Norton Sound Red King Crab Stock Assessment for the fishing year 2015

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Executive Summary

1. Stock. Red king crab, *Paralithodes camtschaticus*, in Norton Sound, Alaska.

2. Catches. This stock supports three main fisheries: summer commercial, winter commercial, and winter subsistence fisheries. Of those, the summer commercial fishery accounts for more than 90% of total harvest. The summer commercial fishery started in 1977, and its catch reached a peak in the late 1970s with retained catch of over 2.9 million pounds. Since 1982, retained catches have been below 0.5 million pounds, averaging 0.275 million pounds, including several low years in the 1990s. Coincident with increasing estimated abundance, retained catches in recent years have increased to about 0.4 million pounds.

3. Stock Biomass. Following a peak in 1977, abundance or the stock collapsed to a historic low in 1982. Estimated mature male biomass (MMB) has shown an increasing trend since 1997. However, uncertainty in historical biomass is high due in part to infrequent trawl surveys (every 3 to 5 years) and limited winter pot surveys.

4. Recruitment. Model estimated recruitment was weak during the late 1970s and high during the early 1980s, with a slight downward trend from 1983 to 1993. Estimated recruitment has been highly variable but on an increasing trend in recent years.

5. Management performance.

Status and catch specifications (million lb.)

Year	MSST	Biomass (MMB)	GHL	Retained Catch	Total Catch	OFL	ABC
2011/12	1.25[A]	4.70	0.36	0.40	0.43	0.66[A]	0.59
2012/13	1.76[B]	4.59	0.47	0.47	0.47	0.53[B]	0.48
2013/14	2.06[C]	5.00	0.50	0.35	0.35	0.58[C]	0.52
2014/15	2.11[D]	3.71	0.38	0.39	0.39	0.46[D]	0.42
2015	2.41[E]	5.13	TBD	TBD	TBD	0.72[E]	0.58

Status and catch specifications (1000t)

Year	MSST	Biomass (MMB)	GHL	Retained Catch	Total Catch	OFL	ABC
2011/12	0.57[A]	2.13	0.16	0.18	0.20	0.30[A]	0.27
2012/13	0.80[B]	2.08	0.21	0.21	0.21	0.24[B]	0.22
2013/14	0.93[C]	2.27	0.23	0.16	0.16	0.26[C]	0.24
2014/15	0.96[D]	1.68	0.17	0.18	0.18	0.21[D]	0.19
2015	1.09[E]	2.33	TBD	TBD	TBD	0.33 [E]	0.26

Notes:
MSST was calculated as $B_{MSY}/2$
A-Calculated from the assessment reviewed by the Crab Plan Team in May 2011
B-Calculated from the assessment reviewed by the Crab Plan Team in May 2012
C-Calculated from the assessment reviewed by the Crab Plan Team in May 2013
D-Calculated from the assessment reviewed by the Crab Plan Team in May 2014
E-Calculated from the assessment reviewed by the Crab Plan Team in Jan 2015
Conversion to Metric ton: 1 Metric ton = 2.2046× 1000 lb

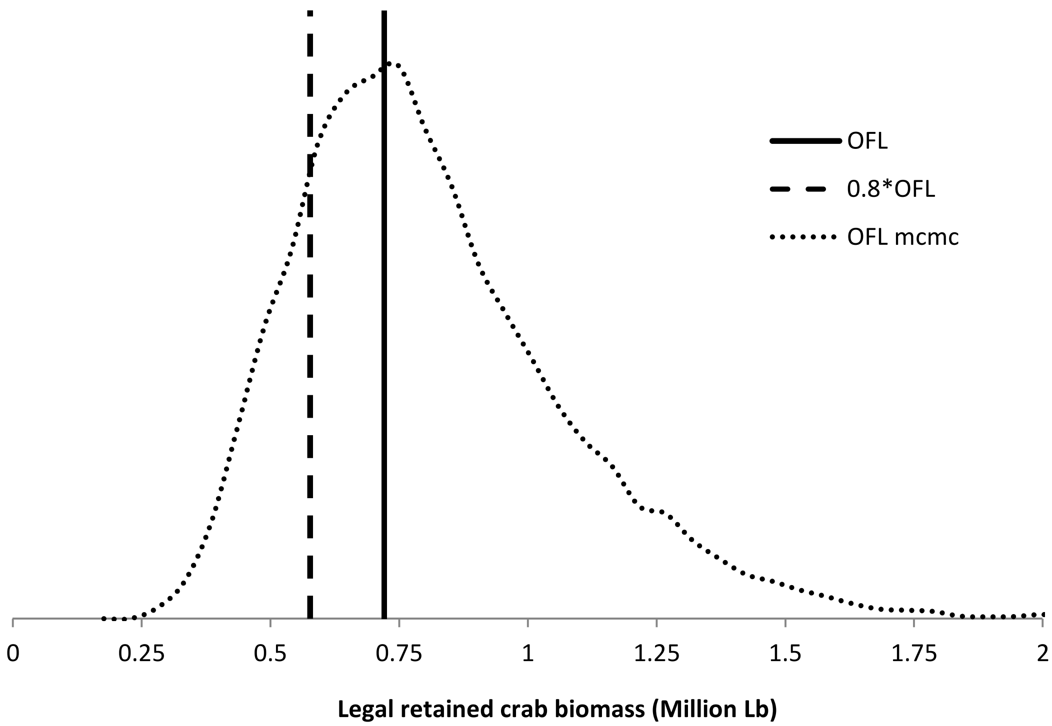
Biomass in millions of pounds

Year	Tier	B_{MSY}	Current MMB	B/B_{MSY} (MMB)	F_{OFL}	Years to define B_{MSY}	M	1-Buffer	ABC
2011/12	4a	2.97	4.70	1.6	0.18	1983-2011	0.18	0.9	0.59
2012/13	4a	3.51	4.59	1.2	0.18	1980-2012	0.18	0.9	0.48
2013/14	4b	4.12	5.00	1.2	0.18	1980-2013	0.18	0.9	0.52
2014/15	4b	4.19	3.71	0.9	0.16	1980-2014	0.18	0.9	0.42
2015	4a	4.81	5.13	1.1	0.18	1980-2015	0.18	0.8	0.58

Biomass in 1000t

Year	Tier	B_{MSY}	Current MMB	B/B_{MSY} (MMB)	F_{OFL}	Years to define B_{MSY}	M	1-Buffer	ABC
2011/12	4a	1.35	2.13	1.6	0.18	1983-2011	0.18	0.9	0.27
2012/13	4a	1.59	2.08	1.2	0.18	1980-2012	0.18	0.9	0.22
2013/14	4a	1.87	2.27	1.2	0.18	1980-2013	0.18	0.9	0.24
2014/15	4b	1.68	1.68	0.9	0.16	1980-2014	0.18	0.9	0.21
2015	4a	2.18	2.33	1.1	0.18	1980-2015	0.18	0.8	0.26

6. Probability Density Function of the OFL



OFL profile. mcmc estimates.

7. The basis for the ABC recommendation

For Tier 4 stocks, the default maximum ABC is based on P*=49% that is essentially identical to the OFL. Accounting for uncertainties in assessment and model results, the SSC chose to use 90% OFL (10% Buffer) for the Norton Sound red king crab stock since 2011. In 2015, CPT increased the buffer to 20% (ABC = 80% OFL) being consistent with other tier 4 stocks.

8. A summary of the results of any rebuilding analyses.
   N/A

A. Summary of Major Changes in 2015

1. Changes to the management of the fishery**:**

   None.

2. Changes to the input data
    a. Data update: 2014 summer commercial fishery (total catch, catch length comp, discards length comp), 2013/2014 winter commercial and subsistence catch
    b. Data update: 1977-2014 standardized commercial catch CPUE and CV. No changes in standardization methodology (SAFE 2013).

3. Changes to the assessment methodology:
    a. Changed modeling schedule from July 01 - June 30 to Feb 01 - Jan 30

4. Changes to the assessment results.
    a. OFL determination is based on Feb 01 mature male biomass (MMB)
    b. Calculation of retained OFL and ABC are for both winter (subsistence + commercial) and summer commercial catches. (See section F for details)

B. Response to SSC and CPT Comments

CPT Sept 15-18 2014

- Evaluate a reduction in the weighting of the winter pot survey data.

  Authors' reply:
  This requests came from the fact that profile likelihood analyses of *M* showed higher *M* for winter pot survey length data, and thus reduction of its weight was suggested (CPT 2014 September). However, profile likelihood of a revised model (Appendix B2) showed winter pot survey likelihood minimized at $M = 0.2$. Hence, we did not pursue this issue further.

- Continue to examine models with a single *M* for all size-classes, and a separate *M* for the largest size class using likelihood profiles, but evaluate whether use of a descending logistic curve for the winter pot selectivity changes the likelihood profile.

  Authors' reply:
  Similar to previous likelihood analyses, negative log likelihood was minimized at $M = 0.3 – 0.4$ (Appendix B2). For winter pot selectivity, it was minimized at $M = 0.2$.

- Explore a separate estimated selectivity for the smallest size class.

  Author's reply:

We implemented reverse-logistic with separate selectivity for the smallest size class for winter pot survey. This reduced negative log likelihood, and is thus the author's preferred alternative model.

SSC Oct 6-8 2014

- The SSC concurs with these (CPT's) recommendations. It also recommends comparing the standard deviation of residuals to the input standard deviation to develop a more objective weighting of the various likelihood components in the model.

  Author's reply:
  We calculated RMSE for trawl abundance and standardized CPUE and compared them with those of observed CV. They were close.

C. Introduction

1. Species: red king crab (*Paralithodes camtschaticus*) in Norton Sound, Alaska.

2. General Distribution: Norton Sound red king crab is one of the northernmost red king crab populations that can support a commercial fishery (Powell et al. 1983). It is distributed throughout Norton Sound with a westward limit of 167-168^{o} W. longitude, depths less than 30 m, and summer bottom temperatures above 4^{o}C. The Norton Sound red king crab management area consists of two units: Norton Sound Section (Q3) and Kotzebue Section (Q4) (Menard et al. 2011). The Norton Sound Section (Q3) consists of all waters in Registration Area Q north of the latitude of Cape Romanzof, east of the International Dateline, and south of 66°N latitude (Figure 1). The Kotzebue Section (Q4) lies immediately north of the Norton Sound Section and includes Kotzebue Sound. Commercial fisheries have not occurred regularly in the Kotzebue Section. This report deals with the Norton Sound Section of the Norton Sound red king crab management area.
3. Evidence of stock structure: Thus far, no studies have been made on possible stock separation within the putative stock known as Norton Sound red king crab.
4. Life history characteristics relevant to management: One of the unique life-history traits of Norton Sound red king crab is that they spend their entire lives in shallow water since Norton Sound is generally less than 40 m in depth. Distribution and migration patterns of Norton Sound red king crab have not been well studied. Based on the 1976-2006 trawl surveys, red king crab in Norton Sound are found in areas with a mean depth range of 19 ± 6 (SD) m and bottom temperatures of 7.4 ± 2.5 (SD) ^{o}C during summer. Norton Sound red king crab are consistently abundant offshore of Nome.

   Norton Sound red king crab migrate between deeper offshore and inshore shallow waters. . Timing of the inshore mating migration is unknown, but is assumed to be during late fall to winter (Powell et al. 1983). Offshore migration occurs in late May - July (Jennifer Bell, ADF&G, personal communication). The results from a study funded by North Pacific Research Board (NPRB) during 2012-2014 suggest that older/large crab (> 104mm CL) stay offshore in winter, based on findings that large crab are not found nearshore during spring offshore migration periods (Jennifer Bell, ADF&G, personal communication). Timing of molting is unknown but is considered to occur in late August – September, based on increase catches of fresh-molted crab later in the fishing season (August- September) (Joyce Soong, ADF&G personal communication); however, blood hormonal studies suggests April-May molting season (Jennifer Bell, ADF&G, personal communication), which is consistent with Powell et al. (1983). Recent observations indicate biennial mating (Robert Foy, NOAA, personal communication). Trawl surveys show that crab distribution is dynamic. Recent surveys show high abundance on the southeast side of the sound, offshore of Stebbins and Saint Michael.

5. Brief management history: Norton Sound red king crab fisheries consist of commercial and subsistence fisheries. The commercial red king crab fishery started in 1977 and occurs in summer (June – August) and in winter (December – May). The majority of red king crab is harvested by the summer commercial fisheries in offshore, whereas the majority of subsistence fisheries occur in winter in nearshore.

<u>Summer Commercial Fishery</u>

The summer commercial crab fishery started in 1977 (Table 1). A large-vessel summer commercial crab fishery existed in the Norton Sound Section from 1977 through 1990. No summer commercial fishery occurred in 1991 because there was no staff to manage the fishery. In March 1993, the Alaska Board of Fisheries (BOF) limited participation in the fishery to small boats. Then on June 27, 1994, a super-exclusive designation went into effect for the fishery. This designation stated that a vessel registered for the Norton Sound crab fishery may not be used to take king crabs in any other registration areas during that registration year. A vessel moratorium was put into place before the 1996 season. This was intended to precede a license limitation program. In 1998, Community Development Quota (CDQ) groups were allocated a portion of the summer harvest; however, no CDQ harvest occurred until the 2000 season. On January 1, 2000 the North Pacific License Limitation Program (LLP) went into effect for the Norton Sound crab fishery. The program dictates that a vessel which exceeds 32 feet in length overall must hold a valid crab license issued under the LLP by the National Marine Fisheries Service. Regulation changes and location of buyers resulted in harvest distribution moving eastward in Norton Sound in the mid-1990s. . In the Norton Sound, a legal crab is defined as ≥ 4-3/4 inch carapace width (CW, Menard et al. 2011; equivalent to ≥ 124 mm carapace length [CL]). Since 2005, commercial buyers started accepting only legal crab of ≥ 5 inch CL.

Not all Norton Sound area is open for commercial fisheries. Since the beginning of the commercial fisheries in 1977, inland waters near Nome area have been closed for the summer commercial crab fishery to protect crab nursery grounds (Figure 2). The spatial extent of closed waters has varied historically.

<u>CDQ Fishery</u>

The Norton Sound and Lower Yukon CDQ groups divide the CDQ allocation. Only fishers designated by the Norton Sound and Lower Yukon CDQ groups are allowed to participate in this portion of the king crab fishery. Fishers are required to have a CDQ fishing permit from the Commercial Fisheries Entry Commission (CFEC) and register their vessel with the Alaska Department of Fish and Game (ADF&G) before they make their first delivery. Fishers operate under authority of the CDQ group and each CDQ group decides how their crab quota is to be harvested. During the March 2002 BOF meeting, new regulations were adopted that affected the CDQ crab fishery and relaxed closed-water boundaries in eastern Norton Sound and waters west of Sledge Island. At its March 2008, the BOF changed the start date of the Norton Sound open-access portion of the fishery to be opened by emergency order and as early as June 15. The CDQ fishery may open at any time (as soon as ice is out), by emergency order.

<u>Winter Commercial Fishery</u>

The winter commercial crab fishery is a small fishery using hand lines and pots through the nearshore ice. On average 10 permit holders harvested 2,500 crab during 1978-2009. During the 2006-2013 periods the winter commercial catch increased to 3,000 – 23,000 (Table 2). Causes for this increase are unclear. The winter commercial fishery catch is influenced not only by crab abundance, but also by changes in near shore crab distribution, ice conditions, the number of participants, and market condition.

