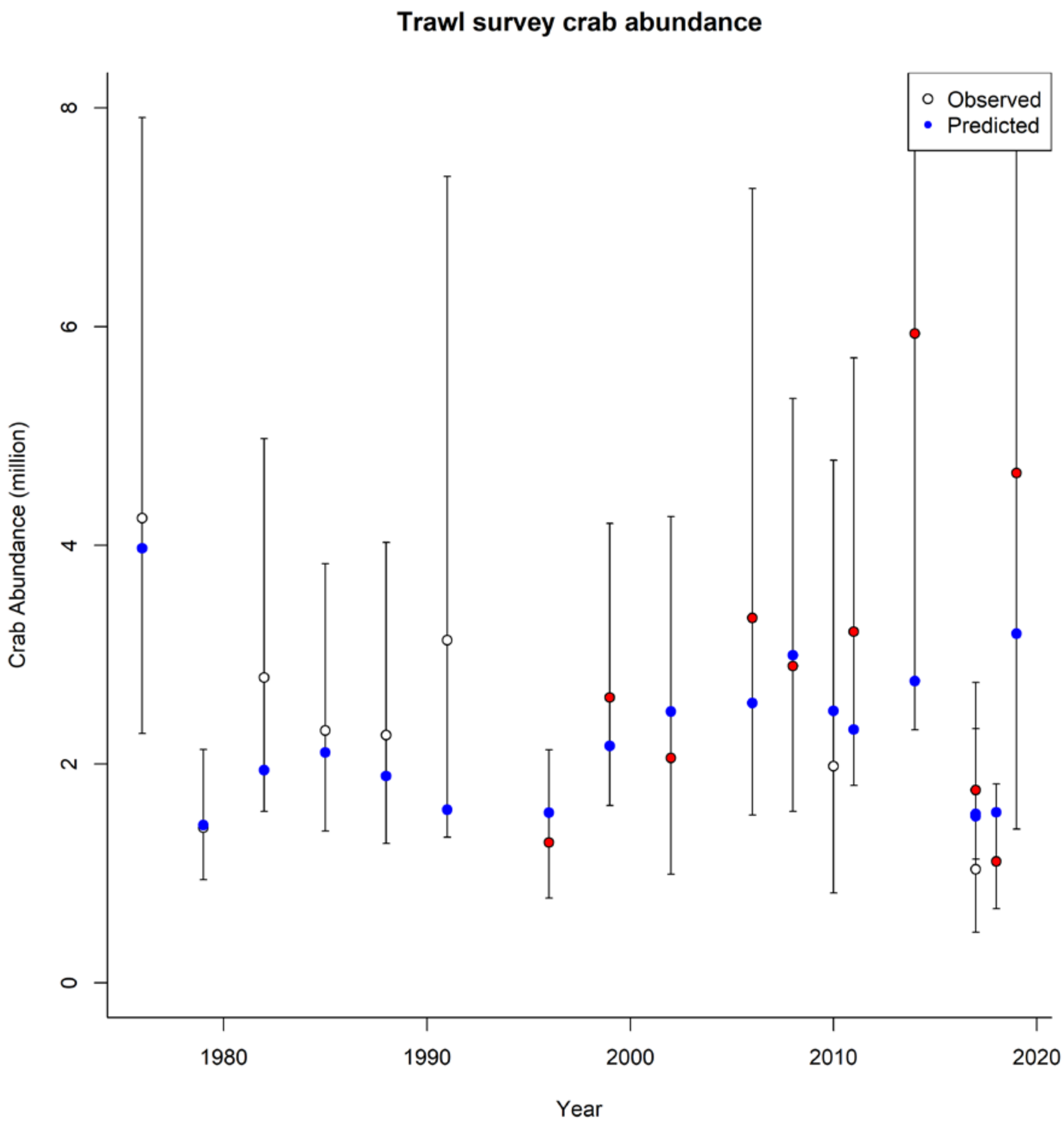


Figure D1-4. Estimated trawl survey male abundance (blue). Observed: white: NOAA trawl Survey, red: ADG&G trawl survey

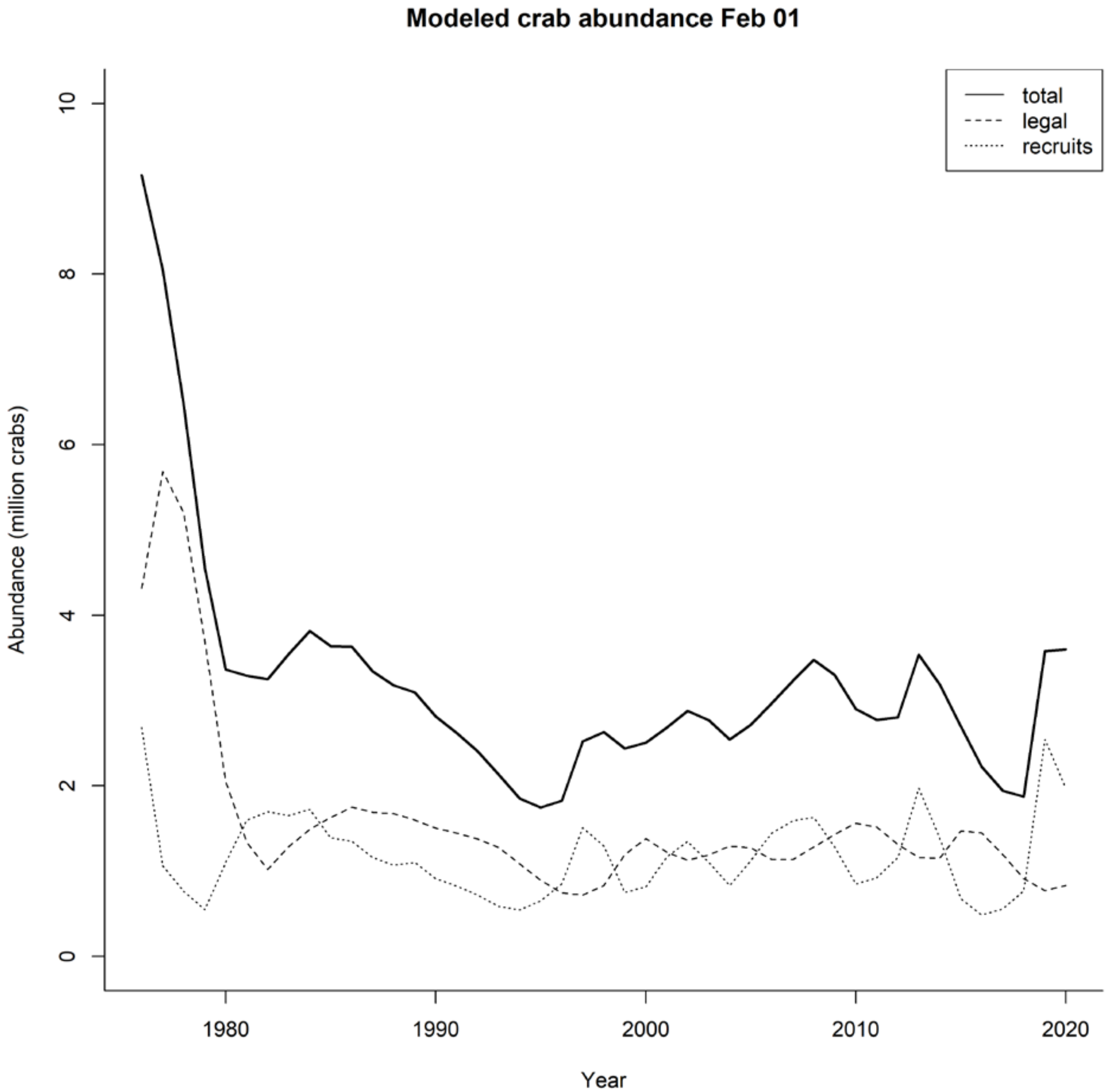


Figure D1-5. Estimated abundance of legal males.

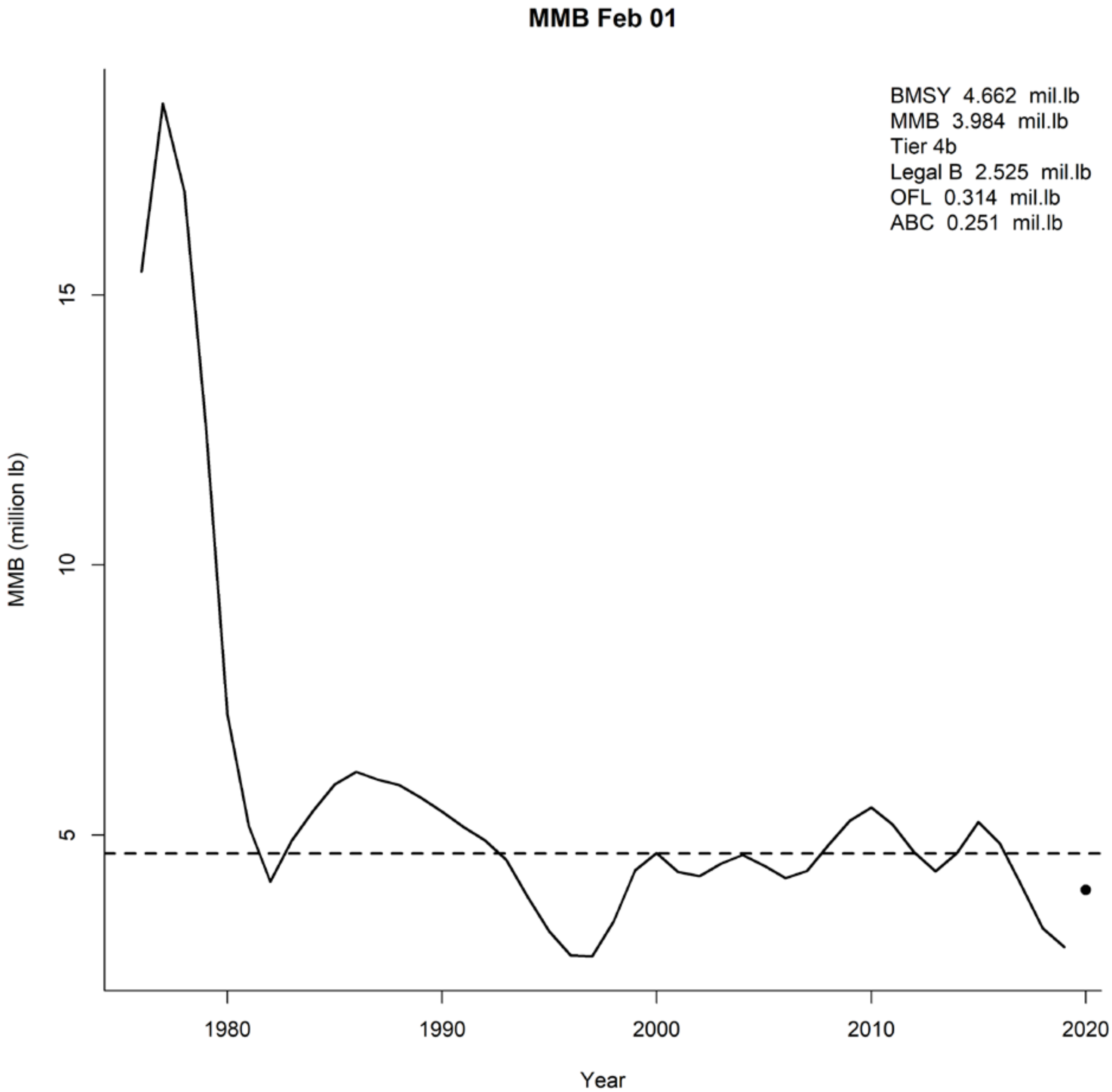


Figure D1-6. Estimated mature male biomass. Dash line shows Bmsy.

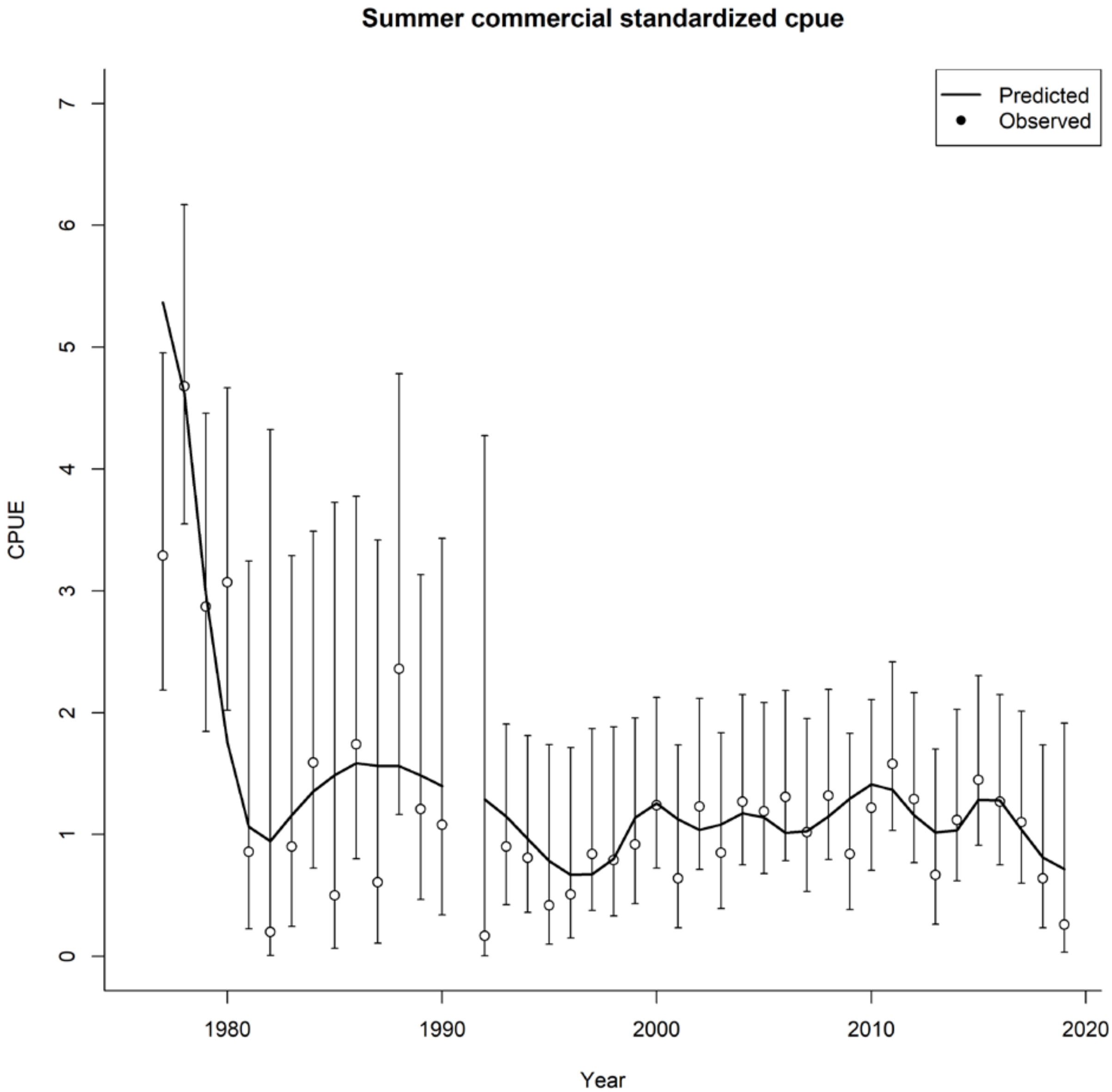


Figure D1-7. Summer commercial standardized cpue. Vertical line incicates lognormal 95%CI

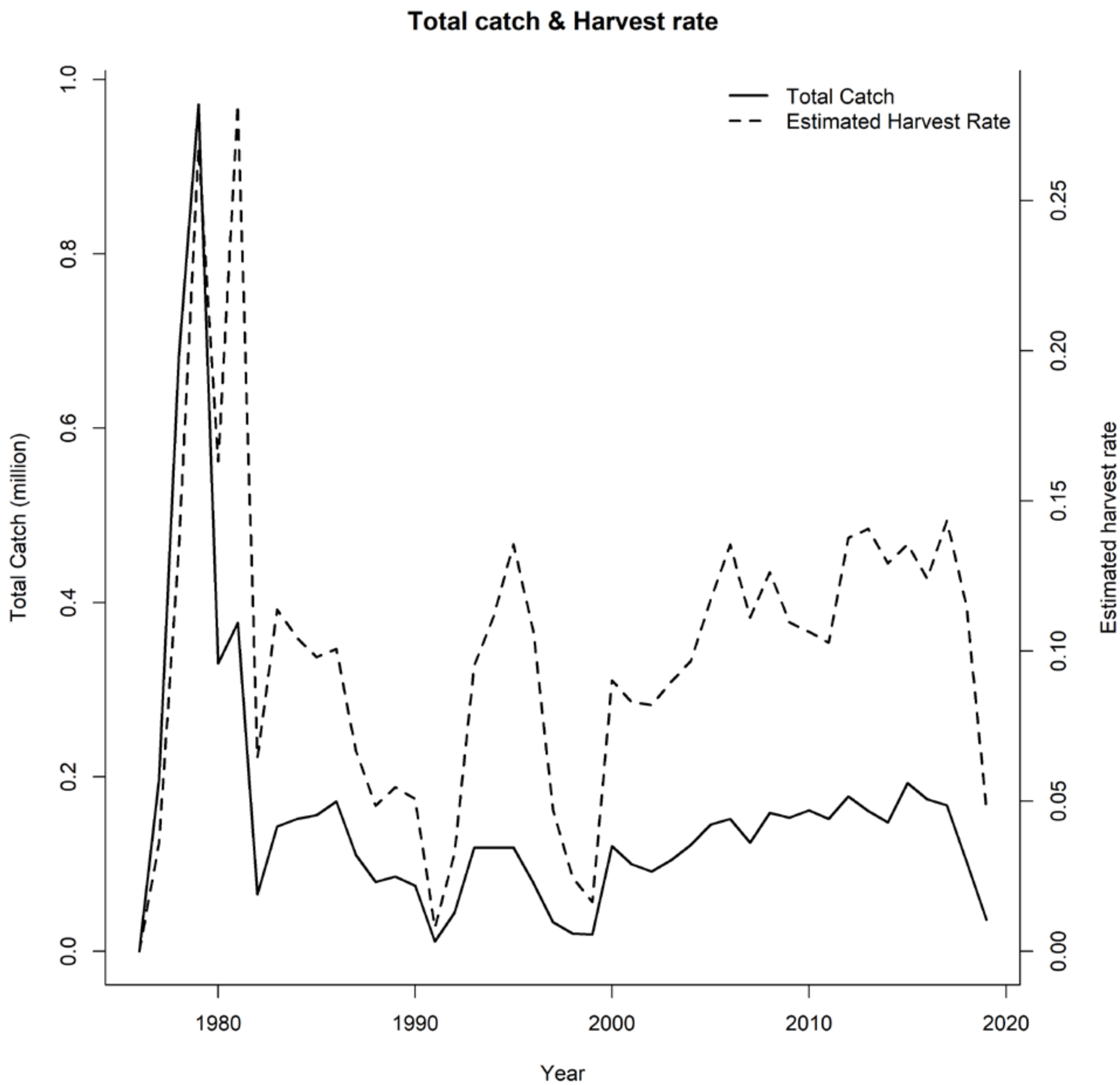


Figure D1-8. Total catch and estimated harvest rate 1976-2019.

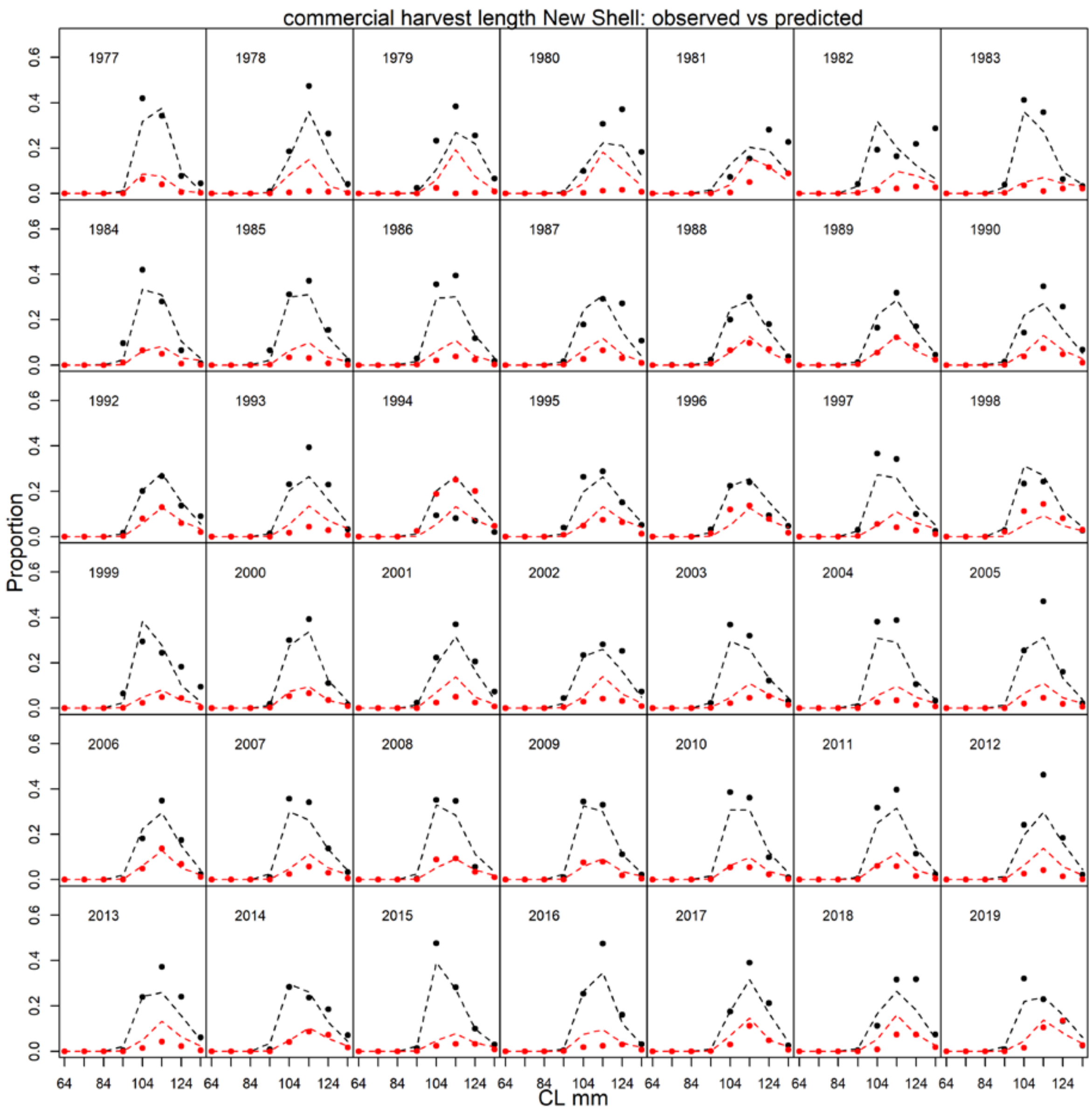


Figure D1-9. Predicted (dashed line) vs. observed (dots) length class proportions for commercial catch. Black: newshell, Red: oldshell

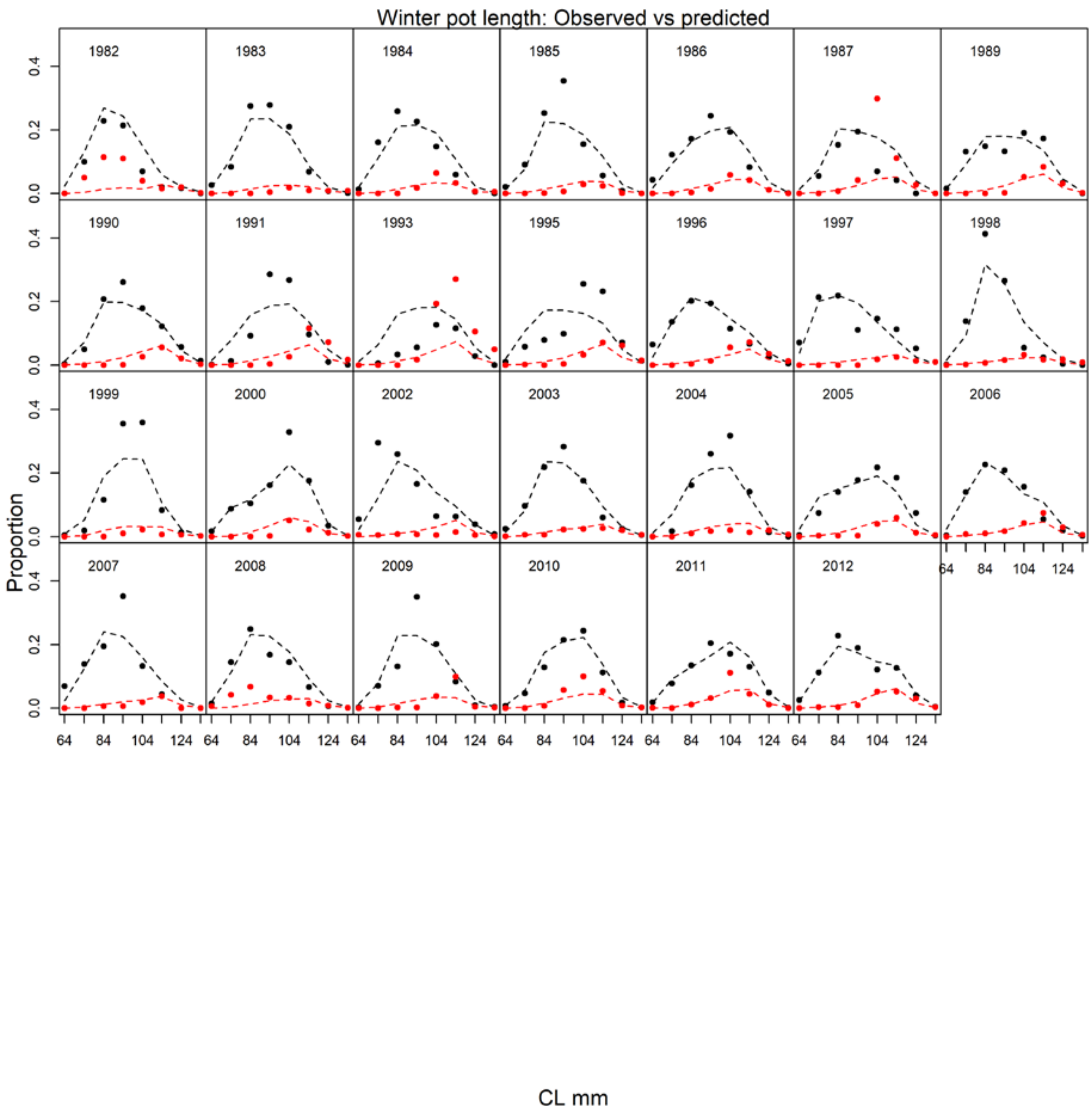


Figure D1-10. Predicted (dashed line) vs. observed (dots) length class proportions for the winter and spring pot survey. Black: newshell, Red: oldshell

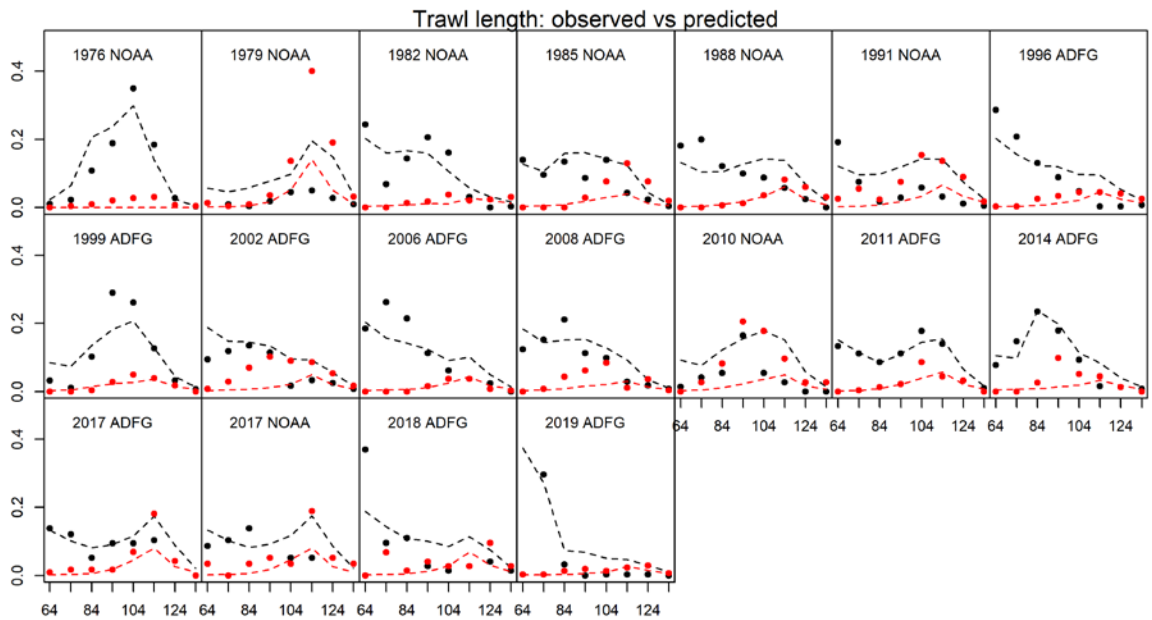


Figure D1-11. Predicted (dashed) vs. observed (dots) length class proportions for Trawl survey. Black: newshell, Red: oldshell

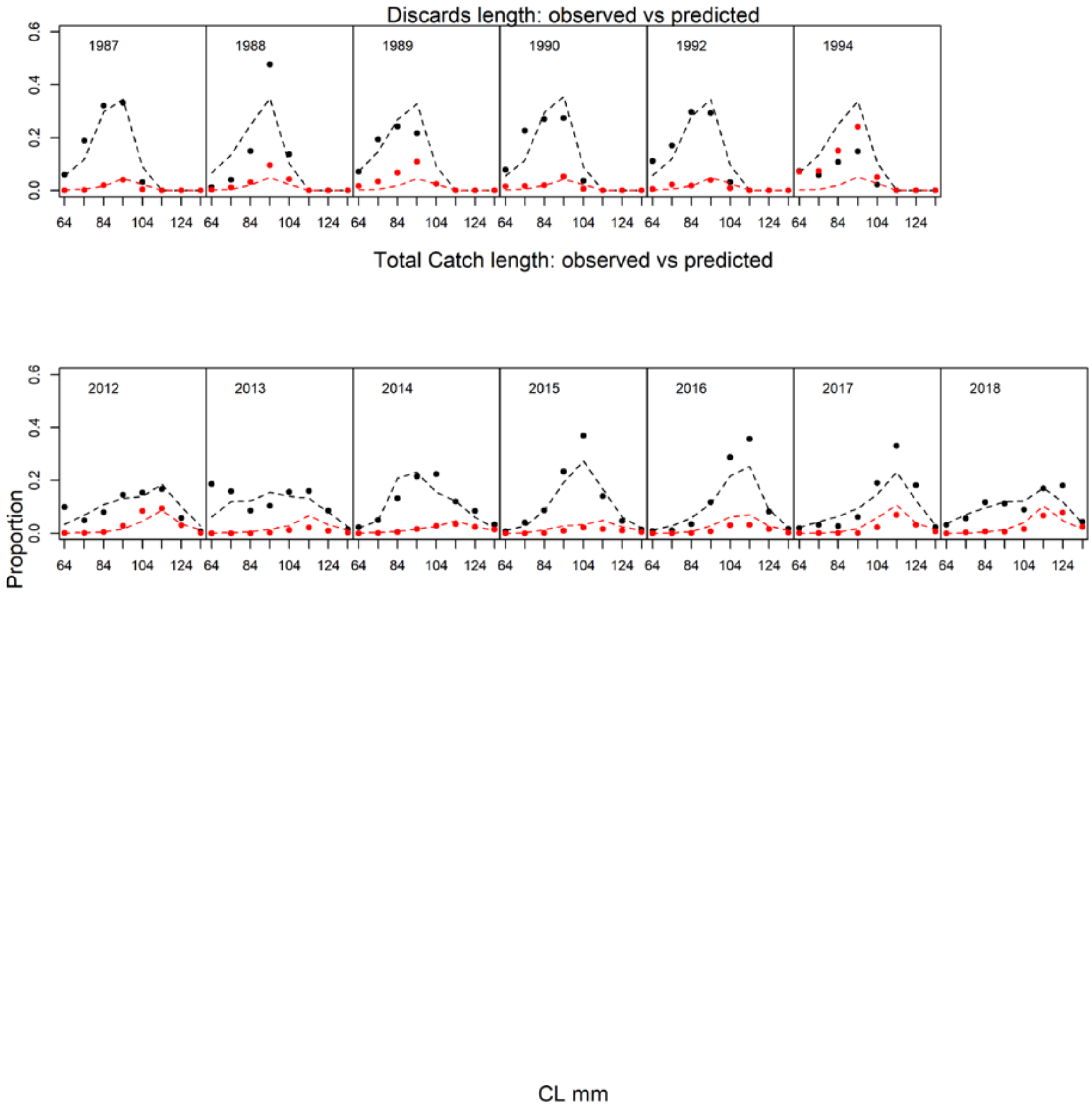


Figure D1-13. Predicted (dashed) vs. observed (dots) length class proportions for the observer survey. Black: newshell, Red: oldshell

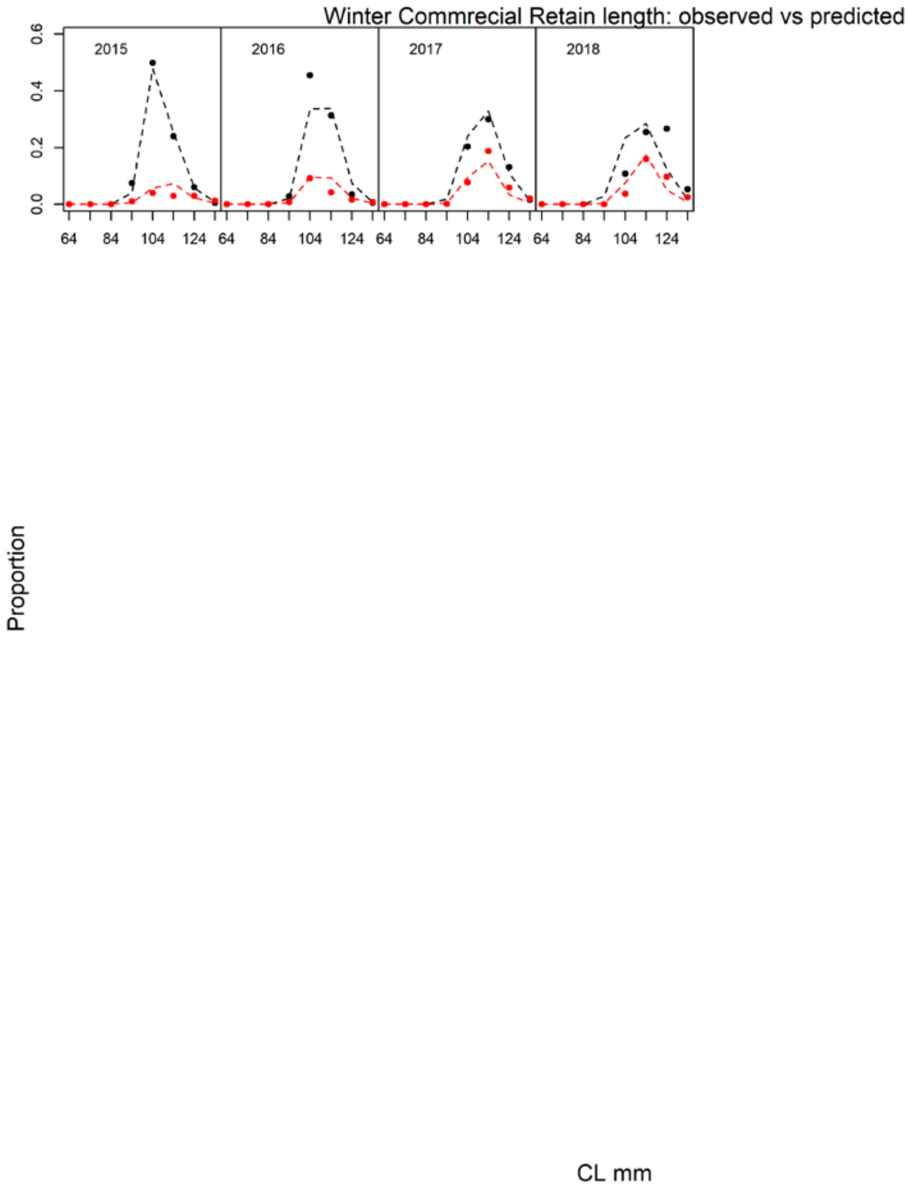


Figure D1-12. Predicted (dashed) vs. observed (dots) length class proportions for the observer survey. Black: newshell, Red: oldshell

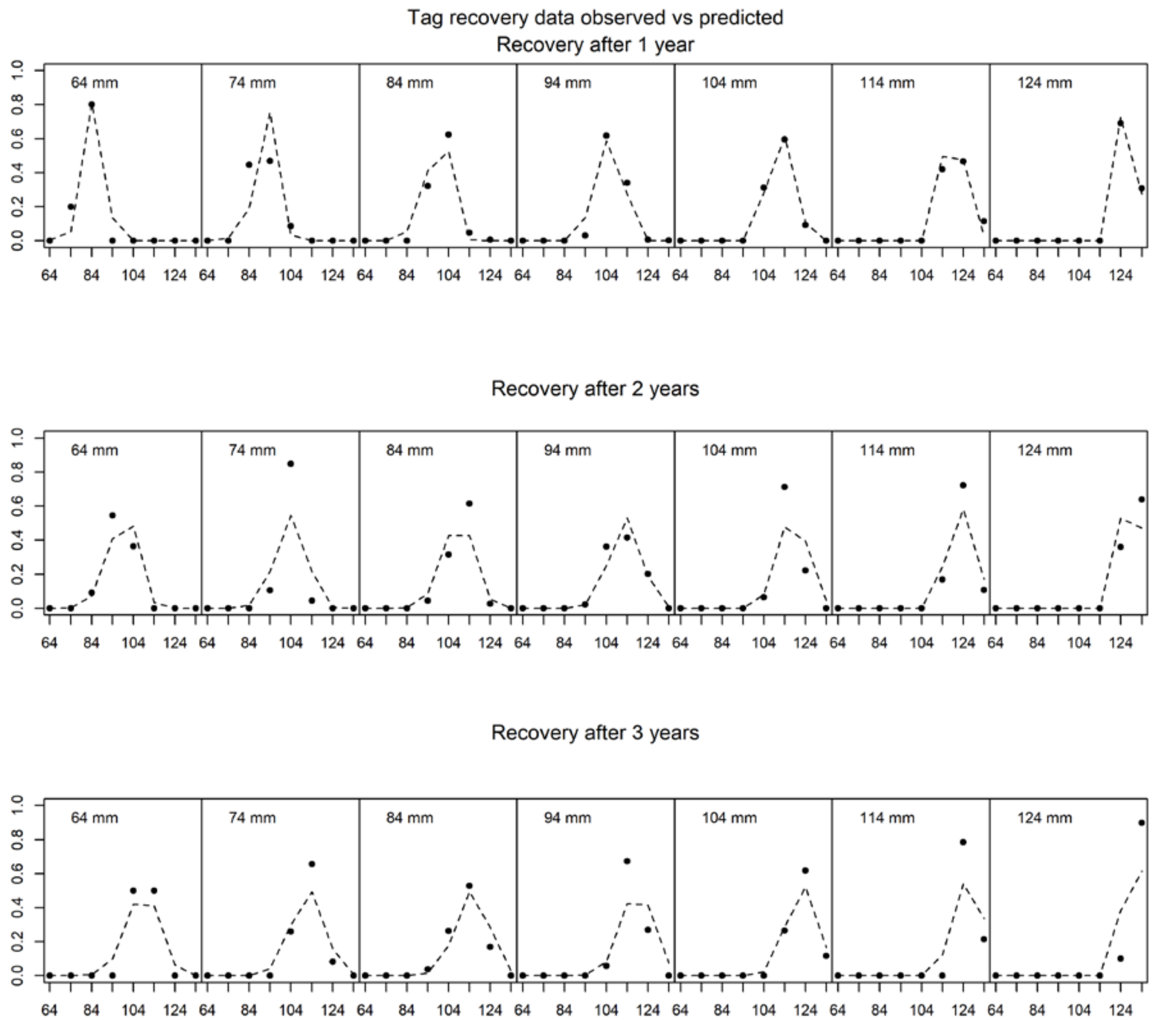


Figure D1-13. Predicted vs. observed length class proportions for tag recovery data.

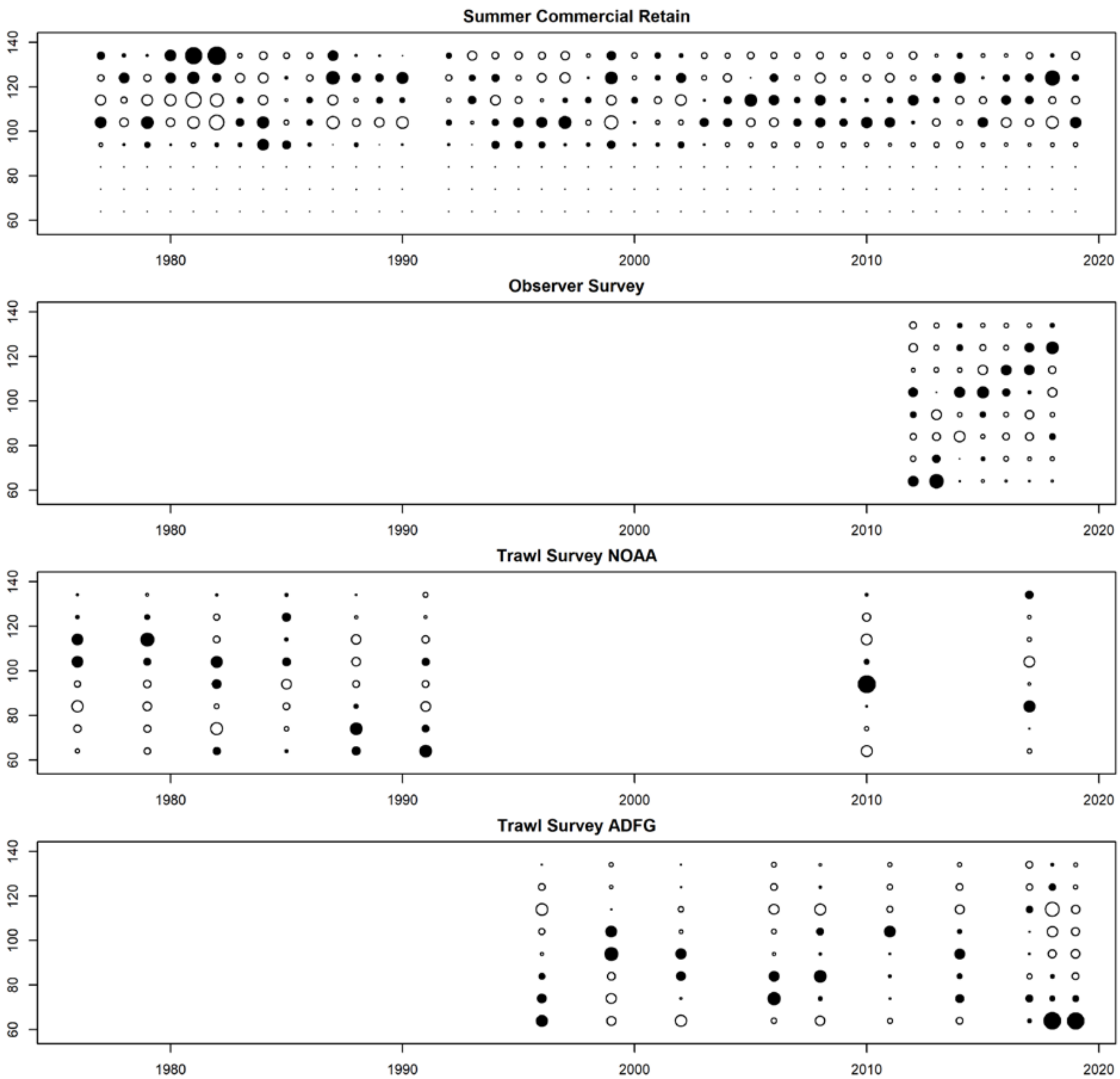


Figure D1-13. Bubble plots of predicted and observed length proportions.
Black circle indicates model estimates lower than observed, white circle indicates model estimates higher than observed. Size of circle indicates degree of deviance (larger circle = larger deviance).

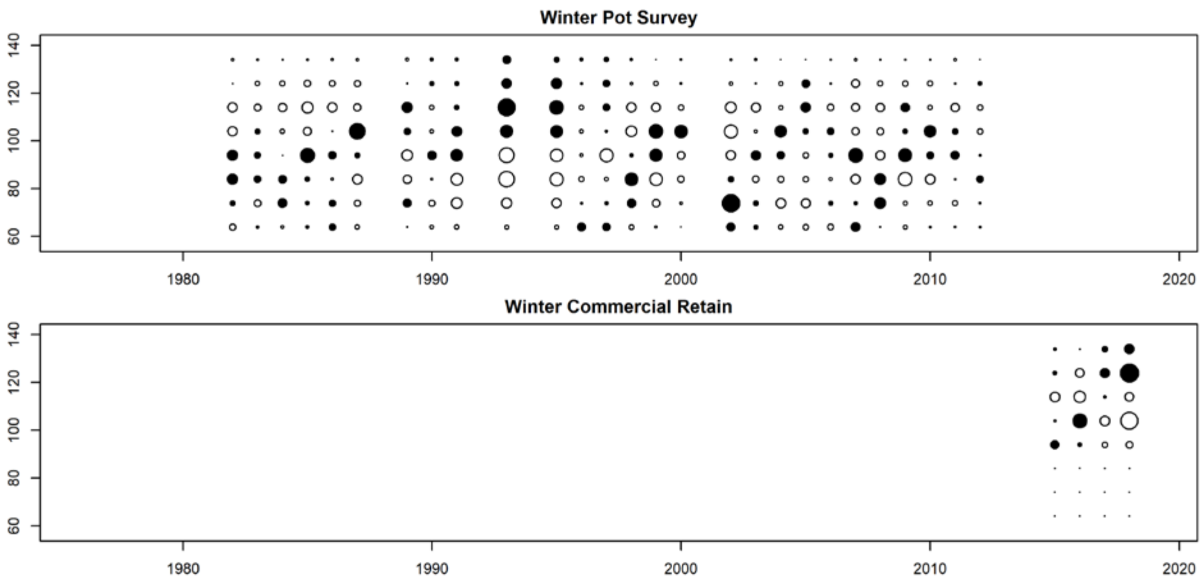


Figure D1-14. Bubble plots of predicted and observed length proportions.
Black circle indicates model estimates lower than observed, white circle indicates model estimates higher than observed. Size of circle indicates degree of deviance (larger circle = larger deviance).

Table D1. Summary of parameter estimates for a length-based stock synthesis population model of Norton Sound red king crab.

name	Estimate	std.dev
log_q_1	-6.783	0.111
log_q_2		
log_N_{76}	9.122	0.109
R_0	6.478	0.083
a_1	1.752	4.587
a_2	2.769	4.260
a_3	3.934	4.107
a_4	4.072	4.094
a_5	4.300	4.085
a_6	3.537	4.114
a_7	2.101	4.383
r1	10.000	0.283
r2	9.655	0.332
log_a	-2.682	0.090
log_b	4.835	0.015
log_ϕ_{st1}	-5.000	0.051
log_ϕ_{wa}	-2.206	0.301
log_ϕ_{wb}	4.796	0.032
Sw1	0.072	0.035
Sw2	0.499	0.126
log_ϕ_1	-2.086	0.057
$log\_\phi ra$	-0.787	0.129
$log\_\phi rb$	4.646	0.008
$log\_\phi wra$	-0.965	0.553
$log\_\phi wrb$	4.654	0.038
w^2_t	0.000	0.000
q	0.700	0.113
σ	3.886	0.208
β_1	12.393	0.700
β_2	7.661	0.171
ms78	3.248	0.255

Model 19.0update

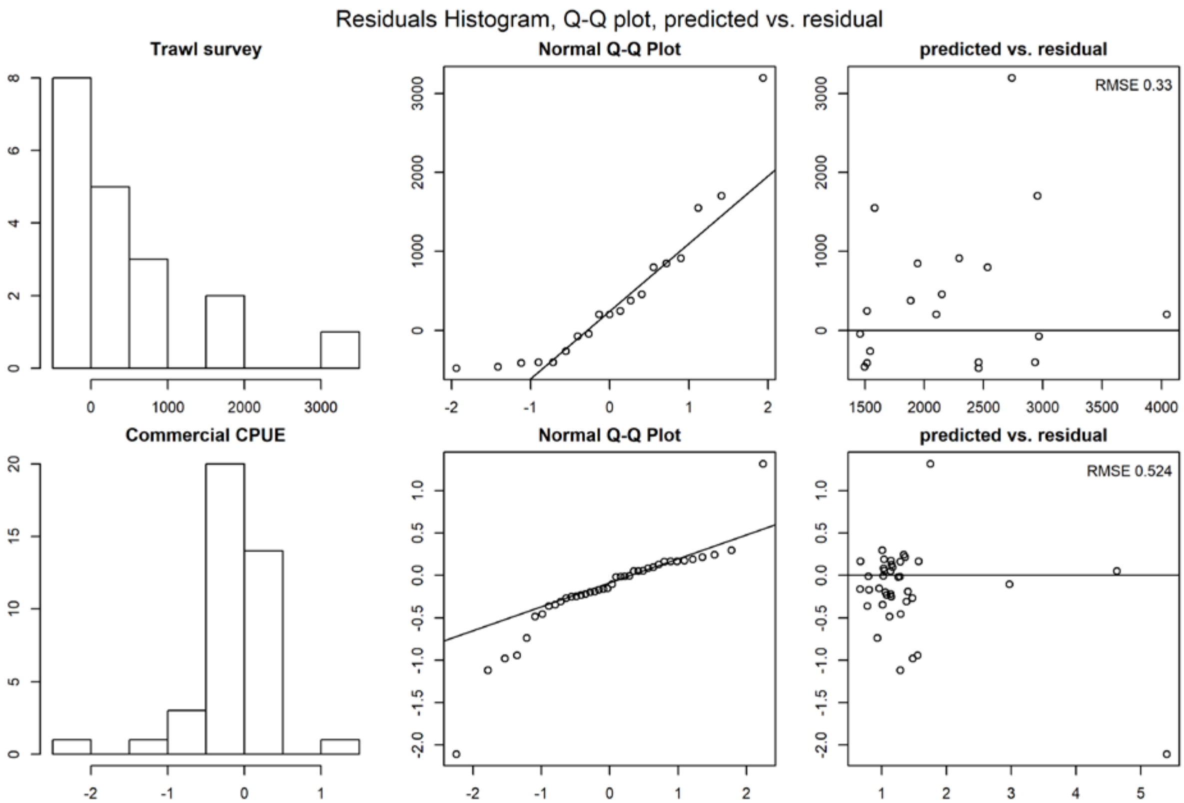


Figure C8-1. QQ plot of trawl survey and commercial CPUE.

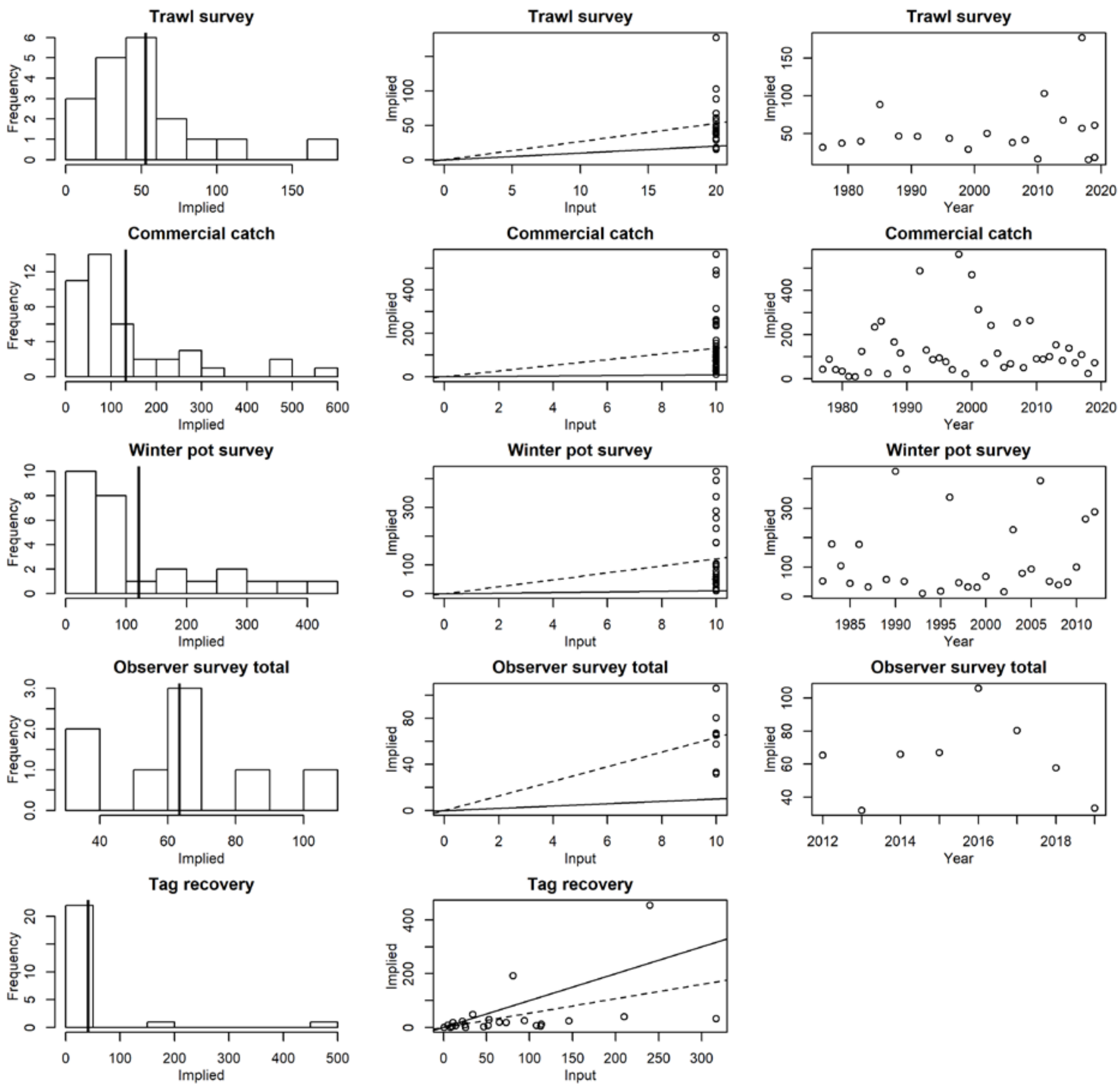


Figure C8-2: Implied effective samples. Figures in the first column show implied effective sample size (x-axis) vs. frequency (y-axis).
Vertical solid line is the mean implied effective sample size.
The second column shows input sample size (x-axis) vs. implied effective sample size (y-axis). Dashed line indicates linear regression slope, and solid line is 1:1 line. The third column show year (x-axis) vs. implied effective sample size (y-axis).

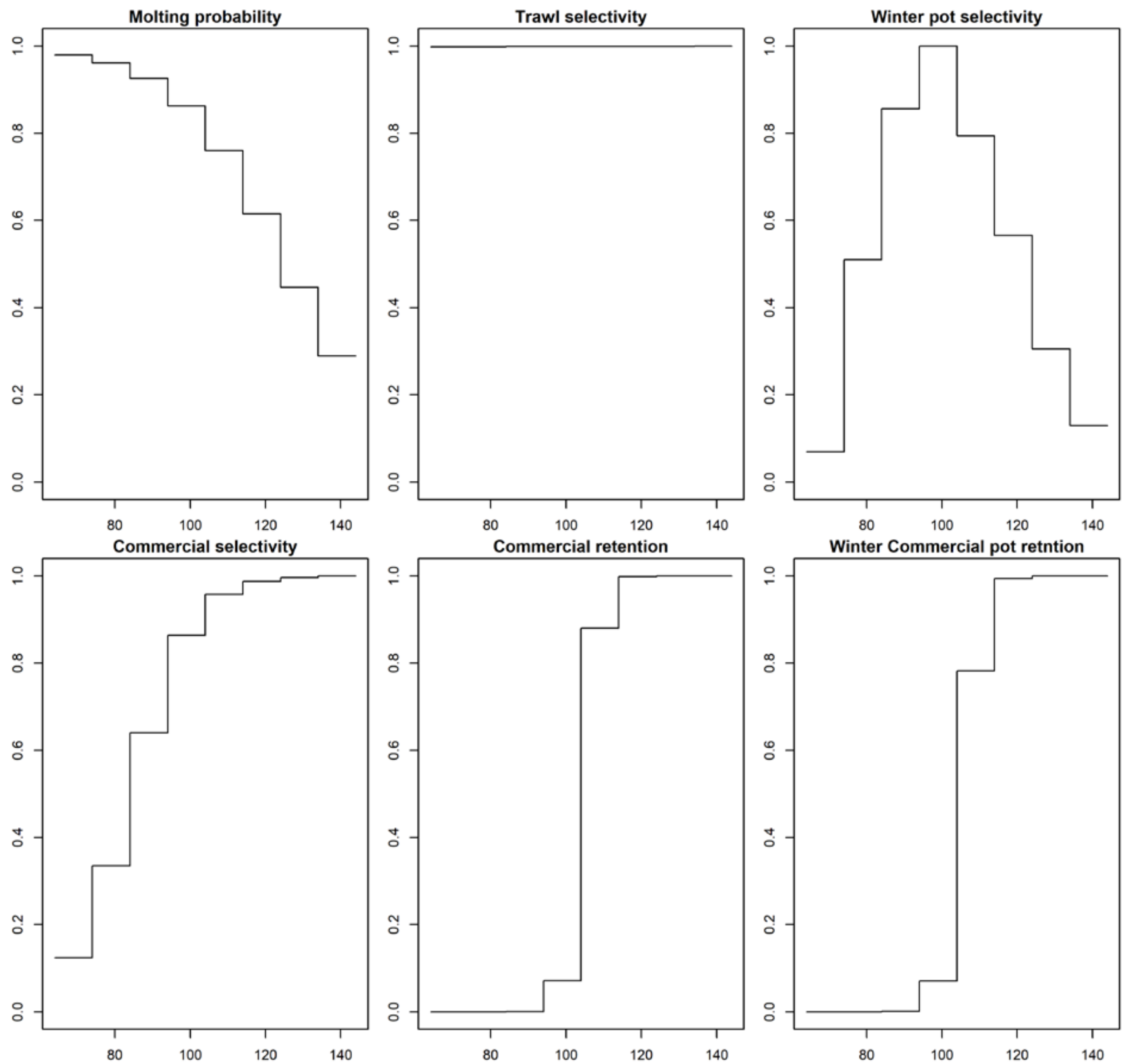


Figure C8-3. Molting probability and trawl/pot selectivity. X-axis is carapace length.

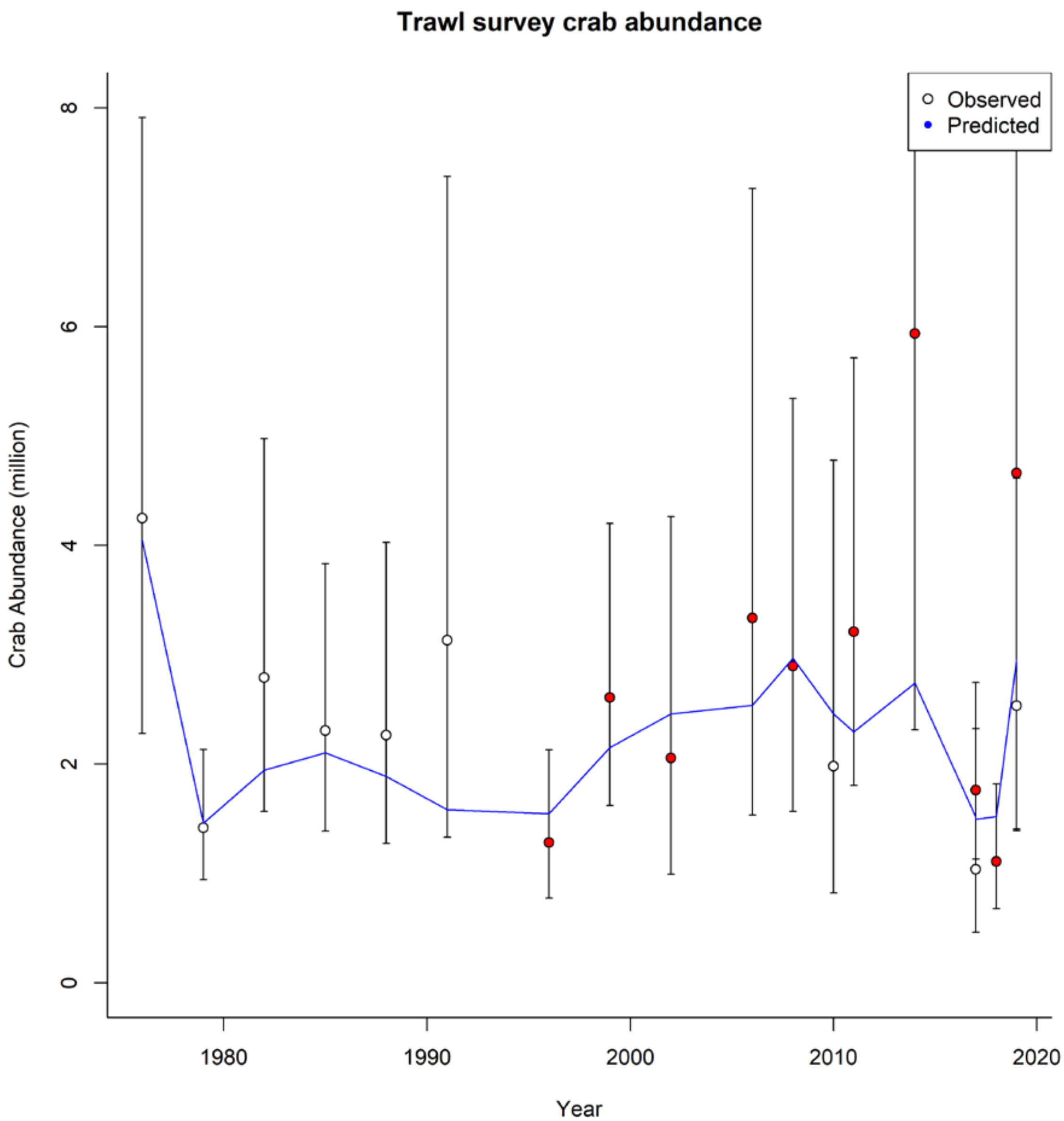


Figure C8-4. Estimated trawl survey male abundance (blue line). Observed: white: NOAA trawl Survey, red: ADG&G trawl survey

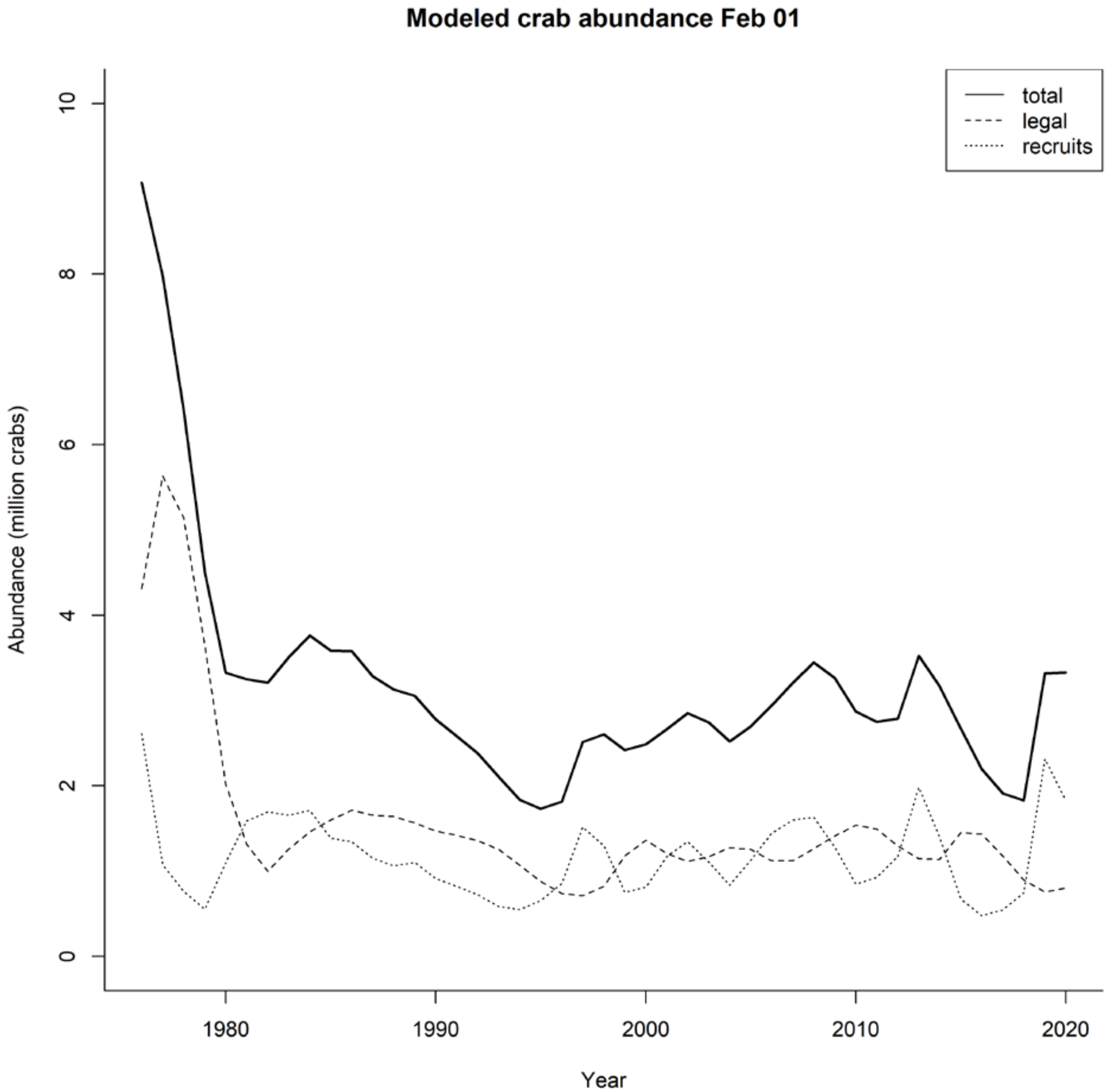


Figure C8-5. Estimated abundance of legal males.

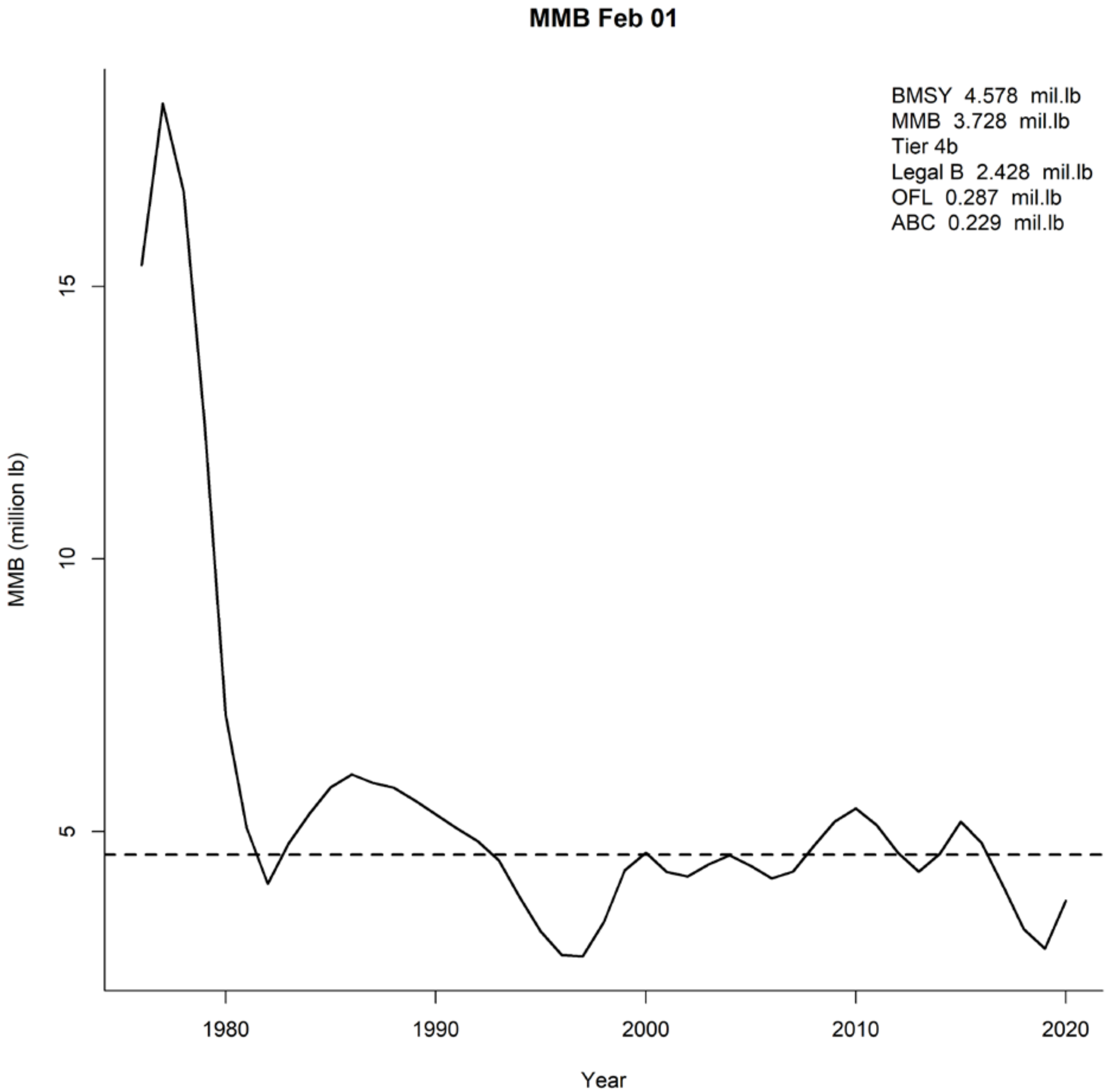


Figure C8-6. Estimated mature male biomass. Dash line shows Bmsy.

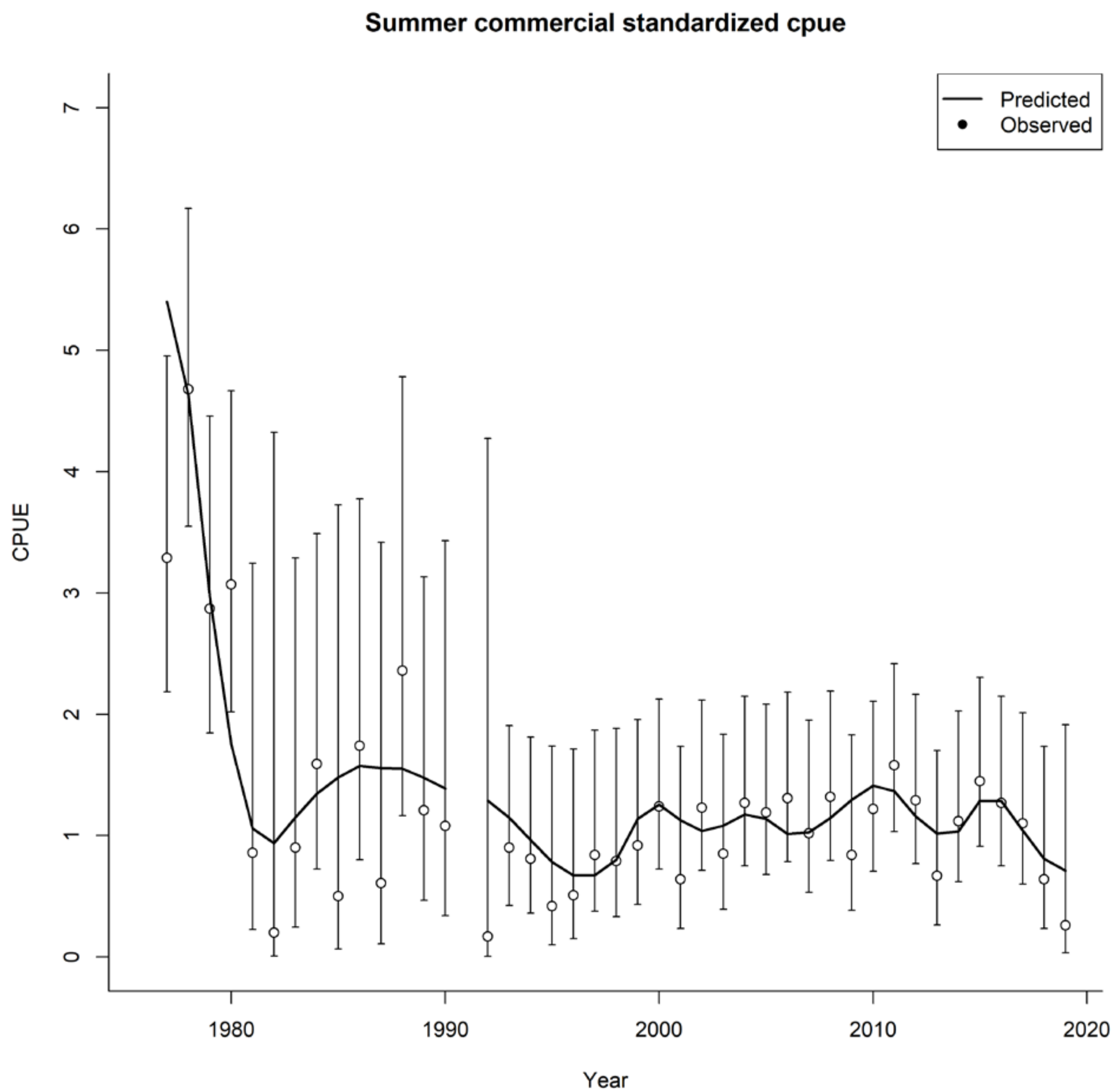


Figure C8-7. Summer commercial standardized cpue. Vertical line incicates lognormal 95%CI

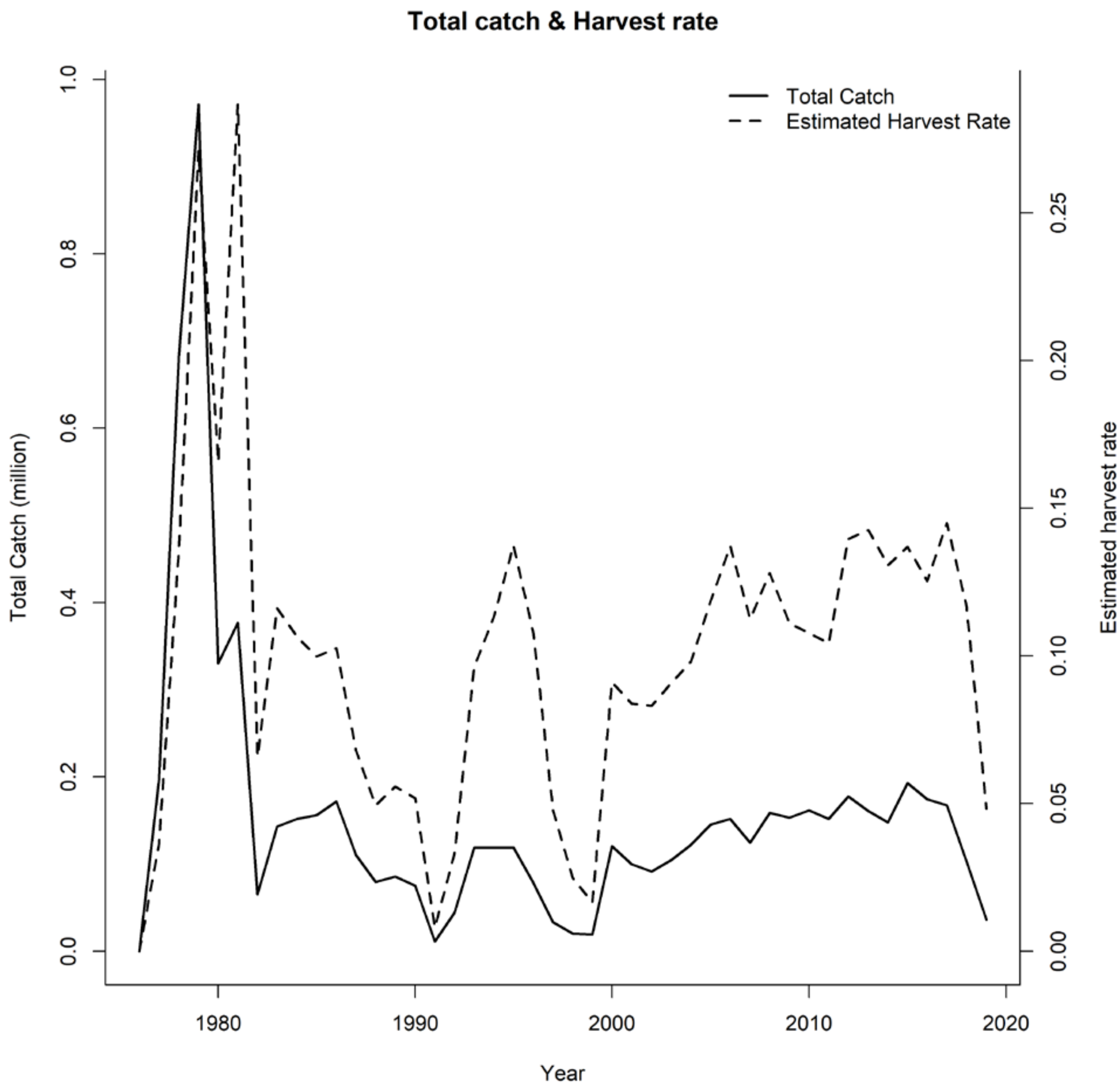


Figure C8-8. Total catch and estimated harvest rate.

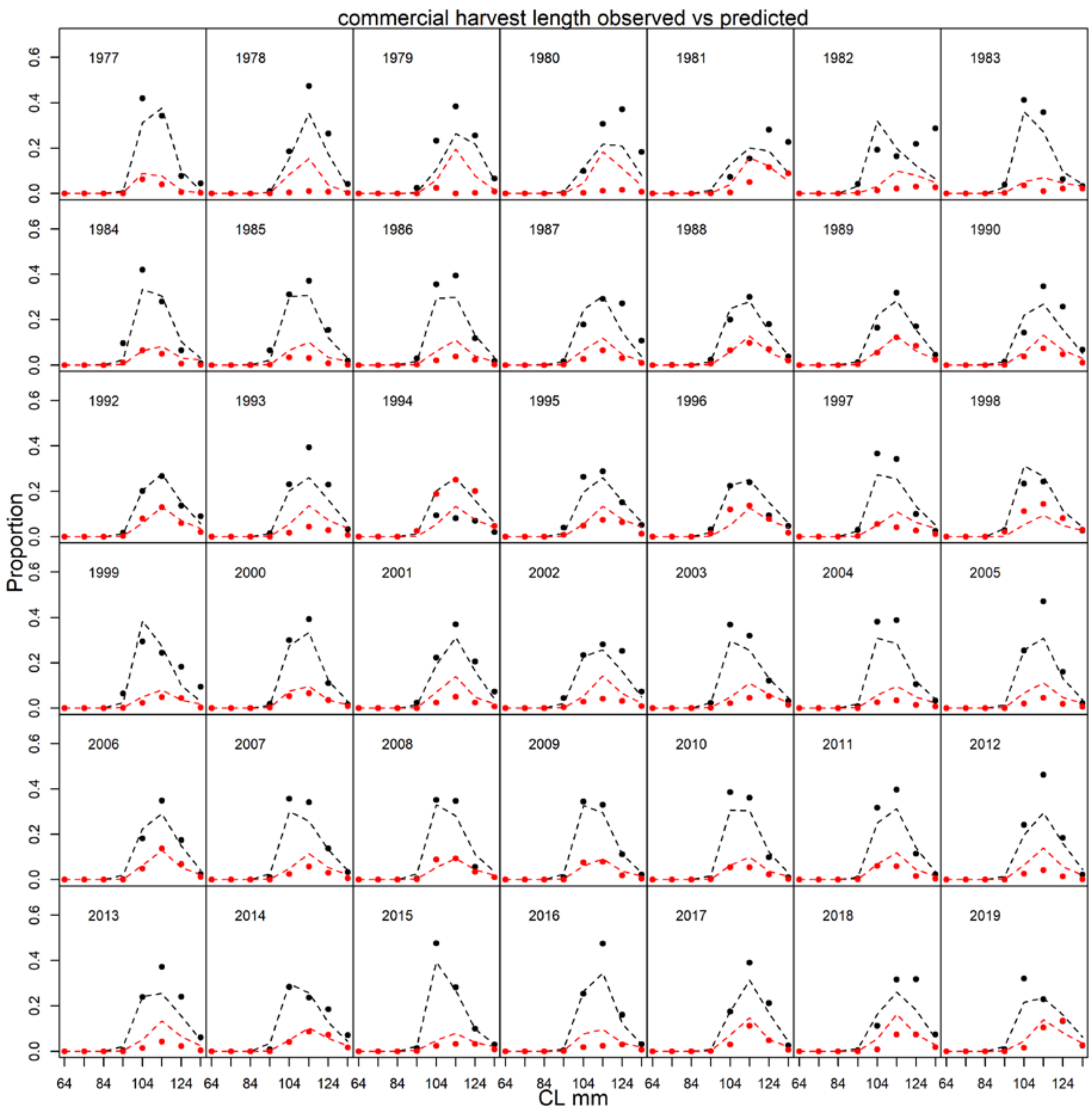


Figure C8-9. Predicted (dashed line) vs. observed (dots) length class proportions for commercial catch. Bladk: newshell, Red: oldshell

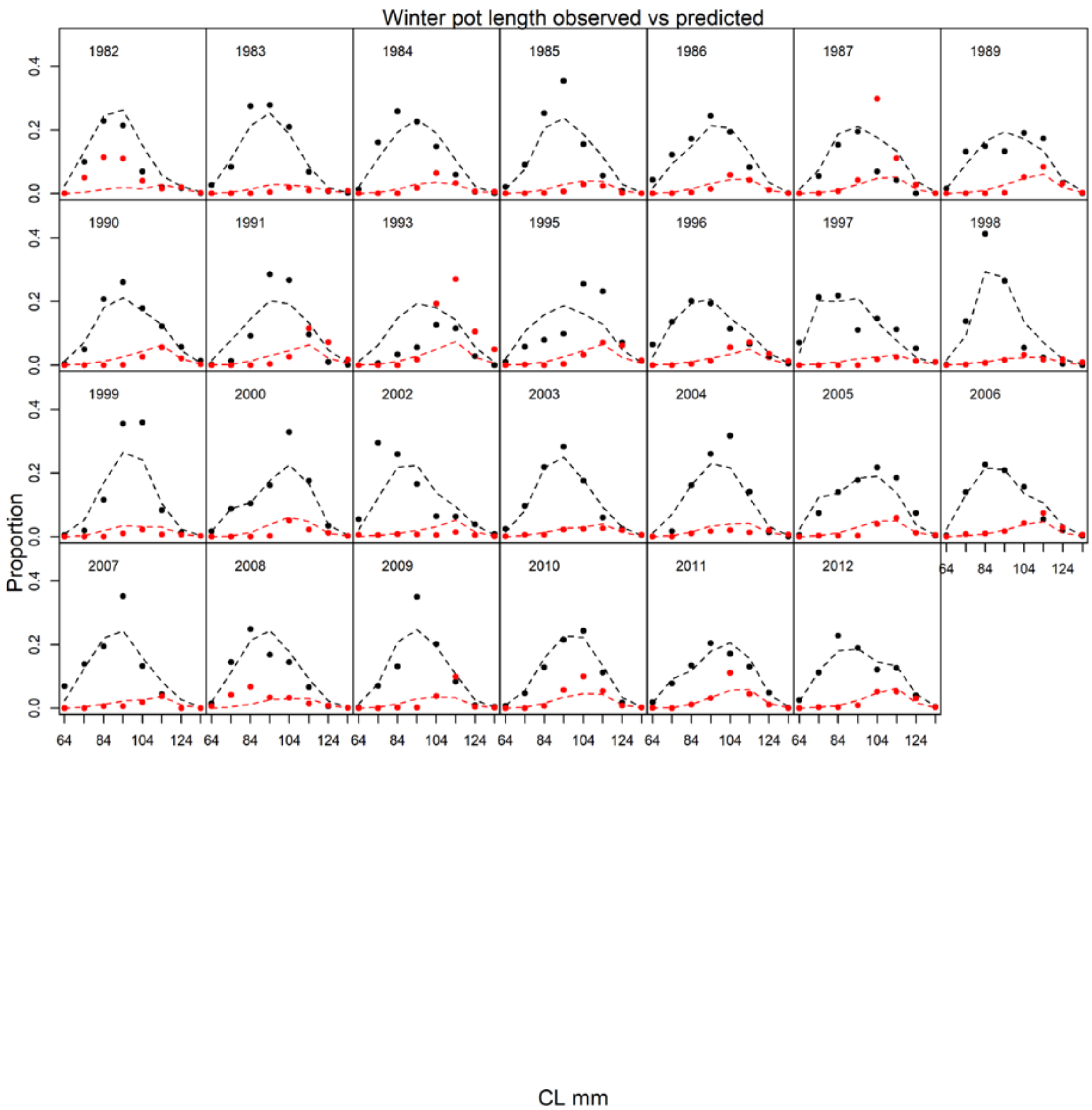


Figure C8-10. Predicted (dashed) vs. observed (dots) length class proportions for the winter pot survey. Black: newsehll, Red: oldshell

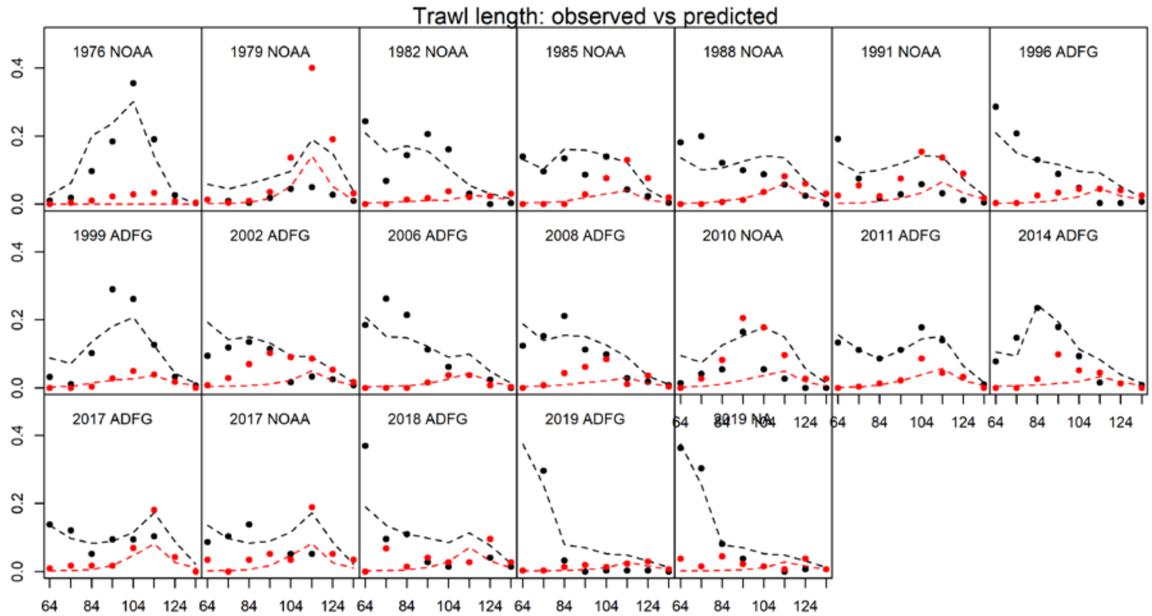


Figure C8-11. Predicted (dashed) vs. observed (dots) length class proportions for trawl survey. Black: newshell, Red: oldshell

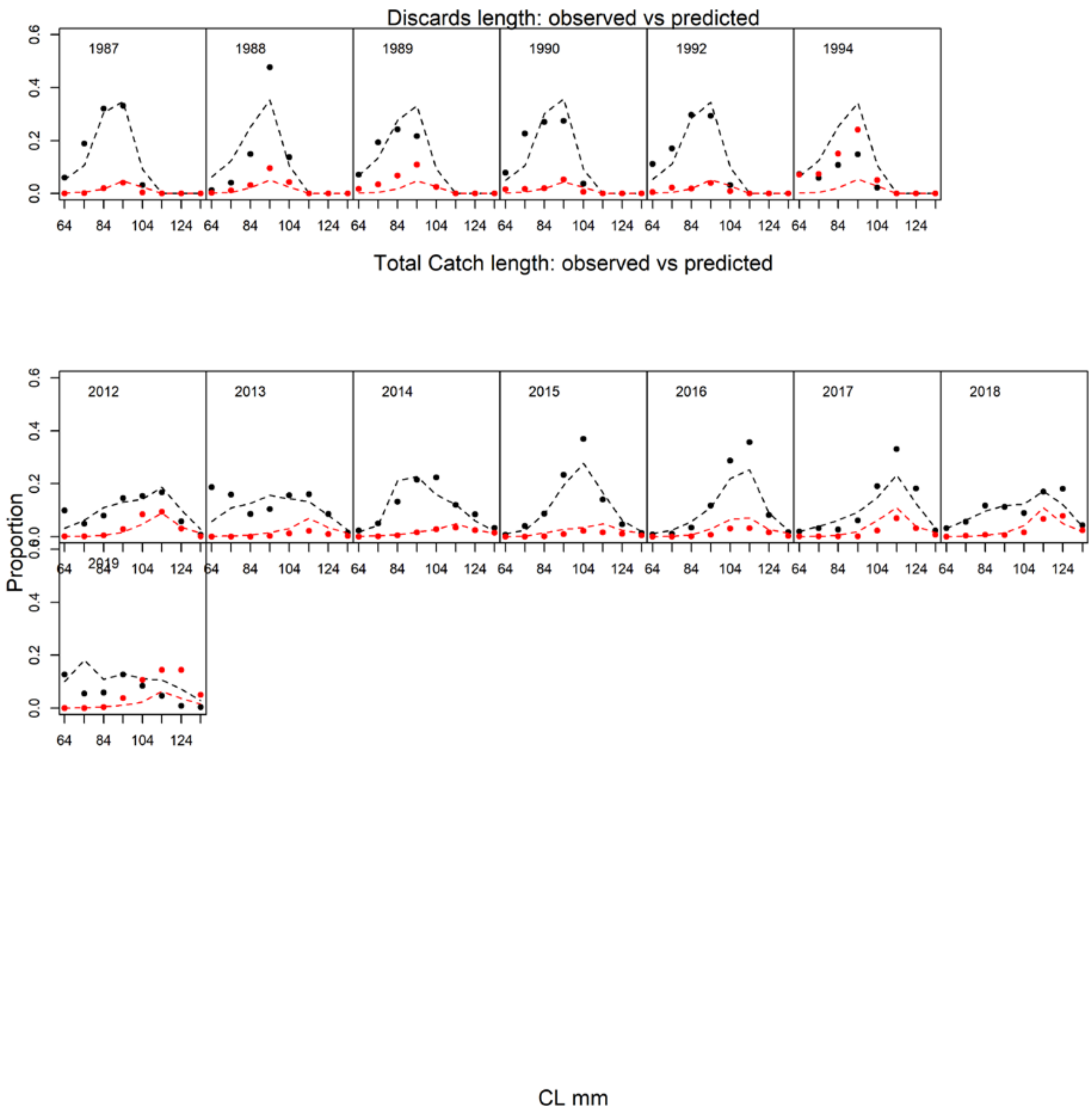


Figure C8-13. Predicted (dashed) vs. observed (dots) length class proportions for the observer survey. Black: newsehll, Red: oldshell

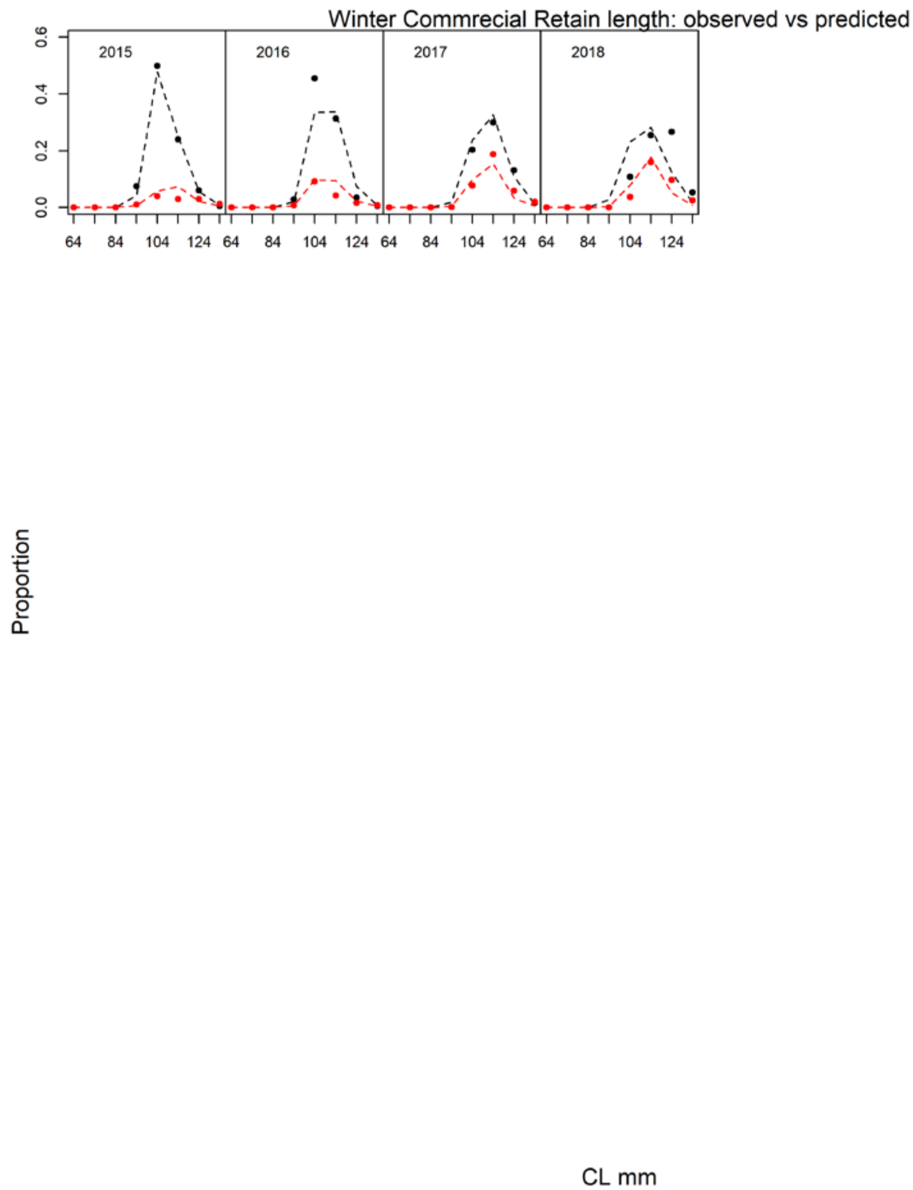


Figure C8-12. Predicted (dashed) vs. observed (dots) length class proportions for the observer survey. Black: newshell, Red: oldshell

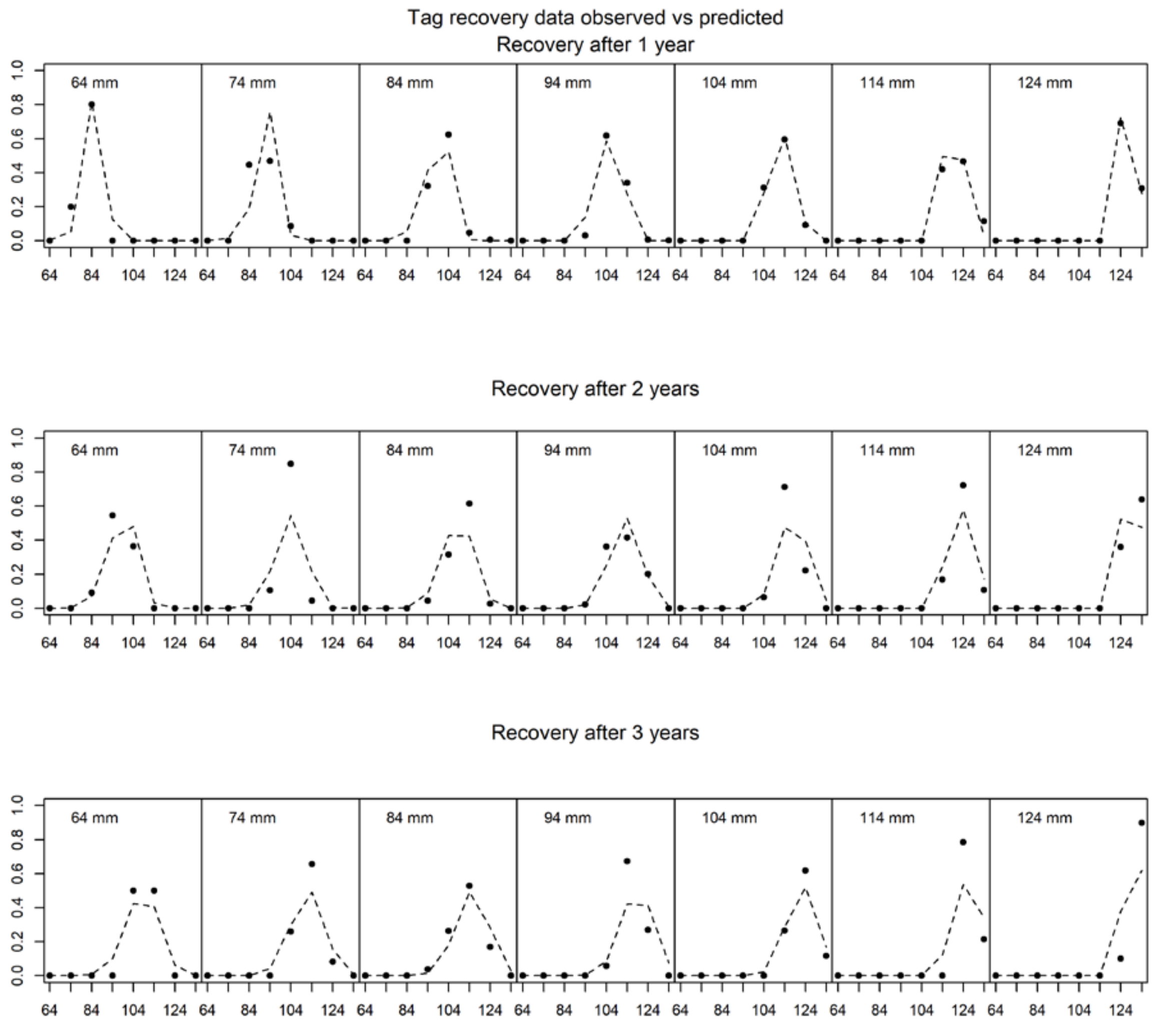


Figure C8-13. Predicted vs. observed length class proportions for tag recovery data.