<u>Subsistence Fishery</u>

While the subsistence fishery has a long history, harvest information is available only since1977/78. The majority of the subsistence crab fishery harvest occurs during winter using hand lines and pots through nearshore ice. Average annual winter subsistence harvest was 5,400 crab (1977-2010). Subsistence harvesters need to obtain a permit before fishing and record daily effort and catch. There is no size limit in the subsistence fishery. The subsistence fishery catch is influenced not only by crab abundance, but also by changes in distribution, changes in gear (e.g., more use of pots instead of hand lines since 1980s), and ice conditions (e.g., reduced catch due to unstable ice conditions: 1987-88, 1988-89, 1992-93, 2000-01, 2003-04, 2004-05, and 2006-07).

The summer subsistence crab fishery harvest has been monitored since 2004 with average harvest of 712 crab per year. Since this harvest is very small, the summer subsistence fishery was not included in the assessment model.

6. Brief description of the annual ADF&G harvest strategy

Since 1997 Norton Sound red king crab have been managed based on a guideline harvest limit (GHL). Detailed historical methods of GHL determination are unknown. From 1999 to 2011 GHL is determined by a prediction model and the model estimated predicted biomass: (1) 0% harvest rate of legal crab when estimated legal biomass < 1.5 million lb; (2) ≤ 5% of legal male abundance when the estimated legal biomass falls within the range 1.5-2.5 million lb; and (3) ≤ 10% of legal male when estimated legal biomass >2.5 million lb.

In 2012 a revised GHL became in effect: (1) 0% harvest rate of legal crab when estimated legal biomass < 1.25 million lb; (2) ≤ 7% of legal male abundance when the estimated legal biomass falls within the range 1.25-2.0 million lb; (3) ≤ 13% of legal male abundance when the estimated legal biomass falls within the range 2.0-3.0 million lb; and (3) ≤ 15% of legal male when estimated legal biomass >3.0 million lb.

Year	Notable historical management changes
1976	The abundance survey started
1977	Large vessel commercial fisheries began
1991	Fishery closed due to staff constraints
1994	Super exclusive designation went into effect. The end of large vessel commercial fishery operation. Participation limited to small boats. The majority of commercial fishery subsequently shifted to east of 164°W line.
1998	Community Development Quota (CDQ) allocation went into effect
1999	Guideline Harvest Limit (GHL) went into effect
2000	North Pacific License Limitation Program (LLP) went into effect.
2002	Change in closed water boundaries (Figure 2)
2005	Commercially accepted legal crab size changed from ≥ 4-3/4 inch CW to ≥ 5 inch CW
2006	The Statistical area Q3 section expanded (Figure 1)
2008	Start date of the open access fishery changed from July1 to after June 15 by emergency order. Pot configuration requirement: at least 4 escape rings (>4½ inch diameter) per pot located within one mesh of the bottom of the pot, or at least ½ of the vertical surface of a square pot or sloping side-wall surface of a conical or pyramid pot with mesh size > 6½ inches.
2012	The Board of Fisheries adopted a revised harvest strategy.

7. Summary of the history of the $B_{MSY.}$

NSRKC is a Tier4 crab stock. Direct estimation of the B_{MSY} is not possible. The B_{MSY} proxy is calculated as mean model estimated mature male biomass (MMB) from 1980 to present. . Choice of this period was based on a hypothesized shift in stock productivity a due to a climatic regime shift indexed by the Pacific Decadal Oscillation (PDO) in 1976-77. Stock status of the NSRKC was Tier 4a. In 2014 the stock fell to Tier 4b.

D. Data

1. Summary of new information:

Trawl survey:

The triennial Norton Sound trawl survey was completed in August of 2014. Due to poor weather of the total number of stations trawled (47) was 28% lower than 2011 (65 stations). The total number of stations with red king crab in Norton Sound (34) was the same as 2011. Estimated total male crab (> 73mm) abundance 5.4816 million crab (CV 48.6%) (Table 3). This was double that of 2011 (2.7017, CV 13%), and was the highest abundance ever recorded (the previous highest record was 1976: 4.2475). However, this estimate is largely due to high crab catch at one survey station, which accounted for 50 % of total abundance.

Summer commercial fishery:

The summer commercial fishery opened June 25 and the last delivery was completed on August 15. A total of 129,956 crab were harvested (Table 1). Standardized CPUE was 1.23, 70% higher than 2013 (0.72), but lower than the 2004-2013 average of 1.27 (Table 4). The catch length compositions were similar to 2013 (Table 5).

2. Available survey, catch, and tagging data

	Years	Data Types	Tables
Summer trawl survey	76,79,82,85,88,91,96, 99, 02,06,08,10,11, 14	Abundance Length proportion	3 5, Figure 3
Winter pot survey	81-87, 89-91,93,95-00,02-12	Length proportion	6, Figure 3
Summer commercial fishery	76-90,92-14	Retained catch Standardized CPUE, Length proportion	1 1 4, Figure 3
Summer commercial Discards	87-90,92,94, 2012-2014	Length proportion (sublegal only)	7, Figure 3
Winter subsistence fishery	76-14	Total catch	2
		Retained catch	2
Winter commercial fishery	78-14	Retained catch	2
Tag recovery	80-14	Recovered tagged crab	8

Data available but not used for assessment

Data	Years	Data Types	Reason for not used
Summer pot survey	80-82,85	Abundance Length proportion	Uncertainties on how estimates were made.
Summer preseason survey	95	Length proportion	Just one year of data
Summer subsistence fishery	2005-2013	retained catch	Too few catches compared to commercial
Winter Pot survey	-87, 89-91,93,95-00,02-12	CPUE	Not reliable due to ice conditions
Preseason Spring pot survey	2011-14	CPUE, Length proportion	Years of data too short
Postseason Fall pot survey	2013-14	CPUE	Years of data too short

Length proportion

Catches in other fisheries

In Norton Sound, no other crab, groundfish, or shellfish fisheries exist.

	Fishery	Data availability
Bycatch in other crab fisheries	Does not exist	NA
Bycatch in ground pot	Does not exist	NA
Bycatch in ground fish trawl	Does not exist	NA
Bycatch in the scallop fishery	Does not exist	NA

3. Other miscellaneous data:

Data aggregated

Proportion of legal size crab, estimated from trawl survey and observer data. (Table 11)

Data estimated outside the model

Summer commercial catch standardized CPUE (Table 1)

E. Analytic Approach

1. History of the modeling approach.

The Norton Sound red king crab stock was assessed using a length-based synthesis model (Zheng et al. 1998).

Since adoption of the model, the major challenge was to resolve conflicts among data sources. Due to very low summer trawl survey abundances of large males in 2002, 2006, 2008 and 2010, which contradicted with the expectation from other data sources The model overestimated the abundance/proportion of large length classes, which resulted in overestimation of the projected biomass. This problem has been dealt with by the following approaches: (1) by increasing M of the last length class, (2) by reducing effective sample size of length composition data, and (3) by increasing M for all length classes (Appendix B2). Although all the 3 approaches improve model fits and projections reasonably well, none are without major criticisms. Approach (1) has been criticized for having little biological support or data. Approach (3) is biologically simpler and a reasonable approach; however, it greatly increases OFL and ABC, without any supportive evidence that the population can withstand higher exploitation rates. Attempts to estimate *M* directly from the model itself have failed. When *M* was set as a free parameter, its estimate stayed at the initial starting value.

At the 2013-2014 crab modeling workshop, extensive examination of the model was conducted, including revision of historical survey abundance data, inclusion and exclusion of data (e.g., exclusion of summer pot survey data, inclusion/exclusion of winter pot survey cpue), reducing the number of parameters (e.g., molting probability, selectivity), and reevaluation of the growth transition matrix.

Historical Model configuration progression

2011 (SAFE 2011)

1. *M* =0.18
2. *M* of the last length class = 0.288
3. Include summer commercial discards mortality = 0.2
4. Weight of fishing effort = 20,
5. The maximum effective sample size for commercial catch and winter surveys = 100,

2012 (SAFE 2012)

1. *M* of the last length class = 3.6×*M*
2. The maximum effective sample size for commercial catch and winter surveys = 50,
3. Weight of fishing effort = 50.

2013 (SAFE 2013)

1. Standardize commercial catch cpue and replace likelihood of commercial catch efforts to standardized commercial catch cpue with weight = 1.0
2. Eliminate summer pot survey data from likelihood
3. Estimate survey *q* of 1976-1991 NMFS survey with maximum of 1.0
4. The maximum effective sample size for commercial catch and winter surveys = 20.

2014 (SAFE 2014)

1. Modify functional form of selectivity and molting probability to improve parameter estimates (2 parameters logistic to 1 parameter logistic)
2. Include additional variance for the standardized cpue.
3. Include winter pot survey cpue (But was removed from the final model due to lack of fit)
4. Estimate growth transition matrix from tagged recovery data.

2. Model Description

a. Description of overall modeling approach:

The model is a male-only size structured model that combines multiple sources of survey, catch, and mark-recovery data using a maximum likelihood approach to estimate abundance, recruitment, catchability of the commercial pot gear, and parameters for selectivity and molting probabilities (See Appendix A for full model description).

b-f. See Appendix A.

g. Critical assumptions of the model:

i. Male crab mature at CL length 94mm.

Bases for this assumption have not been located. No formal study has been conducted to test this assumption.

ii. Molting events in fall after the fishery

This is based on more frequent observations of post-molt crab in September. Recent hormonal study seems to support this. More study is needed to confirm the molting timing.

iii. Instantaneous natural mortality *M* is 0.18 for all length classes, except for the last length group (> 123mm) where *M* is 3.6 times higher (0.648). *M* is constant over time.

This mortality is based on Bristol Bay red king crab, estimated with a maximum age 25 and the 1% rule (Zheng 2005), and was adopted for NSRKC by the CPT. The assumption of the higher *M* for the last length group is not based on biological data. It is a working hypothesis attempting to explain the lower than model predicted proportion of this group in summer commercial fisheries (Figures 10, 13). It is possible, that the last length group moved into areas inaccessible to commercial fisheries (the CPT review 2010). However, this does not explain the low proportion observed in the summer trawl survey, when all of the Norton Sound Area was surveyed. In addition, lowering the catch selectivity did not result in lower log likelihood than increasing the mortality (CPT 2010).

iv. Trawl survey selectivity is a logistic function with 1.0 for length classes 5-6. . Selectivity is constant over time.

This assumption was not based on biological/mechanistic data and reasoning, but rather an attempt to improve model fit.

v. Winter pot survey selectivity is a dome shaped function: logistic function for length classes 1-4, 1.0 for length class 5, and model estimate for the last length group. Selectivity is constant over time.

This assumption is based on the fact that large crab are not caught in near shore area where the winter surveys occur. Causes of this have been argued: (1) large crab do not migrate into near shore in winter, or (2) large crab are fished out by winter fisheries where the survey occurs (i.e., local depletion). Recent studies suggest that the former was more likely the cause (Jennifer Bell, ADFG, personal communication).

In this assessment, we also examined an alternative selectivity model (Alternative models 5 and 6): inverse logistic with the highest selectivity at the smallest crab, and the smallest crab selectivity estimated separately.

vi. Summer commercial fisheries selectivity is an asymptotic logistic function of 1.0 at the length class 5 and 6. It has two selectivity curves: 1977-1992, and 1993-present, reflecting changes in fishing vessel composition and pot configuration. .

Since 2005 commercial buyers accept only legal crab of CW ≥ 5.0 inch and unknown numbers of legal crab with CW < 5.0 are discarded. Further, since 2008, commercial pots are required to install escapement rings for sublegal crab. Hence one can argue that the catch selectivity changed in 2005. However, the model was not able to accurately estimate selectivity parameters for 2005-2013. Consequently, the selectivities for both 1993-2004 and 2005-2013 were combined.

In this assessment, we also examined one selectivity for all years (Alternative model 6).

vii. Winter commercial and subsistence fishery selectivity and length-shell conditions are the same as those of the winter pot survey. All winter commercial and subsistence harvests occur February 1st.

Winter commercial king crab pots can be any dimension (5AAC 34.925(d)). No length composition data exists for crab harvested in the winter commercial or subsistence fisheries. However, because commercial fishers are also subsistence fishers, it is reasonable to assume that the commercial fishers used crab pots that they also used for subsistence harvest, and hence both fisheries have the same selectivity.

viii. Growth increments are a function of length and are constant over time, estimated from tag recovery data.

ix. Molting probability is an inverse logistic function of length for males.

x. A summer fishing season for the directed fishery is short. All summer commercial harvests occur July 1st.

xi. Discards handling mortality for all fisheries is 20%.

No empirical estimate is available.

xii. Annual retained catch is measured without error.

xiii. All legal size crab (≥ 4-3/4 inch CW) are retained.

Since 2005, buyers announced that only legal crab with ≥ 5 inch CW are acceptable for purchase. Since samples are taken at a commercial dock, it was anticipated that this change would lower the proportion of legal crab for length class 4. However, model was not sensitive to this change (SAFE 2013).

xiv. All sublegal size crab or commercially unacceptable size crab (< 5 inch CW, since 2005) are discarded.

xv. Length compositions have a multinomial error structure, and abundance has a log-normal error structure.

h. Changes of assumptions since last assessment:

Winter pot selectivity: Dome shape inverse logistic function (Alternative models 5,6)

Summer commercial pot selectivity: Same for all years (Alternative model 6)

Triennial trawl survey net selectivity: Same for both NMFS and ADF&G (Alternative model 6)

i. Code validation

The model code was reviewed at the CPT modeling workshop in 2013 and 2014. It is available from the authors.

3. Model Selection and Evaluation

a. Description of alternative model configurations.

Following recommendations at the 2014 crab workshop the following alternative model configurations were examined:

1. May 2014 crab assessment model converted to Feb 01 starting dates (Appendix C1)
2. Reduce Weight of tag-recovery: W = 0.5 (Appendix C2)
3. Winter pot survey selectivity is reverse logistic (Appendix C3)
4. Winter pot survey selectivity is an inverse logistic, estimating selectivity of the smallest length group independently. (Appendix C4)
5. Model 4 + 2 (Appendix C5)
6. Model 5 with parsimony: (Assume one trawl survey selectivity and one commercial pot selectivity) (Appendix C6)

Rationales of the alternative models

Alternative model 2: Tag recovery weight reduction (Appendix C2)

Weight of tag recovery likelihood was reduced from 1.0 default to 0.05 (Appendix B1). Among each component, largest changes were observed in trawl length composition, winter pot length composition, and summer commercial length composition. While trawl and winter pot length compositions were minimized at W = 0.05, summer commercial length composition was minimized at W = 1.0. Among parameters, the influence of weight changes was more apparent for NOAA trawl survey selectivity, and 93-2014 summer commercial pot selectivity. However, this does not affect projection of MMB. Considering those, **we chose W = 0.5 as a compromise**.

Alternative model 3: Winter pot selectivity is inverse logistic. (Appendix C3)

This directly responds to CPT and SSC's recommendation. . In 2014 assessment, the model was not able to estimate shape of the winter pot selectivity. Base selectivity model is a logistic curve with peak at length class 5, and separate estimate for the last length class (class 6) (Appendix A, equation 16). This alternative model changes the selectivity form to reverse logistic with peak at length class 1, which is the same form as molting probability (Appendix A, equation 15).