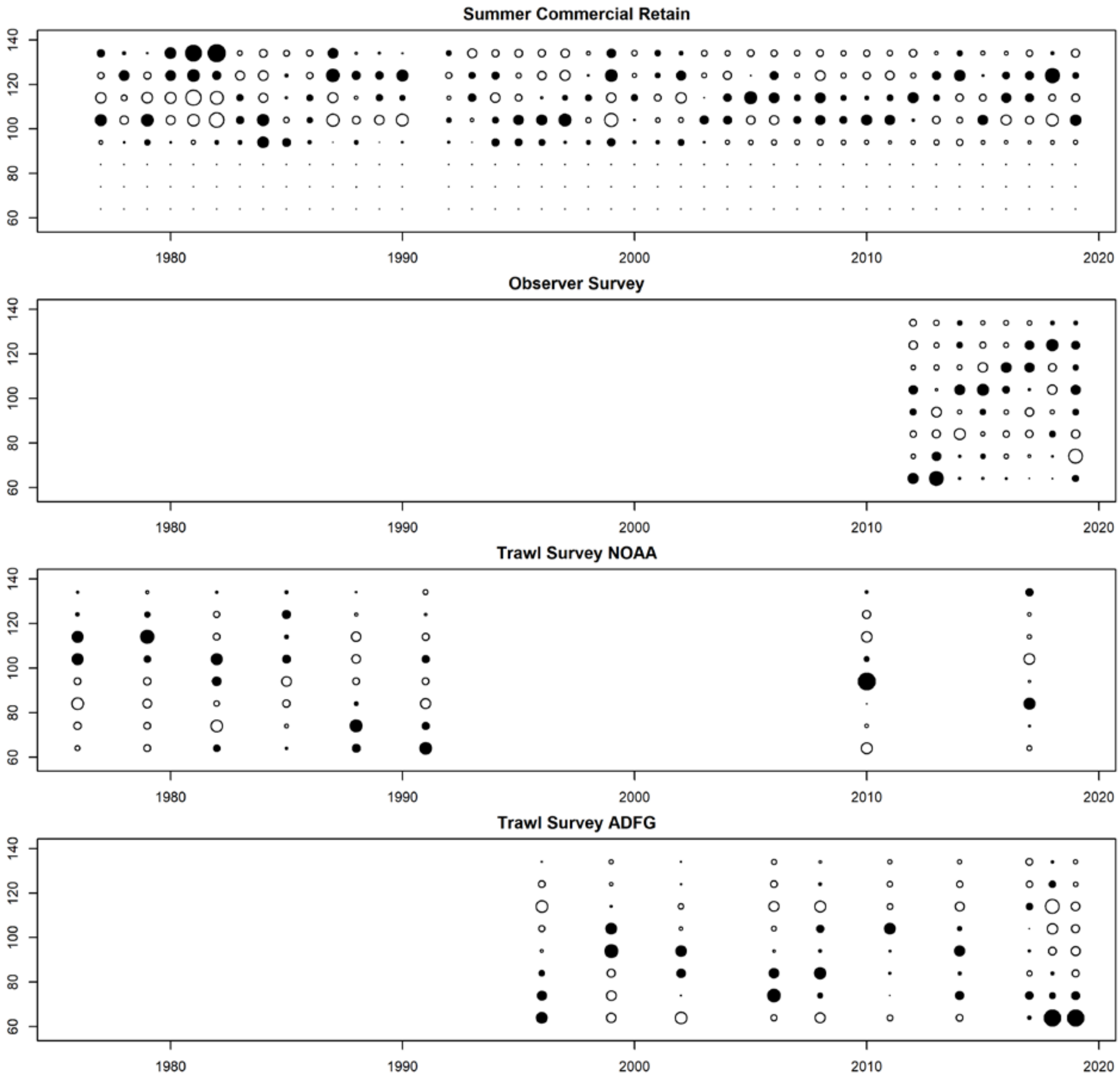


Figure C8-13. Bubble plots of predicted and observed length proportions.
Black circle indicates model estimates lower than observed, white circle indicates model estimates higher than observed. Size of circle indicates degree of deviance (larger circle = larger deviance).

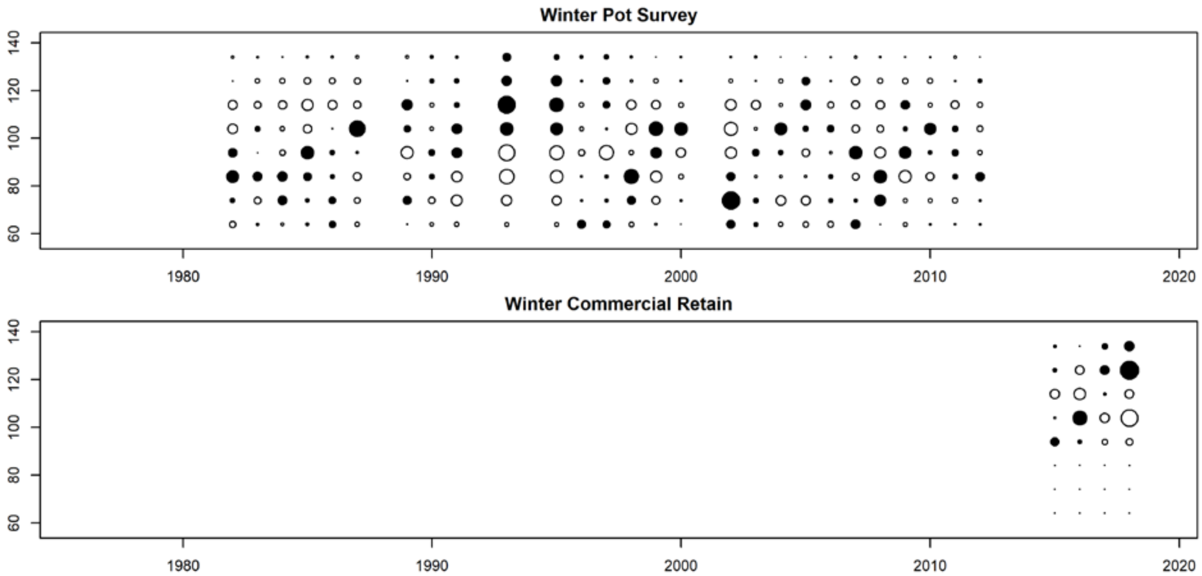


Figure C8-14. Bubble plots of predicted and observed length proportions.
Black circle indicates model estimates lower than observed, white circle indicates model estimates higher than observed. Size of circle indicates degree of deviance (larger circle = larger deviance).

Table C8. Summary of parameter estimates for a length-based stock synthesis population model of Norton Sound red king crab.

name	Estimate	std.dev
log_q_1	-6.768	0.110
log_q_2		
log_N_{76}	9.113	0.108
R_0	6.462	0.081
a_1	1.903	4.455
a_2	2.722	4.207
a_3	3.896	4.024
a_4	4.071	4.008
a_5	4.305	3.997
a_6	3.545	4.026
a_7	2.060	4.297
r1	10.000	0.270
r2	9.578	0.322
log_a	-2.682	0.089
log_b	4.831	0.015
log_ϕ_{st1}	-5.000	0.048
log_ϕ_{wa}	-2.220	0.269
log_ϕ_{wb}	4.795	0.029
Sw1	0.069	0.034
Sw2	0.510	0.121
log_ϕ_1	-2.067	0.052
$log\_\phi ra$	-0.787	0.129
$log\_\phi rb$	4.646	0.008
$log\_\phi wra$	-0.954	0.536
$log\_\phi wrb$	4.656	0.037
w^2_t	0.000	0.000
q	0.710	0.114
σ	3.853	0.209
β_1	12.196	0.704
β_2	7.713	0.173
ms78	3.226	0.252

Model 19.1

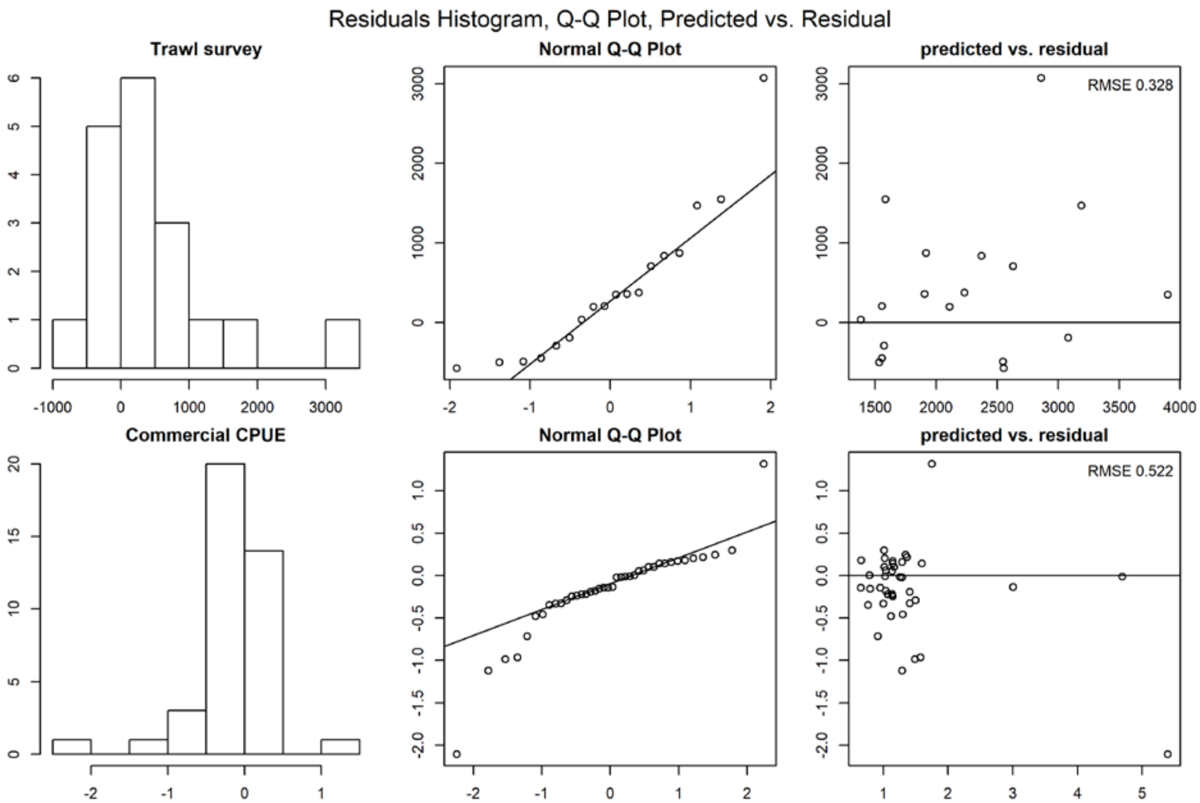


Figure D2-1. QQ Plot of Trawl survey and commercial CPUE.

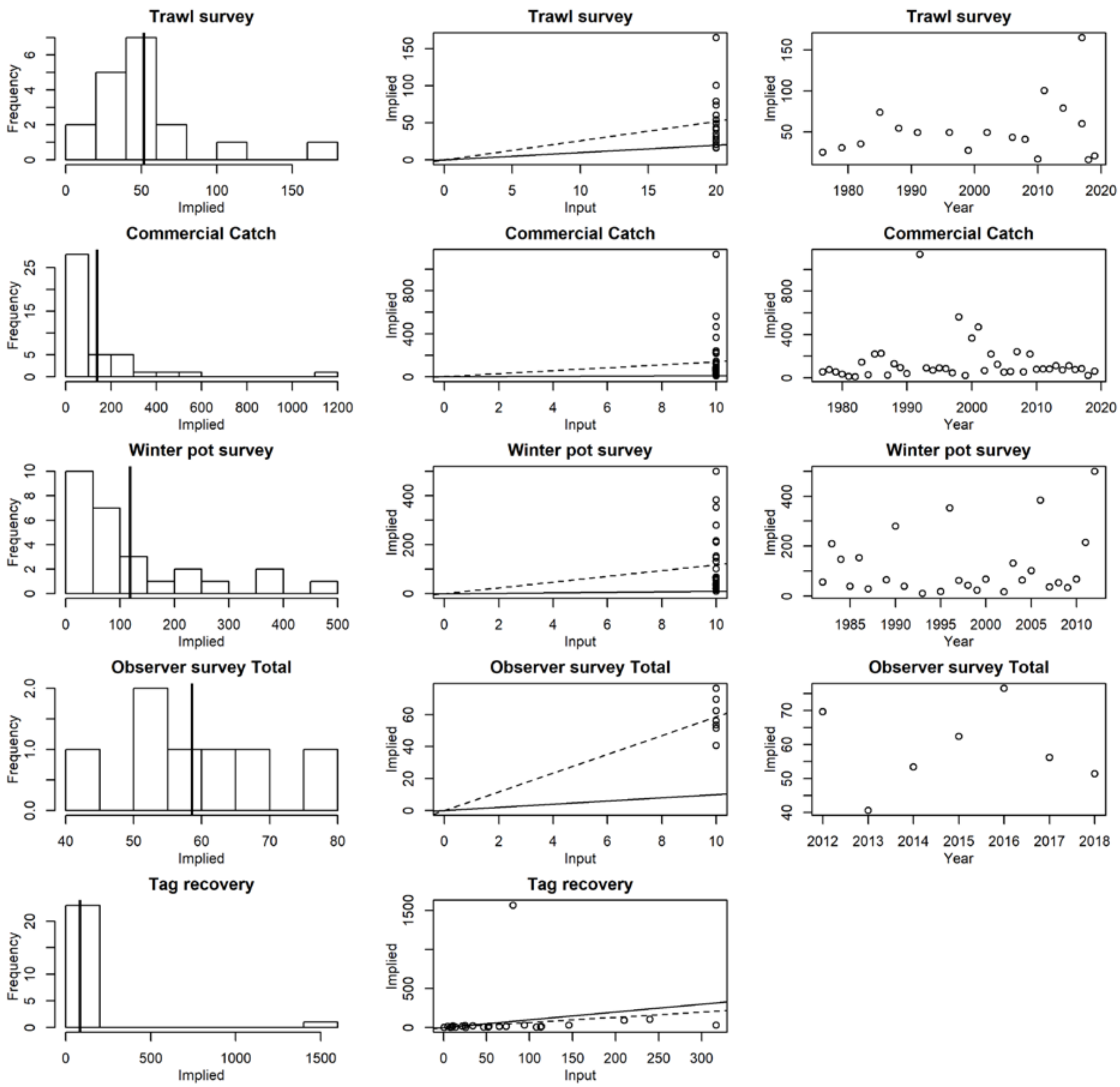


Figure D2-2: Implied effective samples. Figures in the first column show implied effective sample size (x-axis) vs. frequency (y-axis).
Vertical solid line is the mean implied effective sample size.
The second column shows input sample size (x-axis) vs. implied effective sample size (y-axis).
Dashed line indicates linear regression slope, and solid line is 1:1 line. The third column show year (x-axis) vs. implied effective sample size (y-axis).

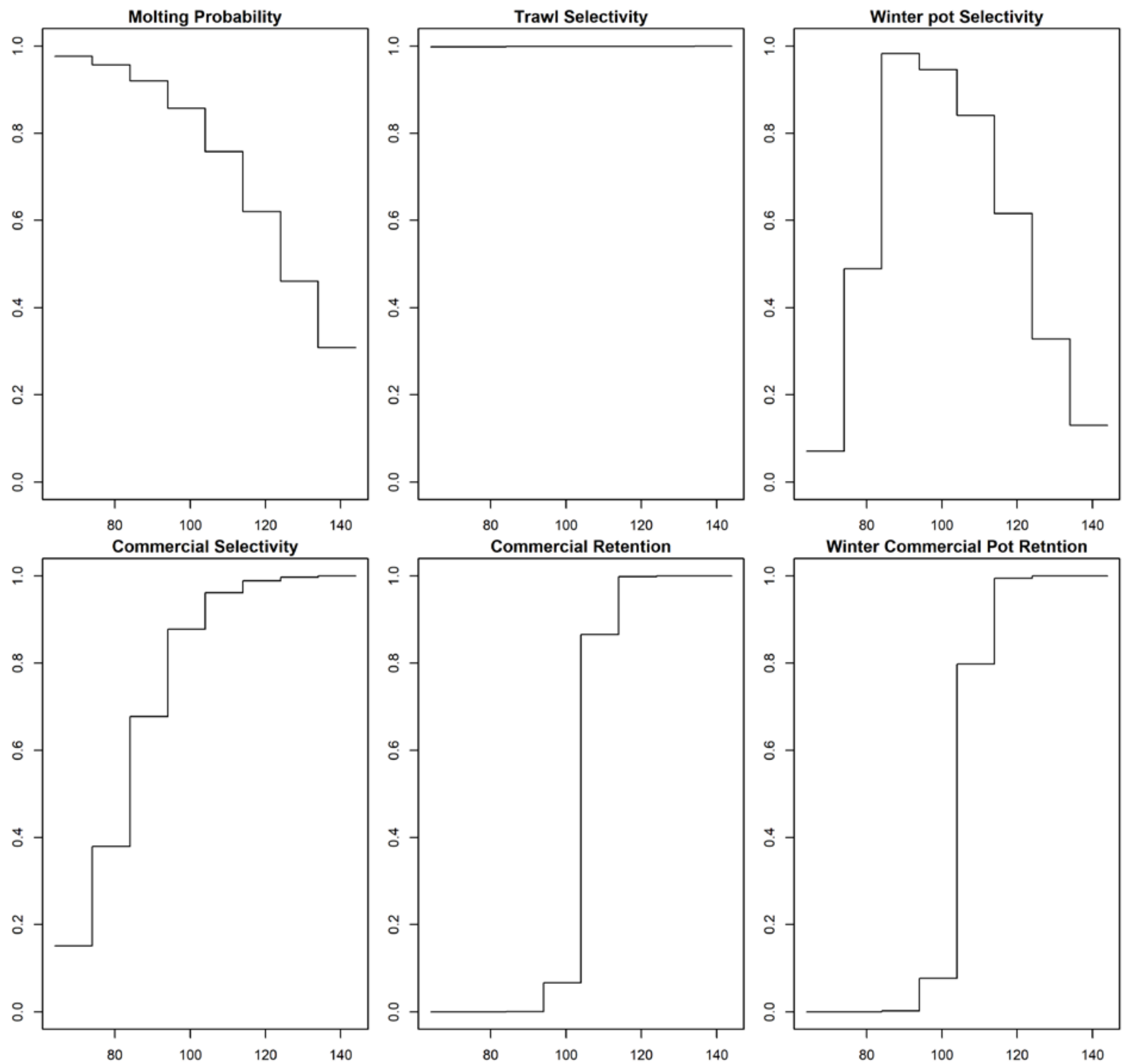


Figure D2-3. Molting probability and trawl/pot selectivity. X-axis is carapace length.

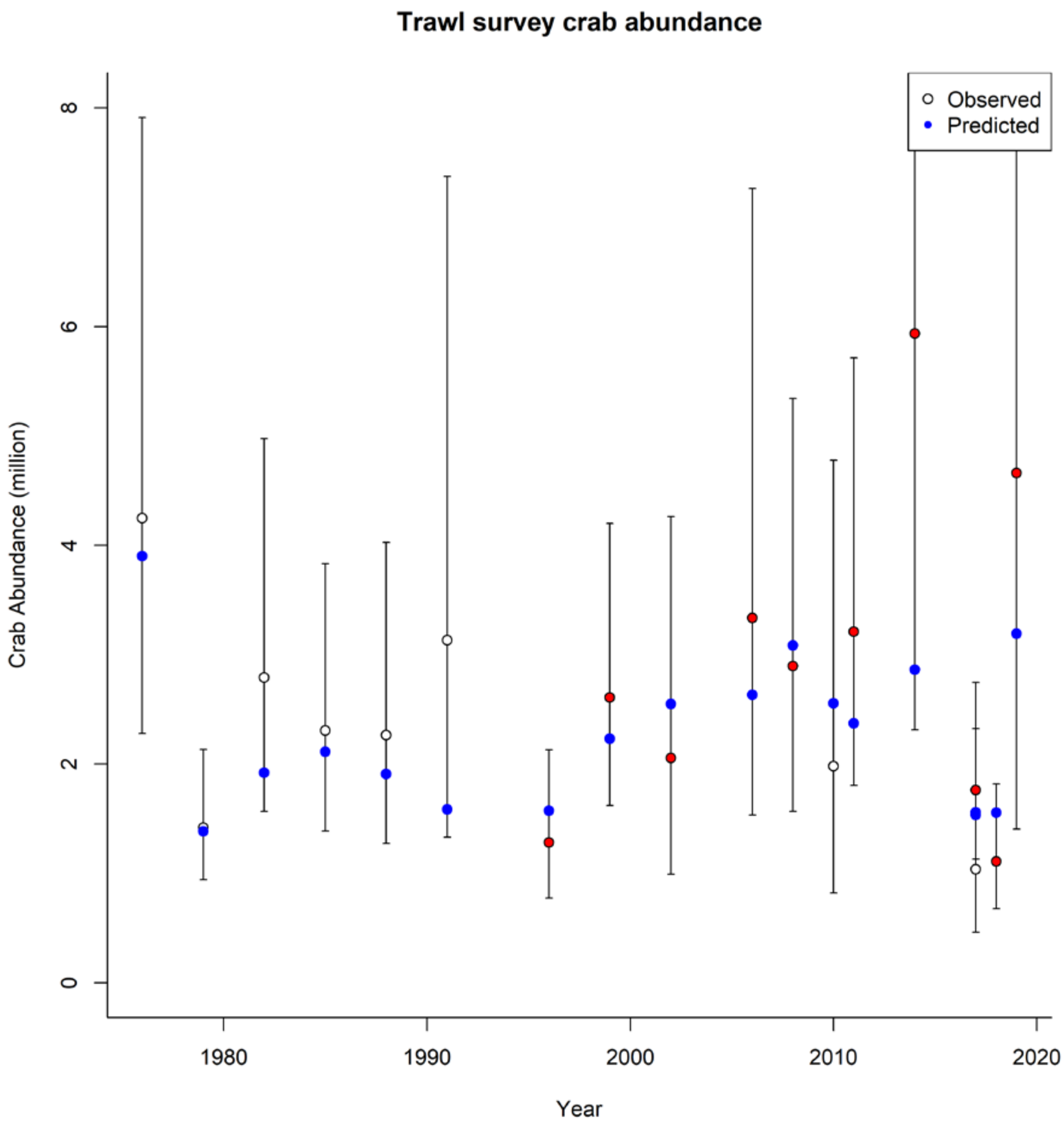


Figure D2-4. Estimated trawl survey male abundance (blue) (crab >= 64 mm CL). Observed: White: NOAA trawl survey, Red: ADG&G trawl survey

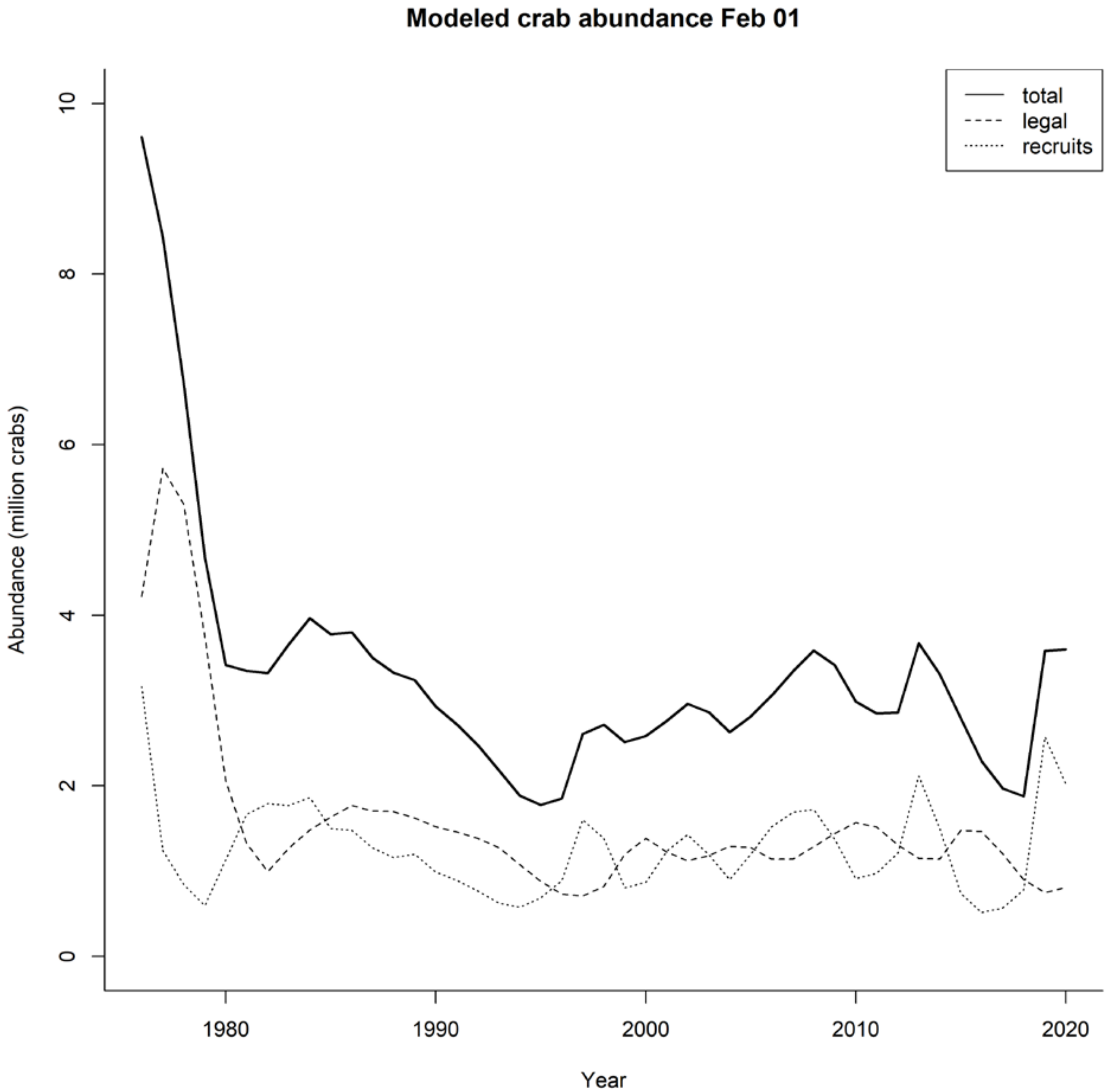


Figure D2-5. Estimated abundance of legal males.

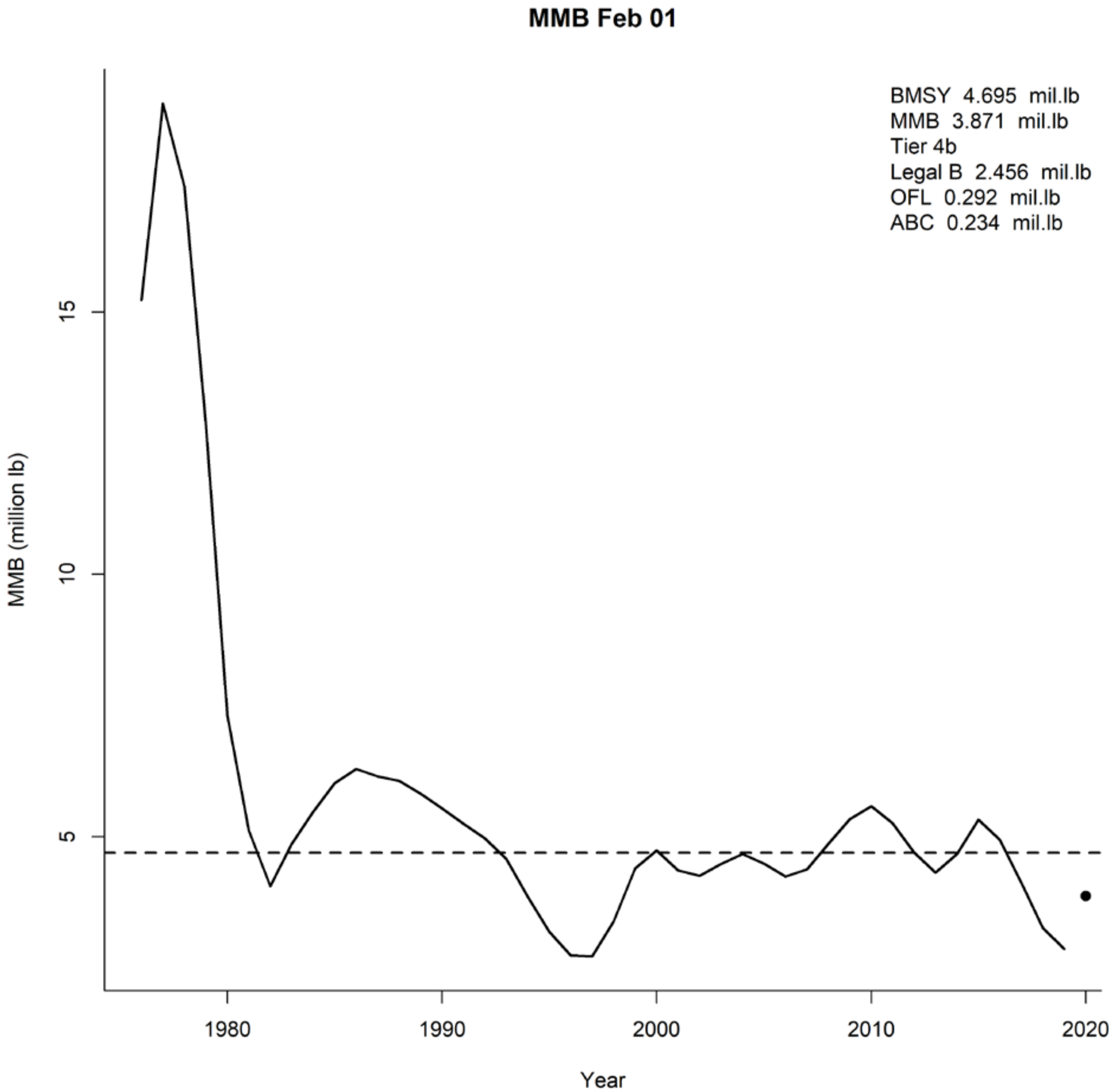


Figure D2-6. Estimated abundance of Mature Male Biomass. Dash line shows Bmsy.

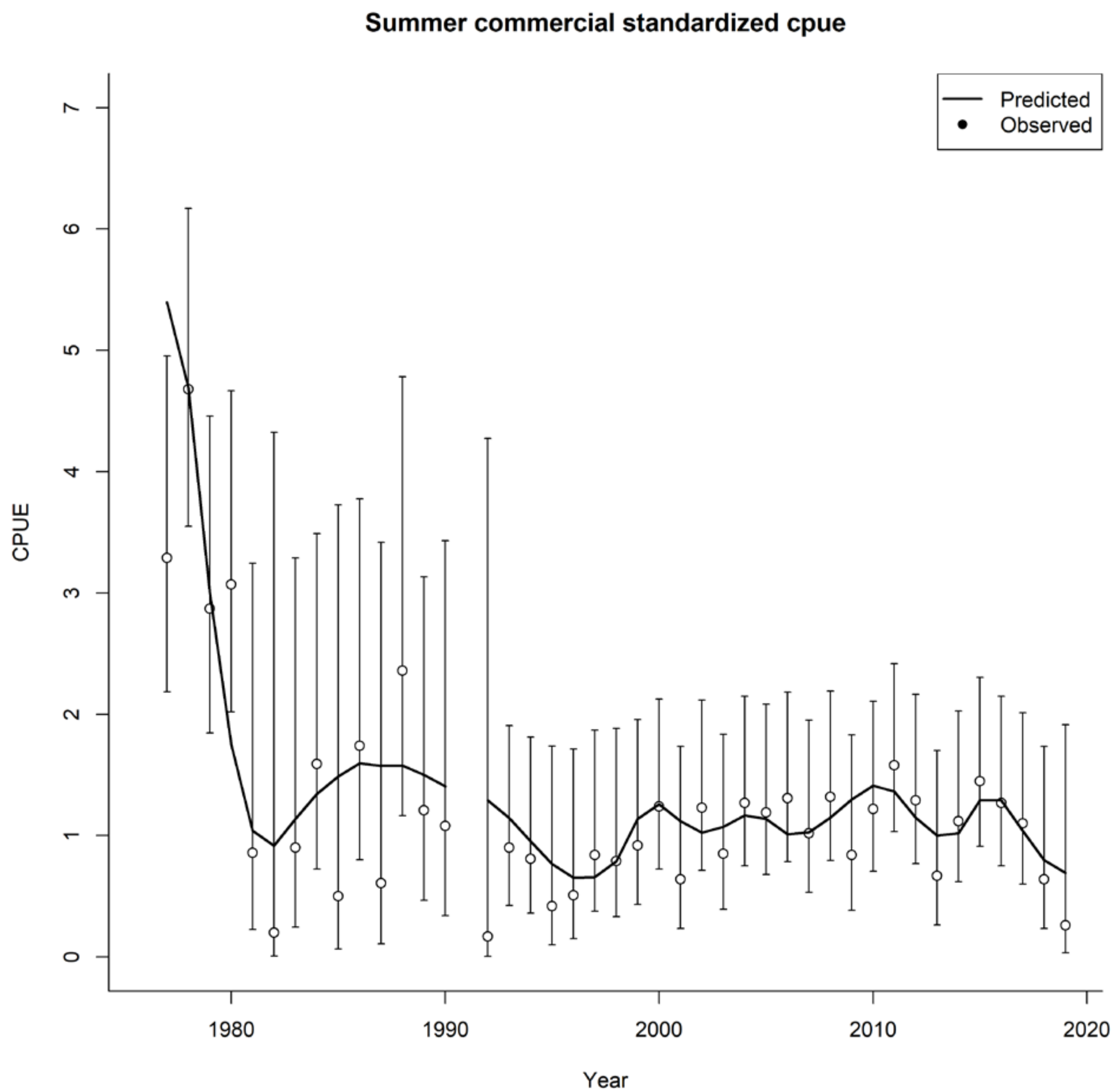


Figure D2-7. Summer commercial standardized cpue.

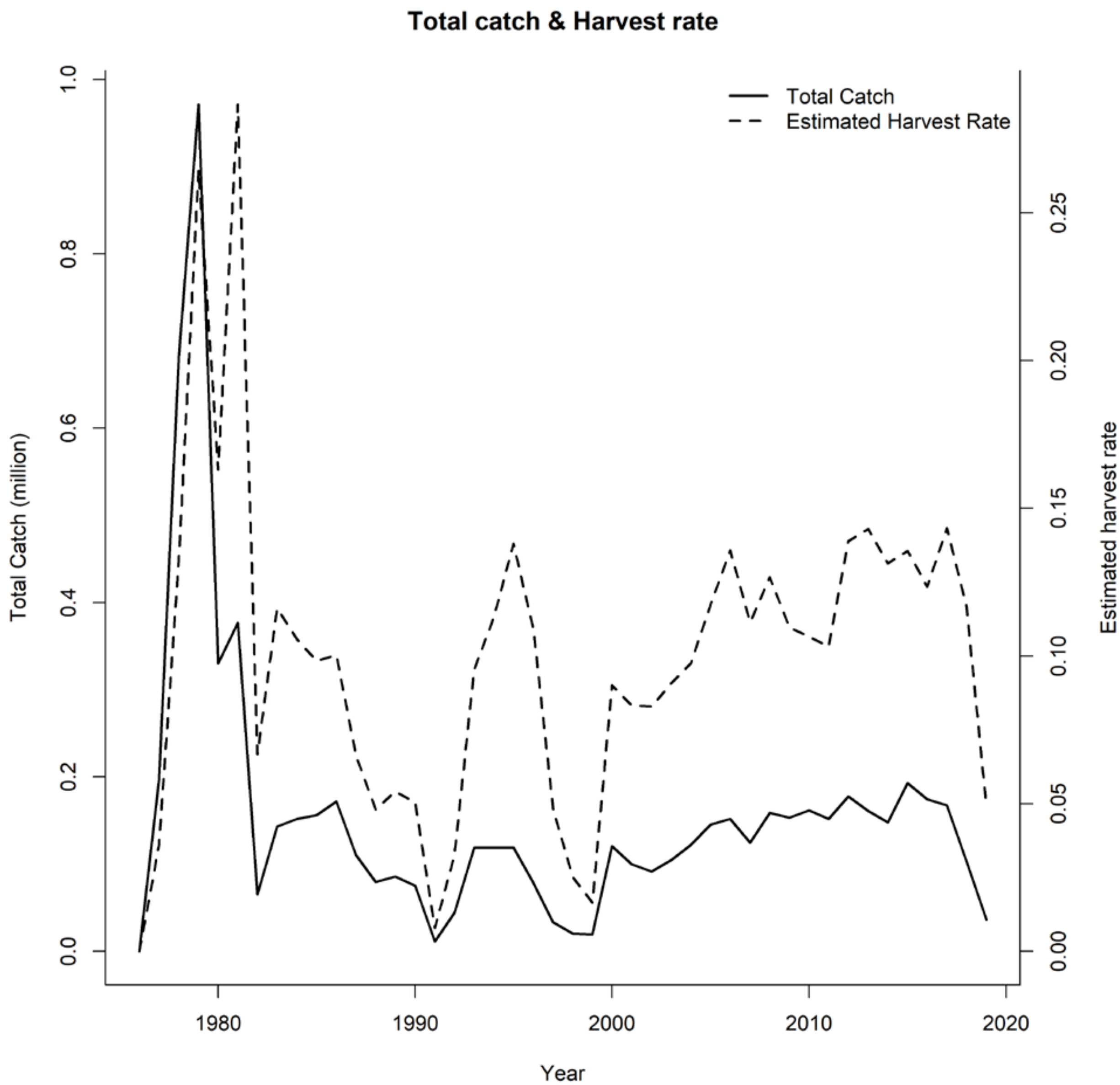


Figure D2-8. Total catch and estimated harvest rate.

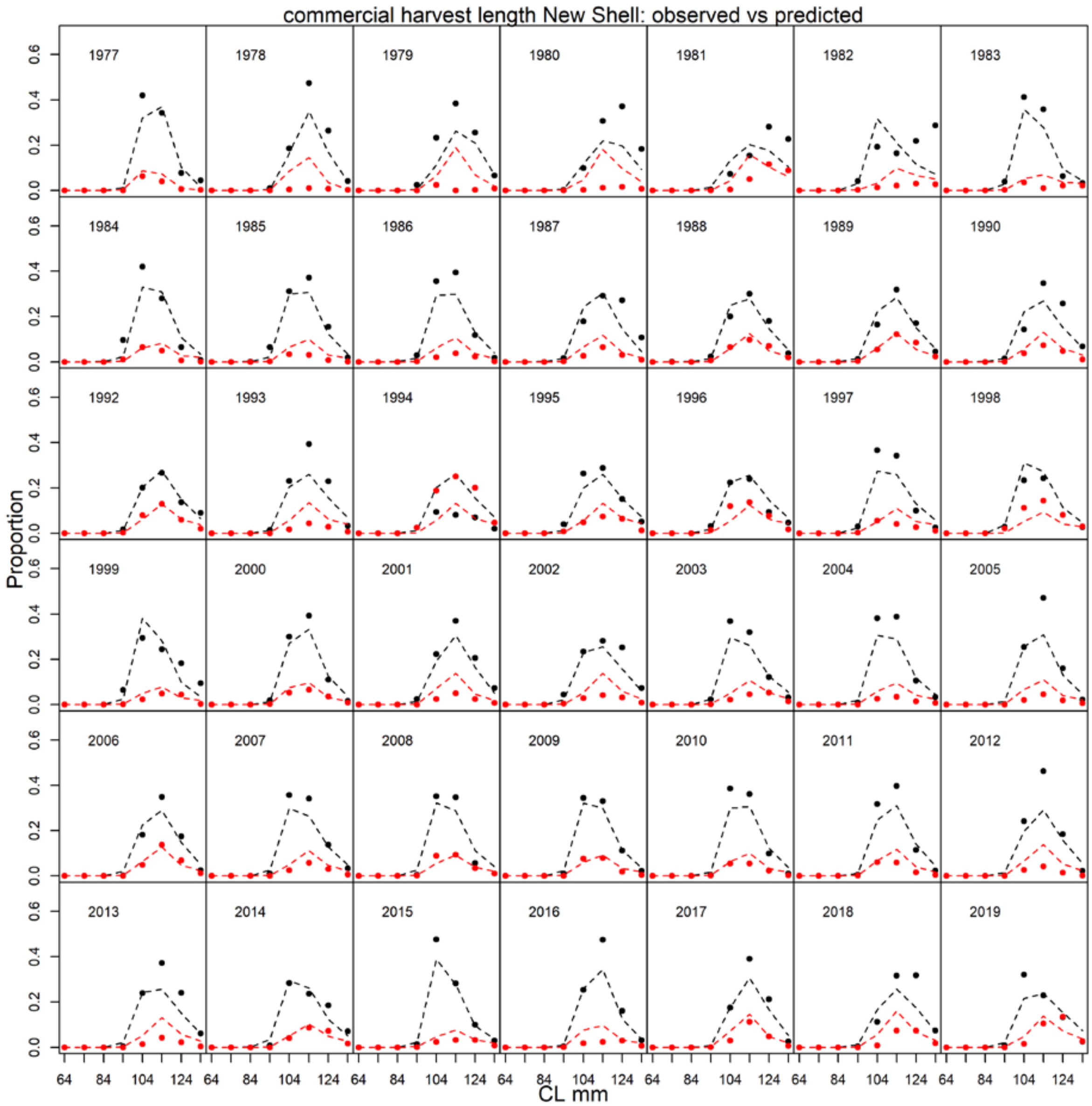


Figure D2-9. Predicted (dashed line) vs. observed (dots) length class proportions for commercial catch. Black: newshell, Red: oldshell

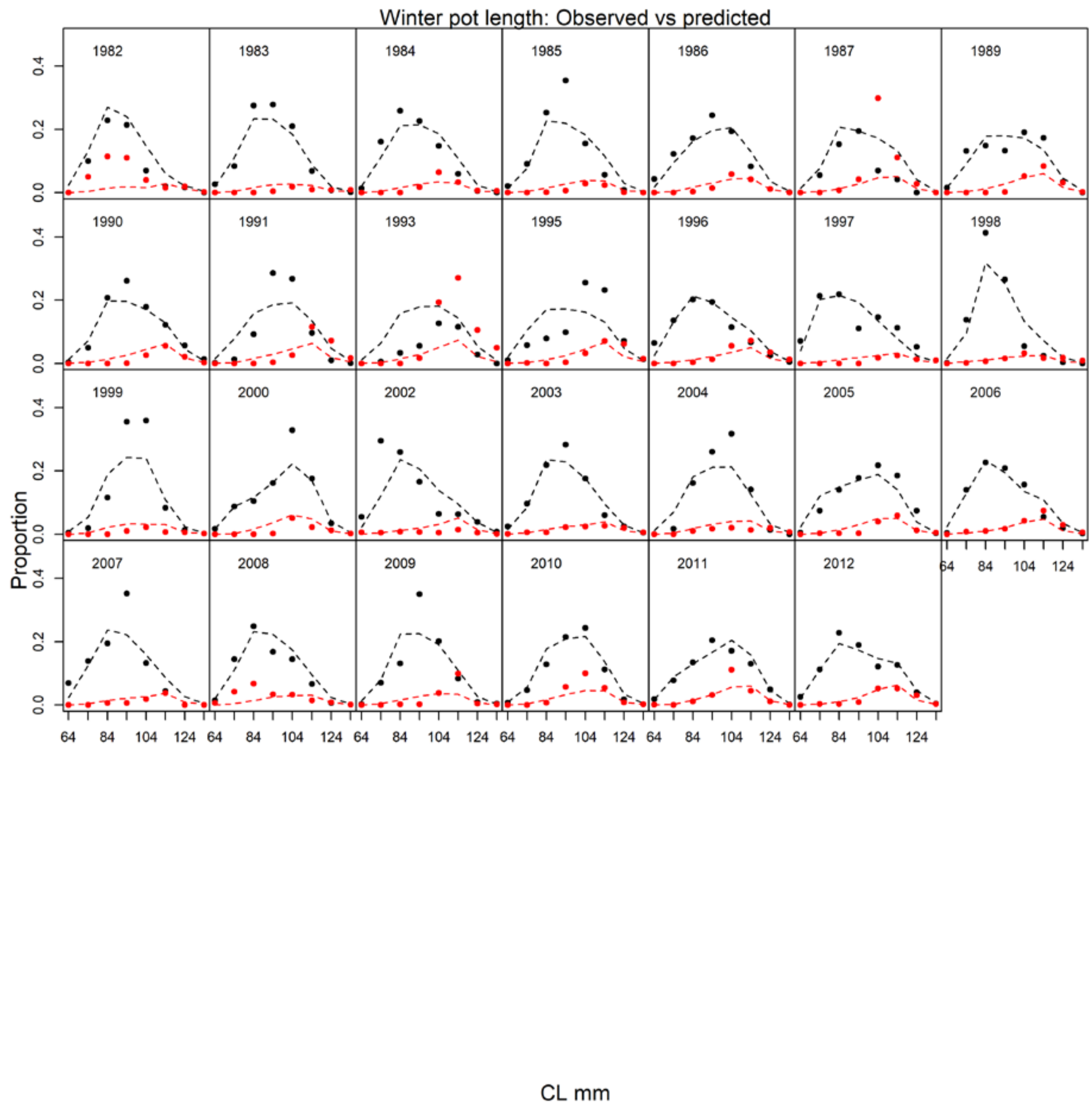


Figure D2-10. Predicted (dashed line) vs. observed (dots) length class proportions for the winter and spring pot survey. Black: newshell, Red: oldshell

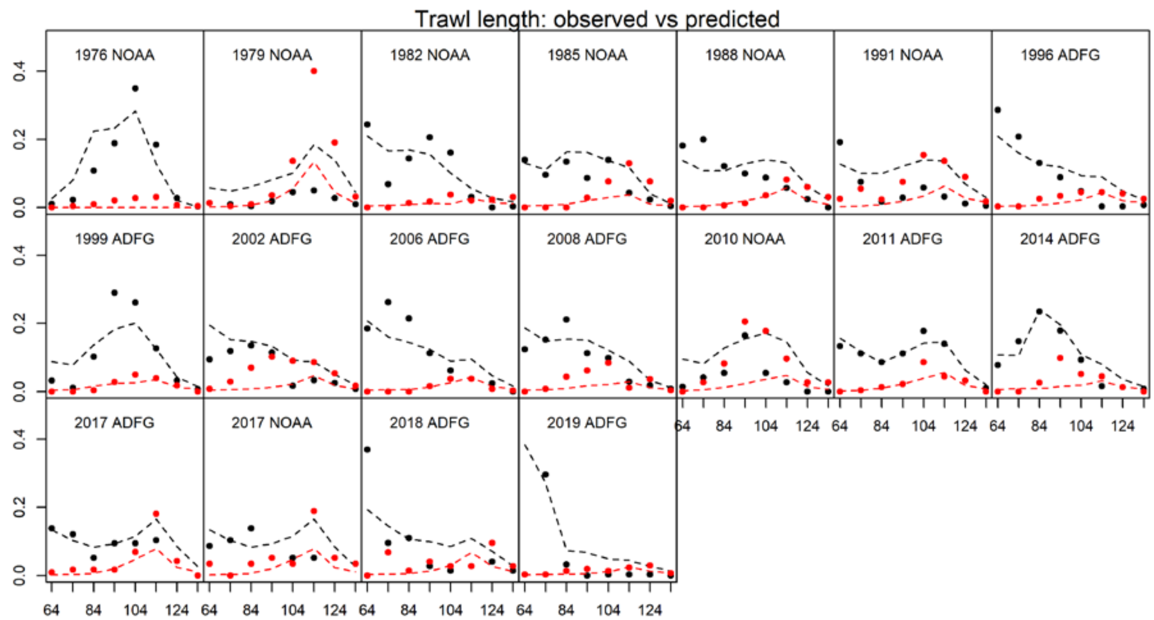


Figure D2-11. Predicted (dashed) vs. observed (dots) length class proportions for trawl survey. Black: newshell, Red: oldshell

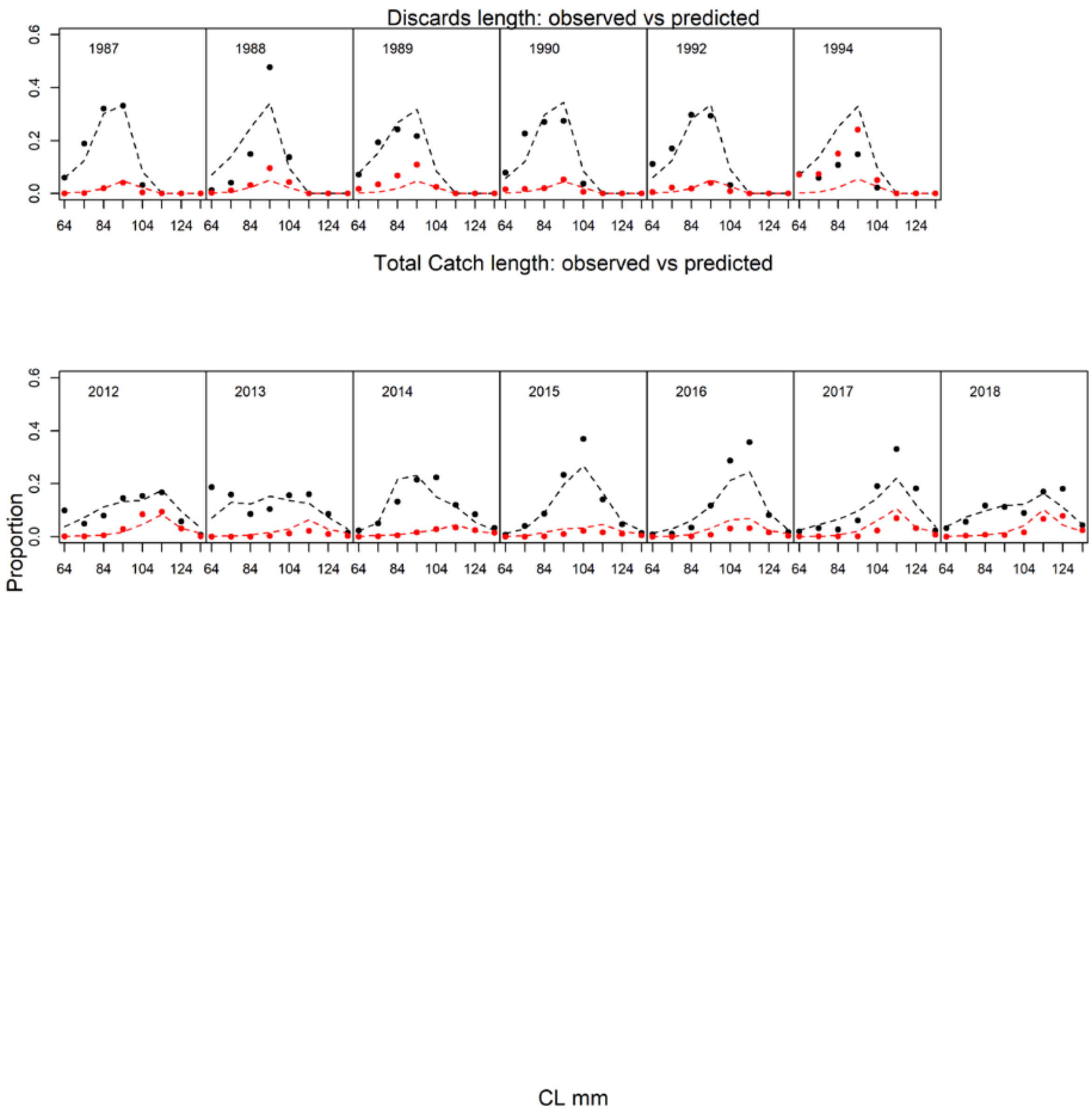


Figure D2-13. Predicted (dashed) vs. observed (dots) length class proportions for the observer survey. Black: newshell, Red: oldshell

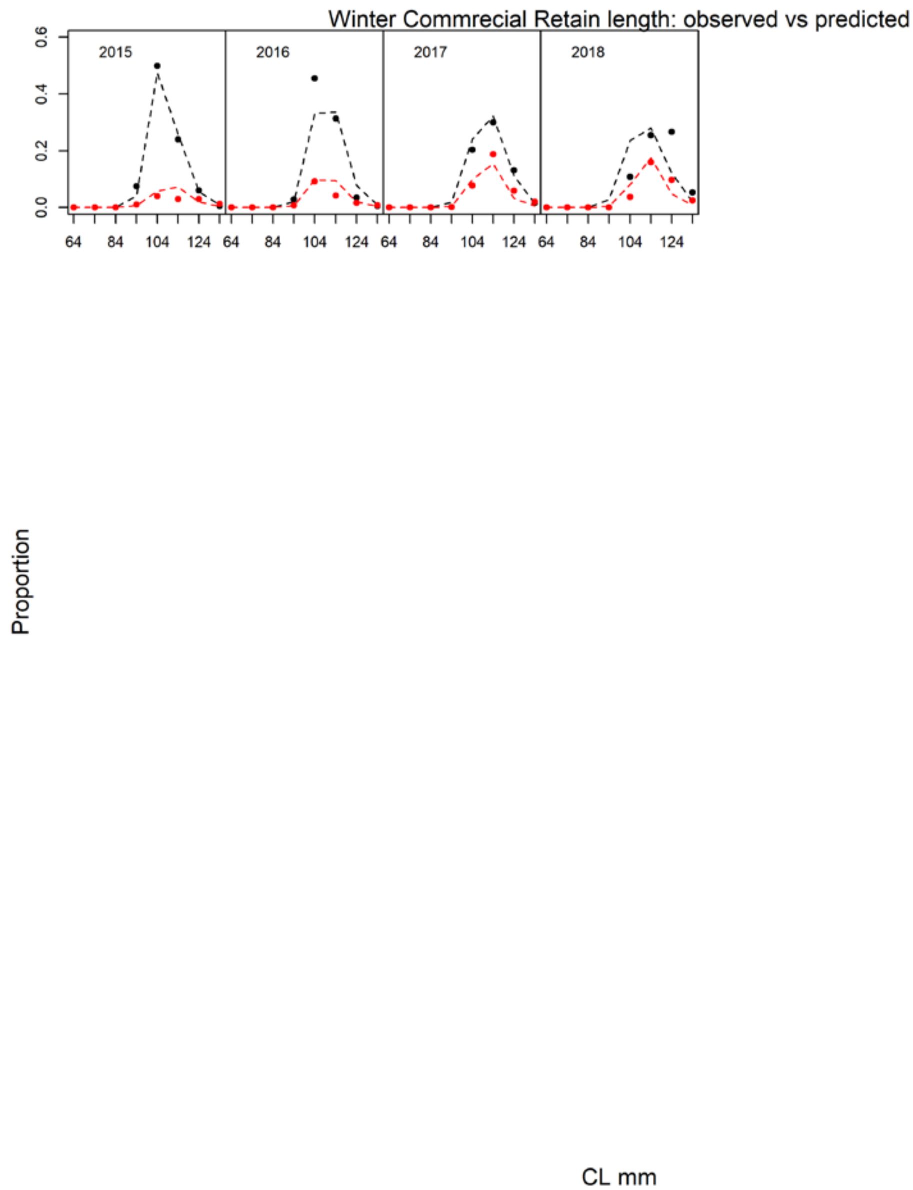


Figure D2-12. Predicted (dashed) vs. observed (dots) length class proportions for the observer survey. Black: newshell, Red: oldshell

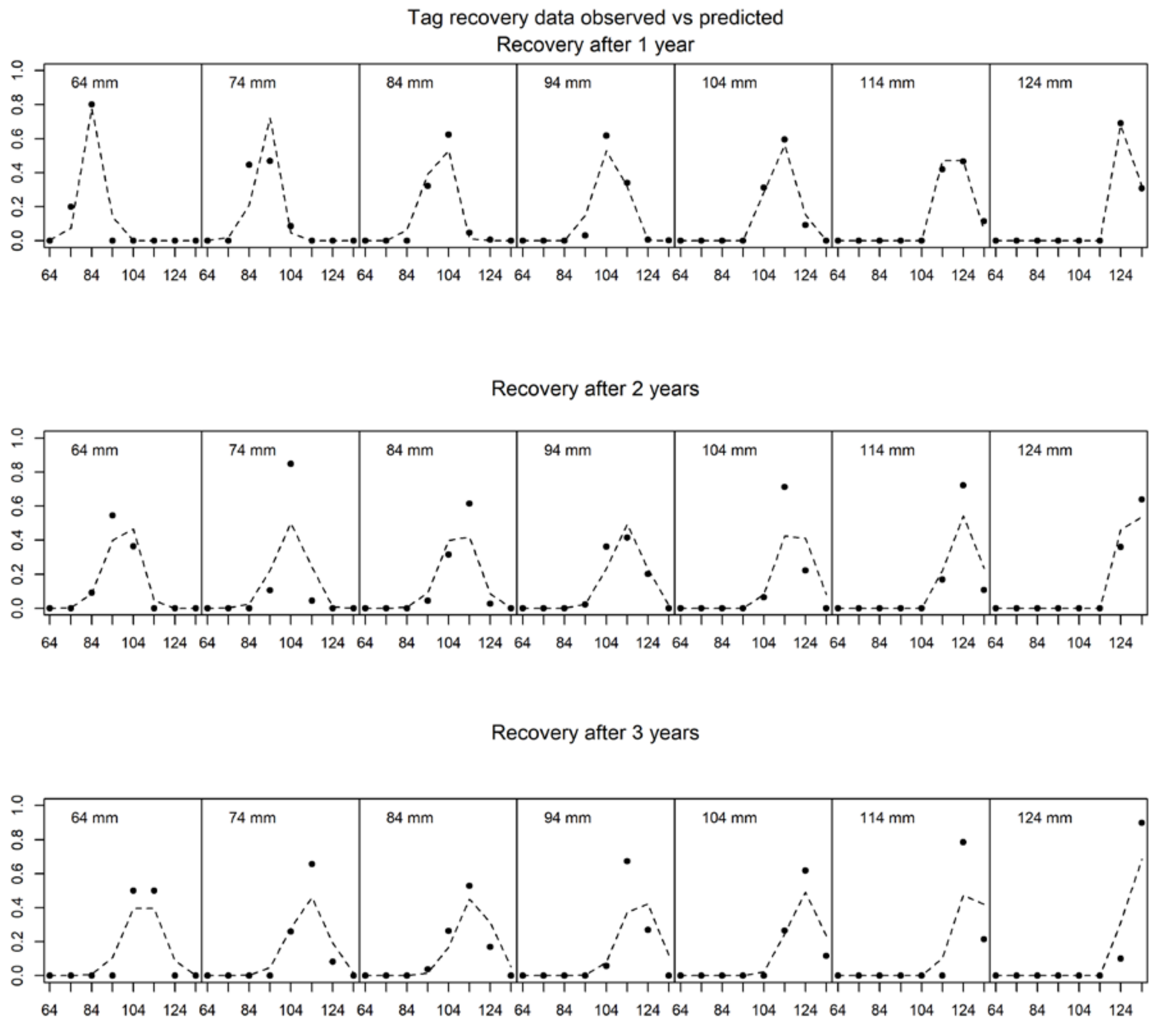


Figure D2-13. Predicted vs. observed length class proportions for tag recovery data.

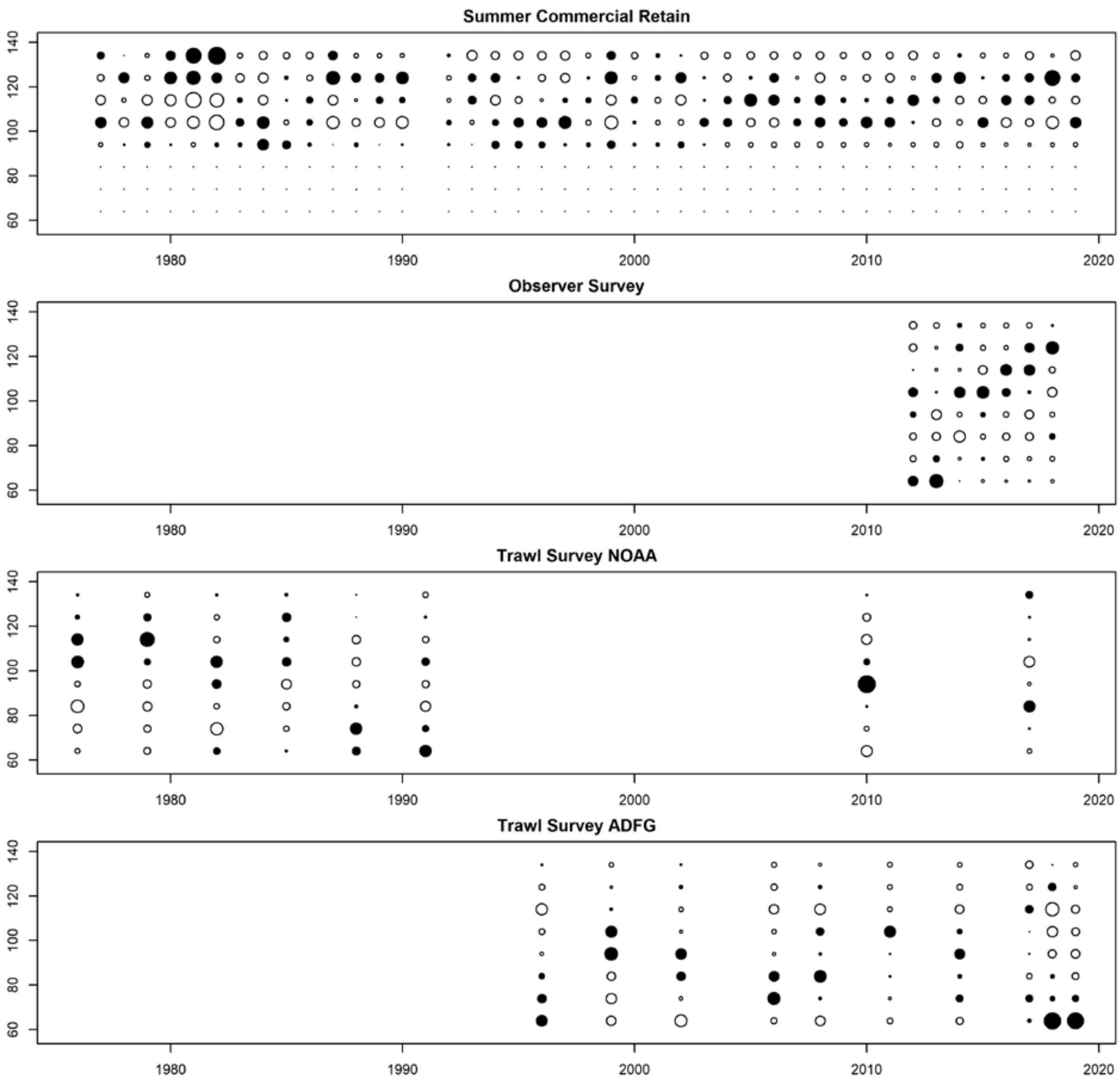


Figure D2-13. Bubble plots of predicted and observed length proportions.
Black circle indicates model estimates lower than observed, white circle indicates model estimates higher than observed. Size of circle indicates degree of deviance (larger circle = larger deviance).

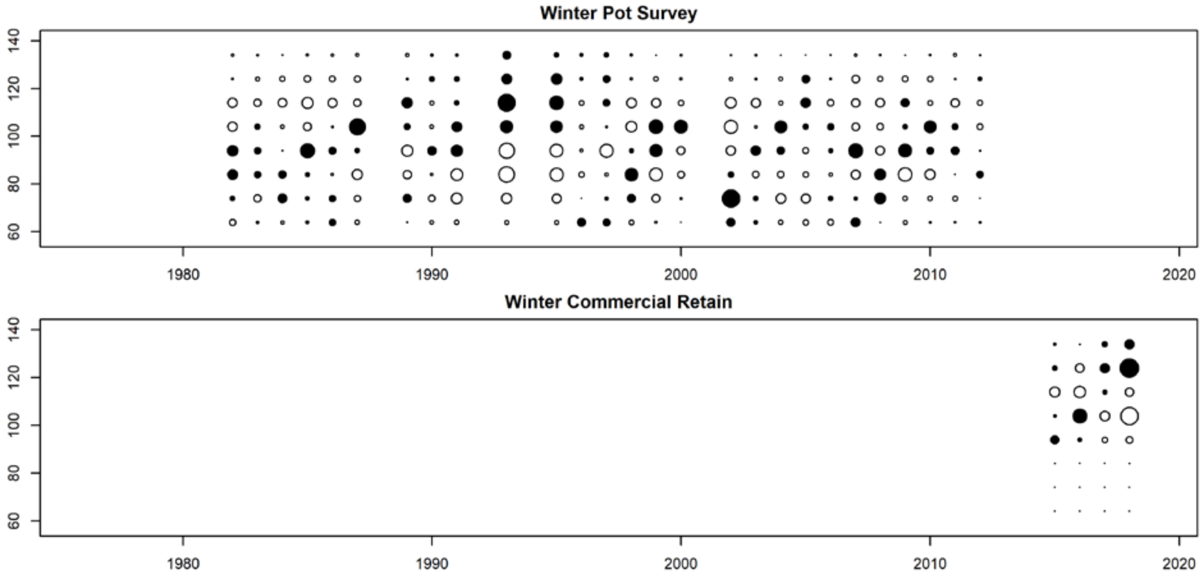


Figure D2-14. Bubble plots of predicted and observed length proportions.
Black circle indicates model estimates lower than observed, white circle indicates model estimates higher than observed. Size of circle indicates degree of deviance (larger circle = larger deviance).

Table D2. Summary of parameter estimates for a length-based stock synthesis population model of Norton Sound red king crab.

name	Estimate	std.dev
log_q_1	-6.775	0.112
log_q_2		
log_N_{76}	9.171	0.112
R_0	6.526	0.084
a_1	2.214	5.073
a_2	3.308	4.774
a_3	4.334	4.654
a_4	4.373	4.646
a_5	4.566	4.637
a_6	3.777	4.663
a_7	2.265	4.871
r1	10.000	0.312
r2	9.616	0.362
log_a	-2.733	0.099
log_b	4.837	0.016
log_ϕ_{st1}	-5.000	0.080
log_ϕ_{wa}	-2.130	0.297
log_ϕ_{wb}	4.808	0.030
Sw1	0.071	0.034
Sw2	0.490	0.120
log_ϕ_1	-2.093	0.055
$log\_\phi ra$	-0.798	0.128
$log\_\phi rb$	4.648	0.008
$log\_\phi wra$	-0.953	0.561
$log\_\phi wrb$	4.653	0.038
$w^2{}_t$	0.000	0.000
q	0.677	0.109
σ	4.232	0.255
β_1	11.829	0.926
β_2	7.919	0.221
ms78	3.554	0.280

Model 19.2

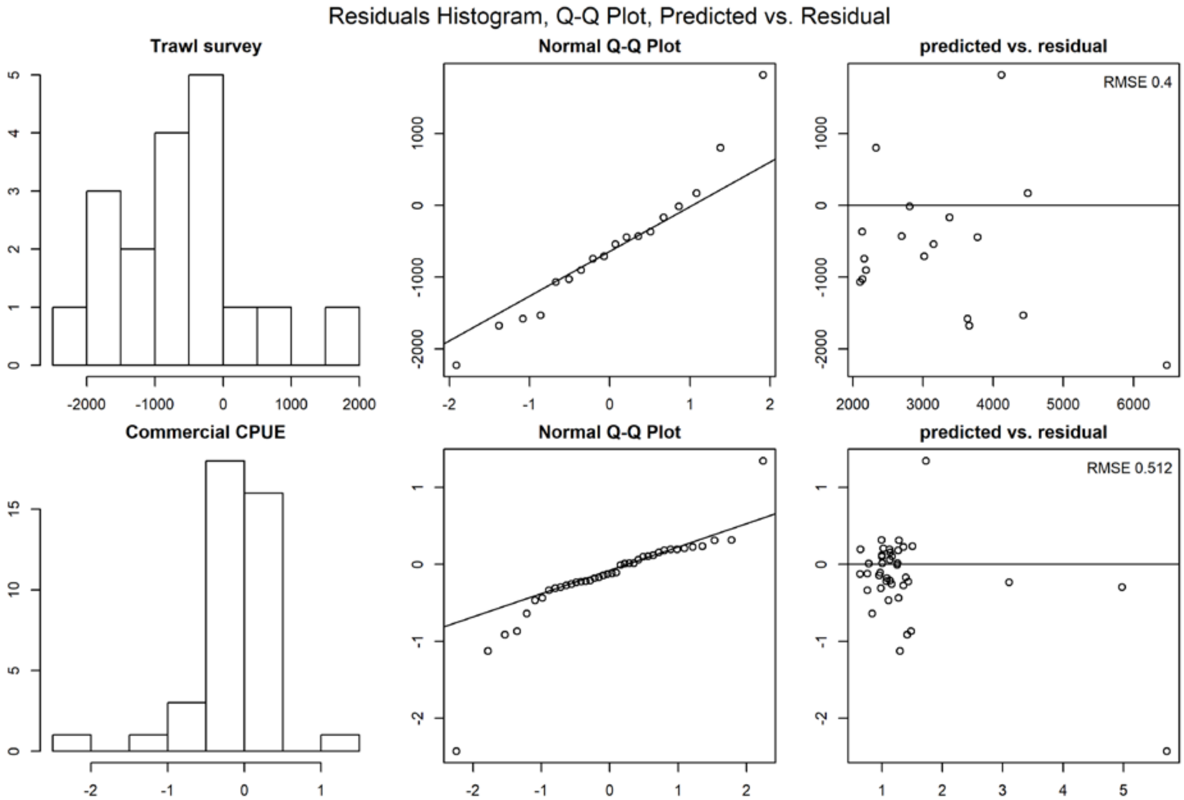


Figure D3-1. QQ Plot of Trawl survey and commercial CPUE.

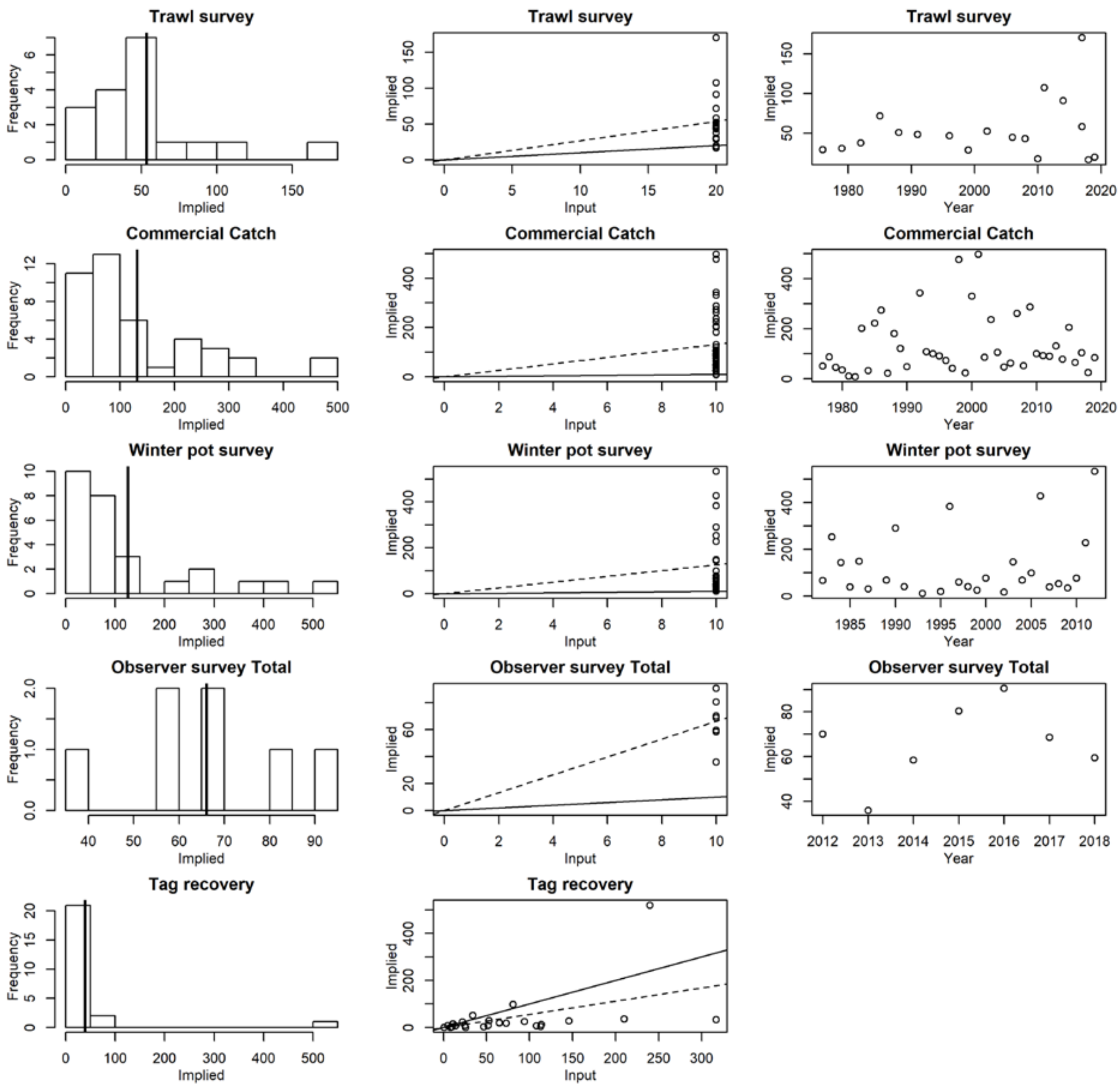


Figure D3-2: Implied effective samples. Figures in the first column show implied effective sample size (x-axis) vs. frequency (y-axis).
Vertical solid line is the mean implied effective sample size.
The second column shows input sample size (x-axis) vs. implied effective sample size (y-axis). Dashed line indicates linear regression slope, and solid line is 1:1 line. The third column show year (x-axis) vs. implied effective sample size (y-axis).

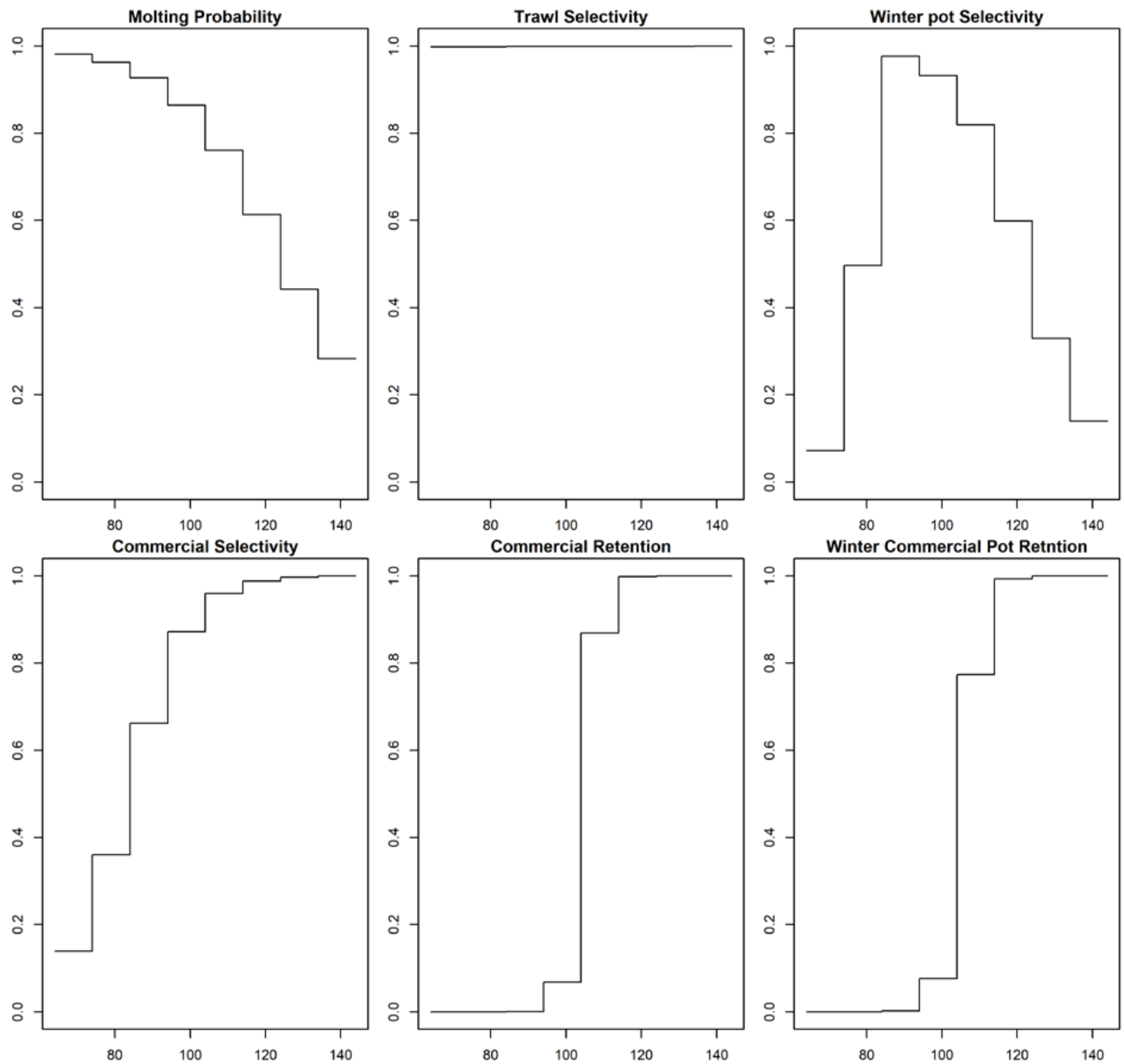


Figure D3-3. Molting probability and trawl/pot selectivity. X-axis is carapace length.

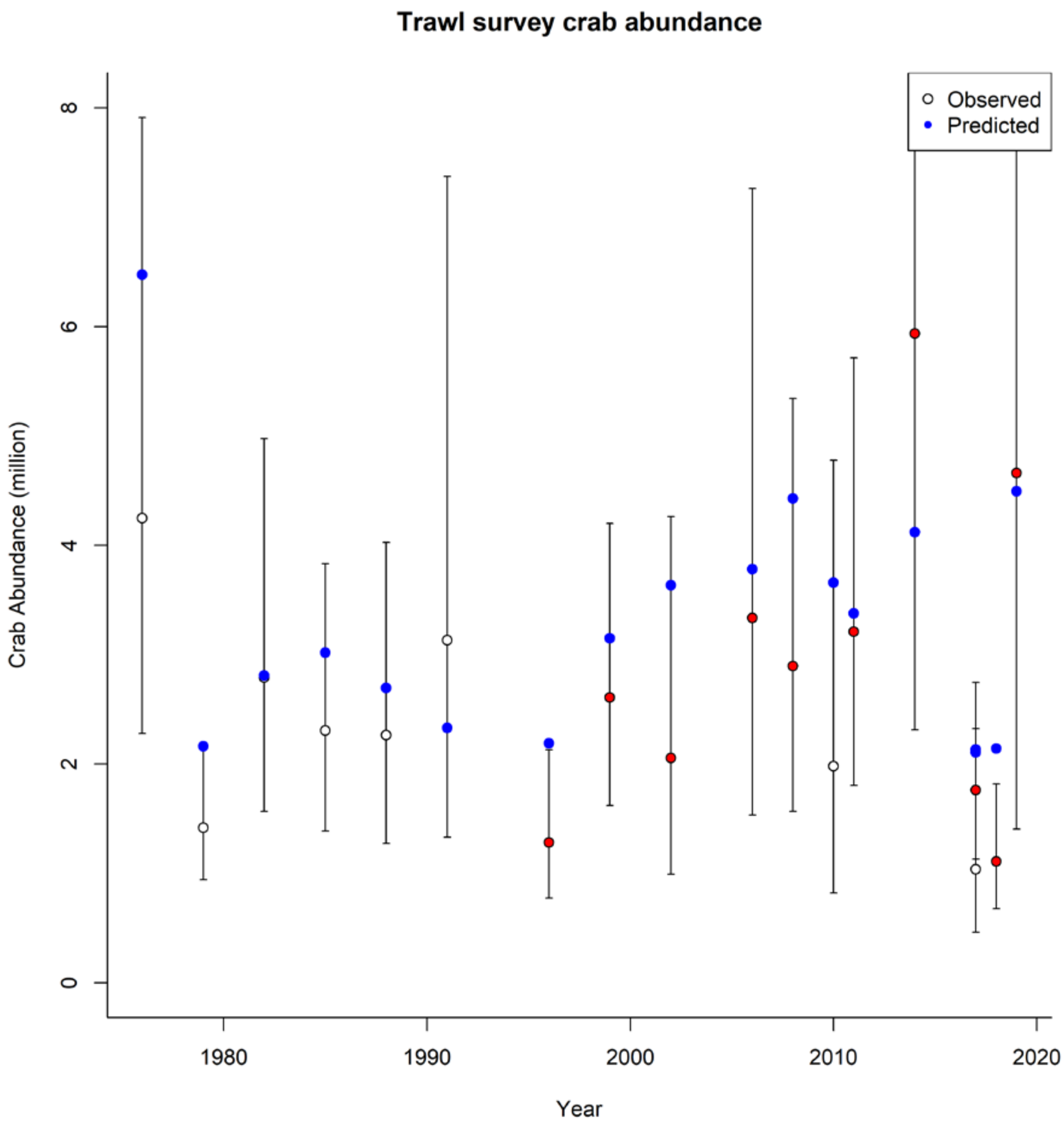


Figure D3-4. Estimated trawl survey male abundance (blue) (crab >= 64 mm CL). Observed: White: NOAA trawl survey, Red: ADG&G trawl survey

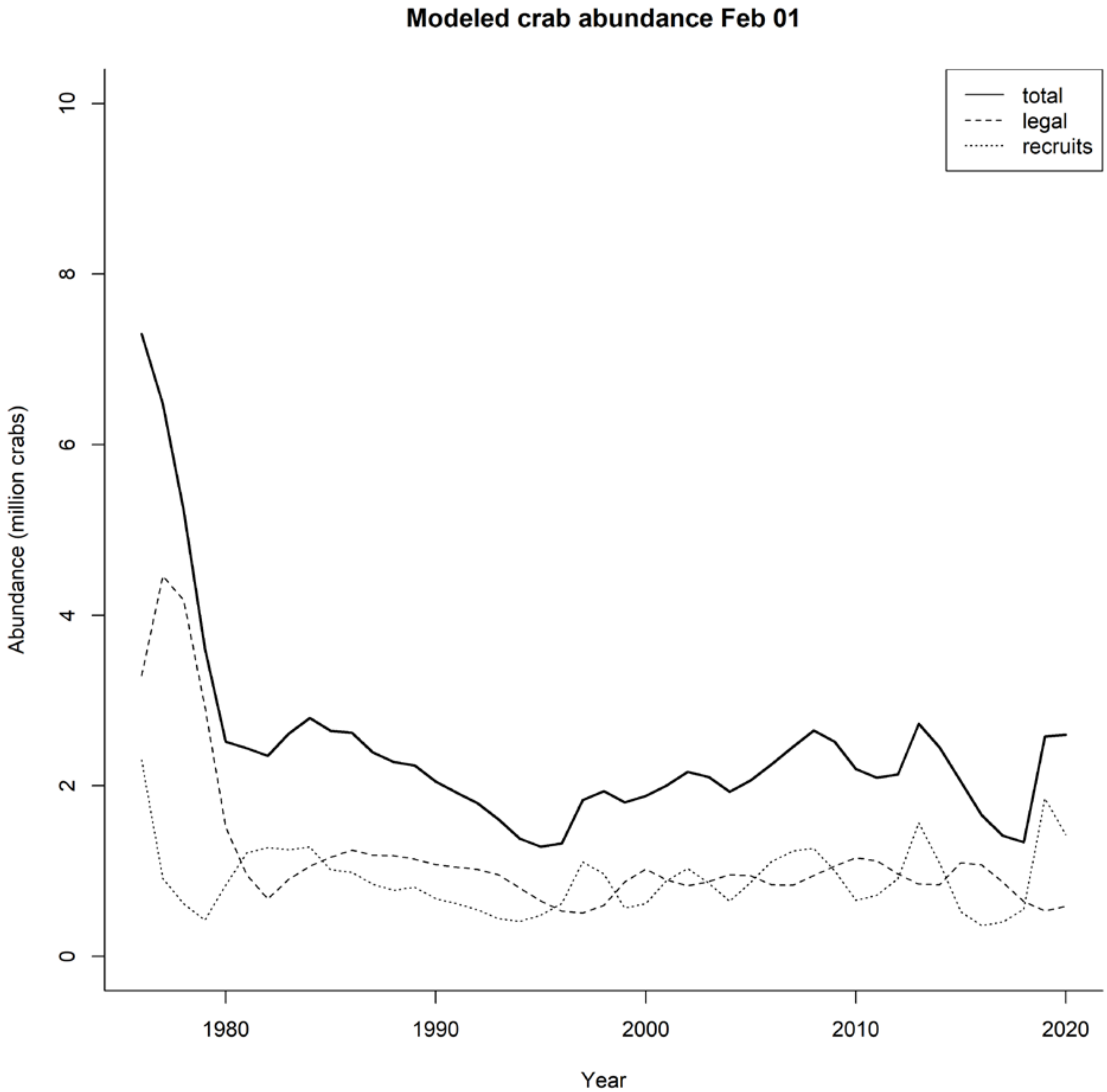


Figure D3-5. Estimated abundance of legal males.

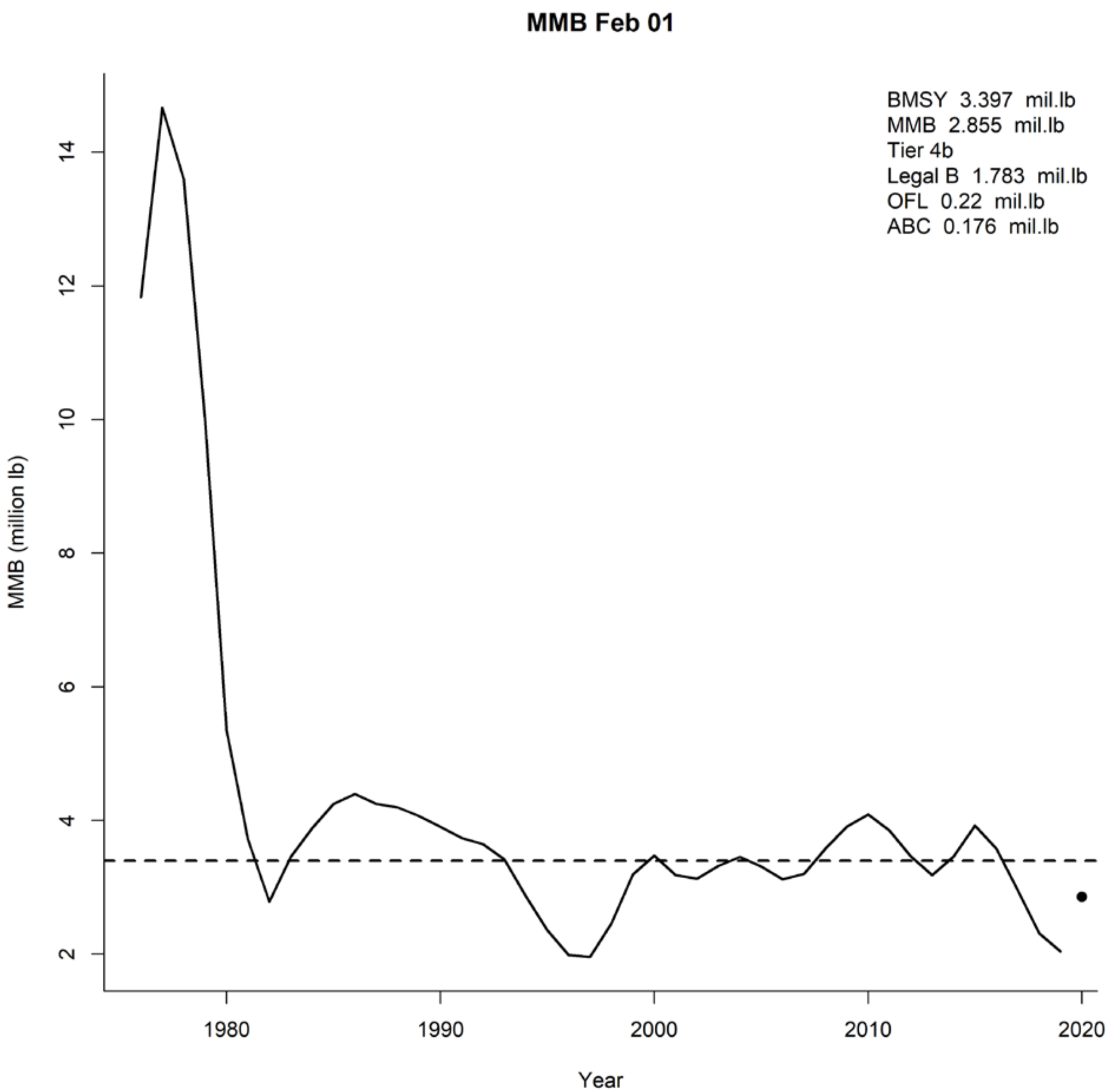


Figure D3-6. Estimated abundance of Mature Male Biomass. Dash line shows Bmsy.

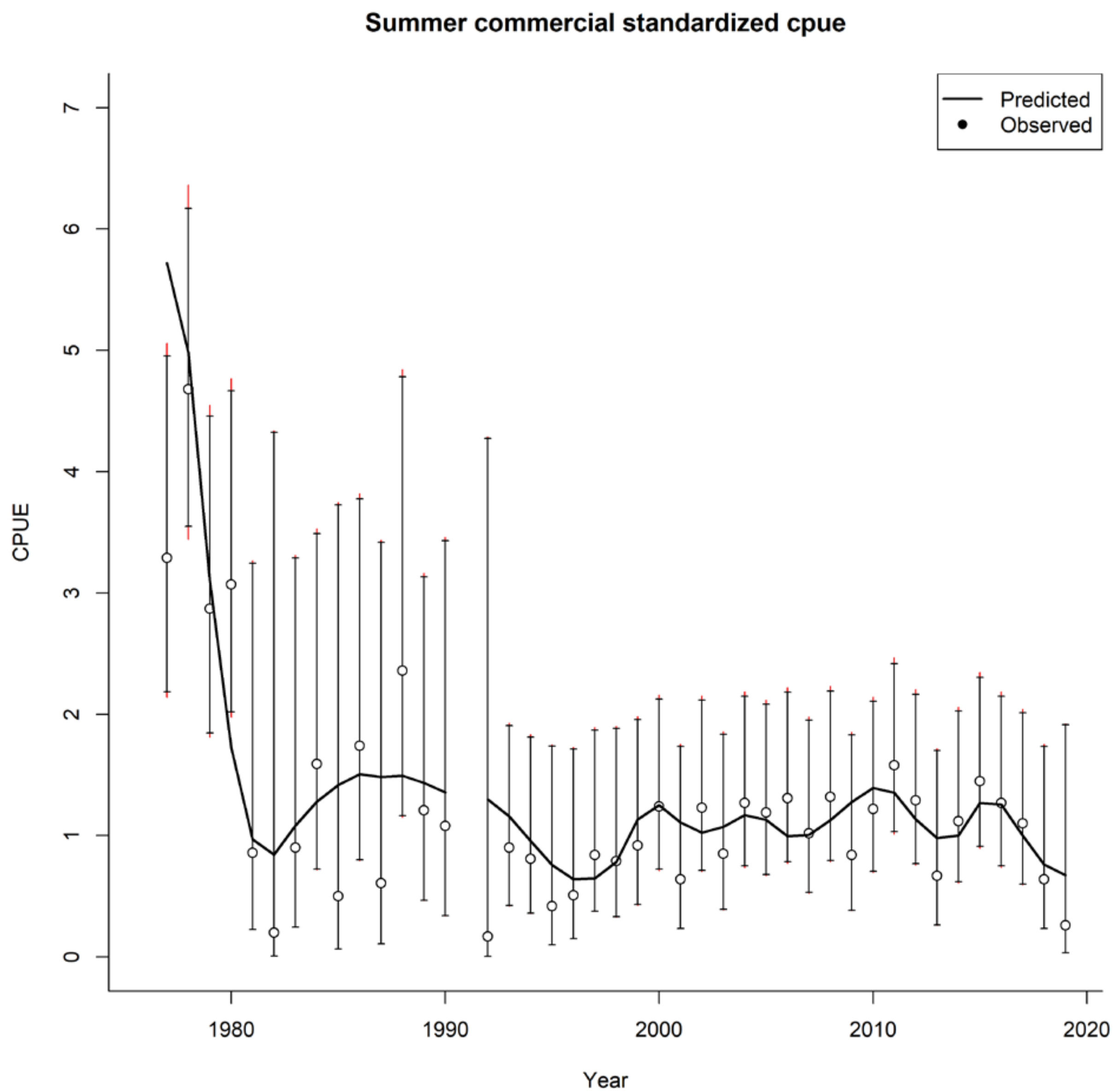


Figure D3-7. Summer commercial standardized cpue.

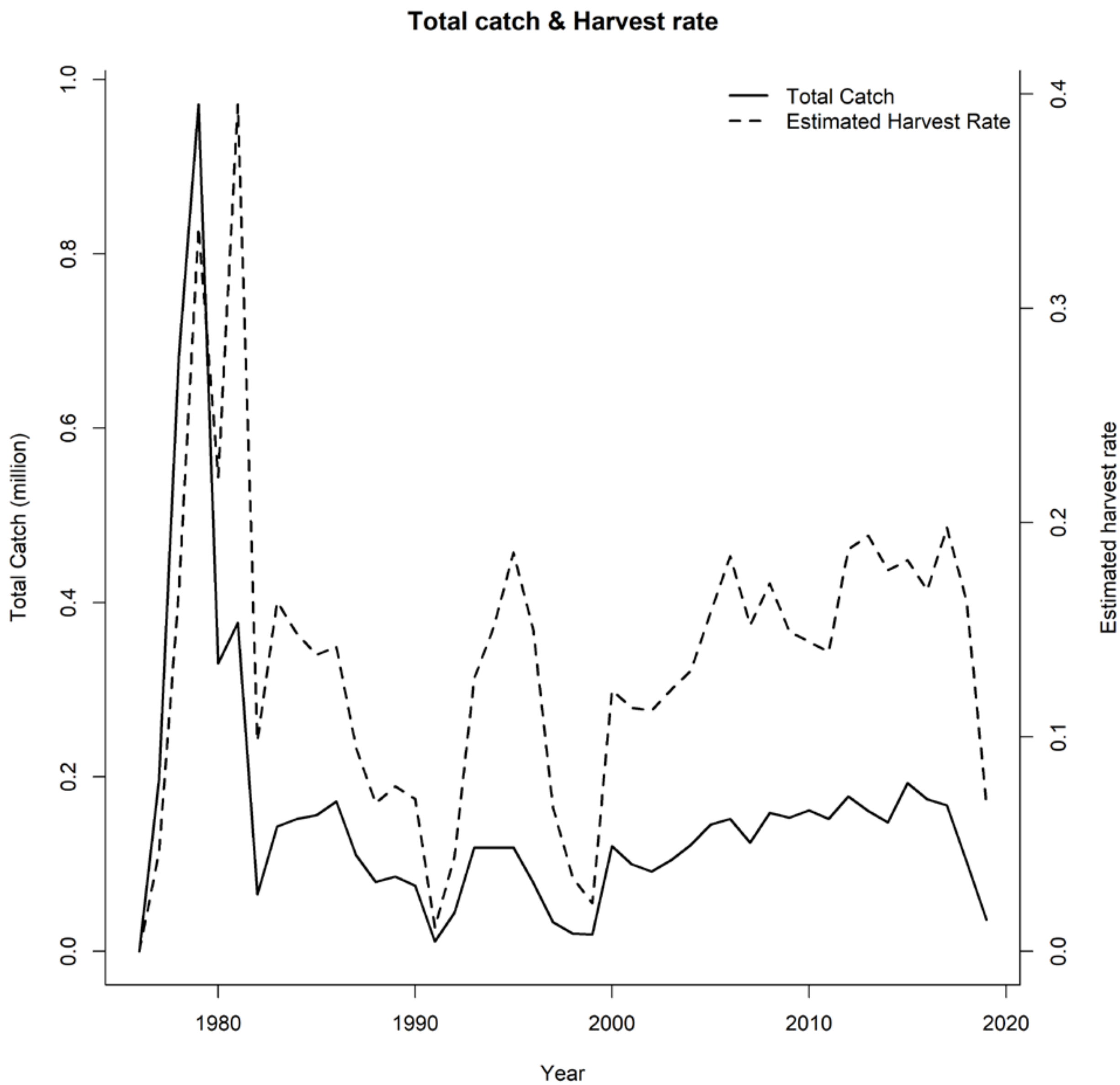


Figure D3-8. Total catch and estimated harvest rate.