Alternative model 4: Winter pot selectivity is an inverse logistic with the first length class estimated independently. (Appendix C4)

This is the same as the alternative model 3, with length class 1 estimated separately. This will provide possibility of the selectivity dome shape.

Alternative model 5: Winter pot selectivity is an inverse logistic with the first length class estimated independently, and reduce tagging data weights. (Appendix C5)

This is a combination of model 4 and model 2.

Alternative model 6: Model 5 + model parsimony. (Appendix C6)

This alternative assumes trawl net selectivity the same for both NOAA and ADFG and commercial pot selectivity for 77-92 and 93-14 periods. This is based on SSC's recommendation for model parsimony.
This reduces the number of parameters estimated by 2.

b. Evaluation of alternative models results

Summary of negative log-likelihood : comparable (scenario: 1,3,4; 2,5,6)

Scenario	1	2	3	4	5	6
Parameters	60	60	59	60	60	58
Total NLL	312.8	269.7	312.1	305.1	262.4	262.5
TBA	9.7	9.6	9.7	9.7	9.7	9.7
CCPUE	-25.5	-25.6	-25.6	-25.6	-25.7	-25.7
TLP (N)	-21.2	-21	-19.2	-20	-18.6	-19.2
TLP (O)	123.2	120.2	121.0	122.0	118.4	119

WLP (N)	12.9	13.3	5.7	1.2	2.3	2.4
WLP (O)	31.1	29.2	37.1	35.4	33.4	33.4
CLP (N)	62.4	67.5	63.0	63.6	68.8	68.8
CLP (O)	-0.5	-3.4	-1.3	-1.0	-3.9	-3.9
OBS (N)	3.1	3.7	3.8	2.4	2.7	2.8
OBS (O)	20.9	20.3	21.3	20.7	20.2	20.3
REC	11.8	11.9	12.1	12	11.9	11.8
TAG	85.1	43.8	84.4	84.6	43.3	43.1
RMSE (Trawl)	0.36	0.36	0.37	0.36	0.36	0.36
RMSE (CPUE)	0.5	0.5	0.5	0.5	0.5	0.5
MMB (2015)	5.10	5.10	5.13	5.15	5.27	5.13

TBA: Trawl survey abundance
CCPUE: Summer commercial catch standardized cpue
TLP: Trawl survey length composition: (N: for newshell, O: for oldshell)
WLP: Winter pot survey length composition
CLP: Summer commercial catch length composition
REC: Recruitment deviation
OBS: Summer Commercial catch Observer discards length composition
TAG: Tagging recovery data composition

c. Search for balance:

Overall, there was little difference in model performance among alternative models. Excluding tagging data, largest change in likelihood was observed in the fits of winter pot length composition (WLP). Even though both models assumes dome shape selectivity, changing selectivity from a logistic with the last length class estimated (Model 1) to inverse logistic with the first length class estimated (Model 5) improved the model fit.
Comparing Model 5 and Model 6, reduced the number of free parameters by assuming one selectivity for trawl survey (NOAA and ADF&G) and one selectivity for commercial catch (1976-1992, and 1993-2014) did not result in change of likelihood.

Considering the above, we recommend Alternative model 6 for the base model, based on advantages of (1) better model fit and (2) model parsimony.

4. Results

1. List of effective sample sizes and weighting factors (Figure 4)

   Effective sample sizes were calculated as

$$n = \sum_l \hat{P}_{y,l}(1-\hat{P}_{y,l}) \Big/ \sum_l (P_{y,l} - \hat{P}_{y,l})^2$$

Where $P_{y,l}$ and $\hat{P}_{y,l}$ are observed and estimated length compositions in year *y* and length group *l*, respectively. Estimated effective sample sizes vary greatly over time.

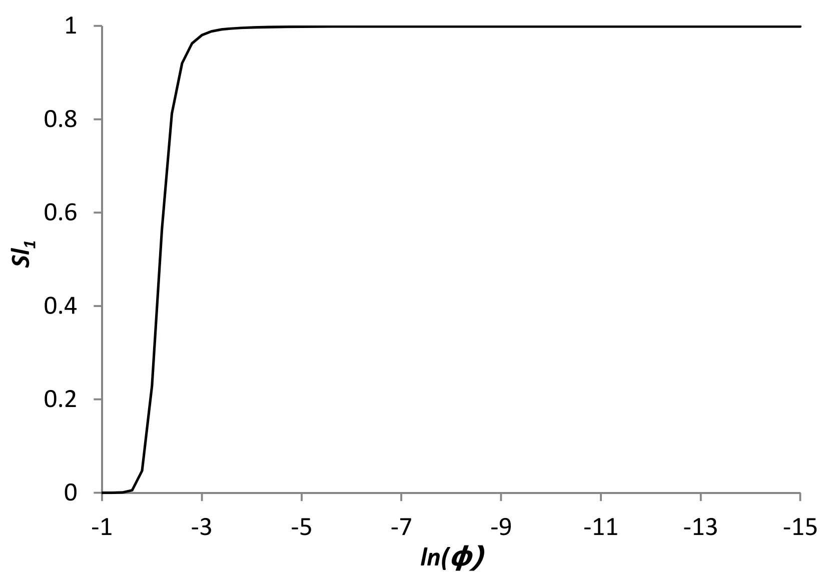
Maximum sample size for length proportion:

Survey data	Sample size
Summer commercial, winter pot, and summer observer	minimum of 0.1× actual sample size or 10
Summer trawl and pot survey	minimum of 0.5× actual sample size or 20

2. Tables of estimates.

a. Model parameter estimates (Tables 10, 11, 12, 13).

Of the 58 parameters estimated, trawl survey selectivity (log_ϕ_{st1}) showed high SD. This is because due to the fact that estimated selectivity 1.0 for all length classes. Any log_ϕ_{st1} less than -3 can reach selectivity close to 1.0.



b. Abundance and biomass time series (Table 14)

c. Recruitment time series (Table 14).

d. Time series of catch/biomass (Table 15)

3. Graphs of estimates.

a. Molting probability and trawl/pot selectivities (Figure 5)

b. Trawl survey and model estimated trawl survey abundance (Figure 6)

c. Estimated male abundances (recruits, legal, and total) (Figure 7)

d. Estimated mature male biomass (Figure 8)

e. Time series of standardized cpue for the summer commercial fishery (Figure 9).

f. Time series of catch and estimated harvest rate (Figure 10).

4. Evaluation of the fit to the data.

a. Fits to observed and model predicted catches.
Not applicable. Catch is assumed to be measured without error; however fits of cpue are available (Figures 9, 11).

b. Model fits to survey numbers (Figures 6, 11).

All model estimated abundances of total crab were within the 95% confidence interval of the survey observed abundance, except for 1976 and 1979, where model estimates were higher than the observed abundances.

c. Fits of catch proportions by lengths (Figures 12, 13).

d. Model fits to catch and survey proportions by length (Figures 12, 14, 15, 16).

e. Marginal distribution for the fits to the composition data

f. Plots of implied versus input effective sample sizes and time-series of implied effective sample size (Figure 4).

g. Tables of RMSEs for the indices:
Trawl survey: 0.36
This is larger than observed survey CV (Table 3).
Summer commercial standardized cpue: 0.5.
This is larger than observed model CV (Table 1), and thus was corrected by including additional variance.

h. QQ plots and histograms of residuals (Figure 11).

5. Retrospective and prospective analyses (Figure 18,19).

6. Uncertainty and sensitivity analyses.

See Sections 2 and 5.

F. Calculation of the OFL

1. Specification of the Tier level and stock status.

The Norton Sound red king crab stock is placed in Tier 4. It is not possible to estimate the spawner-recruit relationship, but some abundance and harvest estimates are available to build a computer simulation model that captures the essential population dynamics. Tier 4 stocks are assumed to have reliable estimates of current survey biomass and instantaneous M; however, the estimates for the Norton Sound red king crab stock are uncertain. Survey biomass is based on triennial trawl surveys with CVs ranging from 15-42% (Table 4).

Tire 4 level and the OFL are determined by the F_{MSY} proxy, B_{MSY} proxy, and estimated legal male abundance and biomass:

level	Criteria	F_{OFL}
a	$B/B_{MSY^{prox}} > 1$	$F_{OFL} = \gamma\, M$
b	$\beta < B/B_{MSY^{prox}} \leq 1$	$F_{OFL} = \gamma\, M\, (B/B_{MSY^{prox}} - \alpha)/(1-\alpha)$
c	$B/B_{MSY^{prox}} \leq \beta$	$F_{OFL} = bycatch\ \ mortality\ \ \&\ directed\ \ fishery\ \ F = 0$

where B is a mature male biomass (MMB), B_{MSY} proxy is average mature male biomass over a specified time period, $M = 0.18$, $\gamma = 1$, $\alpha = 0.1$, and $\beta = 0.25$

For Norton Sound red king crab, MMB is defined as CL > 94 mm **on February 01, which is changed from July 01** (Appendix A)**.** B_{MSY} proxy is

B_{MSY} proxy = average model estimated MMB from 1980-2015

Predicted mature male biomass in 2015 is:

Mature male biomass: 5.13 (SD 0.87) million lb.

Estimated B_{MSY} proxy is:

4.81 million lb.

Since projected MMB (5.18) is greater than B_{MSY} proxy (4.81), **Norton Sound red king crab stock status is Tire 4 a.**

2. Calculation of OFL.

The OFL was calculated for retained, unretained, and total male catch, in which OFL is calculated by applying F_{OFL} control rule to crab abundance estimates.

$$OFL = (1 - \exp(-F_{OFL}))B$$

The Norton Sound red king crab fishery consists of small (1-17% of total catch biomass) winter subsistence and commercial fishery from February to May and summer commercial fishery (83-99% of total catch biomass) from mid-June to September.

The two fisheries use not only different fishing gears and thus have different catch selectivity (Figure 5, Table 11), but also target crab population of different abundances. In the assessment model, crab population subject to the summer commercial fishery is calculated as: (Feb 1st abundance – winter fishery harvests – winter fishery discards × handling mortality) × natural mortality from Feb 1st to June 30th (Appendix A: equation 3).

It is ideal that separate OFLs are set for winter and summer fisheries; however, a dependency of summer crab abundance and OFL on catches of winter fishery make it necessary for further discussions.

Under the direction of the CPT (September 15-18, 2014) and the SSC (October 6-7, 2014), the crab abundance used for calculation of the OFL for winter and summer fishery combined is based on legal crab biomass catchable to summer commercial pot fisheries (*Legal_B*) calculated as: Projected legal abundance (Feb 1st) × Commercial pot selectivity × Proportion of legal crab per length class × Average lb per length class. Previous OFL calculation was based on July 1st legal biomass that was calculated as (Feb 1st legal abundance – (Winter harvests)) × Natural mortality from Feb to July. Because Feb 1st legal crab abundance is higher than July 1st legal crab abundance. **OFL calculated this assessment is higher than previous OFLs based on July 1st legal crab biomass.**

$$Legal\_B = \sum_{l} (N_{w,l,} + O_{w,l,}) S_{s,l} L_l wm_l$$

$$OFL_r = (1 - \exp(-F_{OFL})) Legal\_B$$

The unretained OFL is a sub-legal crab biomass catchable to summer commercial pot fisheries calculated as: Projected legal abundance (Feb 1st) × Commercial pot selectivity × Proportion of sub-legal crab per length class × Average lb per length class × handling mortality.

$$OFL_{nr} = (1-\exp(-F_{OFL}))\sum_{l}(N_{s,l,}+O_{s,l,})S_{s,l}(1-L_l)wm_l\ hm$$

where $N_{s,l}$ and $O_{s,l}$ are summer abundances of newshell and oldshell crab in length class l in the terminal year, L_l is the proportion of legal males in length class l, $S_{s,l}$ is summer commercial catch selectivity, wm_l is average weight in length class l and hm is handling mortality rate. .

The total male OFL is

$$OFL_T = OFL_r + OFL_{nr}$$

For calculation of the OFL 2015

Legal male biomass: 4.38 (SD 0.71) million lb
OFL_r = 0.721 million lb.
OFL_{nr} = 0.099 million lb.
OFL_T = 0.820 million lb.

G. Calculation of the ABC

1. Specification of the probability distribution of the OFL.

Probability distribution of the OFL was determined based on the CPT recommendation in January 2015 of 20% buffer:

Retained ABC for legal male crab is 80% of OFL

ABC = 0.721 × 0.8 = 0.577 million lb.

H. Rebuilding Analyses

Not applicable

I. Data Gaps and Research Priorities

The major data gap is uncertainties regarding biomass of Norton Sound red king crab. In addition, life-history of the Norton Sound red king crab stock is poorly understood. This includes size at maturity, natural mortality rate, timing and locations of reproduction, molt timing, migration patterns, and the location(s) of females during summer.

Acknowledgments

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Table 1. Historical summer commercial red king crab fishery economic performance, Norton Sound Section, eastern Bering Sea, 1977-2014. Bold type shows data that are used for the assessment model.

Year	Guideline Harvest Level (lb) [b]	Commercial Harvest (lb) [a, b] Open Access	CDQ	Harvest	Total Number (Open Access) Vessels	Permits	Landings	Total Pots Registered	Pulls	ST CPUE CPUE	SD	Season Length Days	Dates	Mid-day from July 1
1977	[c]	0.52		**195,877**	7	7	13		5,457	**3.44**	**0.34**	60	[c]	**0.03**
1978	3.00	2.09		**660,829**	8	8	54		10,817	**2.82**	**0.23**	60	6/07-8/15	**0.03**
1979	3.00	2.93		**970,962**	34	34	76		34,773	**2.60**	**0.17**	16	7/15-7/31	**0.063**
1980	1.00	1.19		**329,778**	9	9	50		11,199	**2.43**	**0.25**	16	7/15-7/31	**0.063**
1981	2.50	1.38		**376,313**	36	36	108		33,745	**0.74**	**0.17**	38	7/15-8/22	**0.093**
1982	0.50	0.23		**63,949**	11	11	33		11,230	**0.13**	**0.25**	23	8/09-9/01	**0.14**
1983	0.30	0.37		**132,205**	23	23	26	3,583	11,195	**0.90**	**0.22**	3.8	8/01-8/05	**0.093**
1984	0.40	0.39		**139,759**	8	8	21	1,245	9,706	**1.09**	**0.23**	13.6	8/01-8/15	**0.107**
1985	0.45	0.43		**146,669**	6	6	72	1,116	13,209	**0.37**	**0.21**	21.7	8/01-8/23	**0.132**
1986	0.42	0.48		**162,438**	3	3		578	4,284	**1.00**	**0.43**	13	8/01-8/25	**0.153**
1987	0.40	0.33		**103,338**	9	9		1,430	10,258	**0.63**	**0.32**	11	8/01-8/12	**0.118**
1988	0.20	0.24		**76,148**	2	2		360	2,350	**1.51**	**0.70**	9.9	8/01-8/11	**0.115**
1989	0.20	0.25		**79,116**	10	10		2,555	5,149	**1.61**	**0.33**	3	8/01-8/04	**0.096**
1990	0.20	0.19		**59,132**	4	4		1,388	3,172	**1.18**	**0.42**	4	8/01-8/05	**0.099**
1991	0.34			**0**	No Summer Fishery									
1992	0.34	0.07		**24,902**	27	27		2,635	5,746	**0.26**	**0.31**	2	8/01-8/03	**0.093**
1993	0.34	0.33		**115,913**	14	20	208	560	7,063	**0.91**	**0.08**	52	7/01-8/28	**0.09**
1994	0.34	0.32		**108,824**	34	52	407	1,360	11,729	**0.81**	**0.05**	31	7/01-7/31	**0.044**
1995	0.34	0.32		**105,967**	48	81	665	1,900	18,782	**0.48**	**0.04**	67	7/01-9/05	**0.066**
1996	0.34	0.22		**74,752**	41	50	264	1,640	10,453	**0.45**	**0.06**	57	7/01-9/03	**0.096**
1997	0.08	0.09		**32,606**	13	15	100	520	2,982	**0.86**	**0.08**	44	7/01-8/13	**0.101**
1998	0.08	0.03	0.00	**10,661**	8	11	50	360	1,639	**0.75**	**0.12**	65	7/01-9/03	**0.088**
1999	0.08	0.02	0.00	**8,734**	10	9	53	360	1,630	**0.78**	**0.12**	66	7/01-9/04	**0.101**
2000	0.33	0.29	0.01	**111,728**	15	22	201	560	6,345	**1.28**	**0.06**	91	7/01- 9/29	**0.11**
2001	0.30	0.28	0.00	**98,321**	30	37	319	1,200	11,918	**0.71**	**0.05**	97	7/01- 9/09	**0.085**
2002	0.24	0.24	0.01	**86,666**	32	49	201	1,120	6,491	**1.23**	**0.06**	77	6/15-9/03	**0.074**
2003	0.25	0.25	0.01	**93,638**	25	43	236	960	8,494	**0.91**	**0.05**	68	6/15-8/24	**0.079**
2004	0.35	0.31	0.03	**120,289**	26	39	227	1,120	8,066	**1.40**	**0.05**	51	6/15-8/08	**0.063**
2005	0.37	0.37	0.03	**138,926**	31	42	255	1,320	8,867	**1.32**	**0.05**	73	6/15-8/27	**0.071**
2006	0.45	0.42	0.03	**150,358**	28	40	249	1,120	8,867	**1.46**	**0.05**	68	6/15-8/22	**0.09**
2007	0.32	0.29	0.02	**110,344**	38	30	251	1,200	9,118	**1.15**	**0.05**	52	6/15-8/17	**0.063**
2008	0.41	0.36	0.03	**143,337**	23	30	248	920	8,721	**1.50**	**0.05**	73	6/23-9/03	**0.063**
2009	0.38	0.37	0.03	**143,485**	22	27	359	920	11,934	**0.94**	**0.04**	98	6/15-9/20	**0.1**
2010	0.40	0.39	0.03	**149,822**	23	32	286	1,040	9,698	**1.35**	**0.05**	58	6/28-8/24	**0.096**
2011	0.36	0.37	0.03	**141,626**	24	25	173	1,040	6,808	**1.66**	**0.05**	33	6/28-7/30	**0.038**
2012	0.47	0.44	0.03	**161,113**	40	29	312	1,200	10,041	**1.42**	**0.04**	72	6/29-9/08	**0.077**
2013	0.50	0.37	0.02	**130,603**	37	33	460	1,420	15,058	**0.72**	**0.04**	74	7/3-9/14	**0.107**
2014	0.38	0.36	0.03	**129,656**	52	33	309	1,560	10,127	**1.23**	**0.05**	52	6/25-8/15	**0.052**

[a] Deadloss included in total. [b] Millions of pounds. [c] Information not available.

Table 2. Historical winter commercial and subsistence red king crab fisheries, Norton Sound Section, eastern Bering Sea, 1977-2013. Bold typed data are used for the assessment model.

	Commercial			Subsistence					
					Permits			Total Crab	
Model Year	Year[a]	# of Fishers	# of Crab Harvested	Winter[b]	Issued	Returned	Fished	Caught[c]	Retained[d]
1978	1978	37	**9,625**	1977/78	290	206	149	**NA**	**12,506**
1979	1979	1[f]	**221[f]**	1978/79	48	43	38	**NA**	**224**
1980	1980	1[f]	**22[f]**	1979/80	22	14	9	**NA**	**213**
1981	1981	0	**0**	1980/81	51	39	23	**NA**	**360**
1982	1982	1[f]	**17[f]**	1981/82	101	76	54	**NA**	**1,288**
1983	1983	5	**549**	1982/83	172	106	85	**NA**	**10,432**
1984	1984	8	**856**	1983/84	222	183	143	**15,923**	**11,220**
1985	1985	9	**1,168**	1984/85	203	166	132	**10,757**	**8,377**
1986	1985/86	5	**2,168**	1985/86	136	133	107	**10,751**	**7,052**
1987	1986/87	7	**1,040**	1986/87	138	134	98	**7,406**	**5,772**
1988	1987/88	10	**425**	1987/88	71	58	40	**3,573**	**2,724**
1989	1988/89	5	**403**	1988/89	139	115	94	**7,945**	**6,126**
1990	1989/90	13	**3,626**	1989/90	136	118	107	**16,635**	**12,152**
1991	1990/91	11	**3,800**	1990/91	119	104	79	**9,295**	**7,366**
1992	1991/92	13	**7,478**	1991/92	158	105	105	**15,051**	**11,736**
1993	1992/93	8	**1,788**	1992/93	88	79	37	**1,193**	**1,097**
1994	1993/94	25	**5,753**	1993/94	118	95	71	**4,894**	**4,113**
1995	1994/95	42	**7,538**	1994/95	166	131	97	**7,777**	**5,426**
1996	1995/96	9	**1,778**	1995/96	84	44	35	**2,936**	**1,679**
1997	1996/97	2[f]	**83[f]**	1996/97	38	22	13	**1,617**	**745**
1998	1997/98	5	**984**	1997/98	94	73	64	**20,327**	**8,622**
1999	1998/99	5	**2,714**	1998/99	95	80	71	**10,651**	**7,533**
2000	1999/00	10	**3,045**	1999/00	98	64	52	**9,816**	**5,723**
2001	2000/01	3	**1,098**	2000/01	50	27	12	**366**	**256**
2002	2001/02	11	**2,591**	2001/02	114	61	45	**5,119**	**2,177**
2003	2002/03	13	**6,853**	2002/03	107	70	61	**9,052**	**4,140**
2004	2003/04	2[f]	**522[f]**	2003/04[g]	96	77	41	**1,775**	**1,181**
2005	2004/05	4	**2,091**	2004/05	170	98	58	**6,484**	**3,973**
2006	2005/06	1[f]	**75[f]**	2005/06	98	97	67	**2,083**	**1,239**
2007	2006/07	8	**3,313**	2006/07	129	127	116	**21,444**	**10,690**
2008	2007/08	9	**5,796**	2007/08	139	137	108	**18,621**	**9,485**
2009	2008/09	7	**4,951**	2008/09	105	105	70	**6,971**	**4,752**
2010	2009/10	10	**4,834**	2009/10	125	123	85	**9,004**	**7,044**
2011	2010/11	5	**3,365**	2010/11	148	148	95	**9,183**	**6,640**
2012	2011/12	35	**9,157**	2011/12	204	204	138	**11,341**	**7,311**
2013	2012/13	26	**22,639**	2012/13	149	148	104	**21,524**	**7,622**
2014	2013/14	21	**14,986**	2013/14	103	103	75	**5,421**	**3,252**

a Prior to 1985 the winter commercial fishery occurred from January 1 - April 30. As of March 1985, fishing may occur from November 15 - May 15.
b The winter subsistence fishery occurs during months of two calendar years (as early as December, through May).
c The number of crab actually caught; some may have been returned.
d The number of crab Retained is the number of crab caught and kept.
f Confidentiality was waived by the fishers.
h Prior to 2005, permits were only given out of the Nome ADF&G office. Starting with the 2004-5 season, permits were given out in Elim, Golovin, Shaktoolik, and White Mountain.

Table 3. Summary of triennial trawl survey Norton Sound male red king crab abundance estimates. Trawl survey abundance estimate is based on 10×10 nmil^2 grid, except for 2010 (20×20 nmil^2).

Year	Dates	Survey Agency	Survey method	Survey coverage: surveyed stations	Stations w/ NSRKC	n mile^2 covered	Abundance ≥74 mm	CV
1976	9/02 - 9/05	NMFS	Trawl	103	62	10260	**4247.5**	**0.31**
1979	7/26 - 8/05	NMFS	Trawl	85	22	8421	**1417.2**	**0.20**
1980	7/04 - 7/14	ADFG	Pots				2092.3	N/A
1981	6/28 - 7/14	ADFG	Pots				2153.4	N/A
1982	7/06 - 7/20	ADFG	Pots				1140.5	N/A
1982	9/05 - 9/11	NMFS	Trawl	58	37	5721	**2791.7**	**0.29**
1985	7/01 - 7/14	ADFG	Pots				2320.4	0.083
1985	9/16 -10/01	NMFS	Trawl	78	49	7688	**2306.3**	**0.25**
1988	8/16 - 8/30	NMFS	Trawl	78	41	7721	**2263.4**	**0.29**
1991	8/22 - 8/30	NMFS	Trawl	52	38	5183	**3132.5**	**0.43**
1996	8/07 - 8/18	ADFG	Trawl	50	30	4938	**1264.7**	**0.317**
1999	7/28 - 8/07	ADFG	Trawl	53	31	5221	**2276.1**	**0.194**
2002	7/27 - 8/06	ADFG	Trawl	57	37	5621	**1747.6**	**0.125**
2006	7/25 - 8/08	ADFG	Trawl	101	45	10008	**2549.7**	**0.288**
2008	7/24 - 8/11	ADFG	Trawl	74	44	7330	**2707.1**	**0.164**
2010[a]	7/27 - 8/09	NMFS	Trawl	35	15	13749	**2041.0**	**0.455**
2011	7/18 - 8/15	ADFG	Trawl	65	34	6447	**2701.7**	**0.133**
2014	7/18 - 7/30	ADFG	Trawl	47	34	4700	**5481.5**	**0.486**

Table 4. Summer commercial catch size/shell compositions. Sizes in this and Tables 5-10 and 12 are mm carapace length. Legal size (4.75 inch carapace width is approximately equal to 124 mm carapace length.

		New Shell						Old Shell					
Year	Sample	74-83	84-93	94-103	104-113	114-123	124+	74-83	84-93	94-103	104-113	114-123	124+
1977	1549	0	0	0.0032	0.4196	0.3422	0.1220	0	0	0	0.0626	0.040	0.0103
1978	389	0	0	0.0103	0.1851	0.473	0.3059	0	0	0	0.0051	0.0103	0.0103
1979	1660	0	0	0.0253	0.2325	0.3831	0.3217	0	0	0	0.0253	0.0006	0.0114
1980	1068	0	0	0.0037	0.0983	0.3062	0.5543	0	0	0	0.0028	0.0112	0.0234
1981	1748	0	0	0.0039	0.0734	0.1541	0.5090	0	0	0	0.0045	0.0504	0.2046
1982	1093	0	0	0.0421	0.1921	0.1647	0.5050	0	0	0.0037	0.0128	0.022	0.0576
1983	802	0	0	0.0387	0.4127	0.3579	0.0973	0	0	0.0037	0.0362	0.010	0.0436
1984	963	0	0	0.0966	0.4195	0.2804	0.0717	0	0	0.0104	0.0654	0.0488	0.0073
1985	2691	0	0.0004	0.0643	0.3122	0.3716	0.1747	0	0	0.0026	0.0334	0.0312	0.0097
1986	1138	0	0	0.029	0.3559	0.3937	0.1353	0	0	0.0018	0.0202	0.0378	0.0264
1987	1542	0	0	0.0166	0.1788	0.2912	0.3798	0	0	0.0025	0.0267	0.0650	0.0393
1988	1522	0.0007	0	0.0237	0.2004	0.3003	0.2181	0	0	0.0059	0.0644	0.0972	0.0894
1989	2595	0	0	0.0127	0.1643	0.3185	0.2148	0	0	0.0042	0.0555	0.1215	0.1084
1990	1289	0	0	0.0147	0.1435	0.3468	0.3251	0	0	0.0008	0.0372	0.0737	0.0582
1991													
1992	2566	0	0	0.0172	0.201	0.2662	0.2244	0	0	0.0027	0.0792	0.1292	0.080
1993	1813	0	0	0.0142	0.2312	0.3939	0.263	0	0	0.0004	0.0173	0.0437	0.0362
1994	404	0	0	0.0248	0.0941	0.0817	0.0891	0	0	0.0248	0.1881	0.25	0.2475
1995	1174	0	0	0.0392	0.2615	0.2853	0.207	0	0	0.0077	0.0486	0.0741	0.0767
1996	787	0	0	0.0318	0.2236	0.2389	0.141	0	0	0.014	0.1194	0.136	0.0953
1997	1198	0	0	0.0292	0.3656	0.3414	0.1244	0	0	0.0033	0.0559	0.0417	0.0384
1998	1055	0	0	0.0284	0.2332	0.2427	0.1071	0	0	0.0218	0.1118	0.1431	0.1118
1999	561	0	0	0.0026	0.2434	0.2698	0.3836	0	0	0	0	0.0423	0.0582
2000	17213	0	0	0.0194	0.2991	0.3917	0.1249	0	0	0.0028	0.0531	0.0654	0.0436
2001	20030	0	0	0.0243	0.2232	0.3691	0.2781	0	0	0.0008	0.0241	0.0497	0.0304
2002	5198	0	0	0.0442	0.2341	0.2814	0.3253	0	0	0.0046	0.0282	0.0419	0.0402
2003	5220	0	0	0.0232	0.3680	0.3197	0.1523	0	0	0.0011	0.0218	0.0465	0.0674
2004	9605	0	0	0.0087	0.3811	0.3880	0.1395	0	0	0.0004	0.0255	0.0347	0.0221
2005	5360	0	0	0.0022	0.2539	0.4709	0.1823	0	0	0	0.0205	0.0451	0.025
2006	6707	0	0	0.0021	0.1822	0.3484	0.199	0	0	0.0003	0.0498	0.1375	0.0807
2007	6125	0	0	0.0111	0.3574	0.3407	0.1714	0	0	0.0008	0.0247	0.0573	0.0366
2008	5766	0	0	0.0047	0.3512	0.3476	0.0668	0	0	0.0014	0.0895	0.0928	0.0461
2009	6026	0	0	0.0105	0.3445	0.3294	0.1339	0	0	0.0012	0.0768	0.0795	0.0242
2010	5902	0	0	0.0053	0.3855	0.3617	0.1095	0	0	0.0019	0.0546	0.0546	0.0271
2011	2552	0	0	0.0043	0.3170	0.3969	0.1387	0	0	0.0020	0.0611	0.0588	0.0212
2012	5056	0	0	0.0026	0.2421	0.4620	0.2067	0	0	0.0002	0.0259	0.0423	0.0182
2013	4203	0	0	0.0044	0.2388	0.3710	0.3020	0	0	0.0003	0.0140	0.0422	0.0272
2014	4682	0	0	0.0085	0.2828	0.2360	0.2565	0	0	0.0002	0.0412	0.0865	0.0882

Table 5. Summer Trawl Survey size/shell compositions.