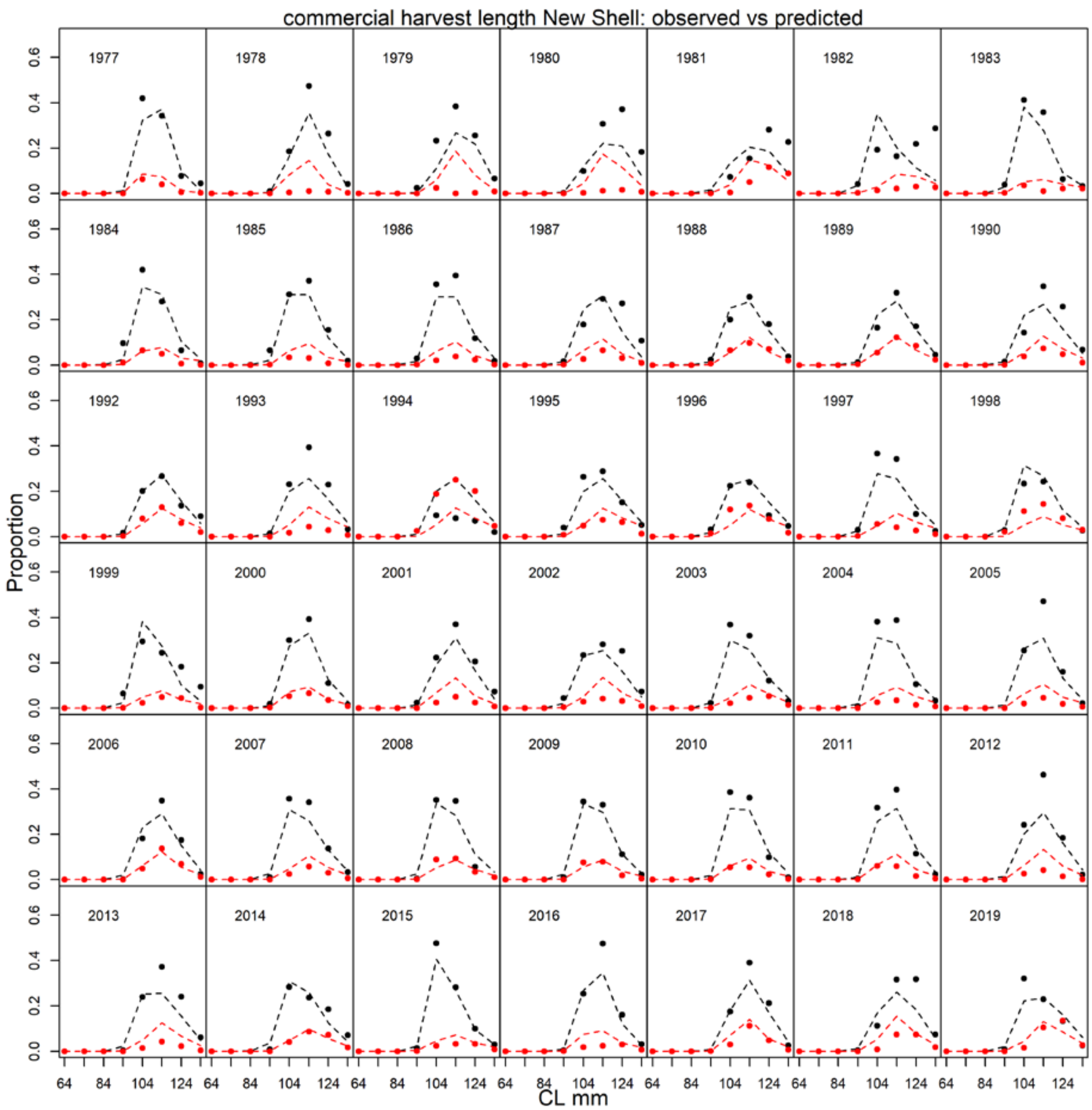


Figure D3-9. Predicted (dashed) vs. observed (dots) length class proportions for commercial catch. Black: newshell, Red: oldshell

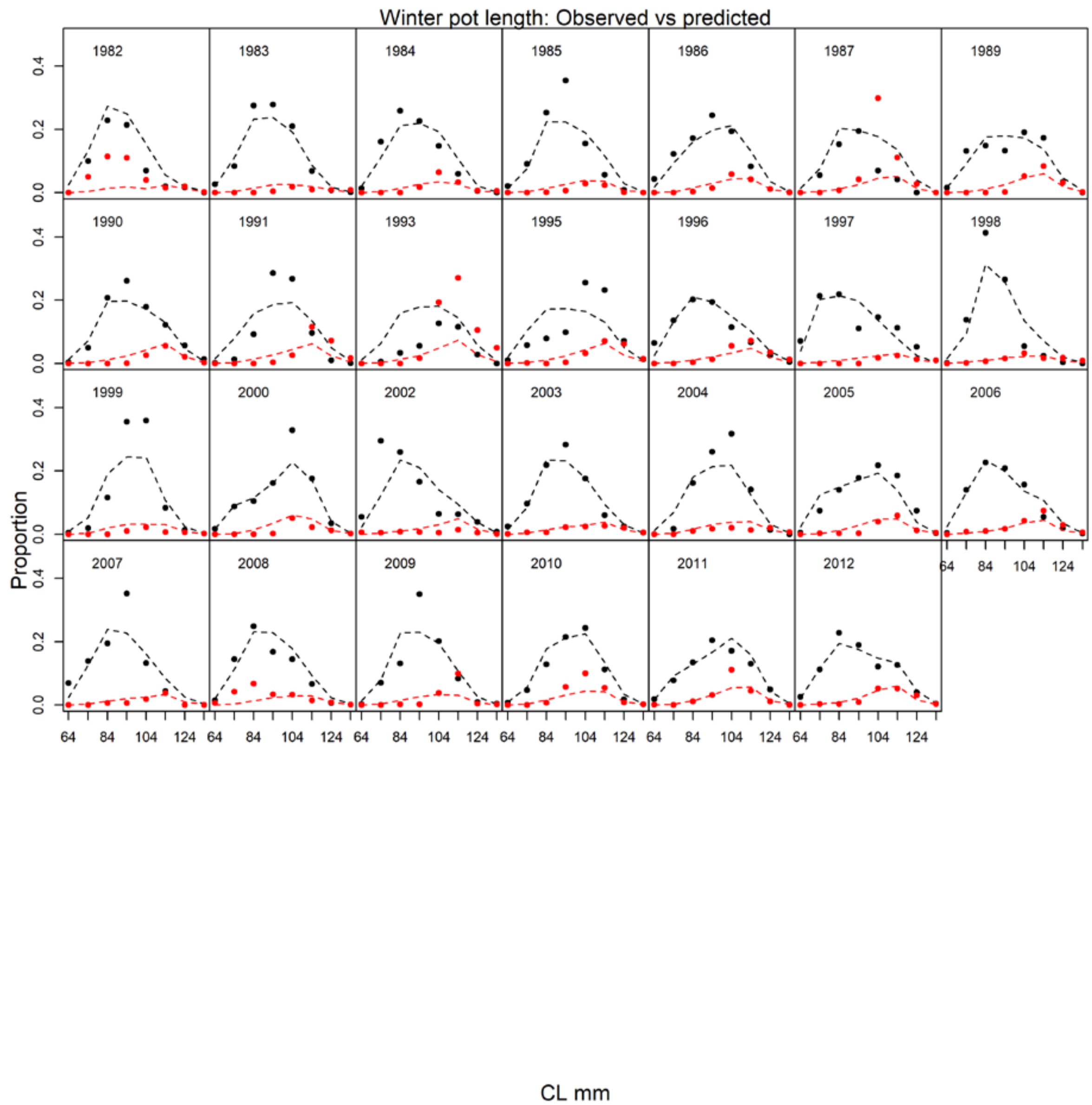


Figure D3-10. Predicted (dashed line) vs. observed (dots) length class proportions for the winter and spring pot survey. Black: newshell, Red: oldshell

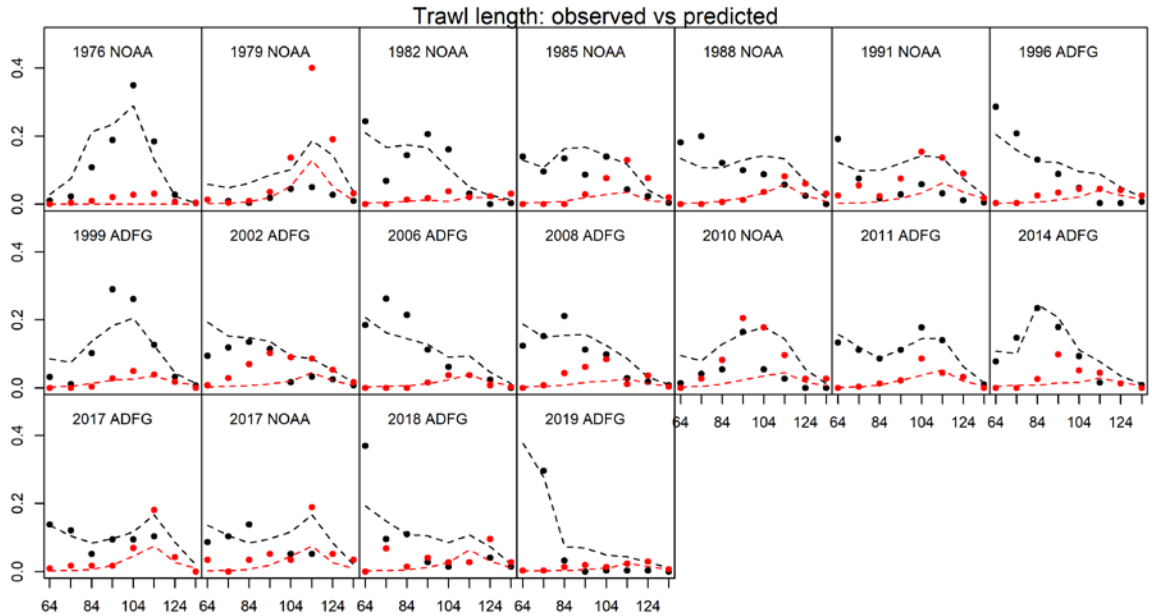


Figure D3-11. Predicted (dashed) vs. observed (dots) length class proportions for trawl survey. Black: newshell, Red: oldshell

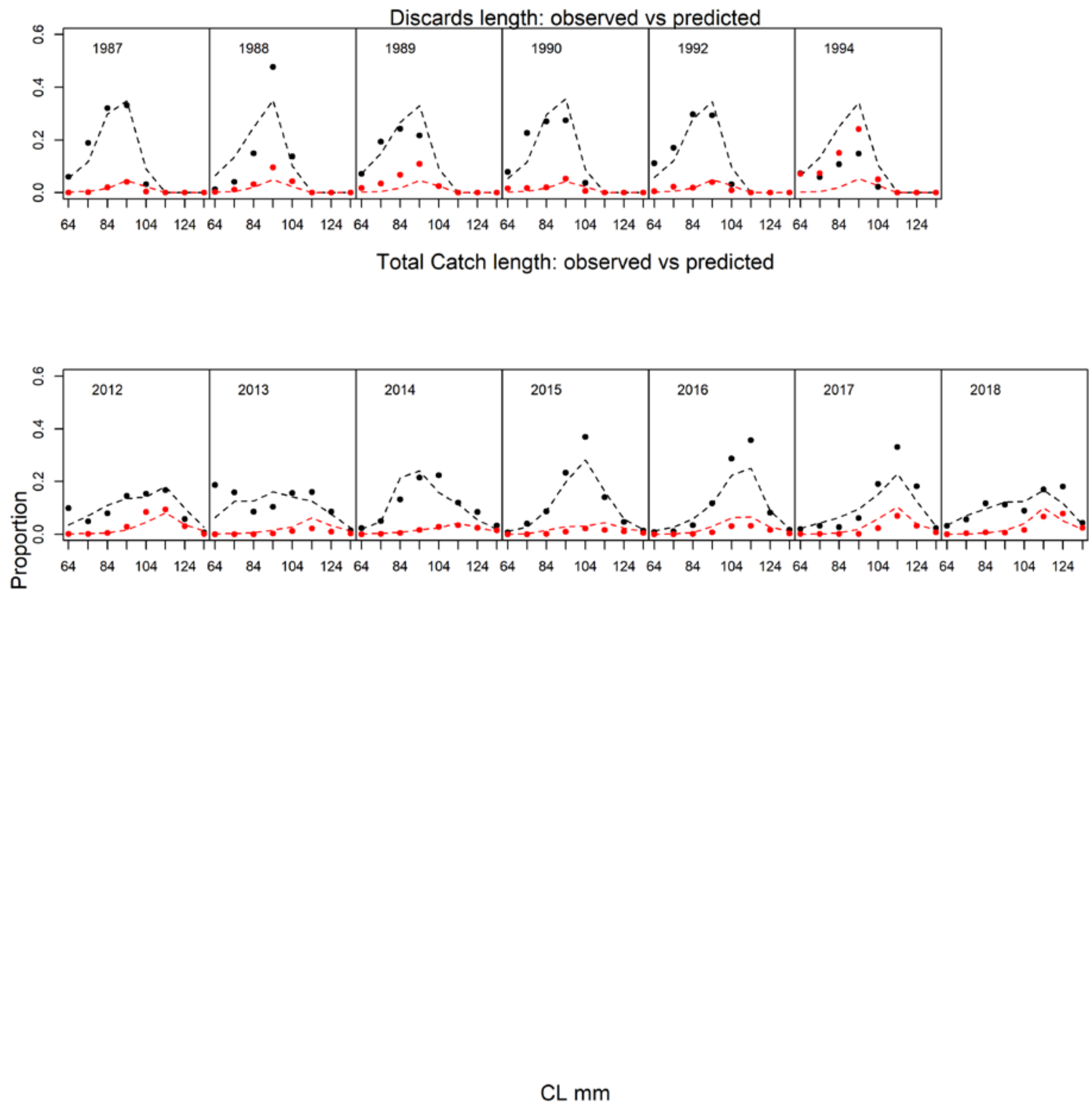


Figure D3-13. Predicted (dashed) vs. observed (dots) length class proportions for the observer survey. Black: newshell, Red: oldshell

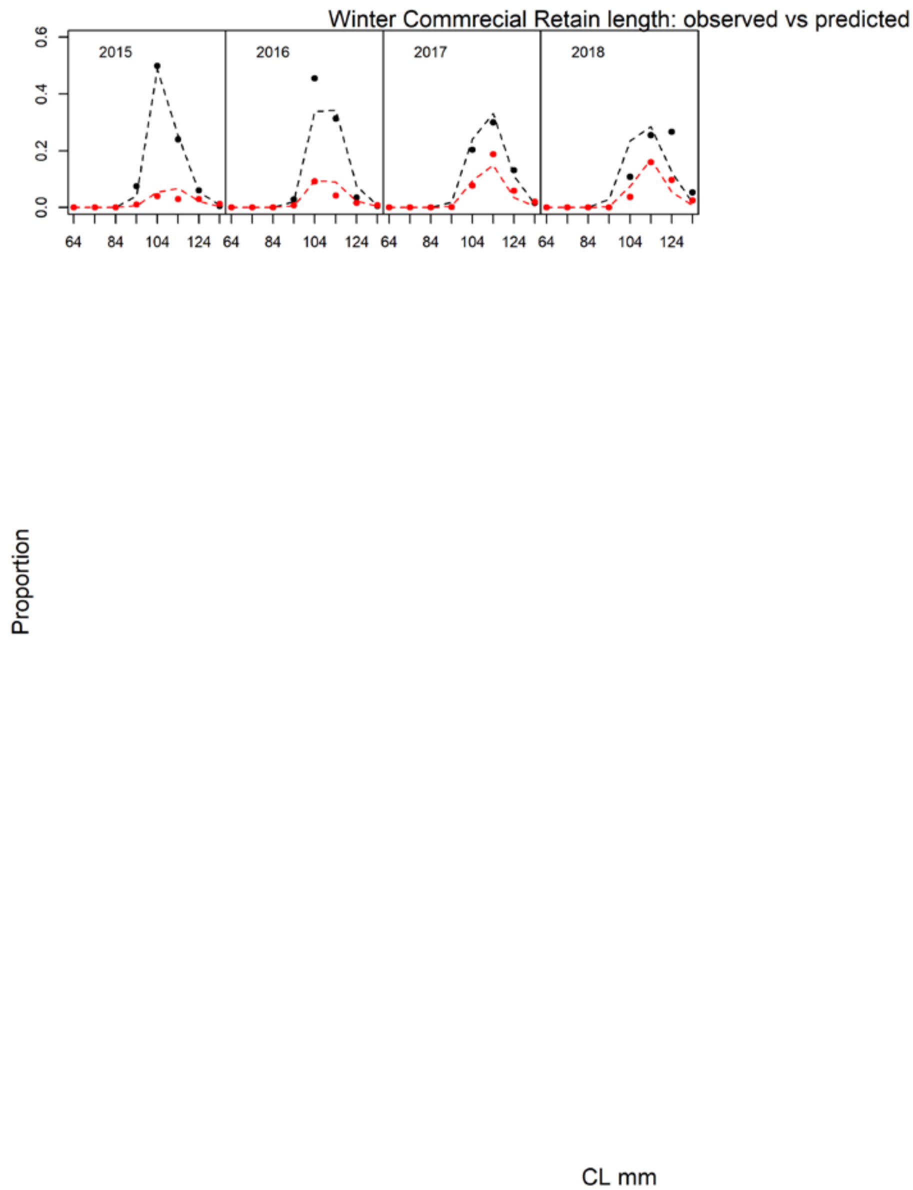


Figure D3-12. Predicted (dashed) vs. observed (dots) length class proportions for the observer survey. Black: newshell, Red: oldshell

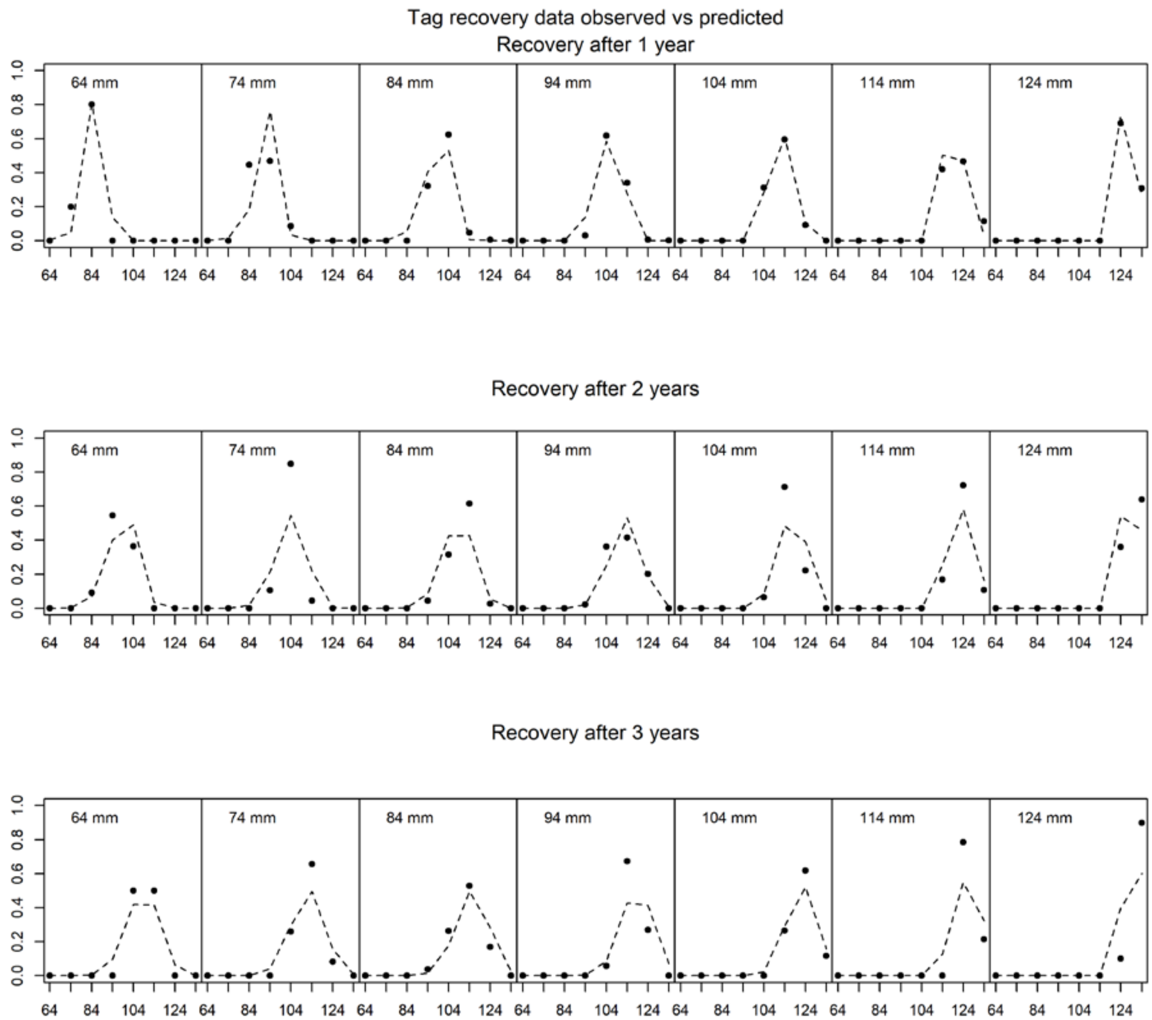


Figure D3-13. Predicted vs. observed length class proportions for tag recovery data.

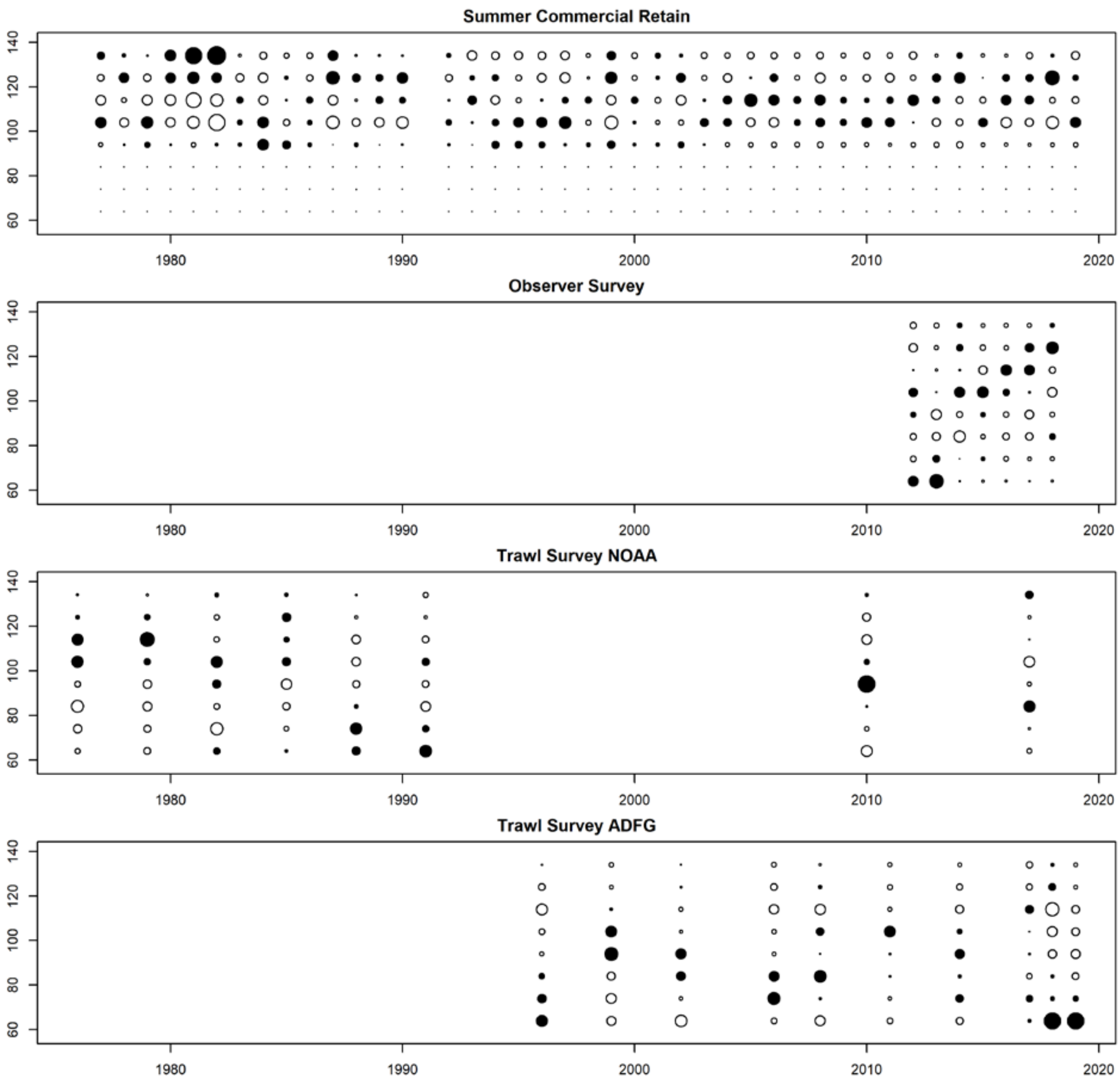


Figure D3-13. Bubble plots of predicted and observed length proportions.
Black circle indicates model estimates lower than observed, white circle indicates model estimates higher than observed. Size of circle indicates degree of deviance (larger circle = larger deviance).

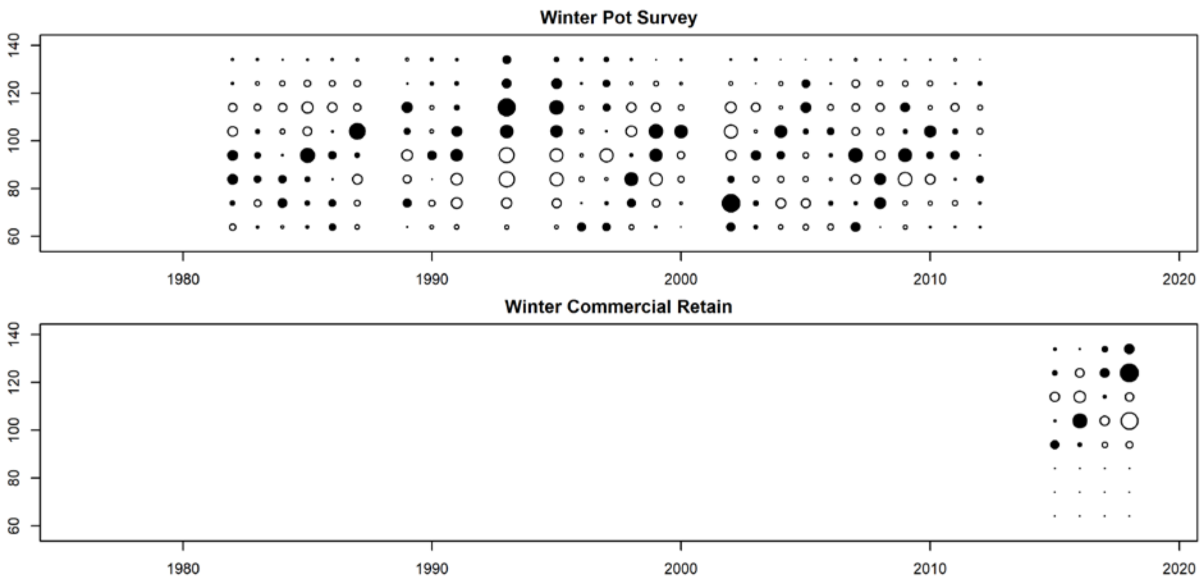


Figure D3-14. Bubble plots of predicted and observed length proportions.
Black circle indicates model estimates lower than observed, white circle indicates model estimates higher than observed. Size of circle indicates degree of deviance (larger circle = larger deviance).

Table D3. Summary of parameter estimates for a length-based stock synthesis population model of Norton Sound red king crab.

name	Estimate	std.dev
log_q_1	-6.471	0.123
log_q_2		
log_N_{76}	8.895	0.091
R_0	6.206	0.095
a_1	2.091	4.628
a_2	3.055	4.325
a_3	4.093	4.166
a_4	4.189	4.152
a_5	4.400	4.142
a_6	3.609	4.172
a_7	2.110	4.440
r1	10.000	0.335
r2	9.671	0.376
log_a	-2.665	0.089
log_b	4.829	0.015
log_ϕ_{st1}	-5.000	0.113
log_ϕ_{wa}	-2.198	0.316
log_ϕ_{wb}	4.805	0.032
Sw1	0.072	0.035
Sw2	0.497	0.124
log_ϕ_1	-2.082	0.056
log_ϕra	-0.796	0.128
log_ϕrb	4.647	0.008
log_ϕwra	-0.988	0.536
log_ϕwrb	4.656	0.037
$w^2{}_t$	0.004	0.019
q ADFG	1.400	0.217
σ	3.870	0.209
β_1	12.524	0.705
β_2	7.636	0.173
ms78	2.883	0.259

Model 19.3

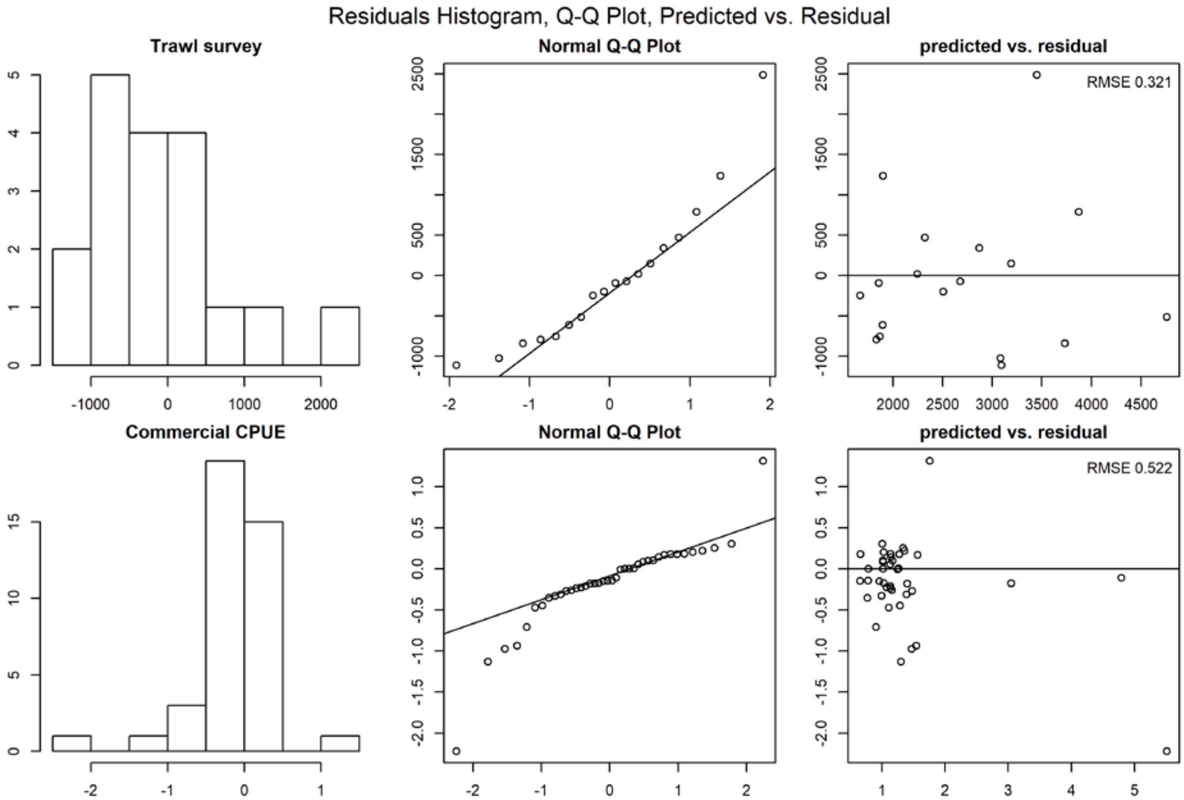


Figure D4-1. QQ Plot of trawl survey and commercial CPUE.

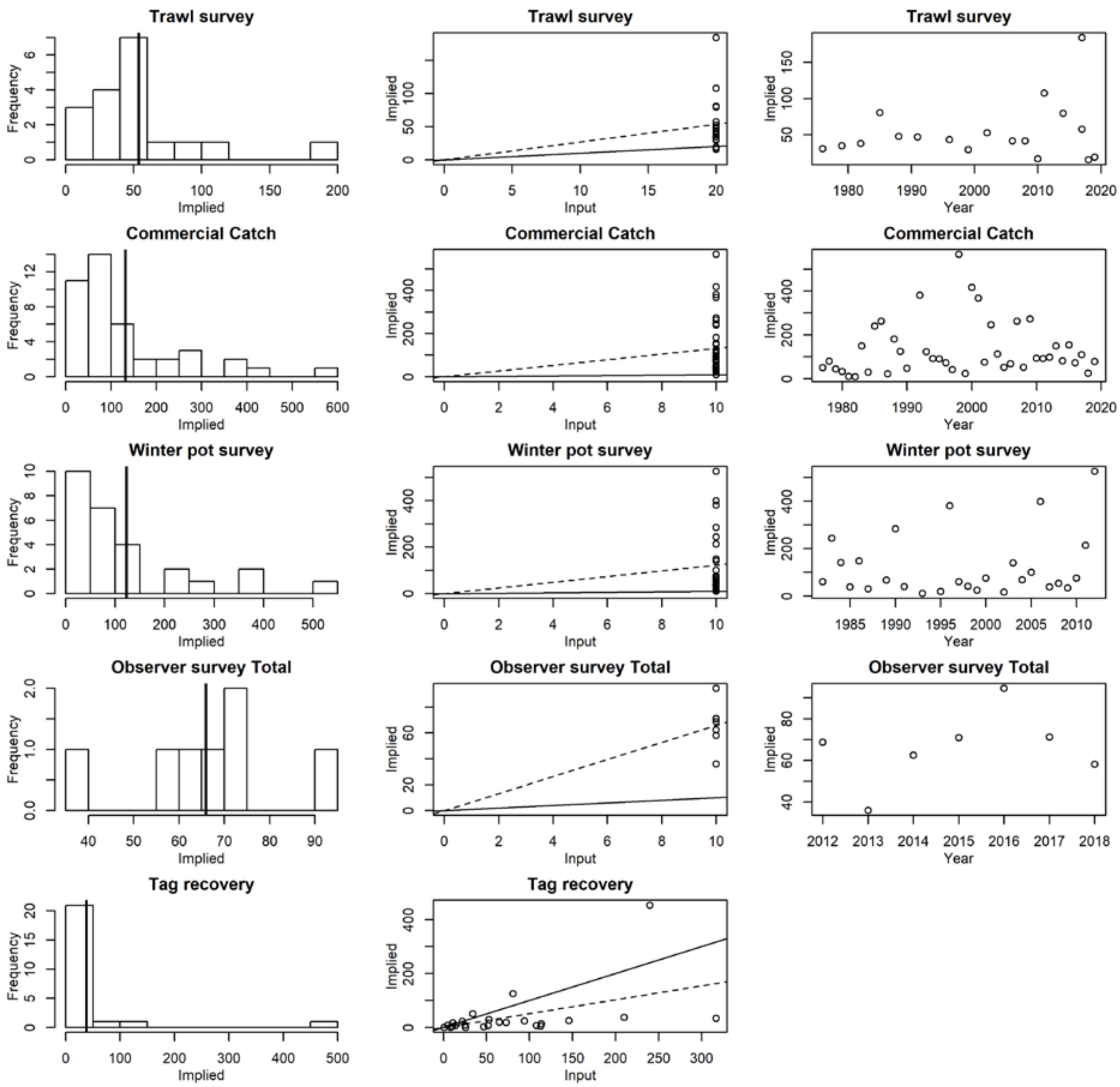


Figure D4-2: Implied effective samples. Figures in the first column show implied effective sample size (x-axis) vs. frequency (y-axis).
Vertical solid line is the mean implied effective sample size.
The second column shows input sample size (x-axis) vs. implied effective sample size (y-axis). Dashed line indicates linear regression slope, and solid line is 1:1 line. The third column show year (x-axis) vs. implied effective sample size (y-axis).

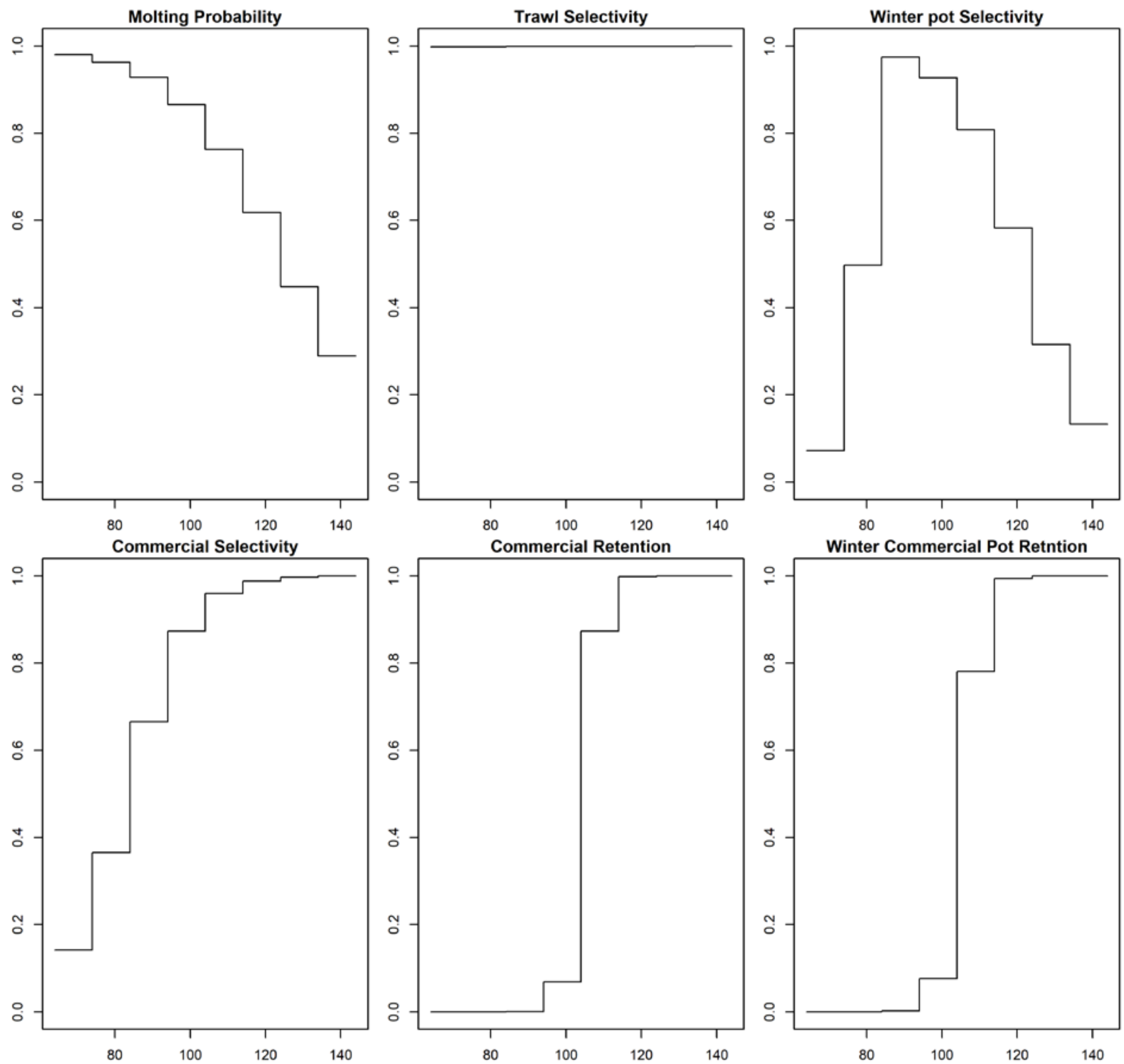


Figure D4-3. Molting probability and trawl/pot selectivity. X-axis is carapace length.

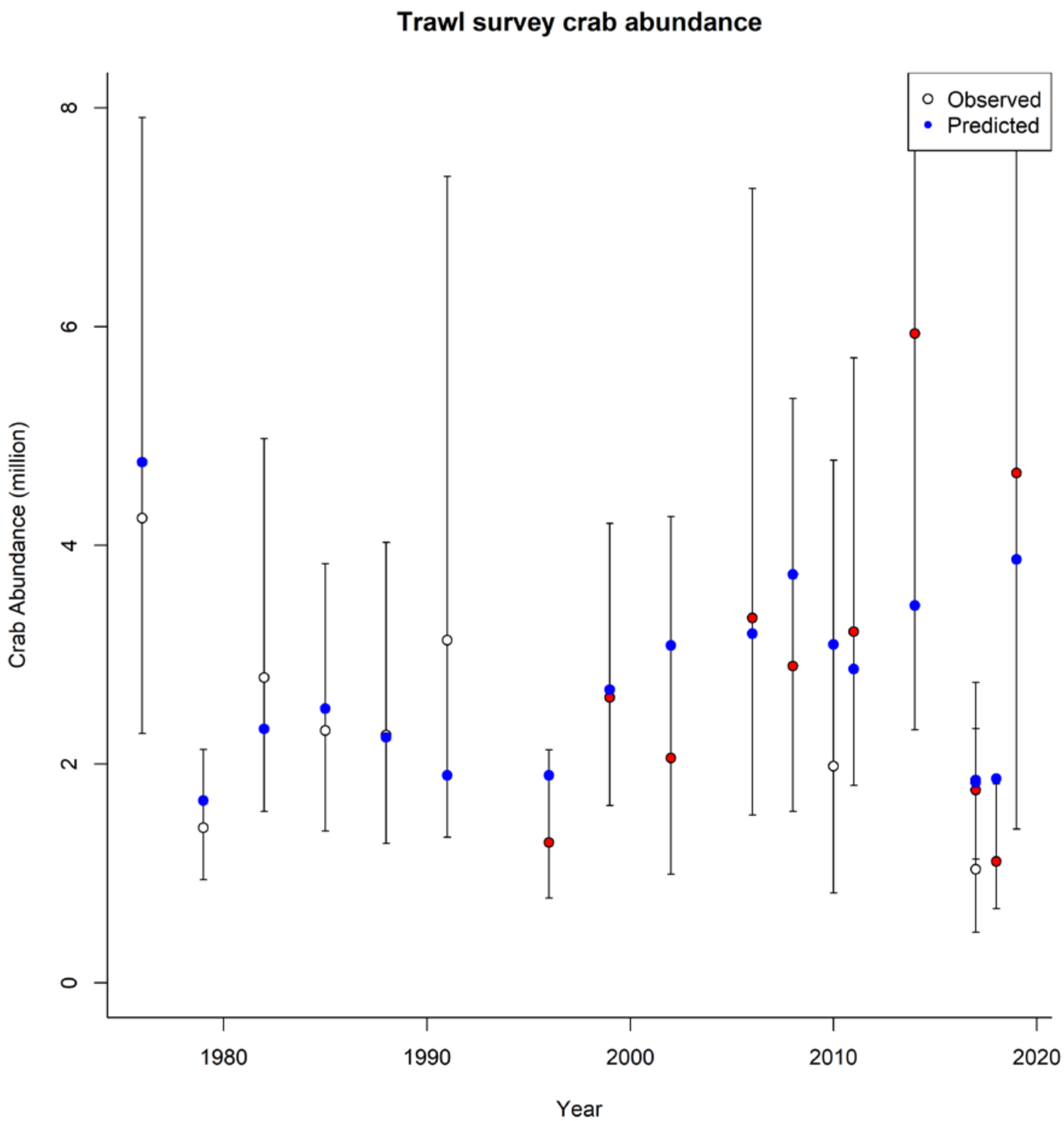


Figure D4-4. Estimated trawl survey male abundance (blue) (crab >= 64 mm CL). Observed: White: NOAA trawl survey, Red: ADG&G trawl survey

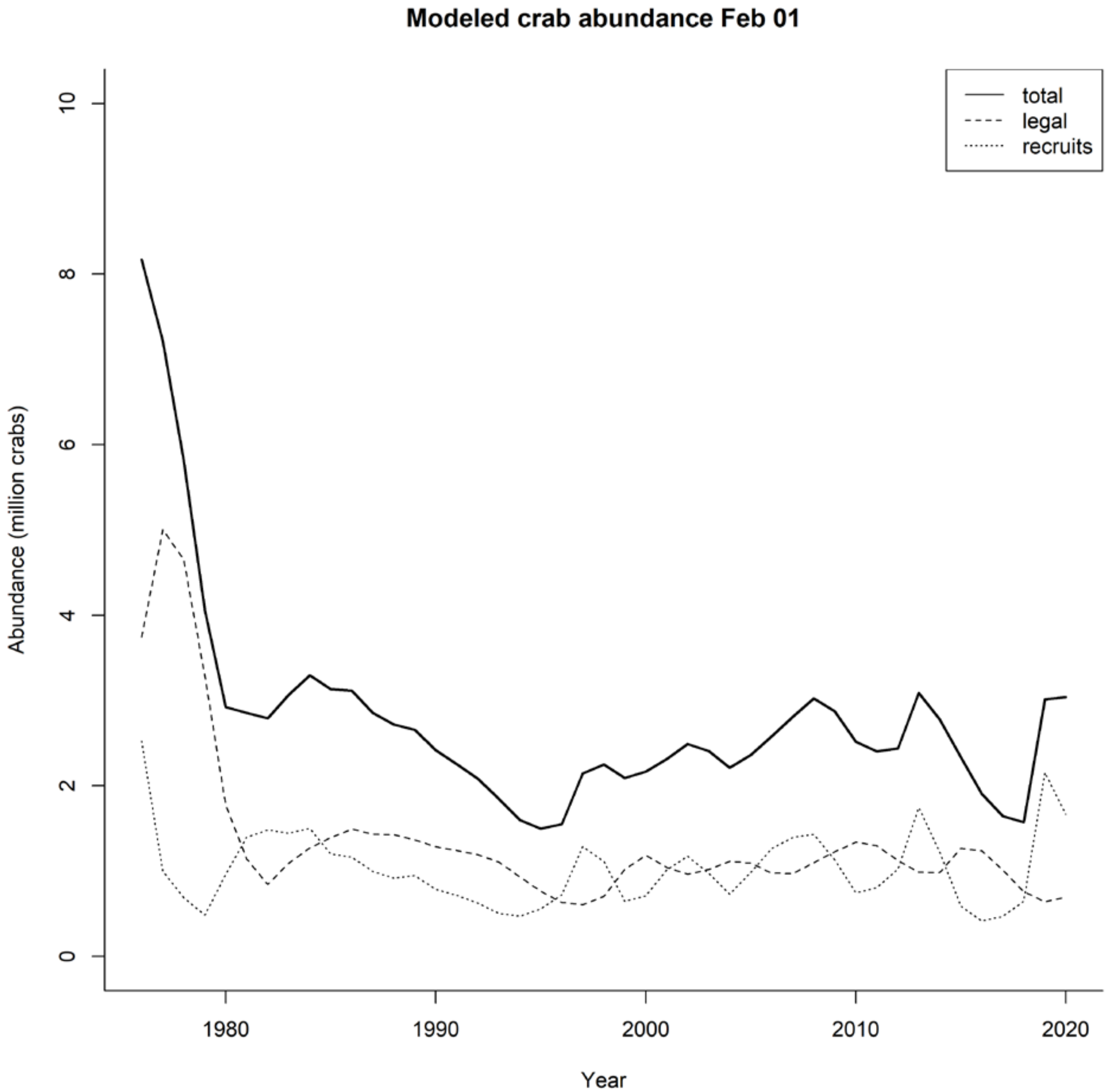


Figure D4-5. Estimated abundance of legal males.

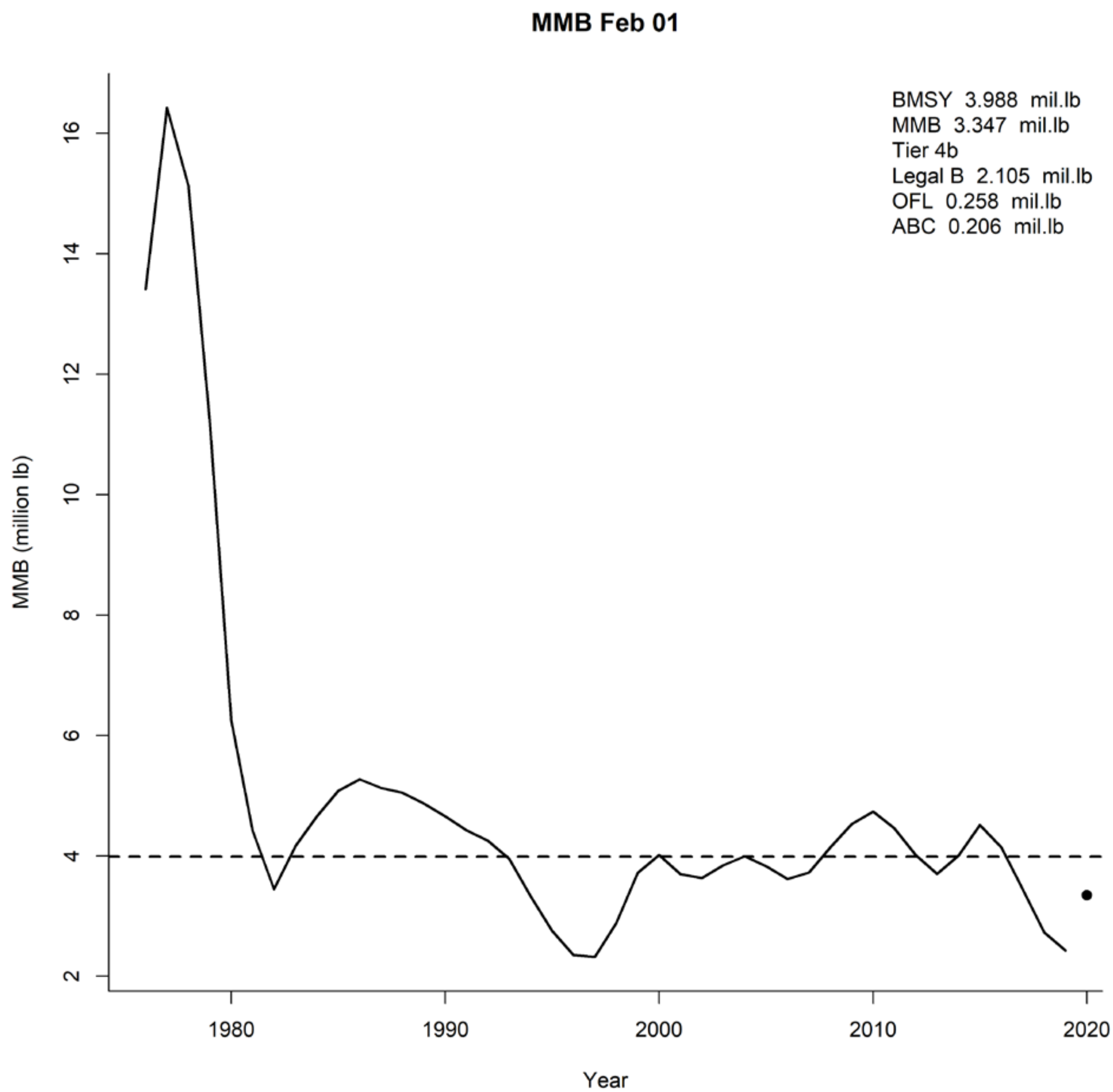


Figure D4-6. Estimated abundance of Mature Male Biomass. Dash line shows Bmsy.

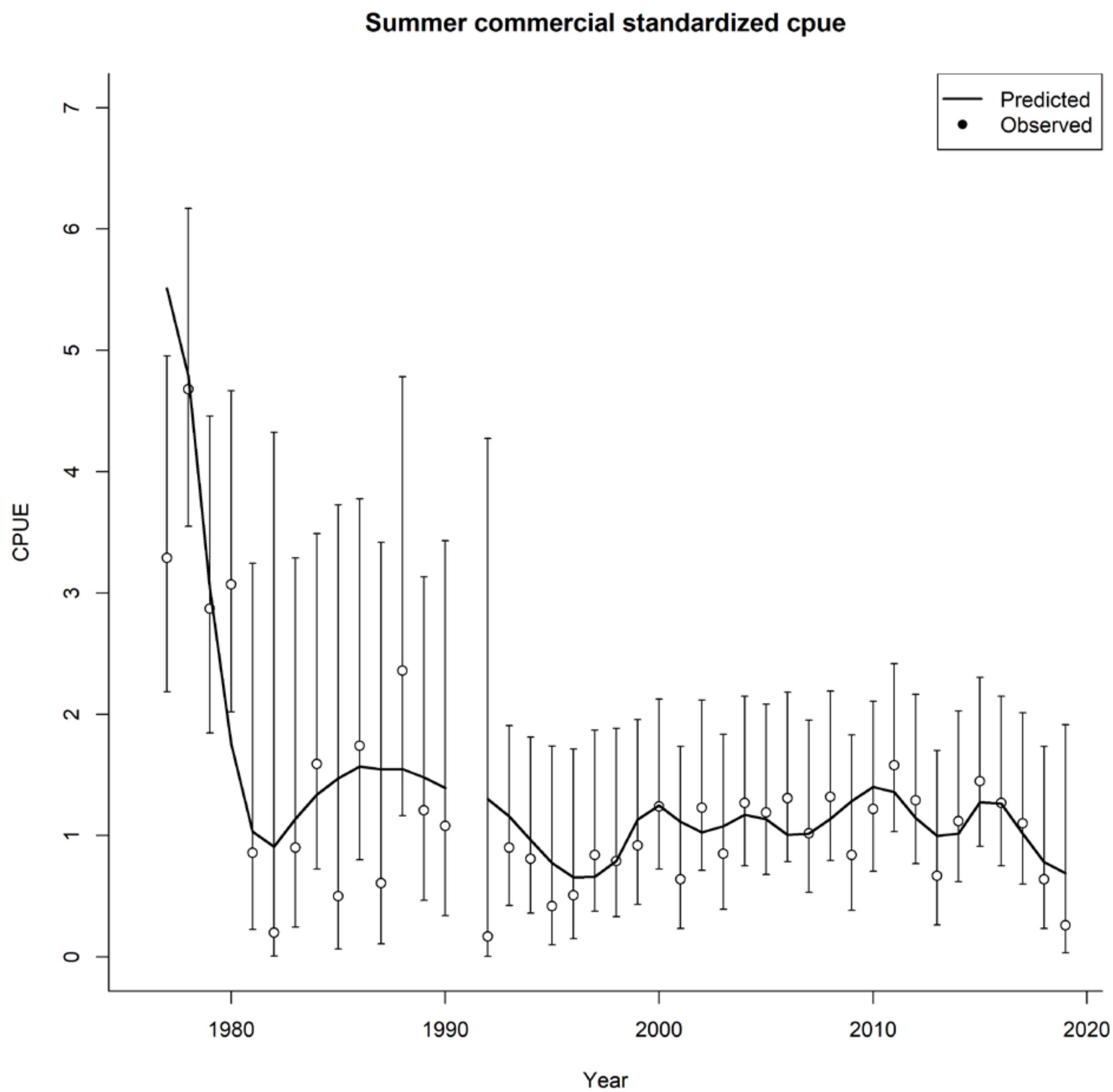


Figure D4-7. Summer commercial standardized cpue.