		New Shell						Old Shell					
Year	Sample	74-83	84-93	94-103	104-113	114-123	124+	74-83	84-93	94-103	104-113	114-123	124+
1976	1311	0.0214	0.1053	0.1915	0.3455	0.1831	0.0290	0.0046	0.0114	0.0252	0.032	0.0366	0.0145
1979	133	0.0151	0.0075	0.0301	0.0752	0.0827	0.0602	0	0.0075	0.0301	0.1203	0.3835	0.188
1982	256	0.0898	0.2031	0.2891	0.2109	0.0352	0.0078	0	0.0156	0.0195	0.043	0.0234	0.0625
1985	311	0.1190	0.2122	0.1865	0.1768	0.0643	0.0193	0	0	0.0193	0.0514	0.0868	0.0643
1988	306	0.2255	0.1405	0.1536	0.1275	0.0686	0.0392	0	0.0065	0.0131	0.0392	0.0882	0.0980
1991	250	0.0967	0.0223	0.0372	0.0743	0.0409	0.0223	0.0706	0.0297	0.0967	0.197	0.1747	0.1375
1996	196	0.2959	0.1786	0.1224	0.0816	0.0051	0.0153	0.0051	0.0357	0.0459	0.0612	0.0612	0.0918
1999	274	0.0109	0.1058	0.2993	0.2701	0.1314	0.0401	0	0.0036	0.0292	0.0511	0.0401	0.0182
2002	230	0.1261	0.1435	0.1565	0.0304	0.0348	0.0348	0.0304	0.0739	0.1087	0.0957	0.0913	0.0739
2006	208	0.3235	0.2614	0.1405	0.0752	0.0458	0.0294	0	0	0.0196	0.0458	0.0458	0.0131
2008	242	0.1743	0.2407	0.1286	0.112	0.0332	0.029	0.0083	0.0498	0.0705	0.0954	0.0125	0.0456
2010	68	0.1202	0.1366	0.2077	0.1257	0.1093	0.0437	0.0109	0.0328	0.082	0.071	0.0383	0.0219
2011	320	0.1282	0.0989	0.1282	0.2051	0.1612	0.0476	0.0037	0.0147	0.0256	0.0989	0.0513	0.0366
2014	361	0.1607	0.2576	0.1939	0.0997	0.0166	0.0233	0	0.0277	0.1053	0.0554	0.0471	0.0139

Table 6. Winter pot survey size/shell compositions.

			New Shell						Old Shell					
Year	CPUE	Sample	74-83	84-93	94-103	104-113	114-123	124+	74-83	84-93	94-103	104-113	114-123	124+
1981/82	NA	243	0.1481	0.3374	0.3169	0.1029	0.0288	0.0247	0	0	0.0041	0.0082	0.0082	0.0206
1982/83	24.2	2520	0.0855	0.2824	0.2854	0.2155	0.0706	0.0085	0	0	0.004	0.0194	0.0097	0.0189
1983/84	24.0	1655	0.1638	0.2626	0.2291	0.1502	0.0601	0.0057	0	0	0.0178	0.065	0.0329	0.0127
1984/85	24.5	773	0.0932	0.2589	0.3618	0.1586	0.057	0.0097	0	0	0.0065	0.0291	0.0239	0.0013
1985/86	19.2	568	0.1276	0.1831	0.2553	0.2025	0.0863	0.0132	0	0	0.015	0.0607	0.044	0.0123
1986/87	5.8	144	0.0556	0.1597	0.1944	0.0694	0.0417	0	0	0	0.0417	0.2986	0.1111	0.0278
1987/88														
1988/89	13.0	492	0.1341	0.1514	0.1352	0.1941	0.1758	0.0346	0	0	0.002	0.0528	0.0854	0.0346
1989/90	21.0	2072	0.0495	0.2075	0.2616	0.1795	0.1221	0.0726	0	0	0.001	0.0263	0.056	0.0239
1990/91	22.9	1281	0.0125	0.0921	0.2857	0.2678	0.096	0.0109	0	0	0.0039	0.0265	0.1163	0.0882
1992/93	5.5	181	0.0055	0.0331	0.0552	0.1271	0.116	0.0276	0	0	0.0166	0.1934	0.2707	0.1547
1993/94														
1994/95	6.2	850	0.0588	0.08	0.0988	0.2576	0.2341	0.0847	0	0	0.0035	0.0329	0.0718	0.0776
1995/96	9.9	776	0.1214	0.1835	0.1733	0.1022	0.0599	0.0265	0	0	0.0181	0.1214	0.1242	0.0695
1996/97	2.9	1582	0.2297	0.2351	0.1189	0.1568	0.1216	0.0676	0	0	0	0.0189	0.027	0.0243
1997/98	10.9	399	0.1395	0.4136	0.2653	0.0544	0.0236	0.0034	0	0	0.0238	0.0317	0.017	0.0272
1998/99	10.7	882	0.0192	0.1168	0.3566	0.3605	0.0838	0.0154	0	0	0.01	0.0223	0.0069	0.0085
1999/00	6.2	1308	0.0885	0.1062	0.1646	0.3345	0.1788	0.0372	0	0	0.0018	0.0513	0.023	0.0142
2000/01	3.1	44												
2001/02	13.0	832	0.3136	0.2763	0.1761	0.0681	0.0668	0.0501	0	0	0.0077	0.0051	0.0154	0.0064
2002/03	9.6	826	0.0994	0.2236	0.2994	0.1801	0.0559	0.0261	0	0	0.0224	0.0273	0.0261	0.0273
2003/04	3.7	286	0.0175	0.1643	0.2622	0.3462	0.1119	0.0105	0	0	0.0175	0.021	0.014	0.0245
2004/05	4.4	406	0.0741	0.1407	0.1827	0.2173	0.1852	0.0765	0	0	0.0025	0.0395	0.0593	0.0173
2005/06	6.0	512	0.1406	0.2266	0.209	0.1563	0.0547	0.0215	0	0	0.0176	0.043	0.0742	0.0352
2006/07	7.3	160	0.1486	0.2095	0.3784	0.1419	0.0473	0	0	0	0.0068	0.0203	0.0405	0
2007/08	25.0	3482	0.1898	0.3219	0.1703	0.1479	0.0672	0.0083	0	0	0.0359	0.0339	0.0155	0.0092
2008/09	21.9	526	0.0706	0.1336	0.3511	0.2023	0.084	0.0134	0	0	0.0019	0.0382	0.0992	0.0057
2009/10	25.3	581	0.047	0.1357	0.2157	0.2452	0.113	0.0191	0	0	0.0591	0.1009	0.0539	0.0104
2010/11	22.1	597	0.0786	0.1368	0.2103	0.1744	0.1333	0.0513	0	0.0120	0.0325	0.1128	0.0462	0.0120
2011/12	29.4	676	0.1155	0.2340	0.1945	0.1246	0.1292	0.0456	0.0030	0.0030	0.0912	0.0532	0.0532	0.0350

Table 7. Summer commercial1987-1994, 2012-2014 observer discards size/shell compositions (Sub legal crab only).

		New Shell						Old Shell					
Year	Sample	74-83	84-93	94-103	104-113	114-123	124+	74-83	84-93	94-103	104-113	114-123	124+
1987	1076	0.2026	0.3625	0.3522	0.0344	0	0	0	0	0.0437	0.0046	0	0
1988	712	0.052	0.184	0.4831	0.139	0	0	0	0	0.0969	0.0449	0	0
1989	911	0.2492	0.3392	0.2371	0.0274	0	0	0	0	0.1196	0.0274	0	0
1990	459	0.2702	0.3203	0.3028	0.0414	0	0	0	0	0.0588	0.0065	0	0
1992	515	0.2175	0.3592	0.332	0.0369	0	0	0	0	0.0447	0.0097	0	0
1994	726	0.1556	0.303	0.1736	0.0262	0	0	0	0	0.2824	0.0592	0	0
2012	738	0.1396	0.2398	0.4106	0.1314	0.0122	0	0.0027	0.0027	0.0298	0.0285	0.0014	0.0014
2013	1457	0.4379	0.2352	0.2520	0.0639	0.0029	0.0012	0.0006	0.0006	0.0035	0.0012	0.0006	0.0006
2014	1675	0.1045	0.2746	0.4322	0.1236	0.0078	0.0024	0.0024	0.0090	0.0230	0.0113	0.0018	0.0006

Table 8 The number of tagged data released and recovered after 1 year (Y1) – 6 year (Y6) by the summer commercial fishery during 1980-1992 and 1993-2014 periods. The two periods were assumed to have different catch selectivities.

Release Length Class	Recap Length Class	1980-1992						1993-2014					
		Y1	Y2	Y3	Y4	Y5	Y6	Y1	Y2	Y3	Y4	Y5	Y6
1	1	0	0	0	0	0	0	0	0	0	0	0	0
1	2	0	0	0	0	0	0	8	0	0	0	0	0
1	3	0	0	0	0	0	0	13	1	0	0	0	0
1	4	0	2	0	0	0	0	3	29	3	0	0	0
1	5	0	0	1	0	2	0	0	2	0	1	0	0
1	6	0	0	0	0	0	0	0	0	0	1	0	0
2	2	0	0	0	0	0	0	0	0	0	0	0	0
2	3	5	0	0	0	0	0	22	2	0	0	0	0
2	4	10	2	0	1	0	0	39	13	3	0	0	0
2	5	0	1	1	1	0	0	3	23	38	2	2	0
2	6	0	0	0	1	1	0	0	1	1	2	1	1
3	3	2	0	0	0	0	0	0	0	0	0	0	0
3	4	32	1	1	0	0	0	77	10	1	0	0	0
3	5	26	3	3	0	0	0	24	3	7	0	0	0
3	6	1	0	2	1	1	0	0	6	2	0	1	0
4	4	15	0	0	0	0	0	8	0	0	0	0	0
4	5	34	14	0	0	0	0	25	0	3	0	1	0
4	6	8	6	3	2	0	0	4	1	1	0	0	1
5	5	15	2	0	0	0	0	19	0	0	0	0	0
5	6	31	10	2	1	0	0	20	1	0	0	0	0
6	6	41	10	3	0	0	0	14	0	0	1	0	0

Length class: 1: 74-83mm, 2:84-93mm, 3:94-103mm, 4:104-113mm, 5:114-123mm, and 6: 124mm+

Table 9. Summary of initial input parameter values and bounds for a length-based population model of Norton Sound red king crab. Parameters with "log_" indicate log scaled parameters.

Parameter	Parameter description	Equation Number in Appendix A	Lower	Upper
log_q_1	Commercial fishery catchability (1977-92)	(20)	-32.5	8.5
log_q_2	Commercial fishery catchability (1993-2014)	(20)	-32.5	10.0
log_N_{76}	Initial abundance	(1)	2.0	15.0
R_0	Mean Recruit	(13)	2.0	12.0
log_σ_R^2	Recruit standard deviation	(13)	-20.0	20.0
a_1	Parameter for intimal length proportion	(2)	-5.0	5.0
a_2	Parameter for intimal length proportion	(2)	-5.0	5.0
a_3	Parameter for intimal length proportion	(2)	-5.0	5.0
a_4	Parameter for intimal length proportion	(2)	-5.0	5.0
a_5	Parameter for intimal length proportion	(2)	-5.0	5.0
r	Proportion of length class 1 for recruit	(14)	0.5	0.9
log_α	Inverse logistic molting parameter	(15)	-5.5	-2.0
log_ϕ_{st1}	Logistic trawl selectivity parameter (NMFS)	(16)	-15.0	-1.0
log_ϕ_{st2}	Logistic trawl selectivity parameter (ADF&G)	(16)	-15.0	-1.0
log_ϕ_w	Logistic winter pot selectivity parameter Or Inverse logistic winter pot selectivity parameter	(15,16)	-10.0	10.0
Sw_6 / Sw_1	Winter pot selectivity of length class 6 (logistic), length class 1 (inverse logistic)	(15,16)	0.1	1.0
log_ϕ_1	Logistic commercial catch selectivity parameter (1977-92)	(16)	-5.0	-1.0
log_ϕ_2	Logistic commercial catch selectivity parameter (1993-2014)	(16)	-5.0	-1.0
w_t^2	Additional varince for standard CPUE	(31)	0.0	6.0
q	Survey q for NMFS trawl 1976-91	(31)	0.1	1.0
σ	Growth transition sigma	(17)	0.0	30.0
β_1	Growth transition mean	(17)	0.0	20.0
β_2	Growth transition increment	(17)	0.0	20.0

Table 10 . Summary of parameter estimates and standard deviations of Norton Sound red king crab.

Name	Estimate	std.dev
log_q_1	-7.1695	0.17949
log_q_2	-7.0052	0.094063
log_N_{76}	9.0903	0.15807
R_0	6.5111	0.069899
$log\_\sigma_R^2$	0.34419	0.4539
log_R_{77}	-0.29935	0.38957
log_R_{78}	-0.74307	0.35276
log_R_{79}	-0.28749	0.37892
log_R_{80}	0.54114	0.27099
log_R_{81}	0.25666	0.28849
log_R_{82}	0.27011	0.32664
log_R_{83}	0.70377	0.26988
log_R_{84}	0.24143	0.30666
log_R_{85}	0.27018	0.30999
log_R_{86}	0.32682	0.268
log_R_{87}	-0.05633	0.2766
log_R_{88}	0.085734	0.26629
log_R_{89}	-0.07167	0.26779
log_R_{90}	-0.55485	0.29819
log_R_{91}	-0.3935	0.27767
log_R_{92}	-0.84682	0.31789
log_R_{93}	-0.61655	0.28252
log_R_{94}	-0.50293	0.27478
log_R_{95}	-0.23298	0.23981
log_R_{96}	0.037987	0.27396
log_R_{97}	0.39147	0.2191
log_R_{98}	-0.67324	0.32479
log_R_{99}	-0.3067	0.30868
log_R_{00}	-0.05292	0.28968
log_R_{01}	0.19657	0.22958
log_R_{02}	0.36501	0.27604
log_R_{03}	-0.2863	0.3422
log_R_{04}	-0.05434	0.29041
log_R_{05}	0.49922	0.20397
log_R_{06}	-0.00669	0.30448
log_R_{07}	0.59322	0.2078
log_R_{08}	0.36102	0.26451
log_R_{09}	-0.00544	0.27545
log_R_{10}	-0.11936	0.2651
log_R_{11}	-0.11415	0.29373
log_R_{12}	0.49332	0.30772
log_R_{13}	0.24683	0.35443
a_1	0.41021	1.8878
a_2	1.873	1.3696
a_3	2.1804	1.3285
a_4	2.4697	1.3048
a_5	1.6508	1.3586
r1	0.62056	0.054306
log_α	-1.7941	0.019085
log_ϕ_{st1}	-14.556	1485
log_ϕ_{st2}		

log_ϕ_w	-1.8158	0.045533
Sw_1	0.42902	0.1003
log_ϕ_1	-1.8039	0.059877
log_ϕ_2		
w^2_t	0.051598	0.017595
q	0.71459	0.1267
σ	4.5222	0.28733
β_1	9.3851	0.79453
β_2	7.8668	0.25217

Table 11. Estimated selectivities, molting probabilities, and proportions of legal crab by length (mm CL) class for Norton Sound male red king crab.

Model 6

			Selectivity			
Length Class	Legal Proportion	Mean weight (lb)	ADFG/ NOAA	Winter Pot	Summer Fishery 77-13	Molting Probability
74 - 83	0.00	0.854	1.00	0.43	0.21	1.00
84 - 93	0.00	1.210	1.00	1.00	0.58	1.00
94 - 103	0.26	1.652	1.00	0.97	0.88	0.97
104 - 113	0.97	2.187	1.00	0.88	0.97	0.87
114 - 123	0.99	2.825	1.00	0.60	0.99	0.56
124+	1.00	3.697	1.00	0.22	1.00	0.20

Table 12: Estimated molting probability incorporated transition matrix.