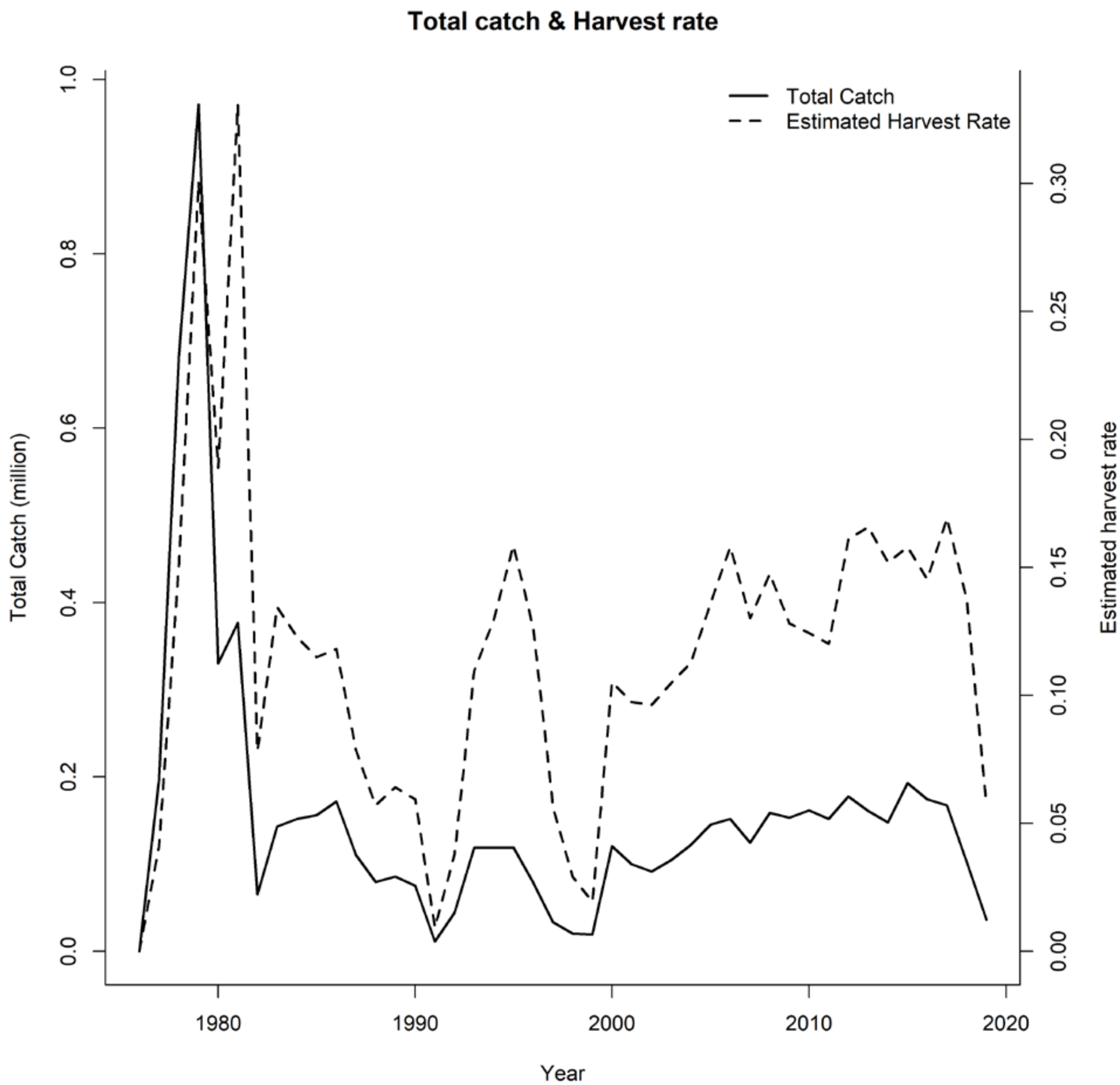


Figure D4-8. Total catch and estimated harvest rate.

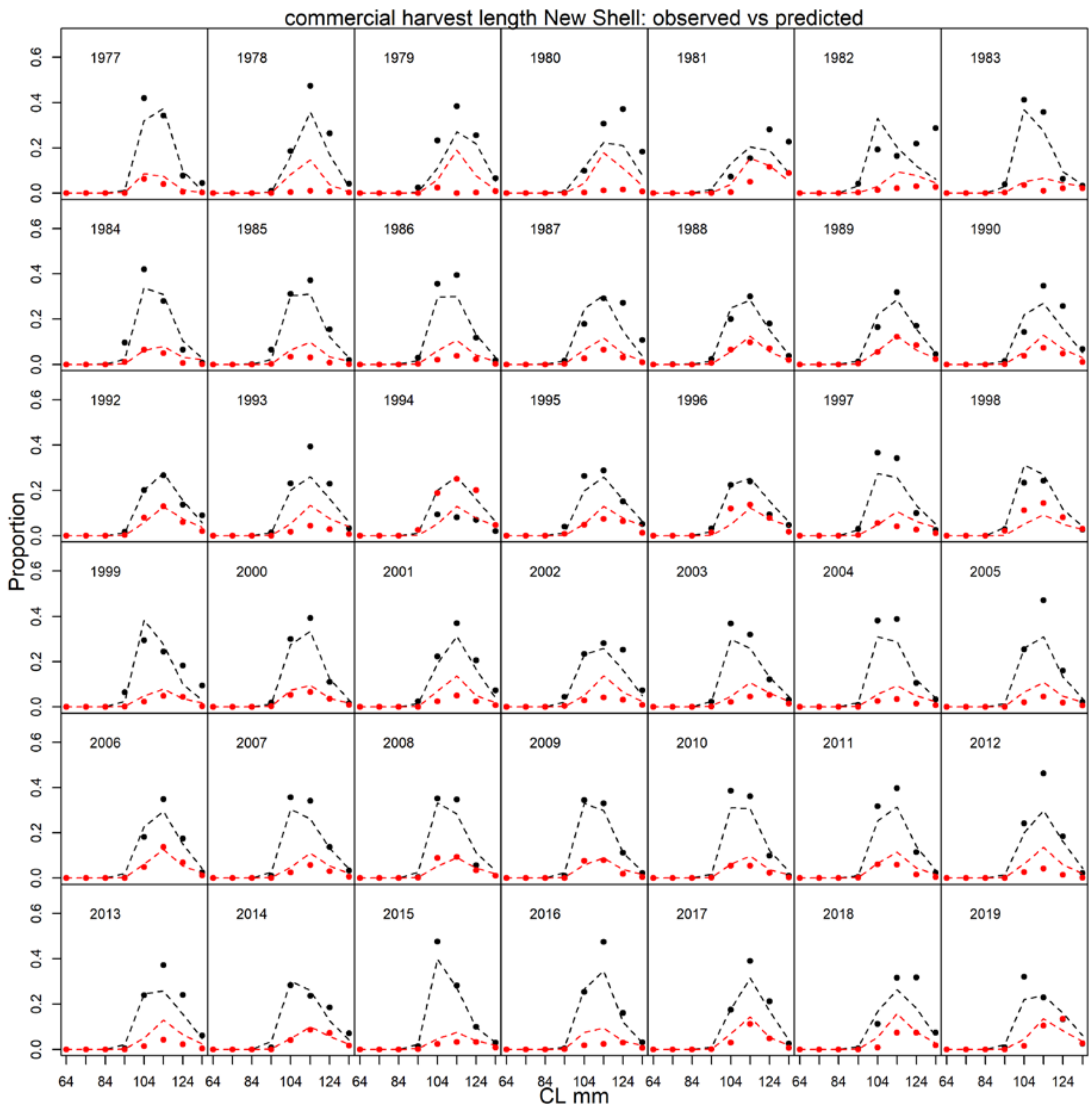


Figure D4-9. Predicted (dashed line) vs. observed (dots) length class proportions for commercial catch. Black: newshell, Red: oldshell

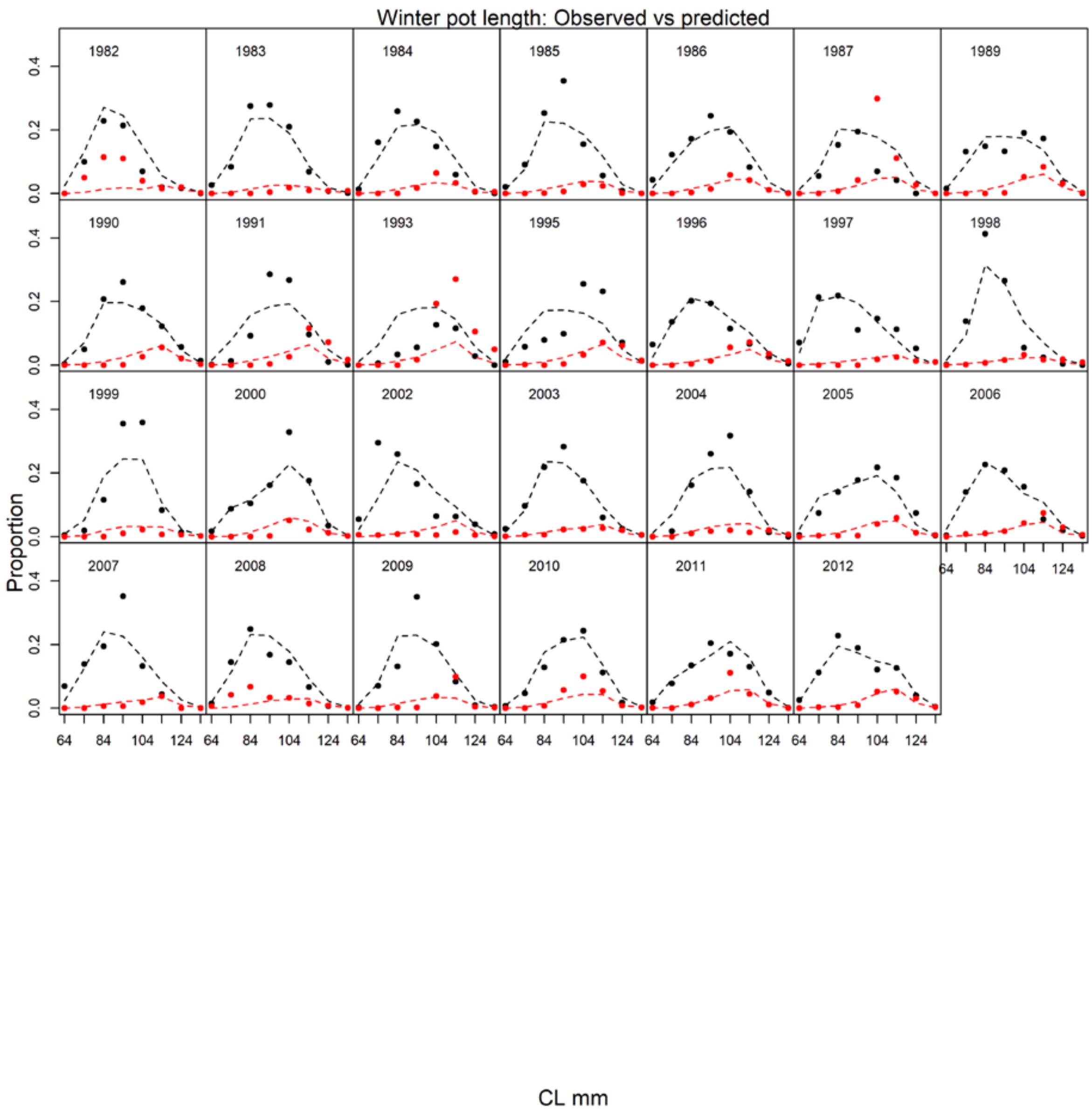


Figure D4-10. Predicted (dashed line) vs. observed (dots) length class proportions for the winter and spring pot survey. Black: newshell, Red: oldshell

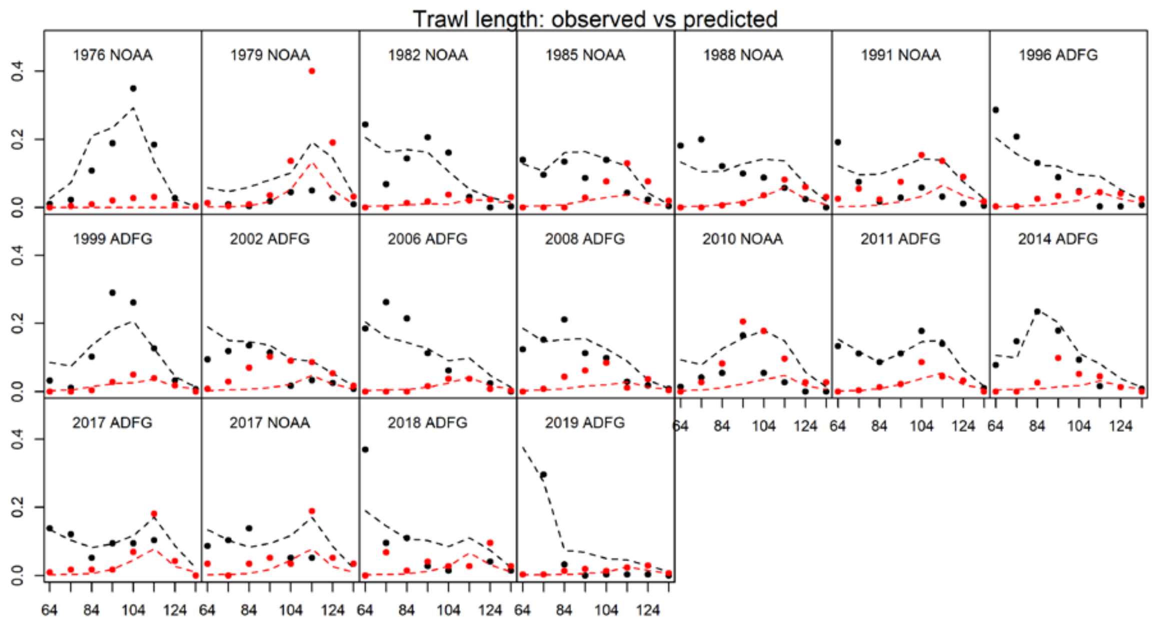


Figure D4-11. Predicted (dashed) vs. observed (dots) length class proportions for trawl survey. Black: newshell, Red: oldshell

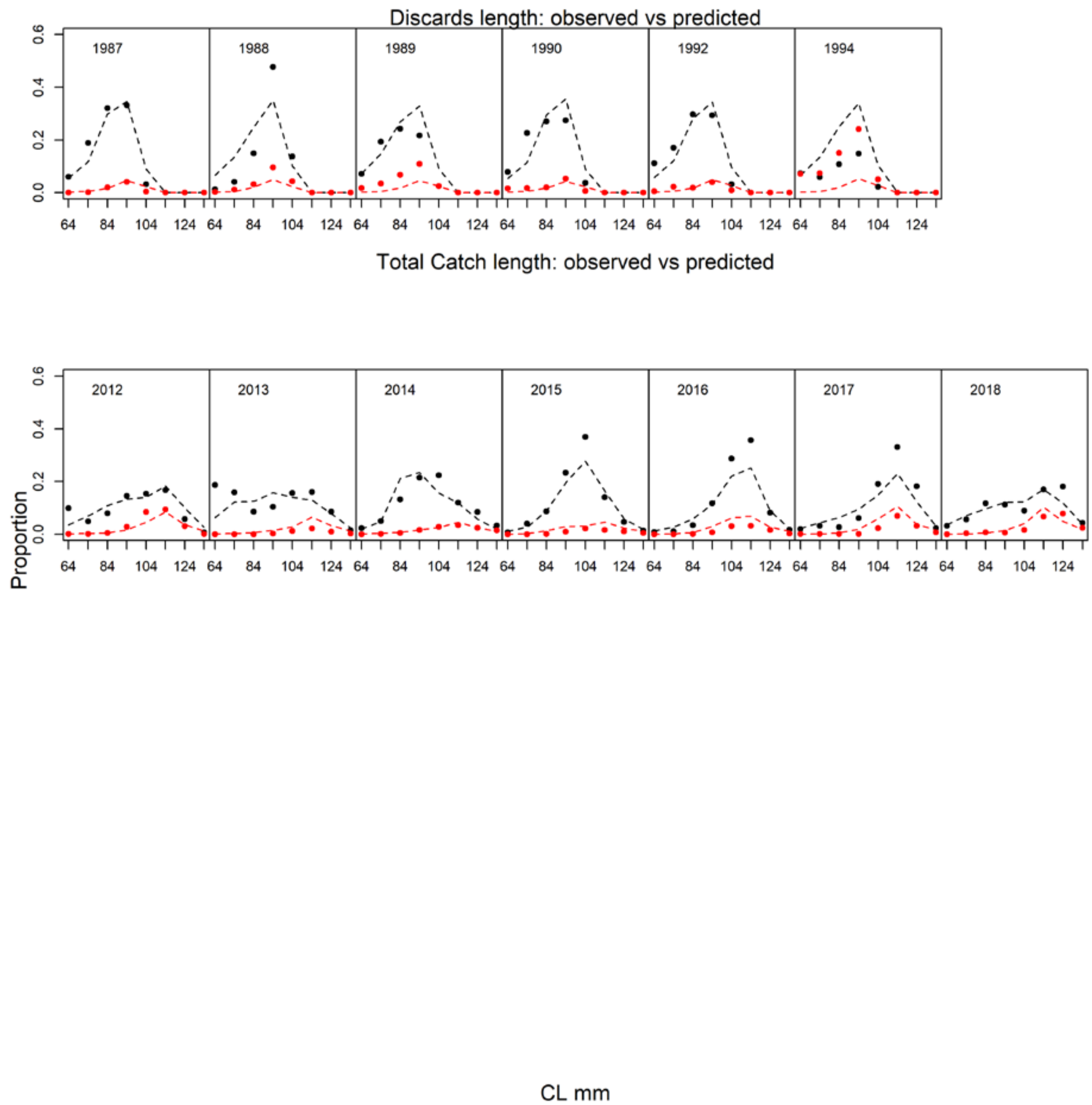


Figure D4-13. Predicted (dashed) vs. observed (dots) length class proportions for the observer survey. Black: newshell, Red: oldshell

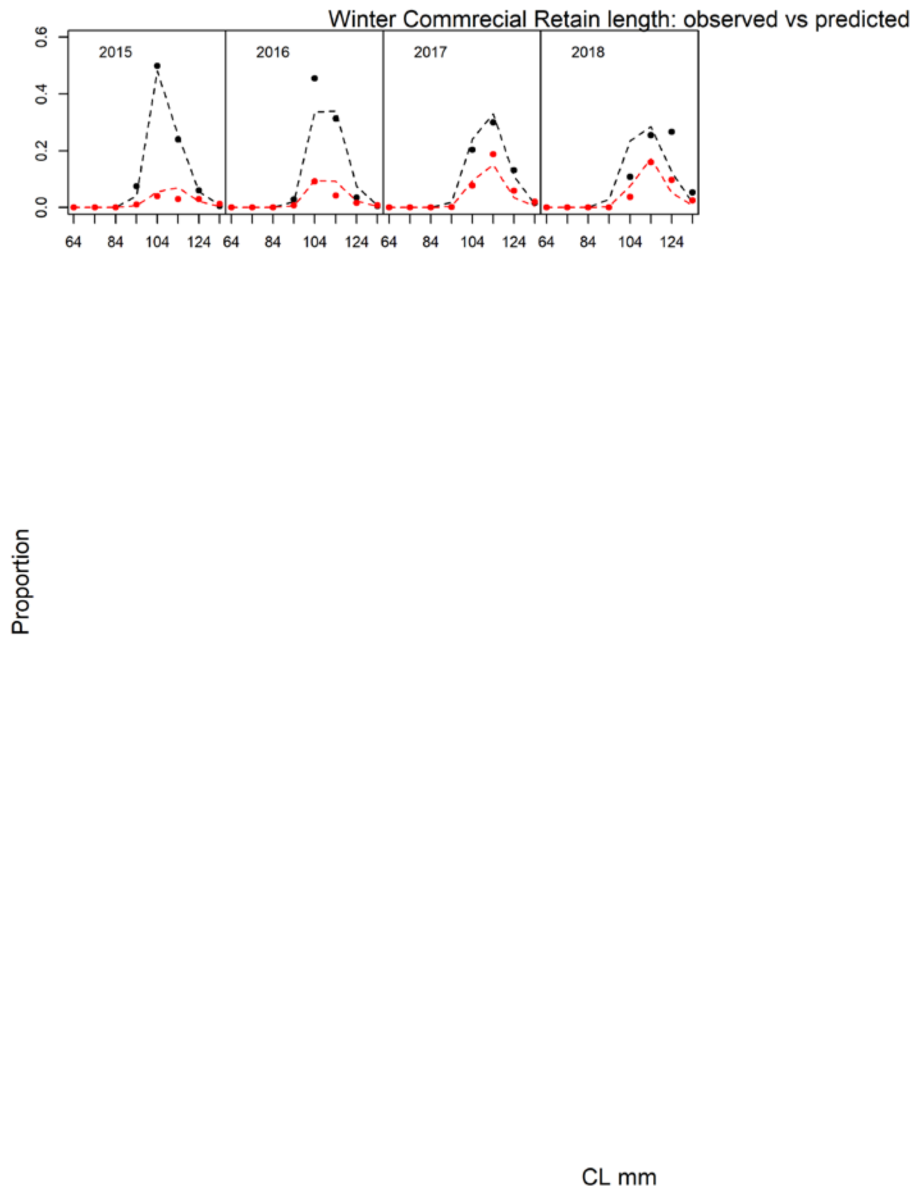


Figure D4-12. Predicted (dashed) vs. observed (dots) length class proportions for the observer survey. Black: newshell, Red: oldshell

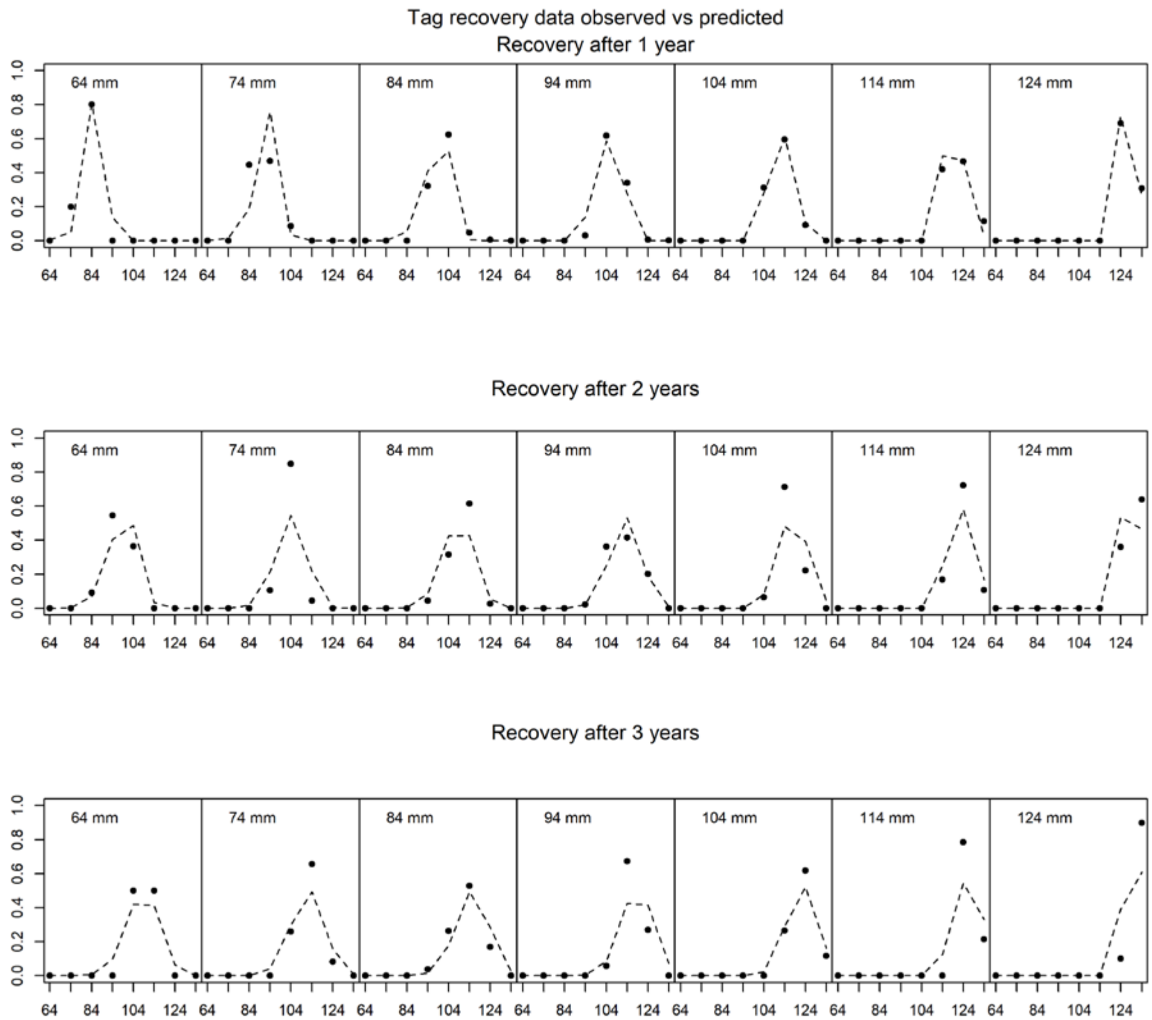


Figure D4-13. Predicted vs. observed length class proportions for tag recovery data.

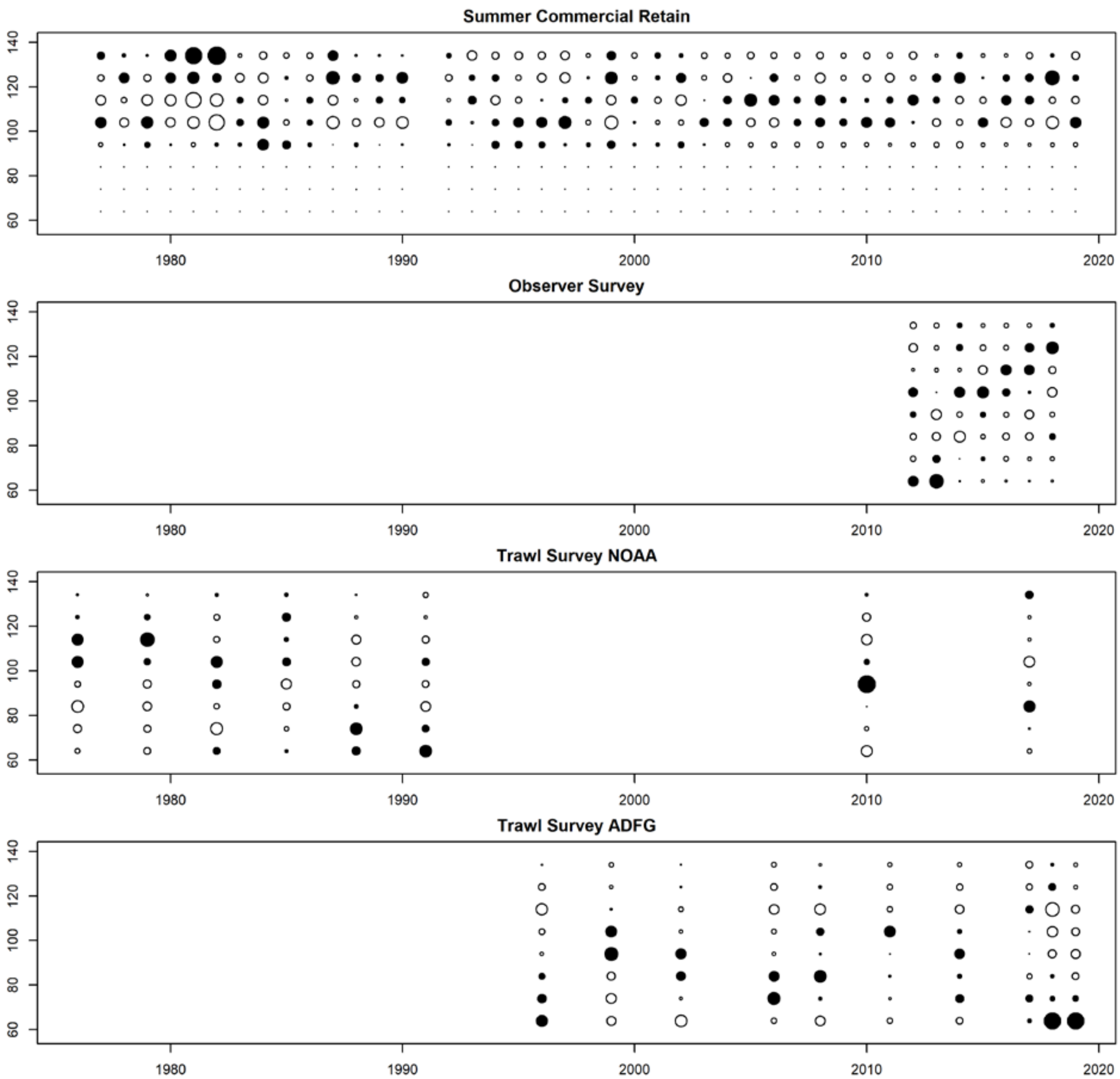


Figure D4-13. Bubble plots of predicted and observed length proportions.
Black circle indicates model estimates lower than observed, white circle indicates model estimates higher than observed. Size of circle indicates degree of deviance (larger circle = larger deviance).

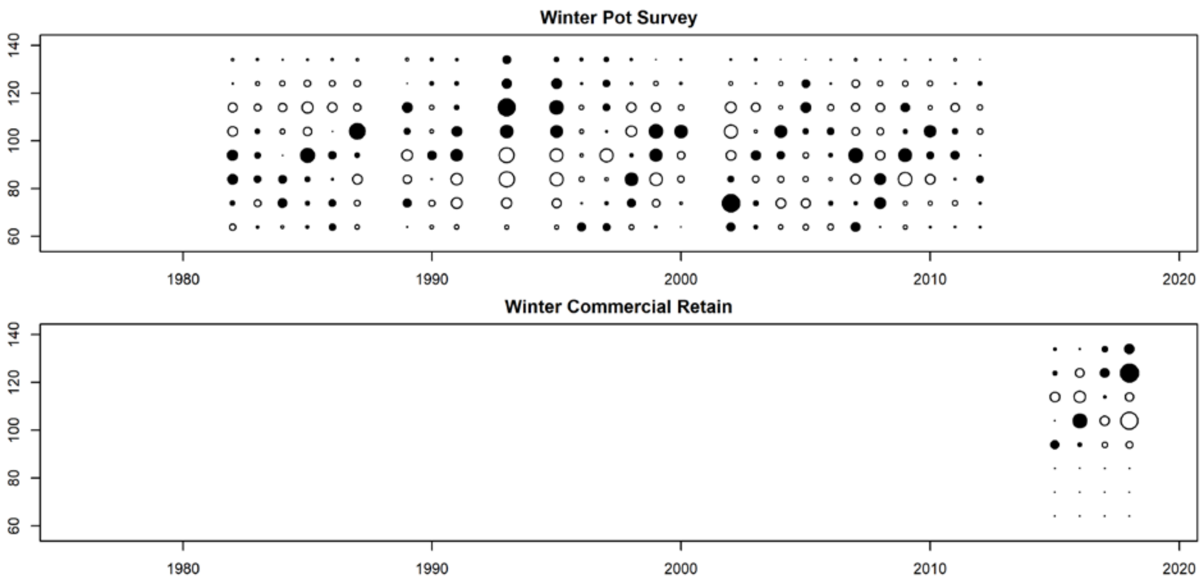


Figure D4-14. Bubble plots of predicted and observed length proportions.
Black circle indicates model estimates lower than observed, white circle indicates model estimates higher than observed. Size of circle indicates degree of deviance (larger circle = larger deviance).

Table D4. Summary of parameter estimates for a length-based stock synthesis population model of Norton Sound red king crab.

name	Estimate	std.dev
log_q_1	-6.627	0.227
log_q_2		
log_N_{76}	9.008	0.174
R_0	6.341	0.191
a_1	1.968	4.606
a_2	2.959	4.289
a_3	4.020	4.140
a_4	4.124	4.127
a_5	4.344	4.117
a_6	3.570	4.146
a_7	2.106	4.414
r1	10.000	0.305
r2	9.663	0.351
log_a	-2.674	0.090
log_b	4.832	0.016
log_ϕ_{st1}	-5.000	0.067
log_ϕ_{wa}	-2.203	0.307
log_ϕ_{wb}	4.800	0.032
Sw1	0.072	0.035
Sw2	0.498	0.125
log_ϕ_1	-2.085	0.056
$log\_\phi ra$	-0.791	0.129
$log\_\phi rb$	4.647	0.008
$log\_\phi wra$	-0.977	0.543
$log\_\phi wrb$	4.655	0.037
$w^2{}_t$	0.000	0.000
q NOAA	0.811	0.197
q ADFG	1.200	0.290
σ	3.878	0.209
β_1	12.453	0.707
β_2	7.649	0.173
ms78	3.083	0.342

Model 19.4

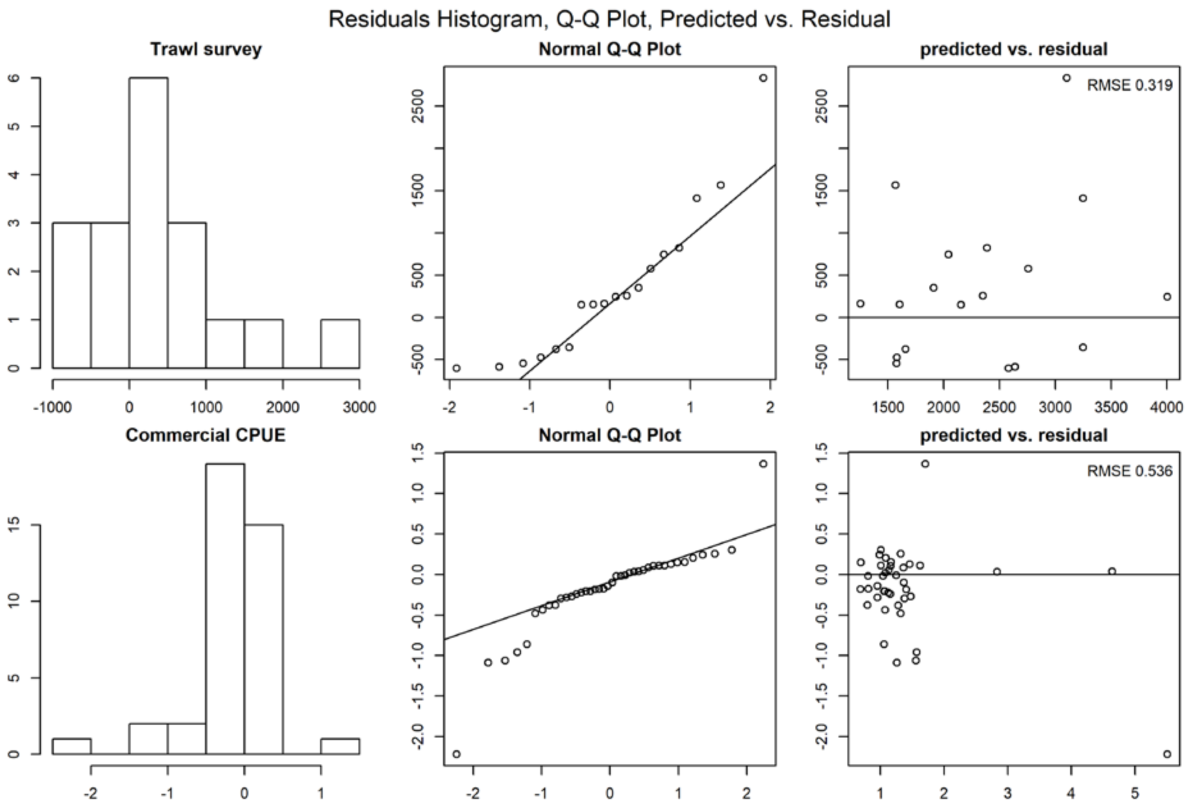


Figure D5-1. QQ Plot of trawl survey and commercial CPUE.

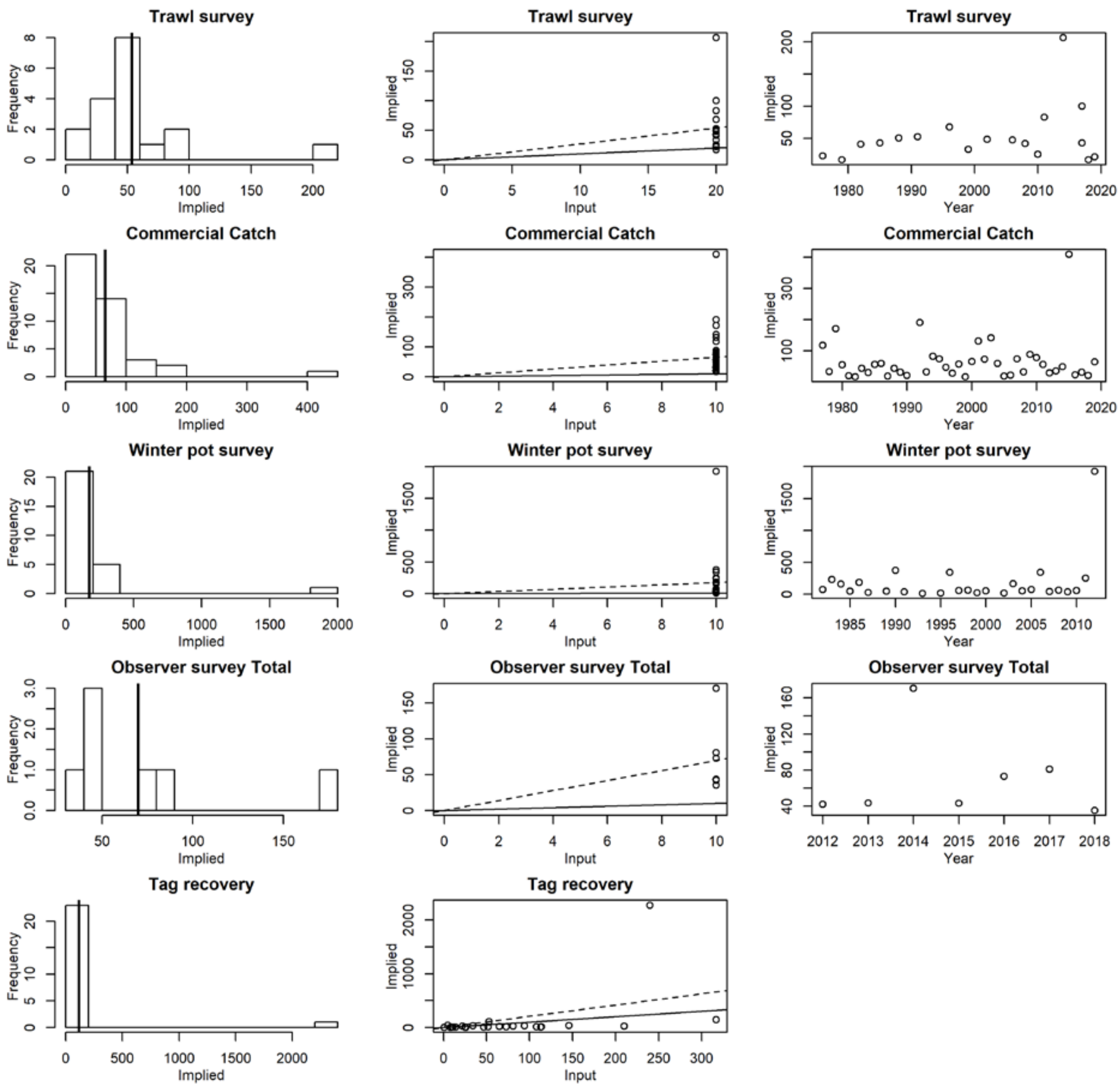


Figure D5-2: Implied effective samples. Figures in the first column show implied effective sample size (x-axis) vs. frequency (y-axis).
Vertical solid line is the mean implied effective sample size.
The second column shows input sample size (x-axis) vs. implied effective sample size (y-axis). Dashed line indicates linear regression slope, and solid line is 1:1 line. The third column show year (x-axis) vs. implied effective sample size (y-axis).

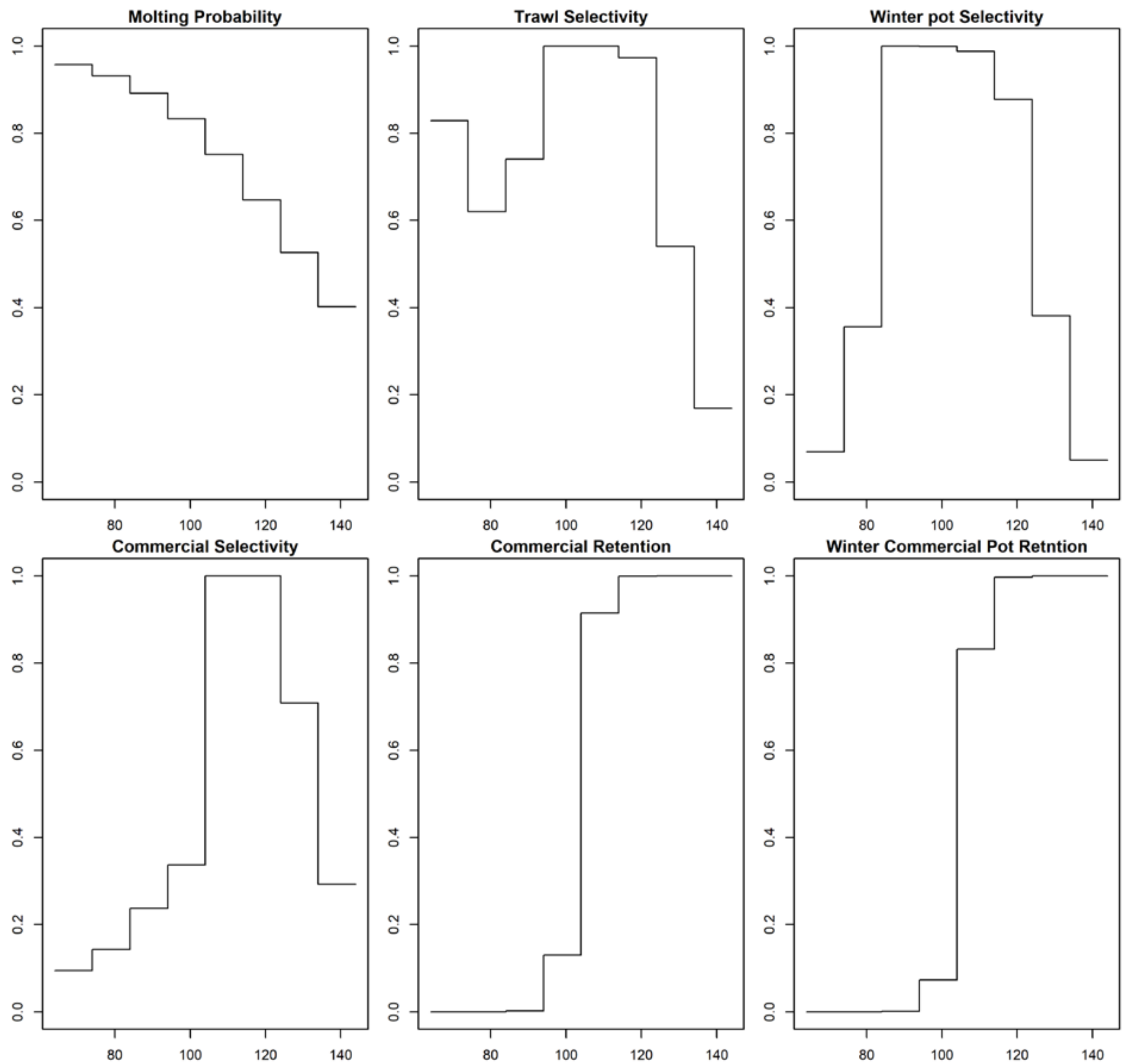


Figure D5-3. Molting probability and trawl/pot selectivity. X-axis is carapace length.

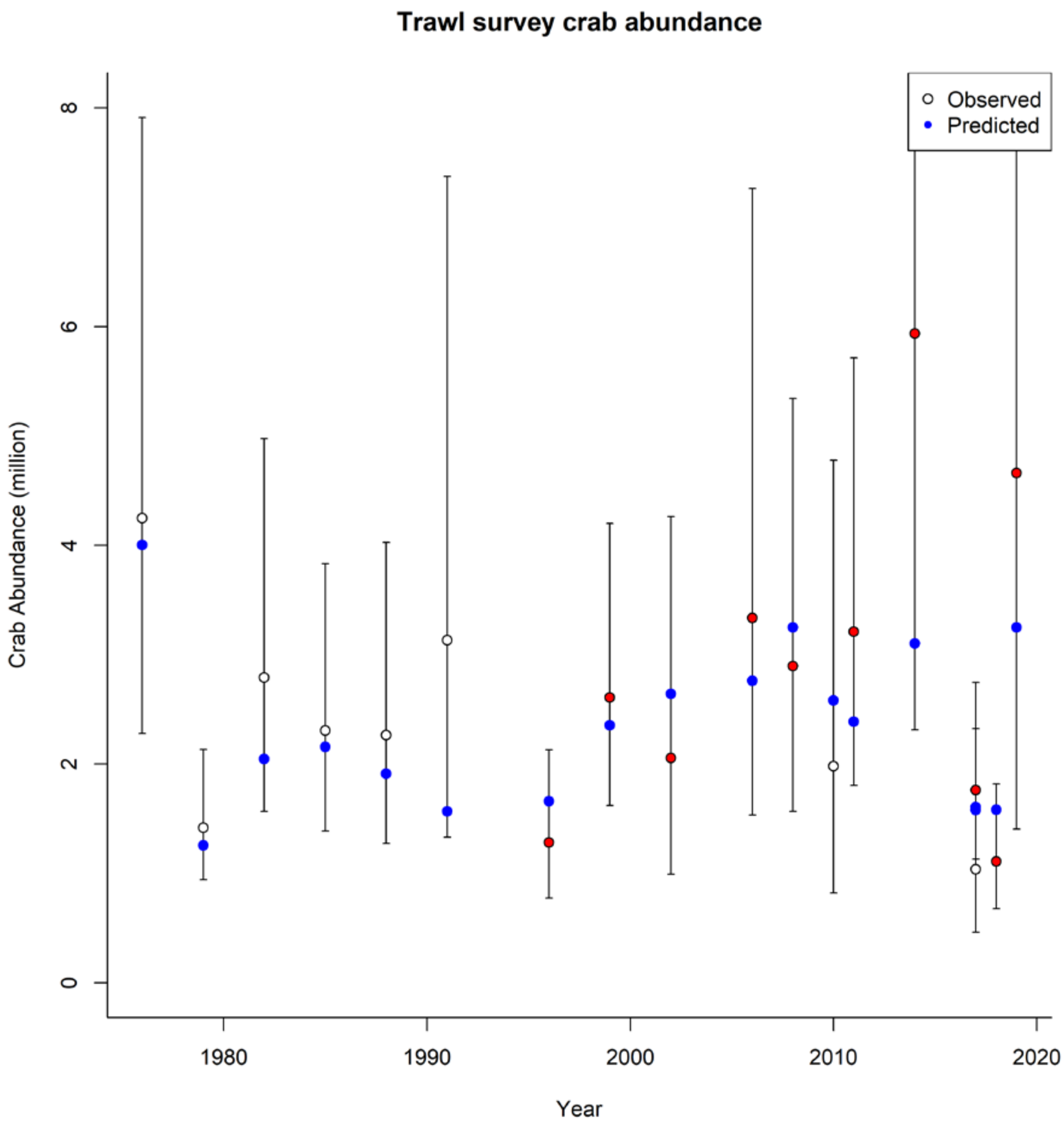


Figure D5-4. Estimated trawl survey male abundance (blue) (crab >= 64 mm CL). Observed: White: NOAA trawl survey, Red: ADG&G trawl survey

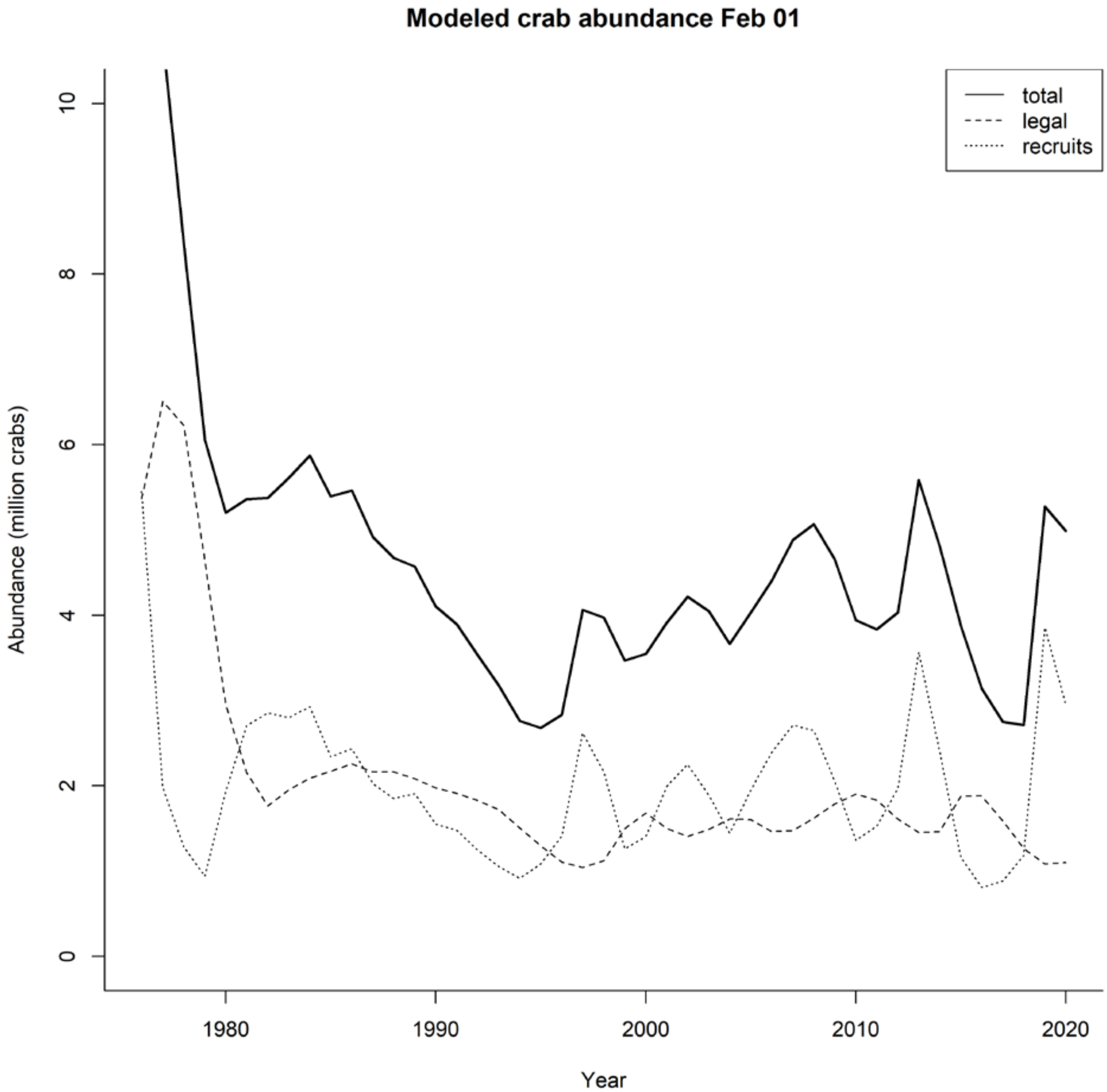


Figure D5-5. Estimated abundance of legal males.