Model 6: without molting probability

Pre-molt Length Class	Post-molt Length Class					
	74-83	84-93	94-103	104-113	114-123	124+
74-83	0.003	0.306	0.647	0.043	0.000	0.000
84-93	0	0.013	0.477	0.496	0.014	0.000
94-103	0	0	0.039	0.633	0.324	0.004
104-113	0	0	0	0.098	0.723	0.179
114-123	0	0	0	0	0.223	0.777
124+	0	0	0	0	0	1

Model 6: with molting probability

Pre-molt Length Class	Post-molt Length Class					
	74-83	84-93	94-103	104-113	114-123	124+
74-83	0.002	0.225	0.720	0.053	0.000	0.000
84-93	0	0.011	0.452	0.522	0.016	0.000
94-103	0	0	0.058	0.616	0.322	0.004
104-113	0	0	0	0.213	0.631	0.156
114-123	0	0	0	0	0.562	0.438
124+	0	0	0	0	0	1

Table 13. Annual abundance estimates (million crab) and mature male biomass (MMB, million lb) for Norton Sound red king crab estimated by a length-based analysis from 1976 to 2014 Model 6.

	Abundance			Legal (≥ 104 mm)				MMB	
Year	Recruits	Total (≥ 74 mm)	Mature (≥ 94 mm)	Abundance	S.D	Biomass	S.D	Biomass	S.D.
1976	0.949	8.868	6.831	5.086	1.129	12.019	2.852	14.966	3.138
1977	0.499	8.066	6.994	6.176	1.007	16.359	2.786	17.781	2.880
1978	0.320	6.509	5.851	5.380	0.777	15.549	2.339	16.378	2.333
1979	0.505	4.489	4.084	3.808	0.545	11.498	1.723	11.986	1.743
1980	1.155	2.866	2.308	2.143	0.383	6.5815	1.226	6.870	1.251
1981	0.869	2.916	1.676	1.464	0.278	4.431	0.879	4.793	0.924
1982	0.881	2.728	1.668	1.218	0.262	3.314	0.751	4.067	0.877
1983	1.360	2.956	1.927	1.519	0.296	4.019	0.806	4.709	0.908
1984	0.856	3.546	2.038	1.643	0.307	4.413	0.845	5.083	0.947
1985	0.881	3.511	2.428	1.861	0.337	4.952	0.916	5.905	1.063
1986	0.933	3.487	2.460	2.036	0.369	5.504	1.011	6.226	1.114
1987	0.636	3.486	2.405	2.006	0.359	5.554	1.014	6.232	1.107
1988	0.733	3.224	2.431	2.014	0.343	5.612	0.978	6.320	1.064
1989	0.626	3.119	2.278	1.963	0.318	5.552	0.916	6.091	0.978
1990	0.386	2.913	2.164	1.837	0.282	5.241	0.821	5.797	0.880
1991	0.454	2.517	2.025	1.732	0.250	4.952	0.729	5.452	0.776
1992	0.288	2.310	1.791	1.590	0.212	4.618	0.624	4.963	0.651
1993	0.363	1.963	1.600	1.395	0.170	4.094	0.512	4.442	0.534
1994	0.407	1.700	1.288	1.143	0.140	3.360	0.418	3.610	0.436
1995	0.533	1.558	1.090	0.932	0.117	2.715	0.345	2.984	0.369
1996	0.699	1.597	0.996	0.818	0.106	2.316	0.305	2.616	0.334
1997	0.995	1.855	1.067	0.840	0.108	2.298	0.298	2.680	0.338
1998	0.343	2.418	1.305	1.007	0.125	2.688	0.329	3.190	0.396
1999	0.495	2.240	1.729	1.310	0.146	3.440	0.386	4.147	0.440
2000	0.638	2.226	1.671	1.458	0.152	4.000	0.416	4.365	0.441
2001	0.819	2.236	1.515	1.299	0.136	3.692	0.389	4.062	0.422
2002	0.969	2.435	1.510	1.236	0.130	3.474	0.365	3.937	0.404
2003	0.505	2.765	1.658	1.308	0.128	3.574	0.353	4.164	0.384
2004	0.637	2.568	1.900	1.482	0.145	3.966	0.380	4.672	0.472
2005	1.108	2.517	1.793	1.53	0.179	4.180	0.472	4.636	0.514
2006	0.668	2.914	1.700	1.420	0.170	3.969	0.475	4.443	0.516
2007	1.217	2.795	1.942	1.489	0.169	4.028	0.468	4.790	0.525
2008	0.965	3.273	1.941	1.608	0.173	4.363	0.476	4.930	0.523
2009	0.669	3.380	2.211	1.712	0.170	4.605	0.469	5.447	0.520
2010	0.597	3.171	2.339	1.889	0.176	5.084	0.480	5.846	0.540
2011	0.600	2.906	2.196	1.866	0.181	5.160	0.497	5.723	0.534
2012	1.102	2.679	1.978	1.699	0.161	4.807	0.461	5.285	0.485
2013	0.861	2.973	1.771	1.500	0.156	4.265	0.433	4.725	0.489
2014	0.766	3.006	1.962	1.515	0.198	4.147	0.505	4.900	0.645

Table 14. Summary of catch and estimated discards (million lb) for Norton Sound red king crab. Assumed average crab weight is 2.5 lb for the winter commercial catch, 2.0 lb for the subsistence catch, and 1.0 lb for Winter subsistence discards. Summer and winter commercial discards were estimated from the model.

Year	Summer Com	Winter Com	Winter Sub	Discards Summer	Discards Winter Sub	Discards Winter com	Total	Catch/ MMB
1977	0.52	0.000	0.000	0.011	0.000	0.000	0.531	0.03
1978	2.09	0.024	0.025	0.027	0.008	0.000	2.174	0.13
1979	2.93	0.001	0.000	0.034	0.000	0.000	2.965	0.25
1980	1.19	0.000	0.000	0.016	0.000	0.000	1.206	0.18
1981	1.38	0.000	0.001	0.045	0.000	0.000	1.426	0.30
1982	0.23	0.000	0.003	0.012	0.001	0.000	0.246	0.06
1983	0.37	0.001	0.021	0.019	0.006	0.000	0.417	0.09
1984	0.39	0.002	0.022	0.021	0.005	0.000	0.44	0.09
1985	0.43	0.003	0.017	0.022	0.002	0.000	0.474	0.08
1986	0.48	0.005	0.014	0.018	0.004	0.000	0.521	0.08
1987	0.33	0.003	0.012	0.011	0.002	0.000	0.358	0.06
1988	0.24	0.001	0.005	0.008	0.001	0.000	0.255	0.04
1989	0.25	0.001	0.012	0.007	0.002	0.000	0.272	0.04
1990	0.19	0.009	0.024	0.006	0.004	0.000	0.233	0.04
1991	0	0.010	0.015	0.000	0.002	0.000	0.027	0.00
1992	0.07	0.019	0.023	0.002	0.003	0.001	0.118	0.02
1993	0.33	0.004	0.002	0.008	0.000	0.000	0.344	0.08
1994	0.32	0.014	0.008	0.008	0.001	0.000	0.351	0.10
1995	0.32	0.019	0.011	0.011	0.002	0.001	0.364	0.12
1996	0.22	0.004	0.003	0.010	0.001	0.000	0.238	0.09
1997	0.09	0.000	0.001	0.005	0.001	0.000	0.097	0.04
1998	0.03	0.002	0.017	0.002	0.012	0.000	0.063	0.02
1999	0.02	0.007	0.015	0.001	0.003	0.000	0.046	0.01
2000	0.3	0.008	0.011	0.009	0.004	0.000	0.332	0.08
2001	0.28	0.003	0.001	0.010	0.000	0.000	0.294	0.07
2002	0.25	0.006	0.004	0.012	0.003	0.000	0.275	0.07
2003	0.26	0.017	0.008	0.015	0.005	0.001	0.306	0.07
2004	0.34	0.001	0.002	0.016	0.001	0.000	0.36	0.08
2005	0.4	0.005	0.008	0.013	0.003	0.000	0.429	0.09
2006	0.45	0.000	0.002	0.020	0.001	0.000	0.473	0.11
2007	0.31	0.008	0.021	0.016	0.011	0.000	0.366	0.08
2008	0.39	0.014	0.019	0.019	0.009	0.001	0.452	0.09
2009	0.4	0.012	0.010	0.022	0.002	0.001	0.447	0.08
2010	0.42	0.012	0.014	0.017	0.002	0.001	0.466	0.08
2011	0.4	0.008	0.013	0.013	0.003	0.000	0.437	0.08
2012	0.47	0.023	0.015	0.014	0.004	0.001	0.527	0.10
2013	0.35	0.057	0.015	0.017	0.014	0.003	0.456	0.10
2014	0.39	0.037	0.007	0.020	0.002	0.002	0.458	0.09

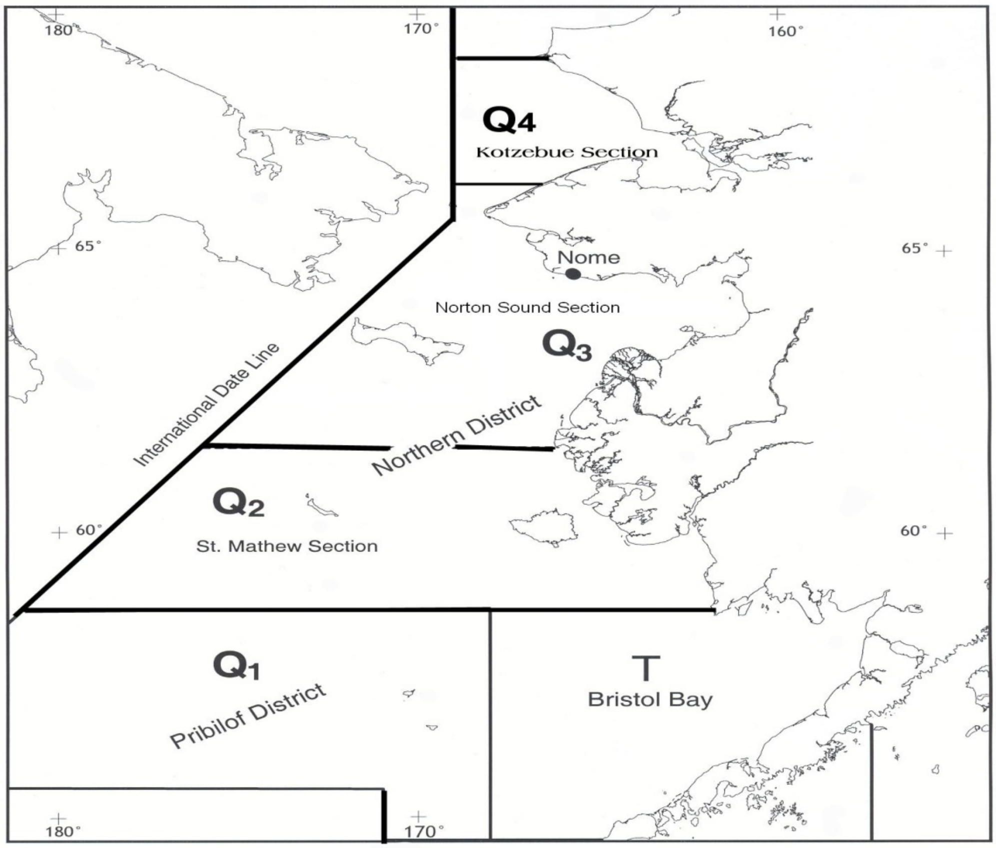


Figure 1. King crab fishing districts and sections of Statistical Area Q.

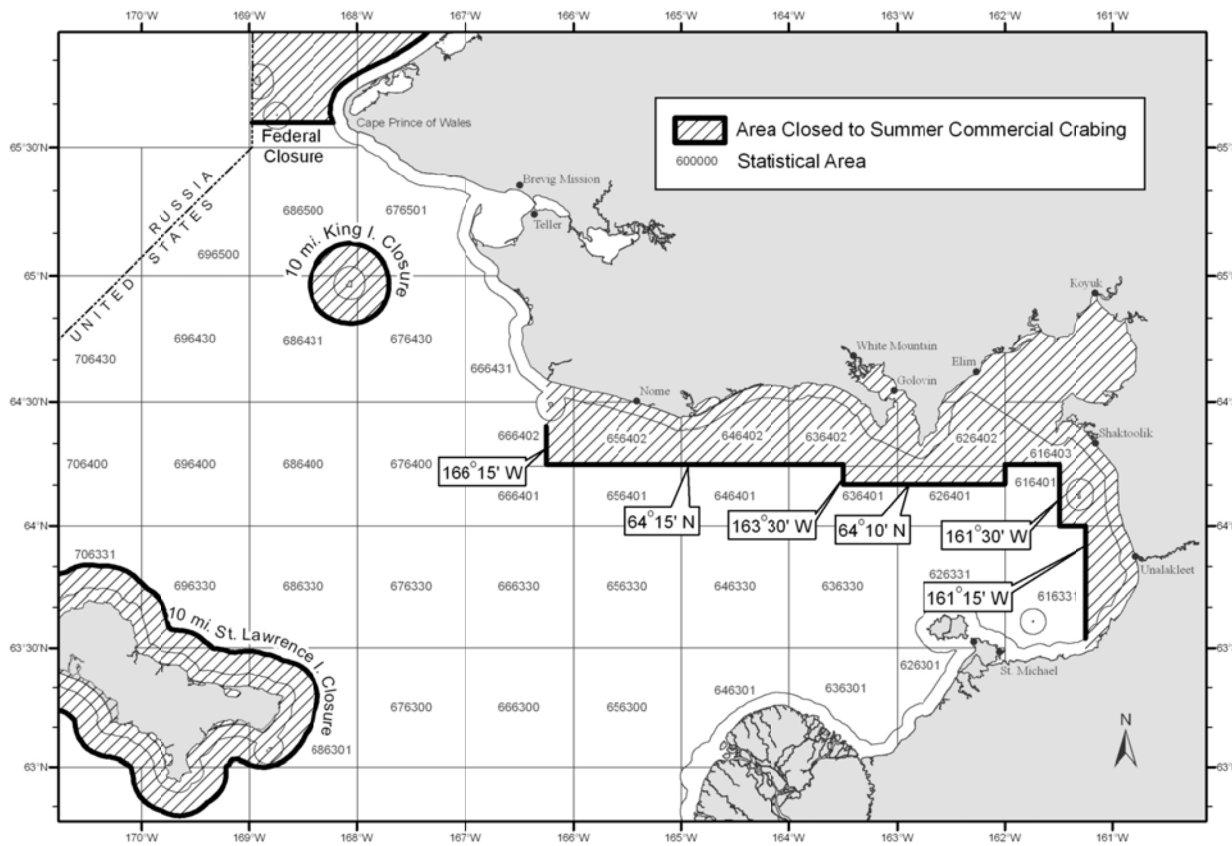
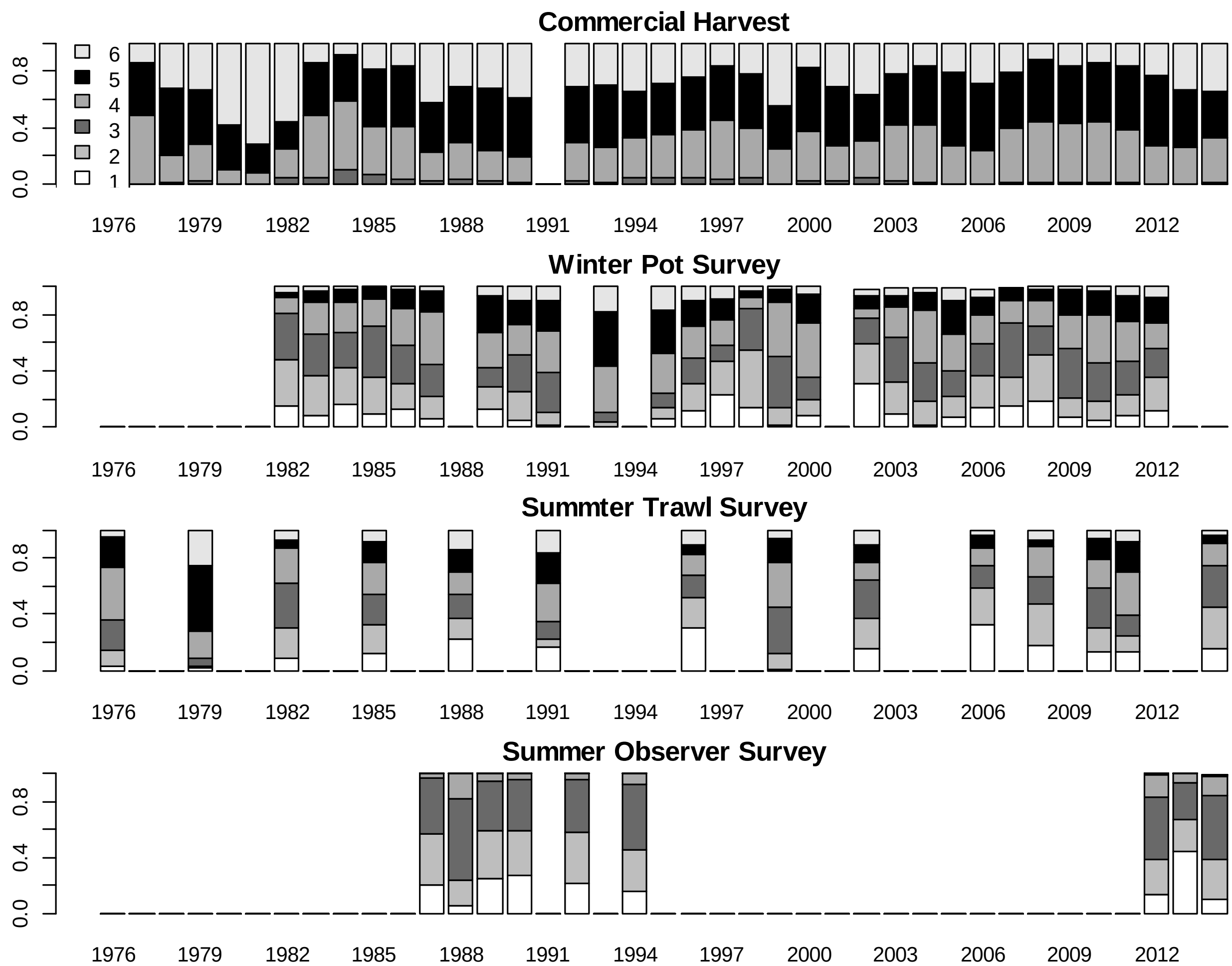


Figure 2. Closed water regulations in effect for the Norton Sound commercial crab fishery.



1: 74-83, 2: 84-93, 3: 94-103, 4: 104-113, 5: 114-123, 6: >124

Figure 3. Observed length compositions 1976-2014.

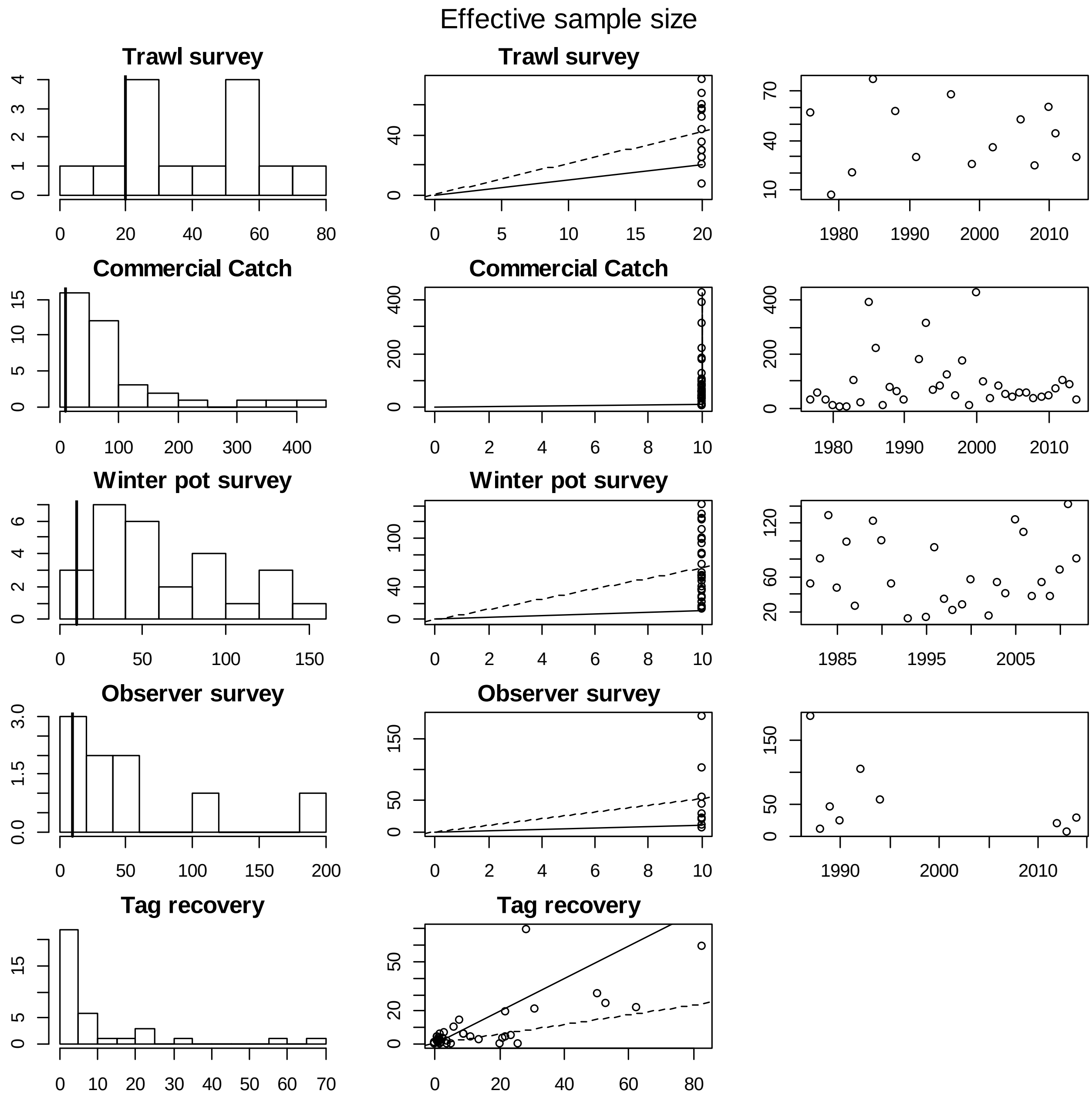


Figure 4. Effective sample size vs. implied sample size. Figures in the first column show effective sample size (x-axis) vs. frequency (y-axis). Vertical solid line is the implied sample size. Figures in the second column show implied sample size (x-axis) vs. effective sample size (y-axis). Dashed line indicates linear regression slope, and solid line is 1:1 line. Figures in the third column show year (x-axis) vs. effective sample size (y-axis).

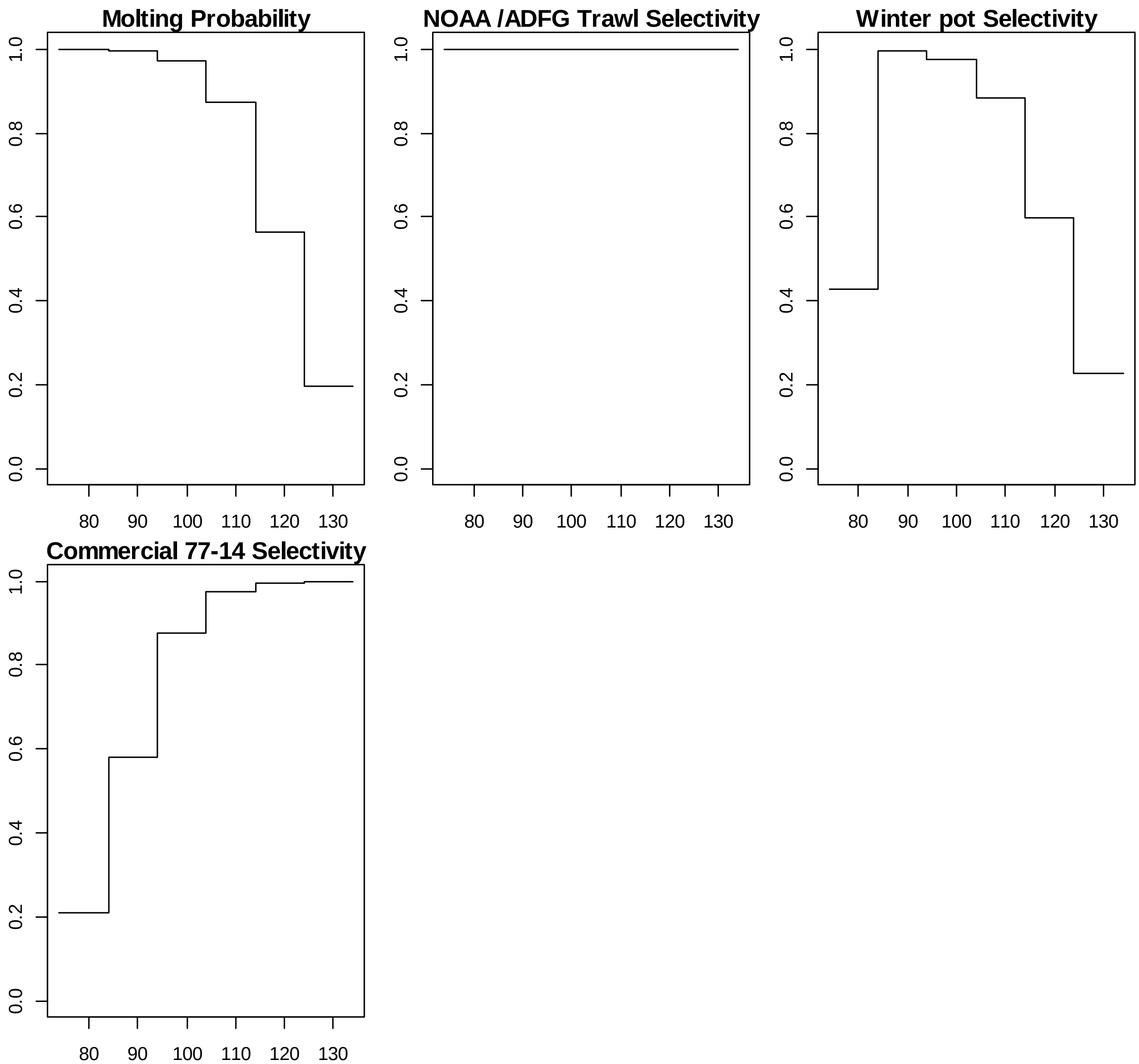


Figure 5. Molting probability and trawl/pot selectivities.

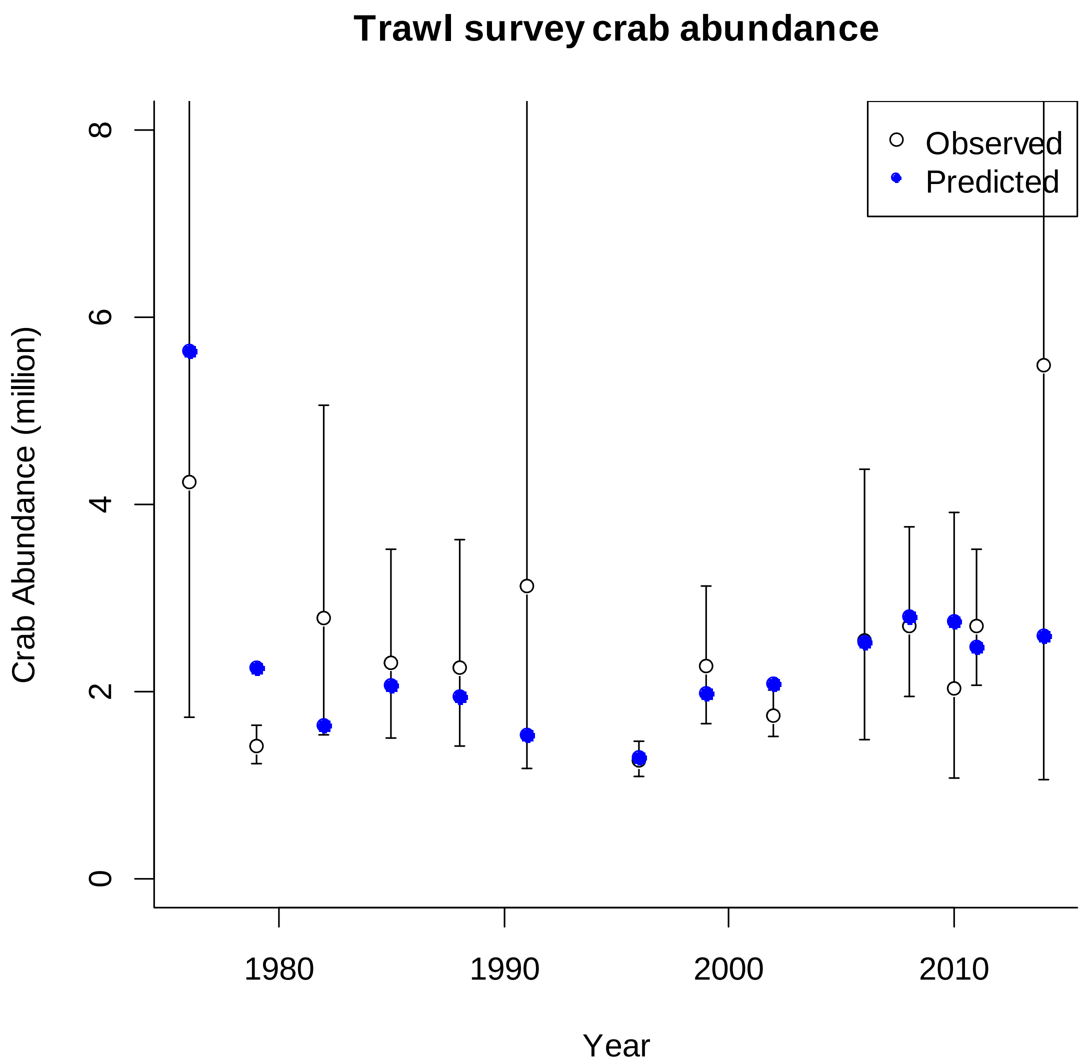


Figure 6. Estimated trawl survey male abundance (crab ≥ 74 mm CL).