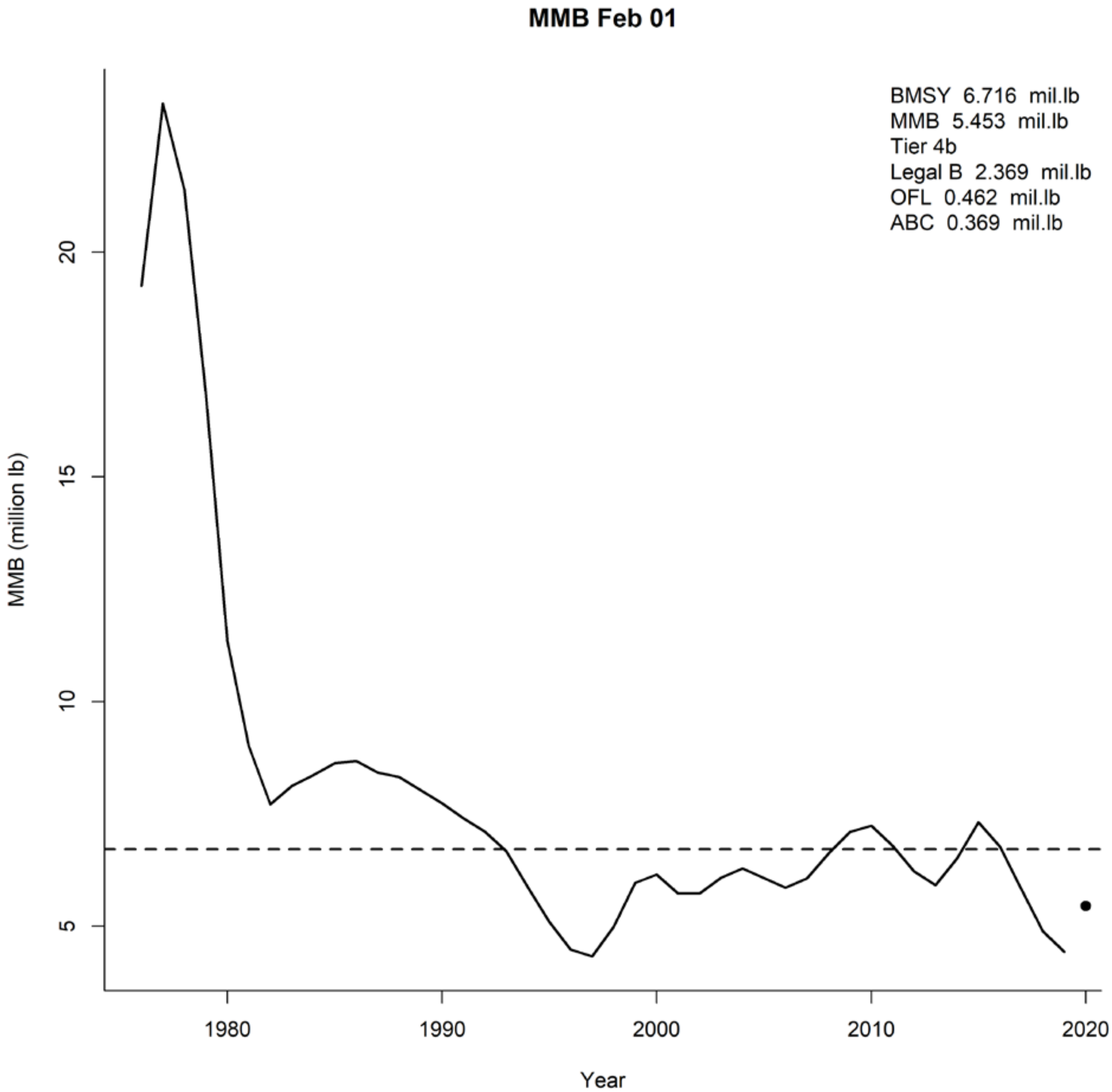


Figure D5-6. Estimated abundance of Mature Male Biomass. Dash line shows Bmsy.

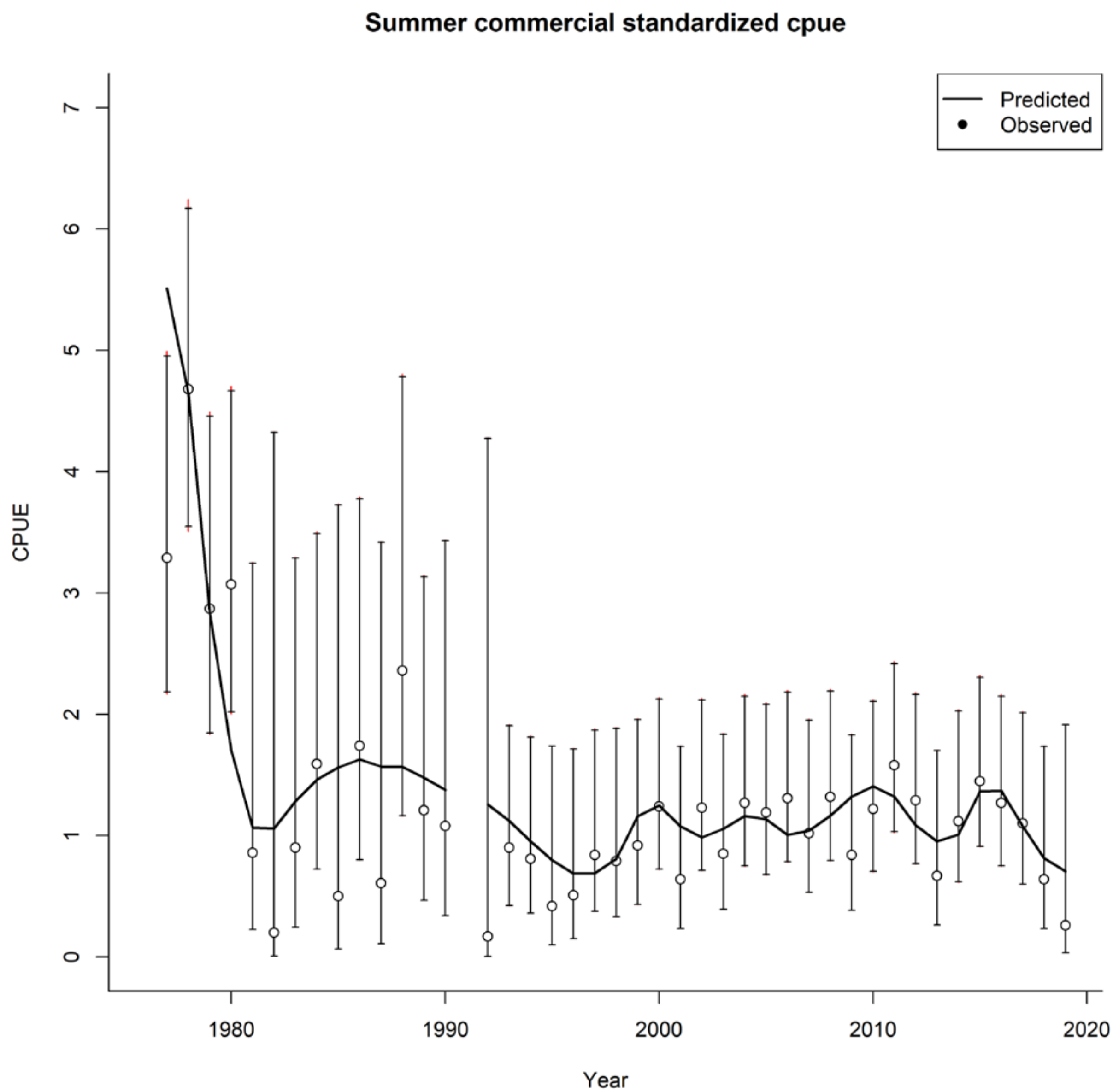


Figure D5-7. Summer commercial standardized cpue.

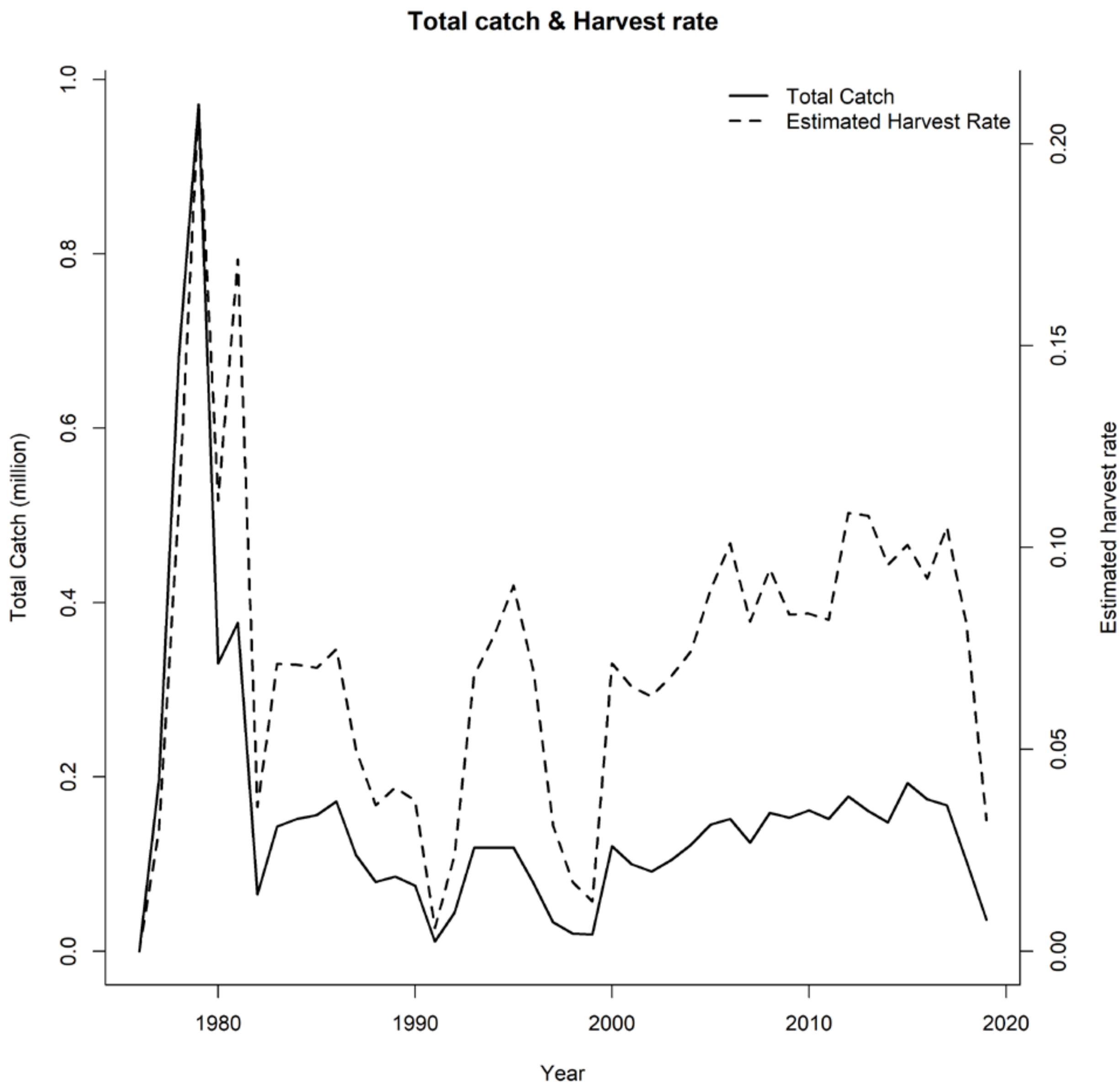


Figure D5-8. Total catch and estimated harvest rate.

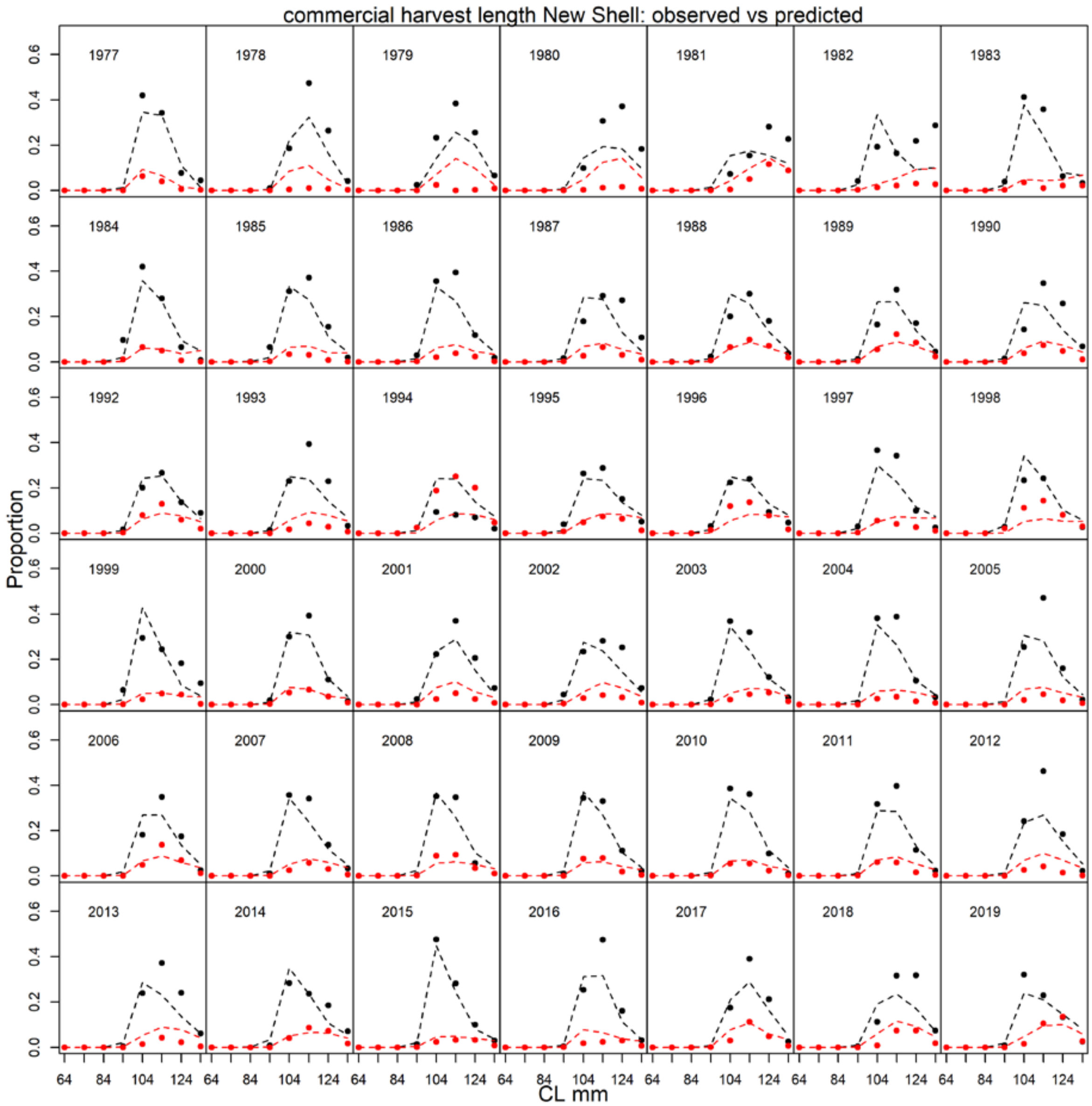


Figure D5-9. Predicted (dashed line) vs. observed (dots) length class proportions for commercial catch. Black: newshell, Red: oldshell

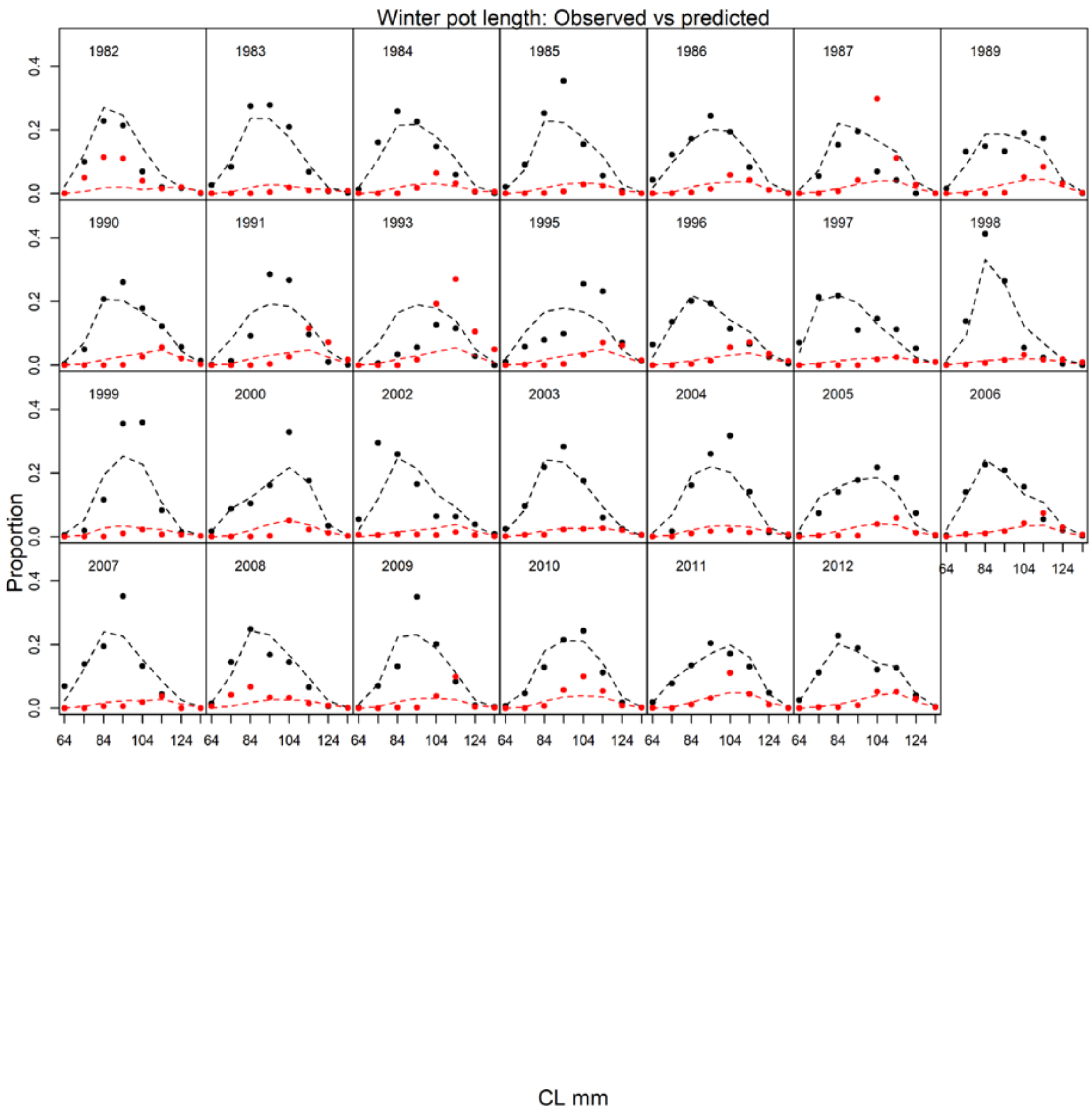


Figure D5-10. Predicted (dashed line) vs. observed (dots) length class proportions for the winter and spring pot survey. Black: newshell, Red: oldshell

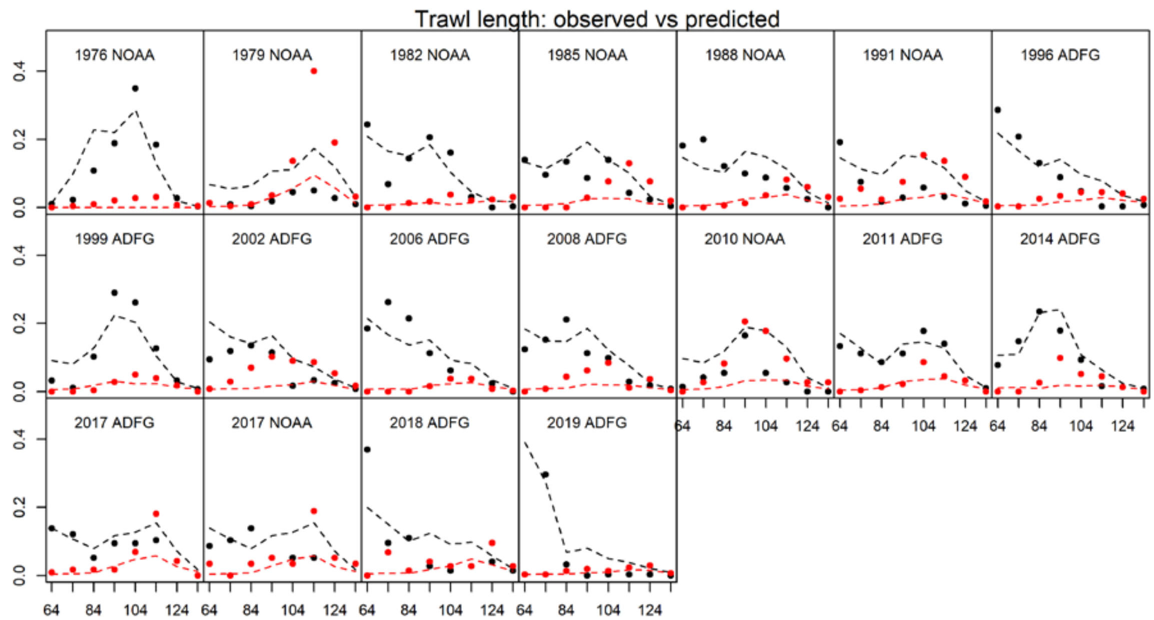


Figure D5-11. Predicted (dashed) vs. observed (dots) length class proportions for trawl survey. Black: newshell, Red: oldshell

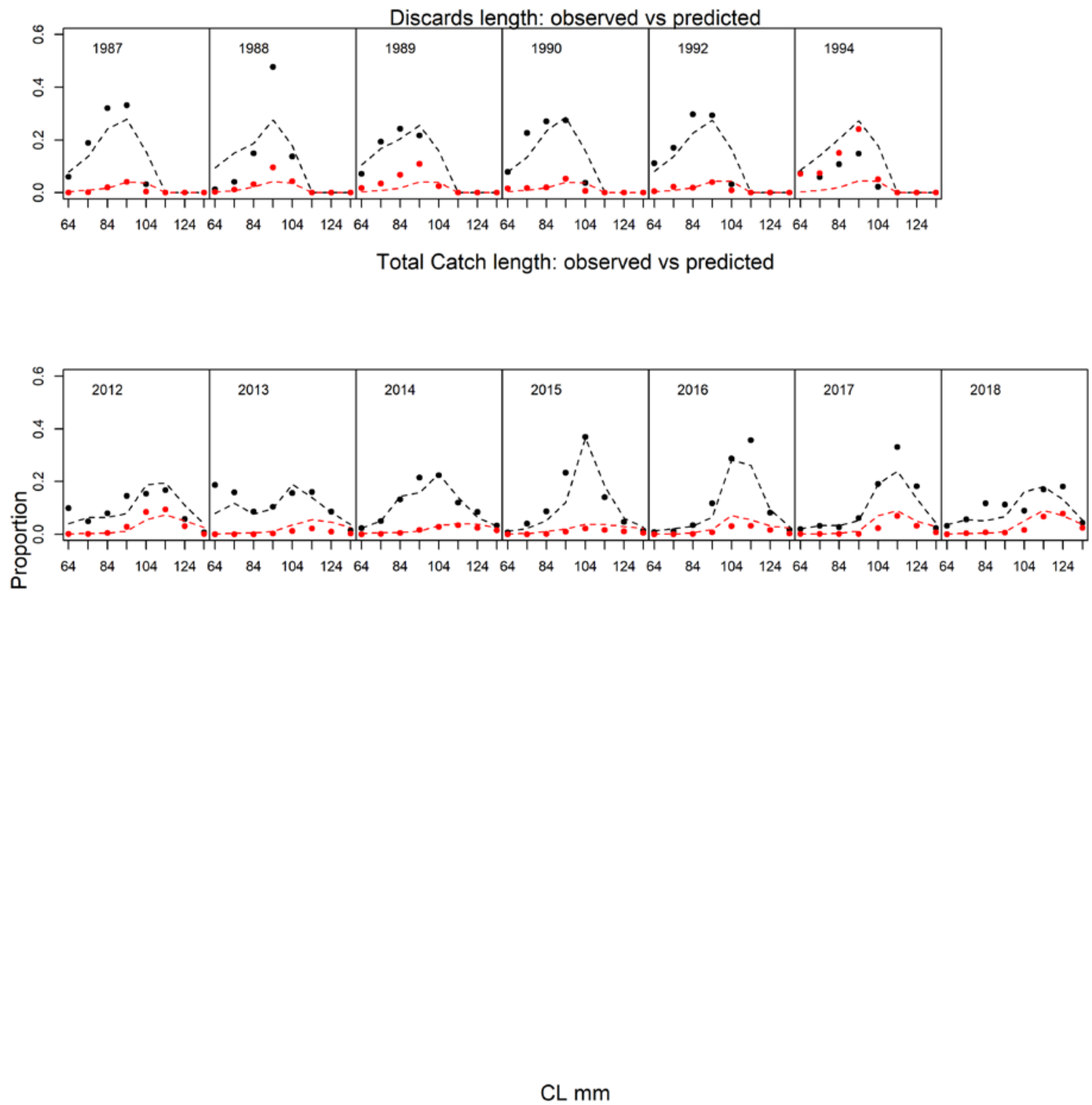


Figure D5-13. Predicted (dashed) vs. observed (dots) length class proportions for the observer survey. Black: newshell, Red: oldshell

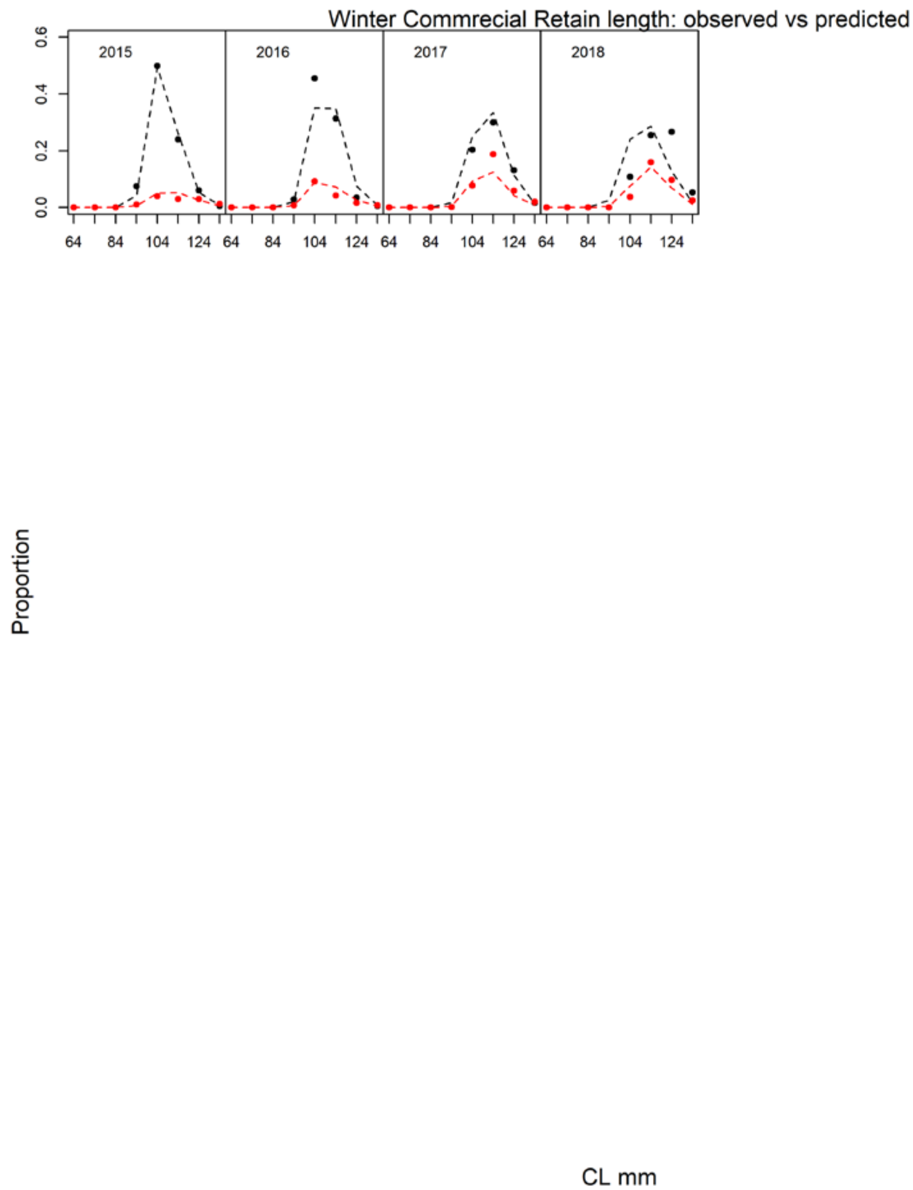


Figure D5-12. Predicted (dashed) vs. observed (dots) length class proportions for the observer survey. Black: newshell, Red: oldshell

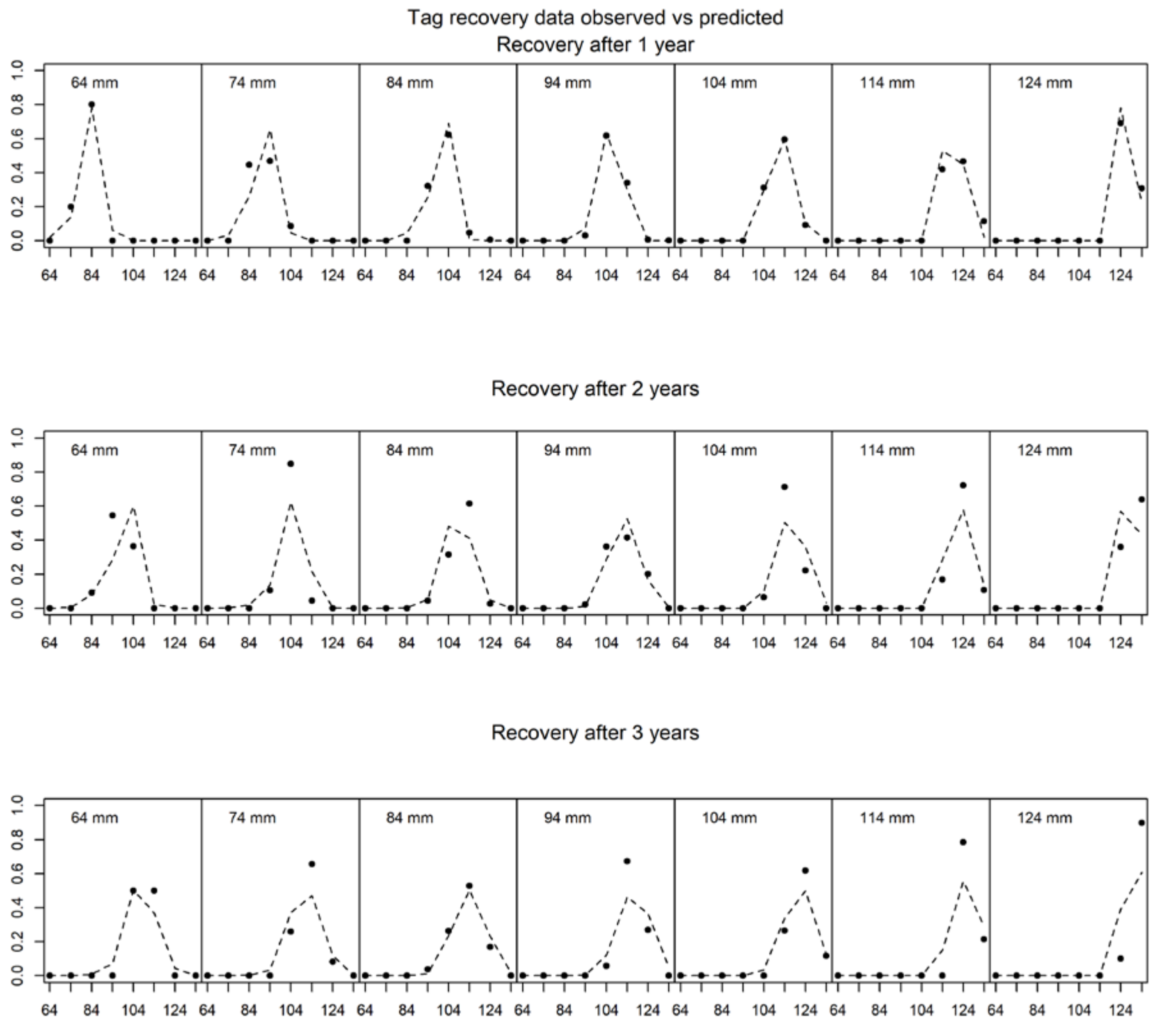


Figure D5-13. Predicted vs. observed length class proportions for tag recovery data.

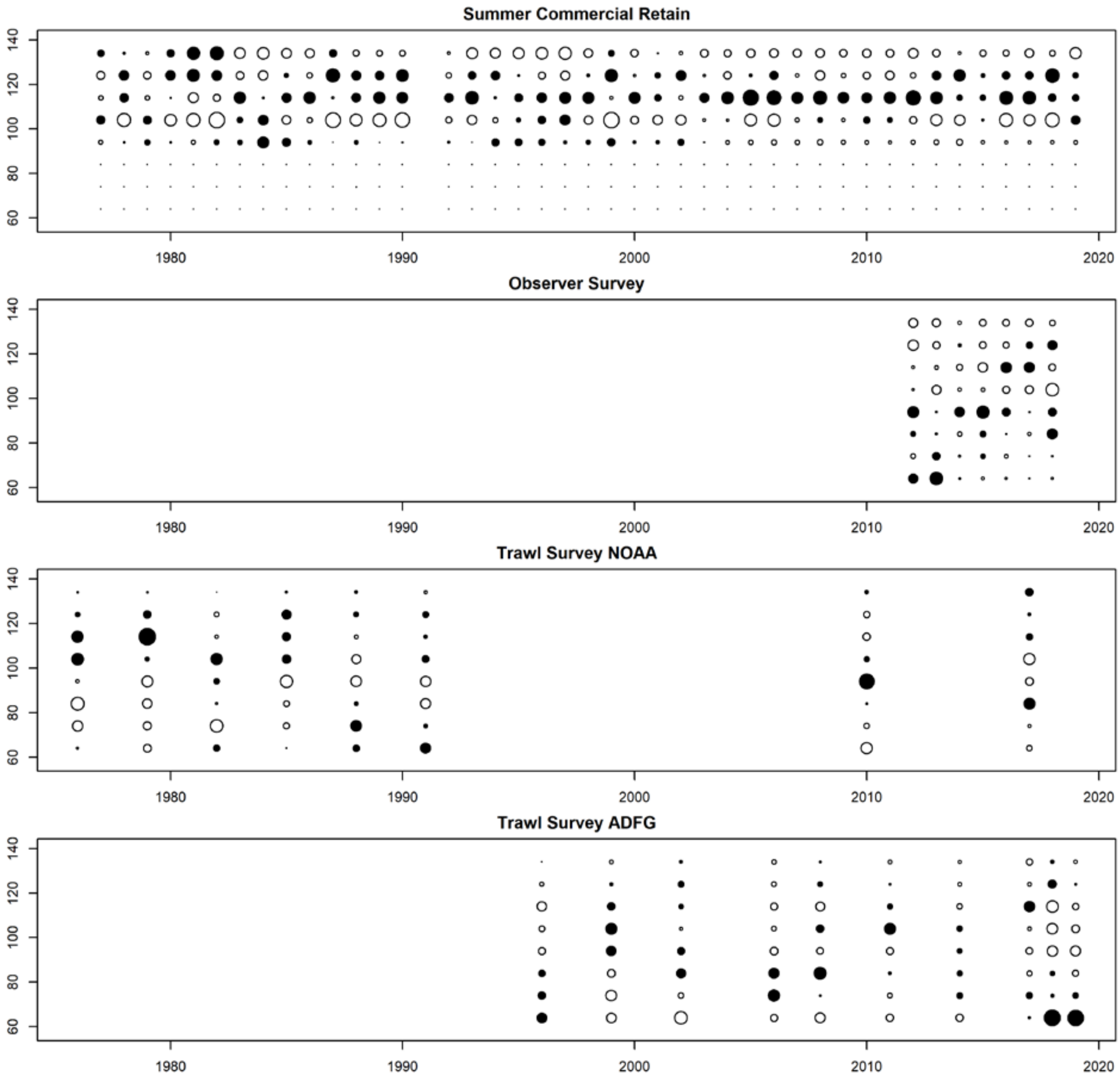


Figure D5-13. Bubble plots of predicted and observed length proportions.
Black circle indicates model estimates lower than observed, white circle indicates model estimates higher than observed. Size of circle indicates degree of deviance (larger circle = larger deviance).

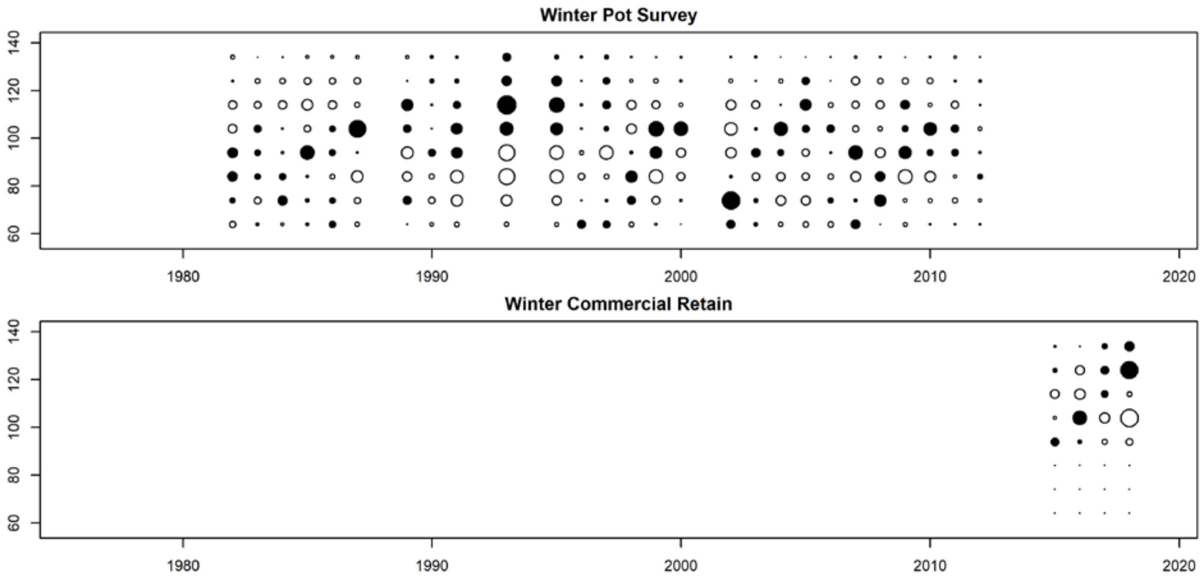


Figure D5-14. Bubble plots of predicted and observed length proportions.
Black circle indicates model estimates lower than observed, white circle indicates model estimates higher than observed. Size of circle indicates degree of deviance (larger circle = larger deviance).

Table D5. Summary of parameter estimates for a length-based stock synthesis population model of Norton Sound red king crab.

name	Estimate	std.dev
log_q_1	-6.808	0.138
log_q_2		
log_N_{76}	9.495	0.152
R_0	6.992	0.160
a_1	-0.371	3.653
a_2	1.857	2.993
a_3	2.514	2.818
a_4	2.178	2.818
a_5	2.439	2.803
a_6	1.663	2.856
a_7	0.349	3.350
r1	10.000	0.574
r2	9.895	0.660
log_a	-2.994	0.123
log_b	4.872	0.028
log_ϕ_{st1}		
log_ϕ_{wa}	-1.405	0.272
log_ϕ_{wb}	4.840	0.018
Sw1	0.069	0.034
Sw2	0.356	0.090
log_ϕ_1		
log_ϕra	-0.852	0.146
log_ϕrb	4.634	0.010
log_ϕwra	-0.883	0.607
log_ϕwrb	4.650	0.040
$w^2{}_t$	0.002	0.020
q	0.658	0.109
σ	0.310	0.041
β_1	3.978	0.240
β_2	9.764	1.053

name	Estimate	std.dev
selc 1	0.094	0.039
selc 2	0.143	0.044
selc 3	0.237	0.060
selc 4	0.337	0.055
selc 5	0.653	0.198
selc 6	1.000	0.000
selc 7	0.708	0.099
selc 8	0.292	0.121
selt 1	0.829	0.212
selt 2	0.620	0.129
selt 3	0.741	0.144
selt 4	0.890	0.281
selt 5	1.000	0.000
selt 6	0.973	0.170
selt 7	0.540	0.148
selt 8	0.169	0.092

Model 19.5

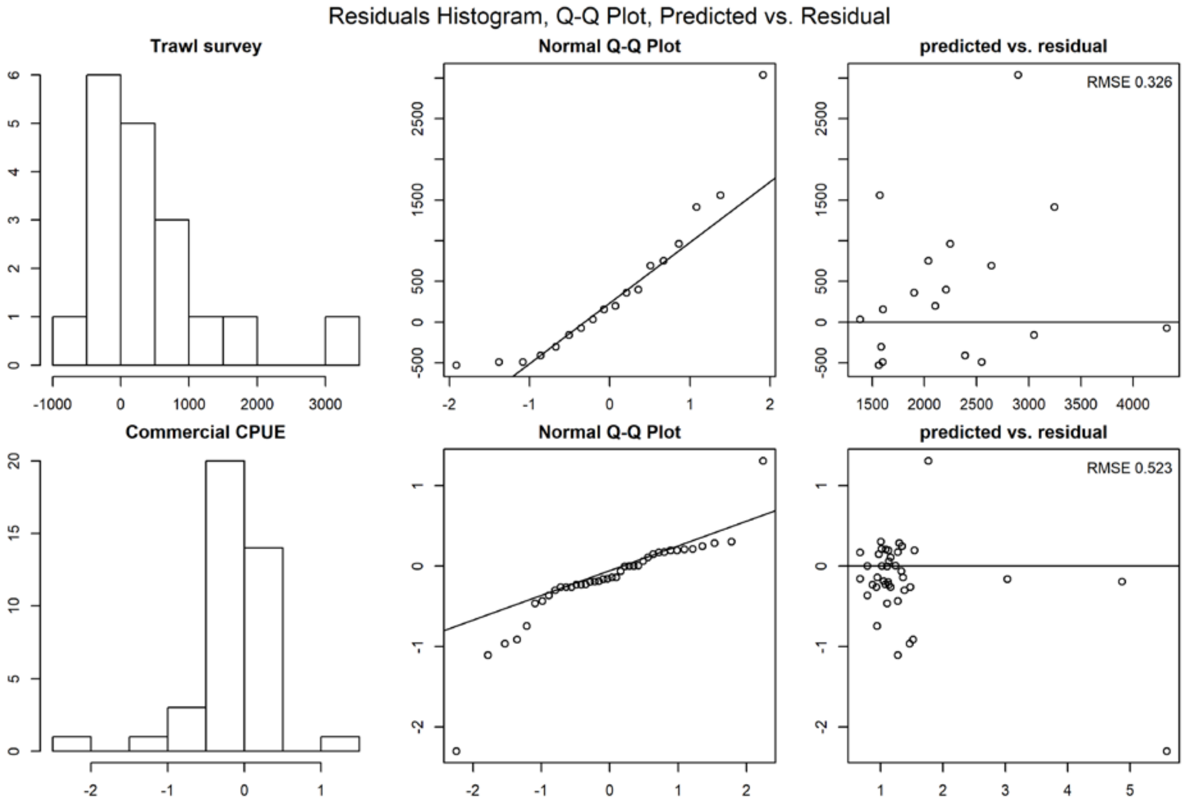


Figure D6-1. QQ Plot of Trawl survey and commercial CPUE.

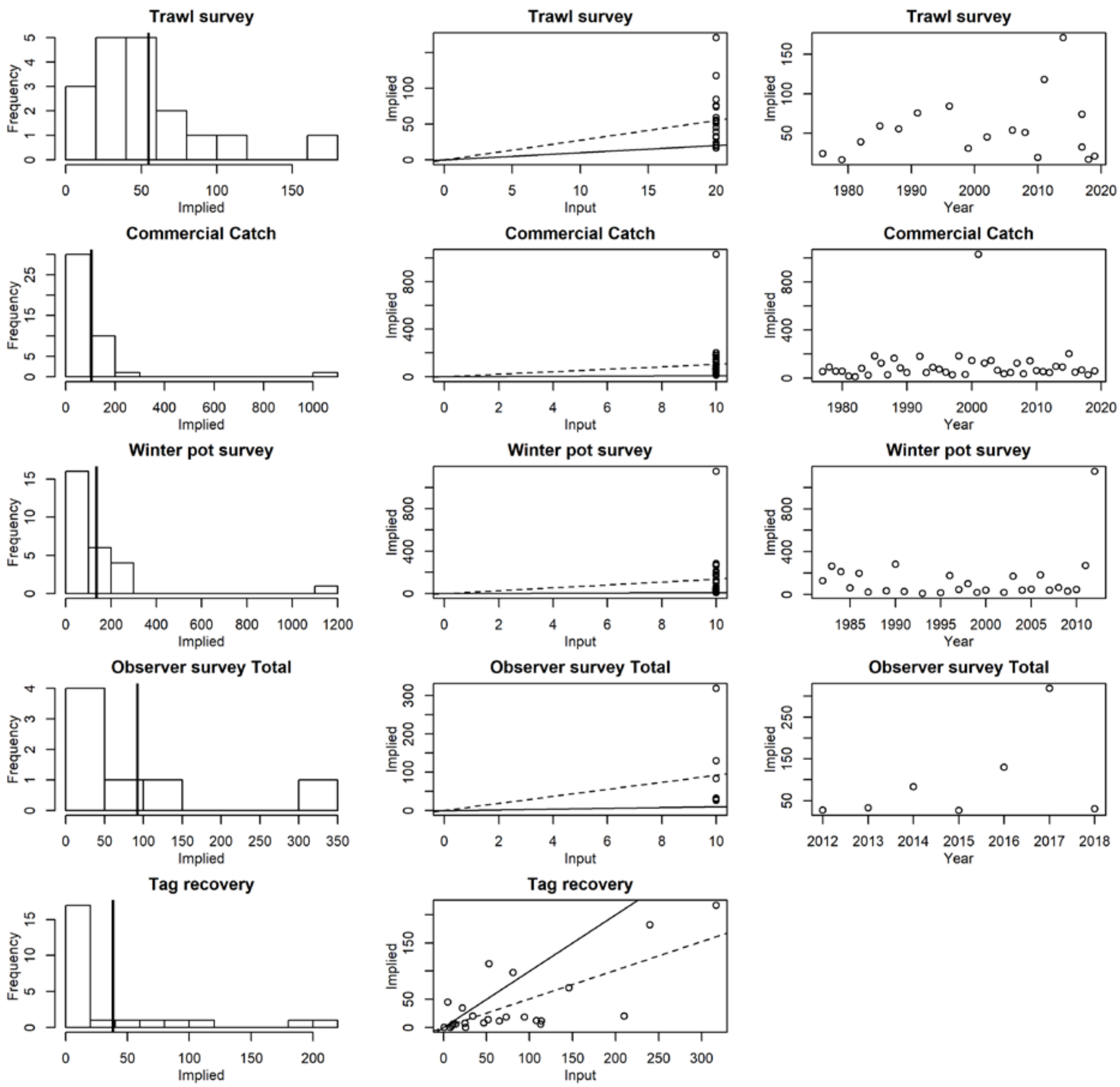


Figure D6-2: Implied effective samples. Figures in the first column show implied effective sample size (x-axis) vs. frequency (y-axis).
Vertical solid line is the mean implied effective sample size.
The second column shows input sample size (x-axis) vs. implied effective sample size (y-axis). Dashed line indicates linear regression slope, and solid line is 1:1 line. The third column show year (x-axis) vs. implied effective sample size (y-axis).

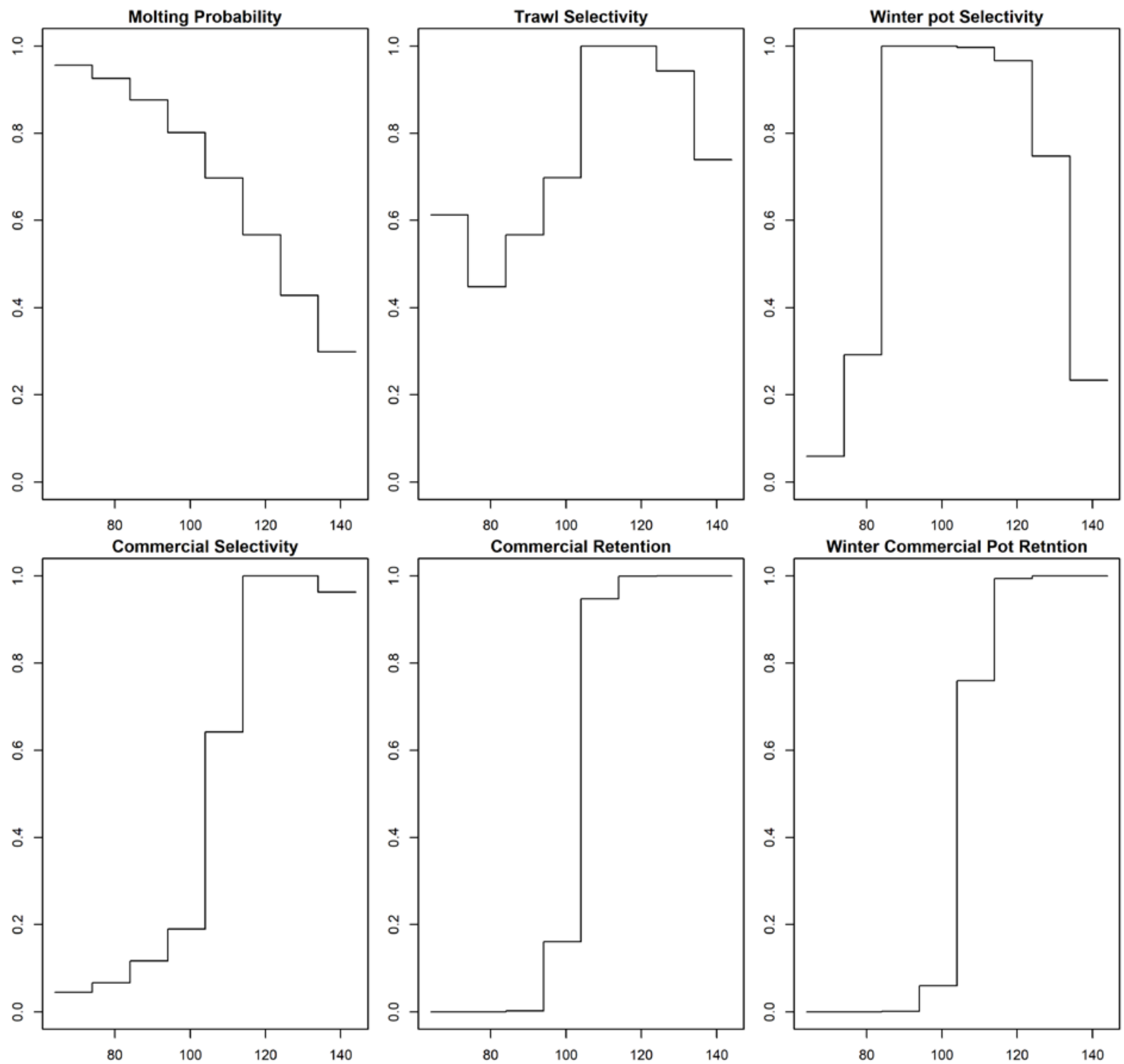


Figure D6-3. Molting probability and trawl/pot selectivity. X-axis is carapace length.

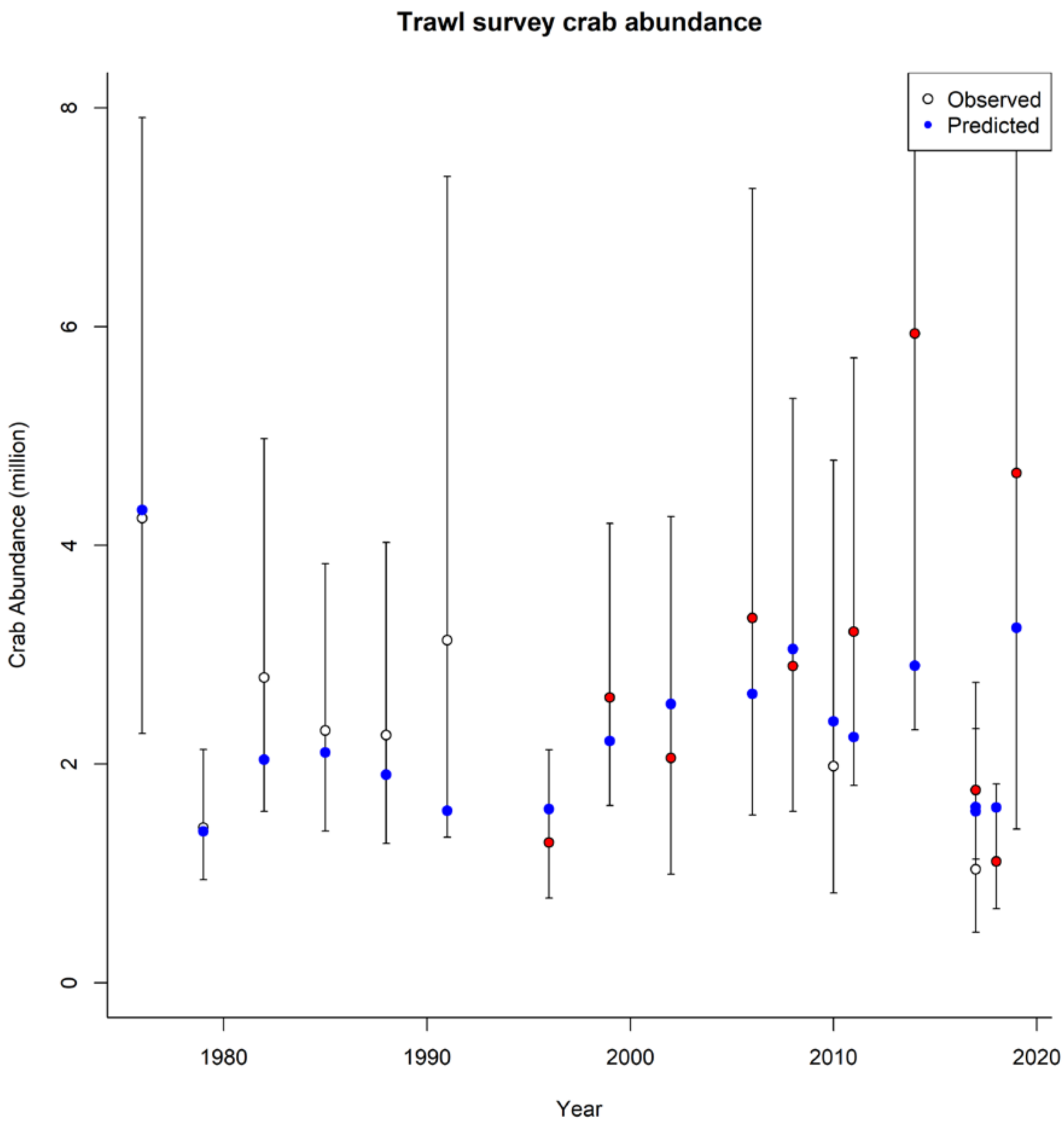


Figure D6-4. Estimated trawl survey male abundance (blue) (crab >= 64 mm CL). Observed: White: NOAA trawl survey, Red: ADG&G trawl survey

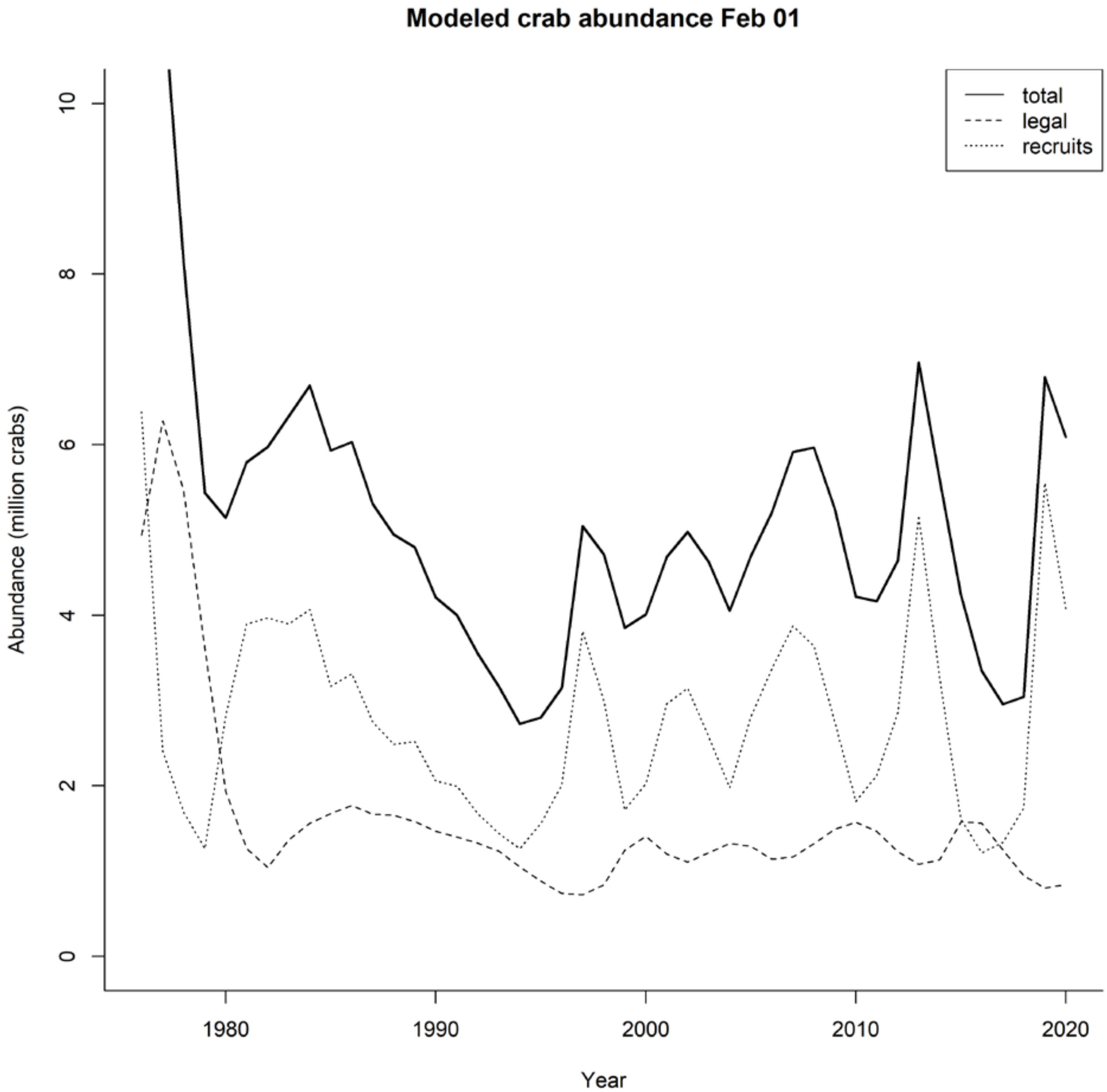


Figure D6-5. Estimated abundance of legal males.

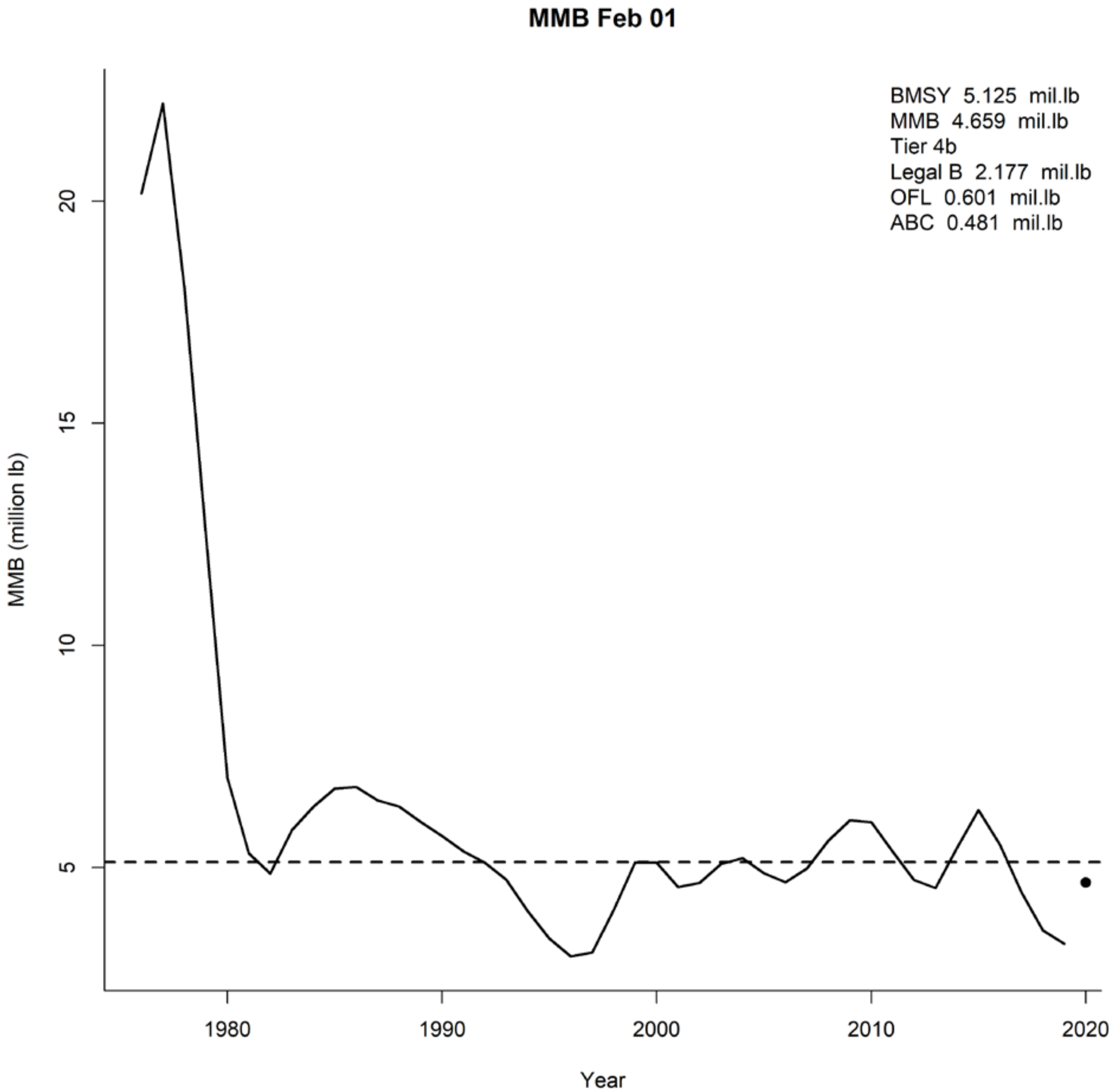


Figure D6-6. Estimated abundance of Mature Male Biomass. Dash line shows Bmsy.

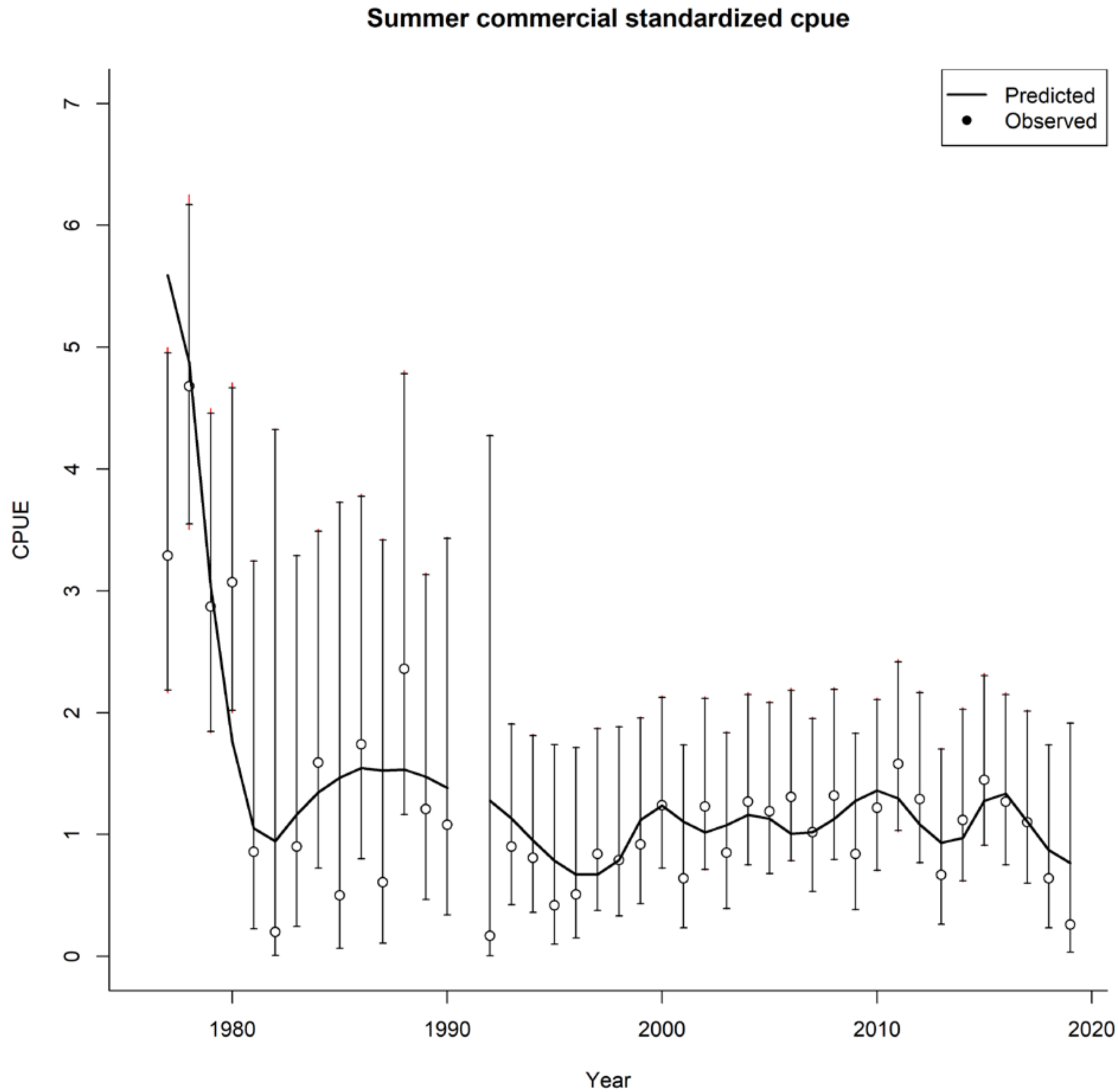


Figure D6-7. Summer commercial standardized cpue.

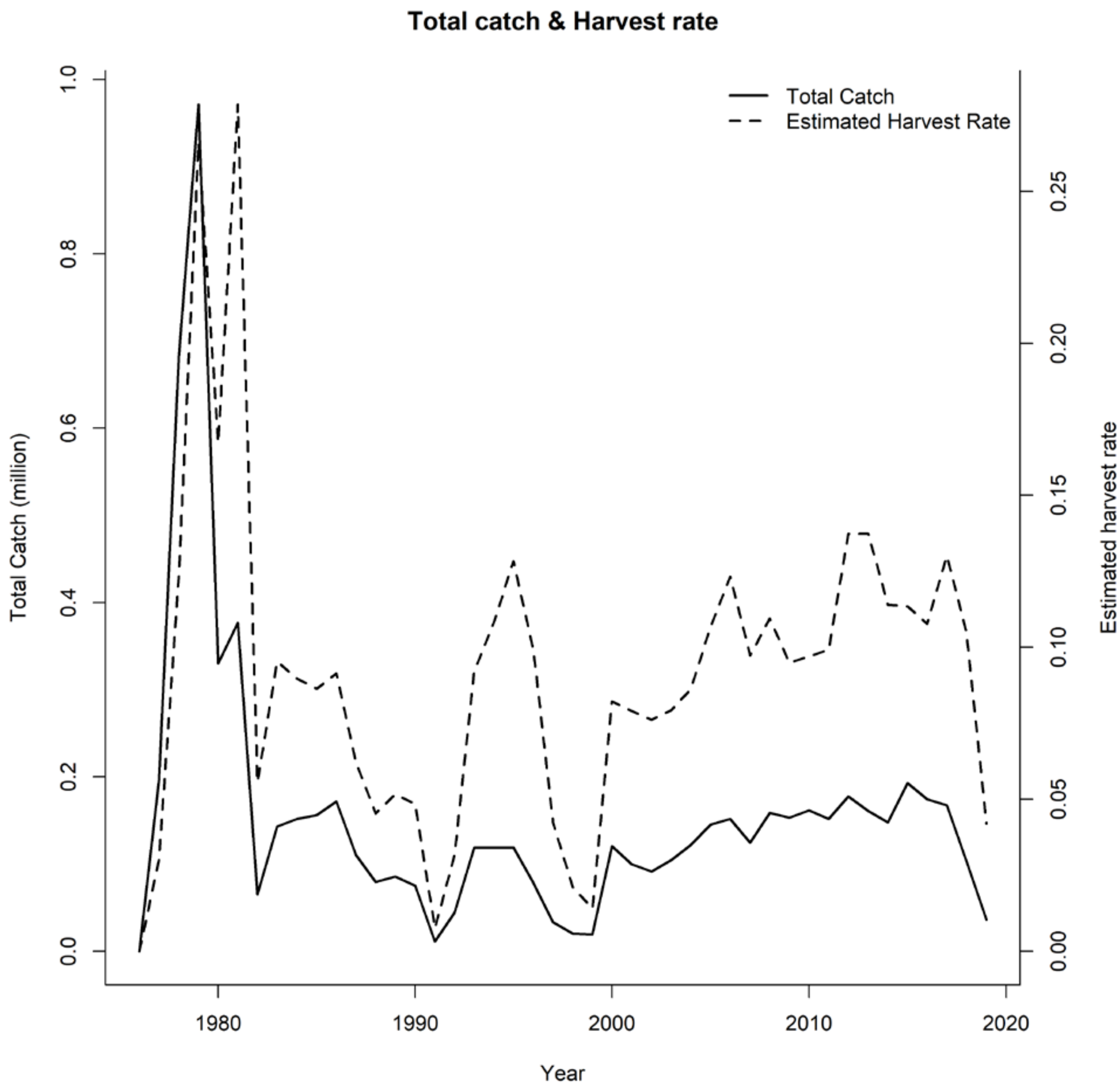


Figure D6-8. Total catch and estimated harvest rate.

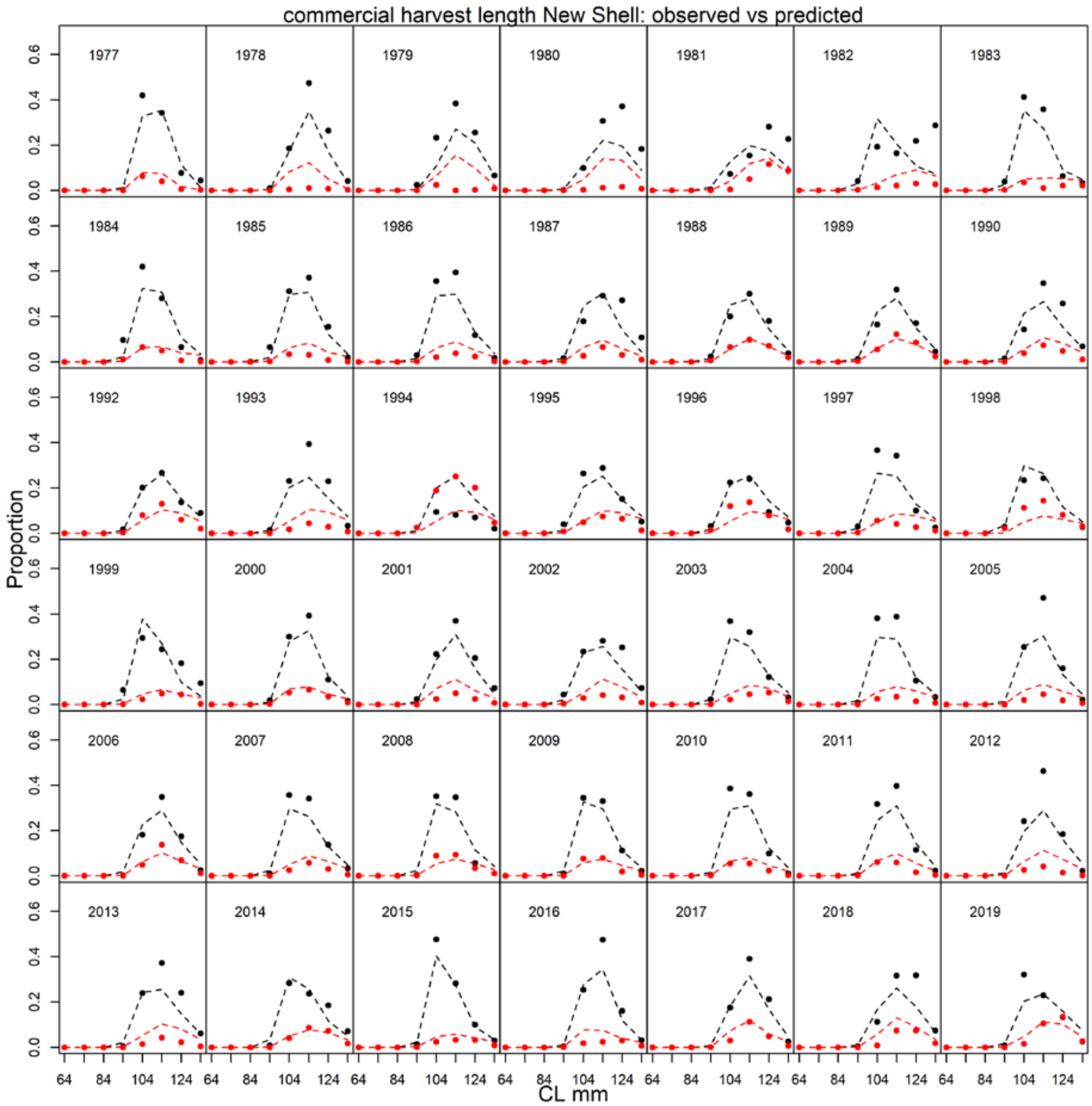


Figure D6-9. Predicted (dashed line) vs. observed (dots) length class proportions for commercial catch. Black: newshell, Red: oldshell

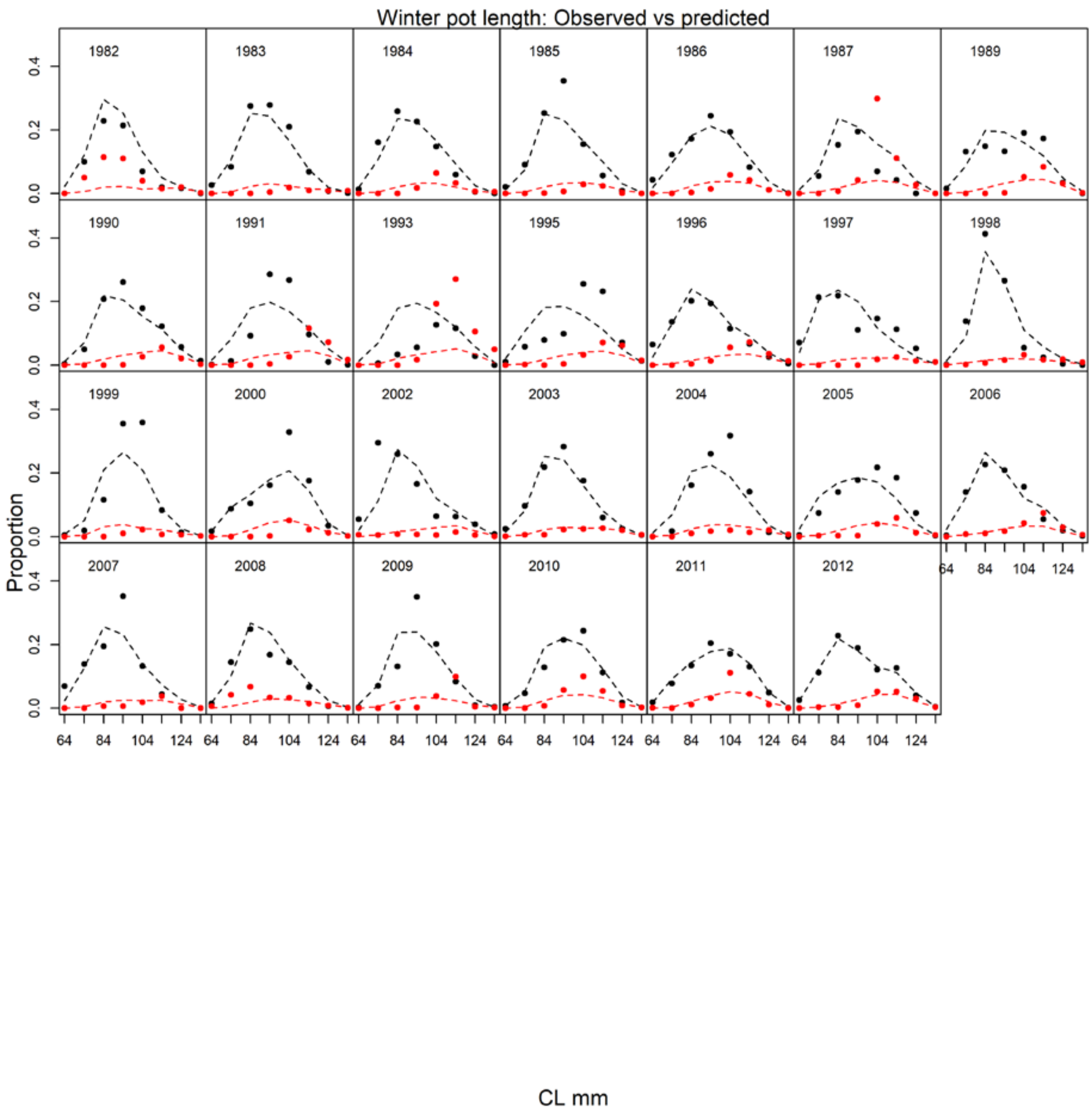


Figure D6-10. Predicted (dashed line) vs. observed (dots) length class proportions for the winter and spring pot survey. Black: newshell, Red: oldshell

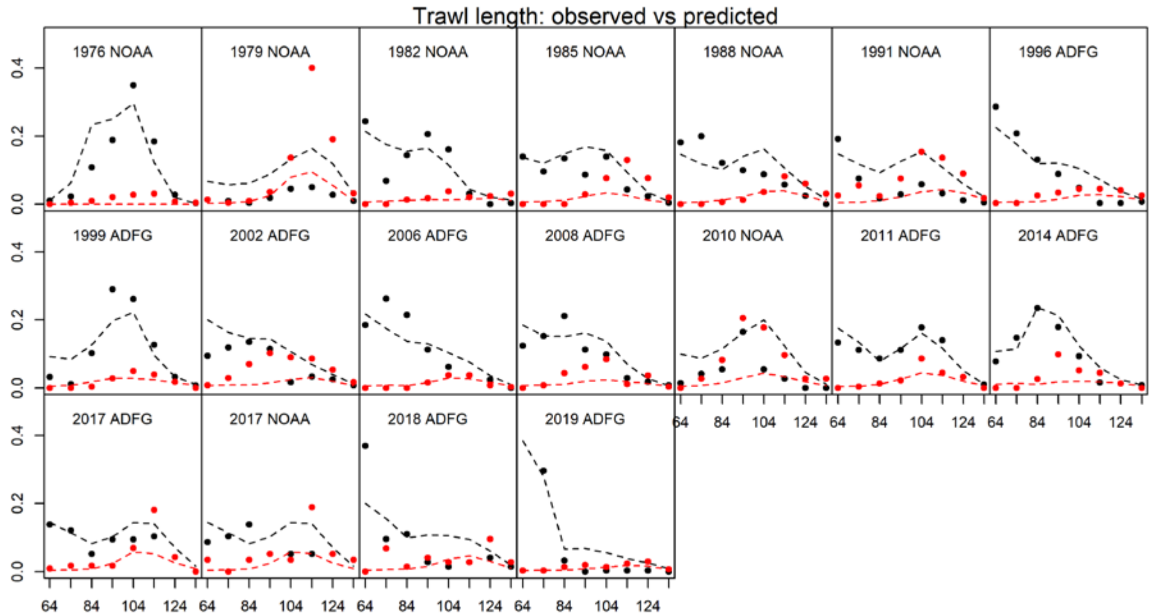


Figure D6-11. Predicted (dashed) vs. observed (dots) length class proportions fo Black: newshell, Red: oldshell r trawl survey.

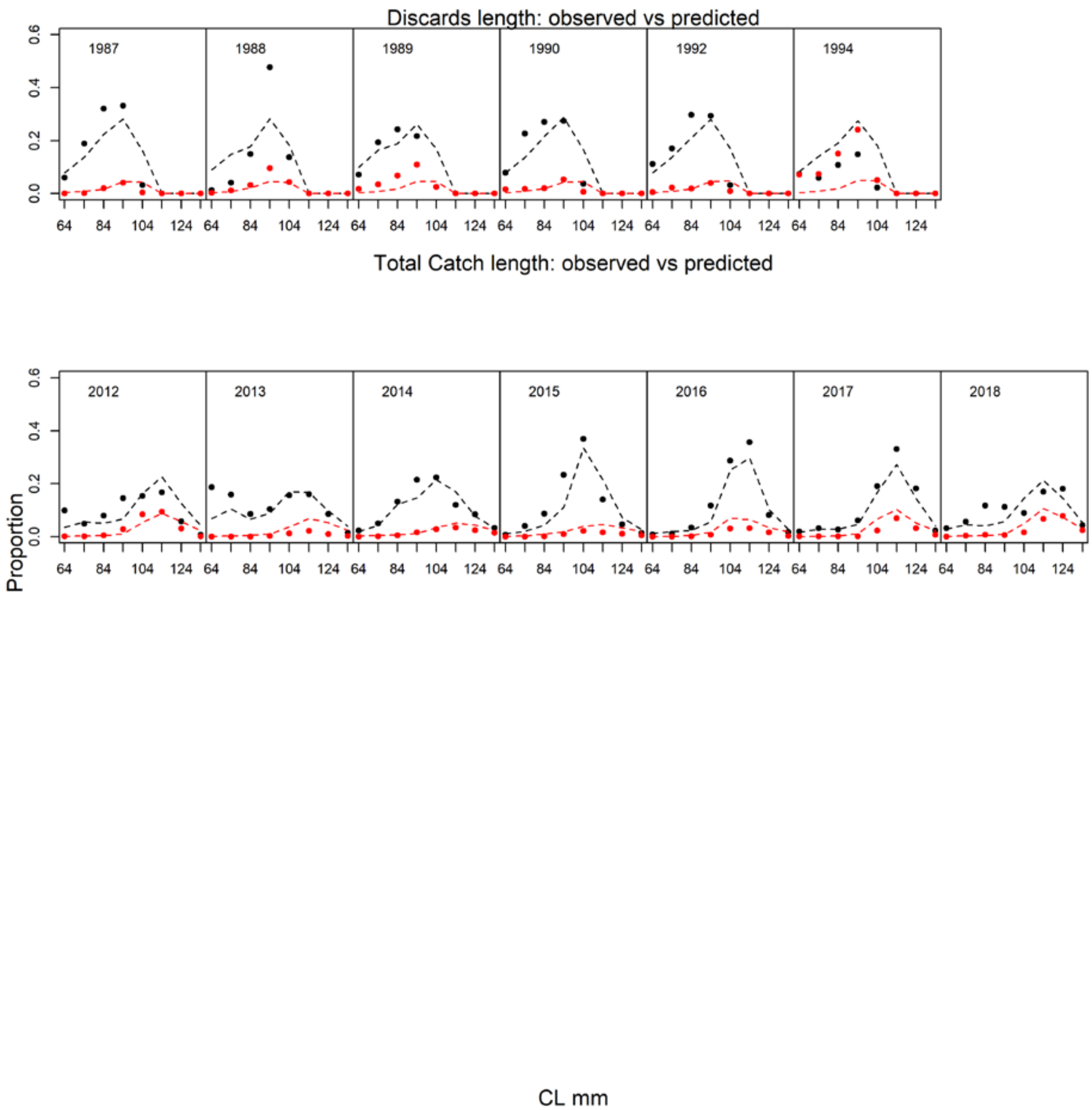


Figure D6-13. Predicted (dashed) vs. observed (dots) length class proportions for the observer survey. Black: newshell, Red: oldshell

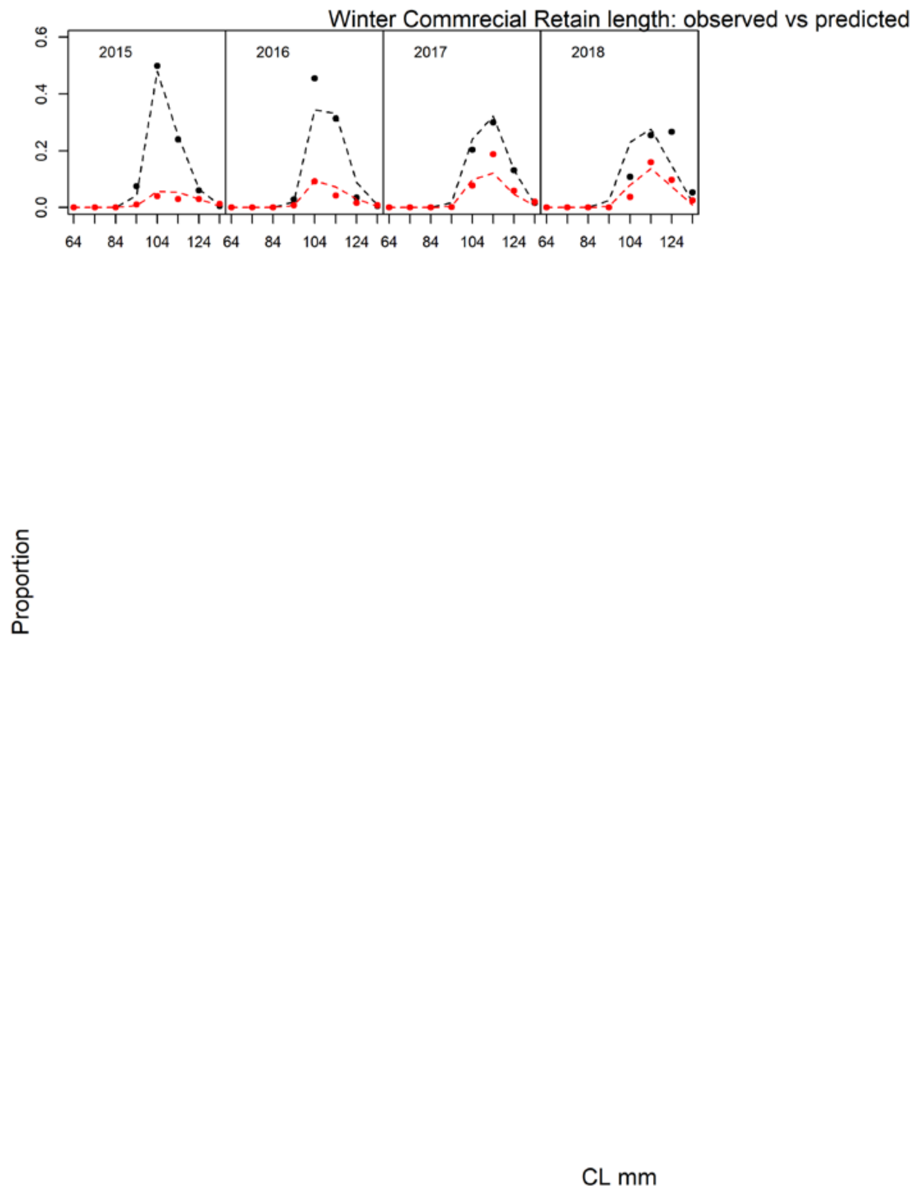


Figure D6-12. Predicted (dashed) vs. observed (dots) length class proportions for the observer survey. Black: newshell, Red: oldshell

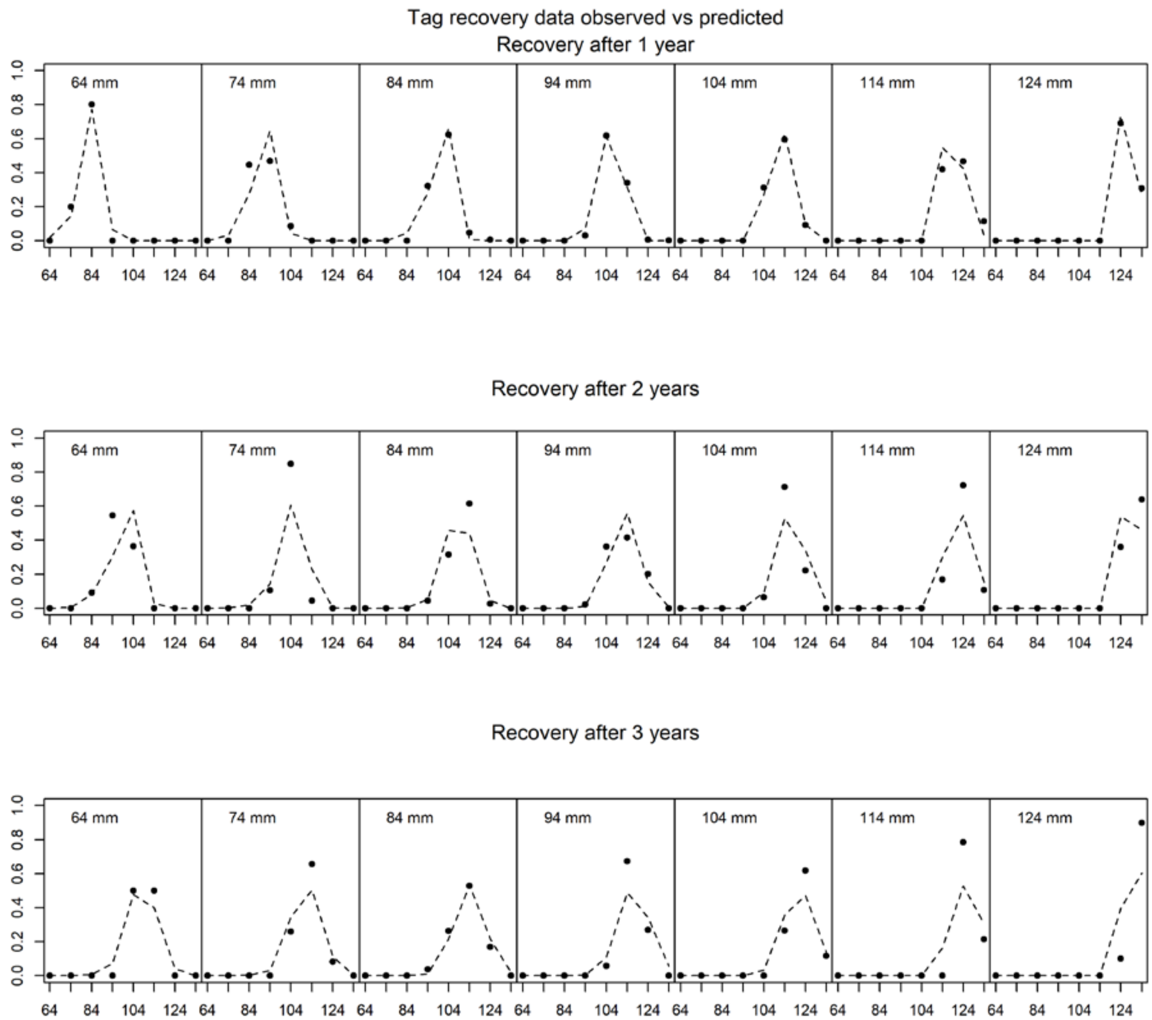


Figure D6-13. Predicted vs. observed length class proportions for tag recovery data.

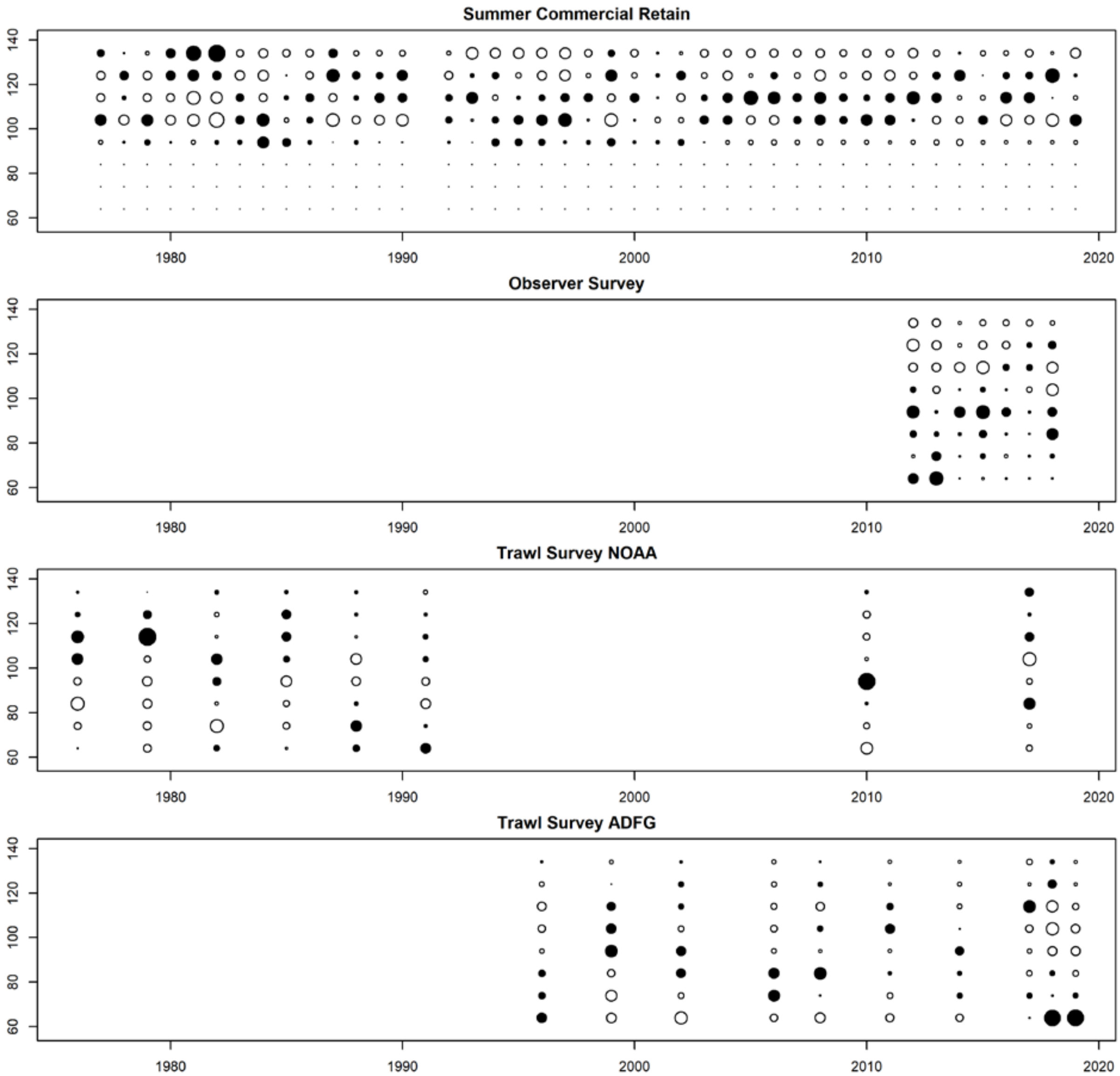


Figure D6-13. Bubble plots of predicted and observed length proportions.
Black circle indicates model estimates lower than observed, white circle indicates model estimates higher than observed. Size of circle indicates degree of deviance (larger circle = larger deviance).

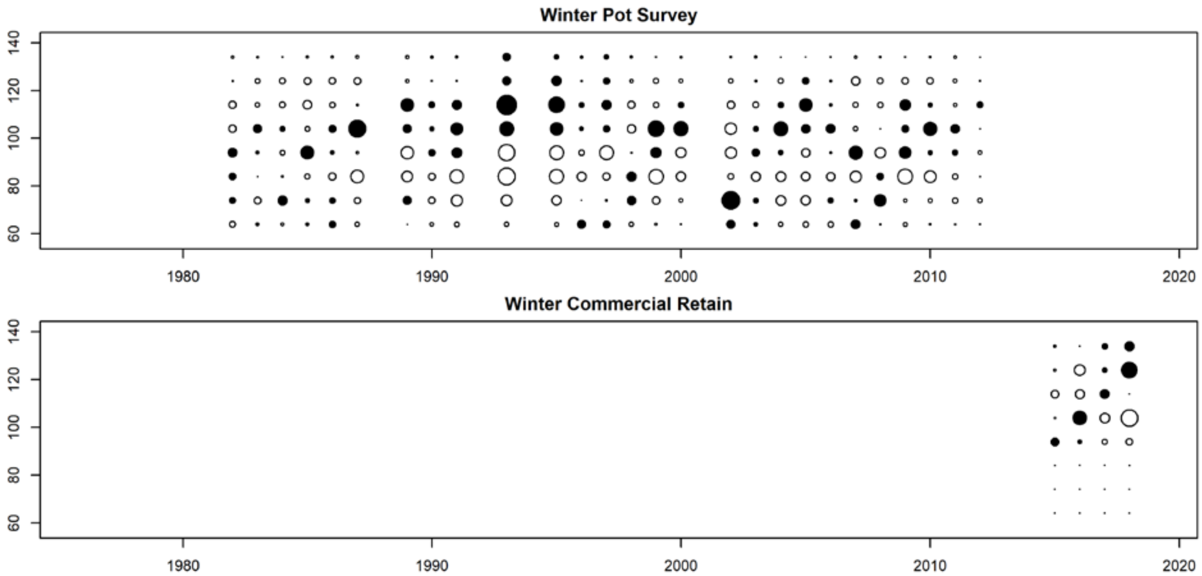


Figure D6-14. Bubble plots of predicted and observed length proportions.
Black circle indicates model estimates lower than observed, white circle indicates model estimates higher than observed. Size of circle indicates degree of deviance (larger circle = larger deviance).

Table D6. Summary of parameter estimates for a length-based stock synthesis population model of Norton Sound red king crab.

name	Estimate	std.dev
log_q_1	-6.600	0.133
log_q_2		
log_N_{76}	9.637	0.169
R_0	7.359	0.202
a_1	1.858	4.830
a_2	3.838	4.409
a_3	4.907	4.227
a_4	4.770	4.211
a_5	4.580	4.201
a_6	3.691	4.233
a_7	1.937	4.514
r1	10.000	0.531
r2	9.951	0.630
log_a	-2.879	0.115
log_b	4.815	0.020
log_ϕ_{st1}		
log_ϕ_{wa}	-1.481	0.434
log_ϕ_{wb}	4.892	0.028
Sw1	0.059	0.030
Sw2	0.292	0.075
log_ϕ_1		
$log\_\phi ra$	-0.791	0.138
$log\_\phi rb$	4.626	0.009
$log\_\phi wra$	-0.940	0.470
$log\_\phi wrb$	4.659	0.033
$w^2{}_t$	0.002	0.019
q	0.712	0.117
σ	0.433	0.034
β_1	4.010	0.230
β_2	9.762	0.964

name	Estimate	std.dev
selc 1	0.045	0.020
selc 2	0.067	0.023
selc 3	0.117	0.035
selc 4	0.190	0.039
selc 5	0.642	0.062
selc 6	0.988	0.295
selc 7	1.000	0.000
selc 8	0.963	0.252
selt 1	0.613	0.168
selt 2	0.448	0.108
selt 3	0.567	0.118
selt 4	0.698	0.125
selt 5	0.874	0.271
selt 6	1.000	0.000
selt 7	0.943	0.209
selt 8	0.739	0.348