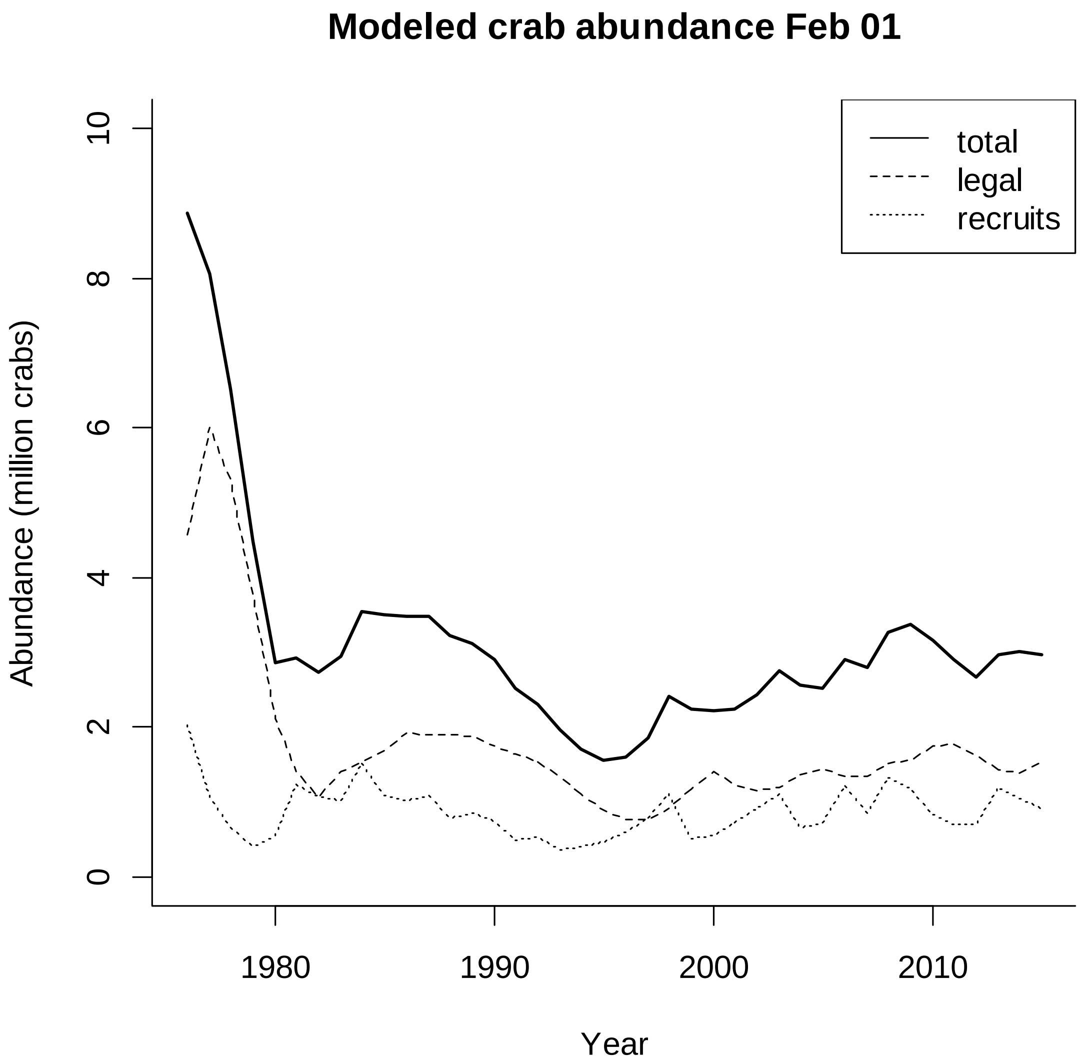


Figure 7. Estimated abundances of legal and recruits males from 1976-2014.

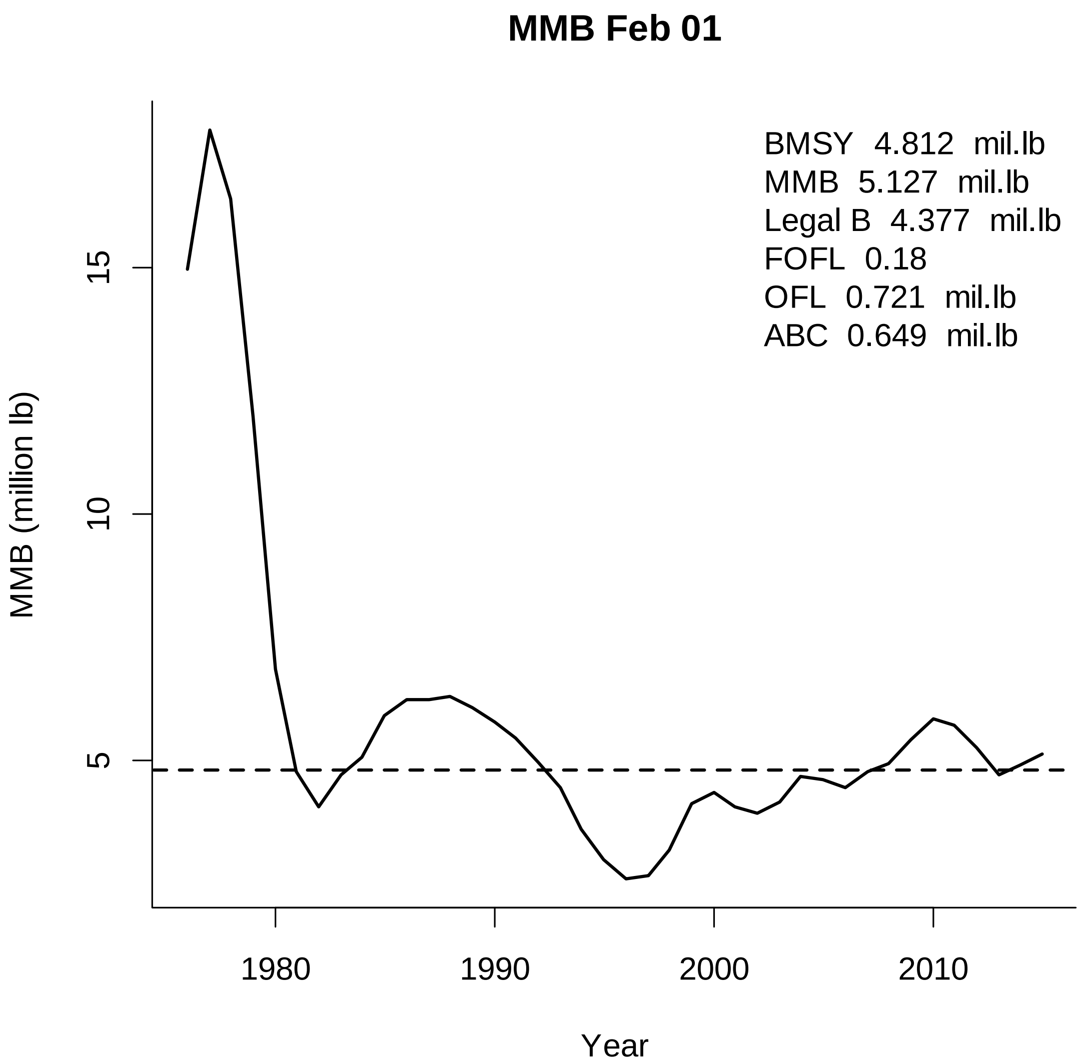


Figure 8. Estimated MMB from 1976-2015. Dash line shows Bmsy (Average MMB of 1980-2015).

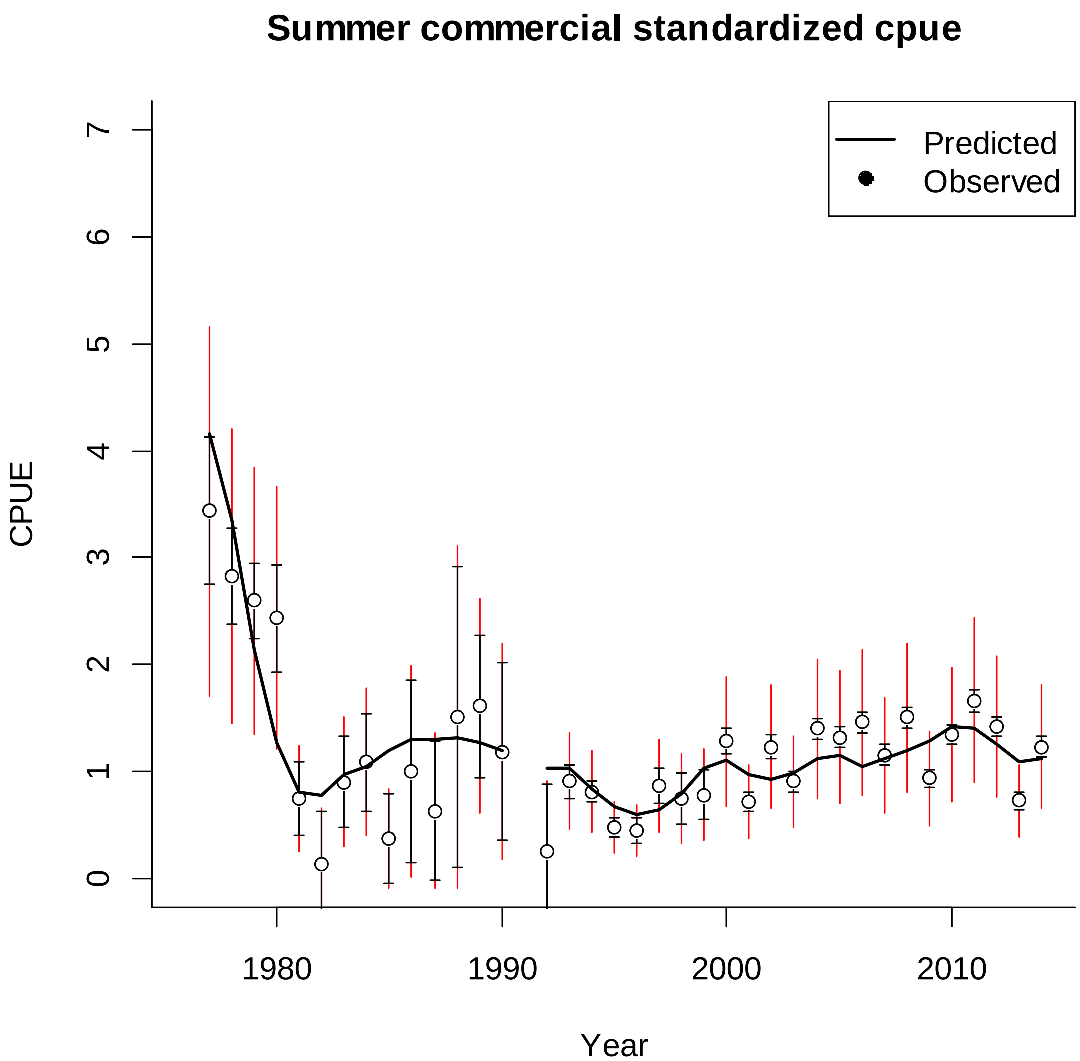


Figure 9. Summer commercial standardized cpue. Black line is input SD and red line is input and estimated additional SD.

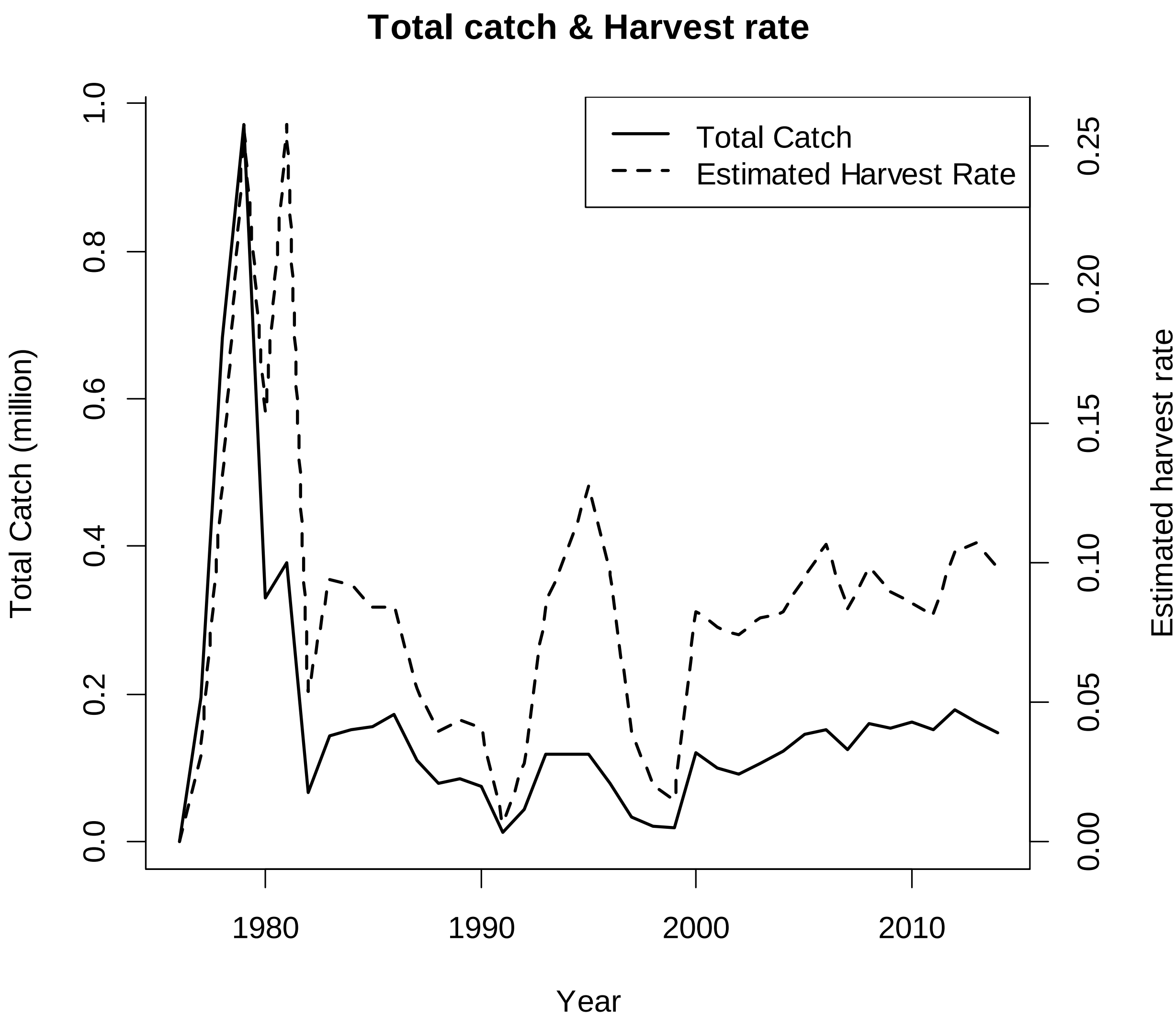


Figure 10. Commercial Catch and estimated harvest rate of legal male.

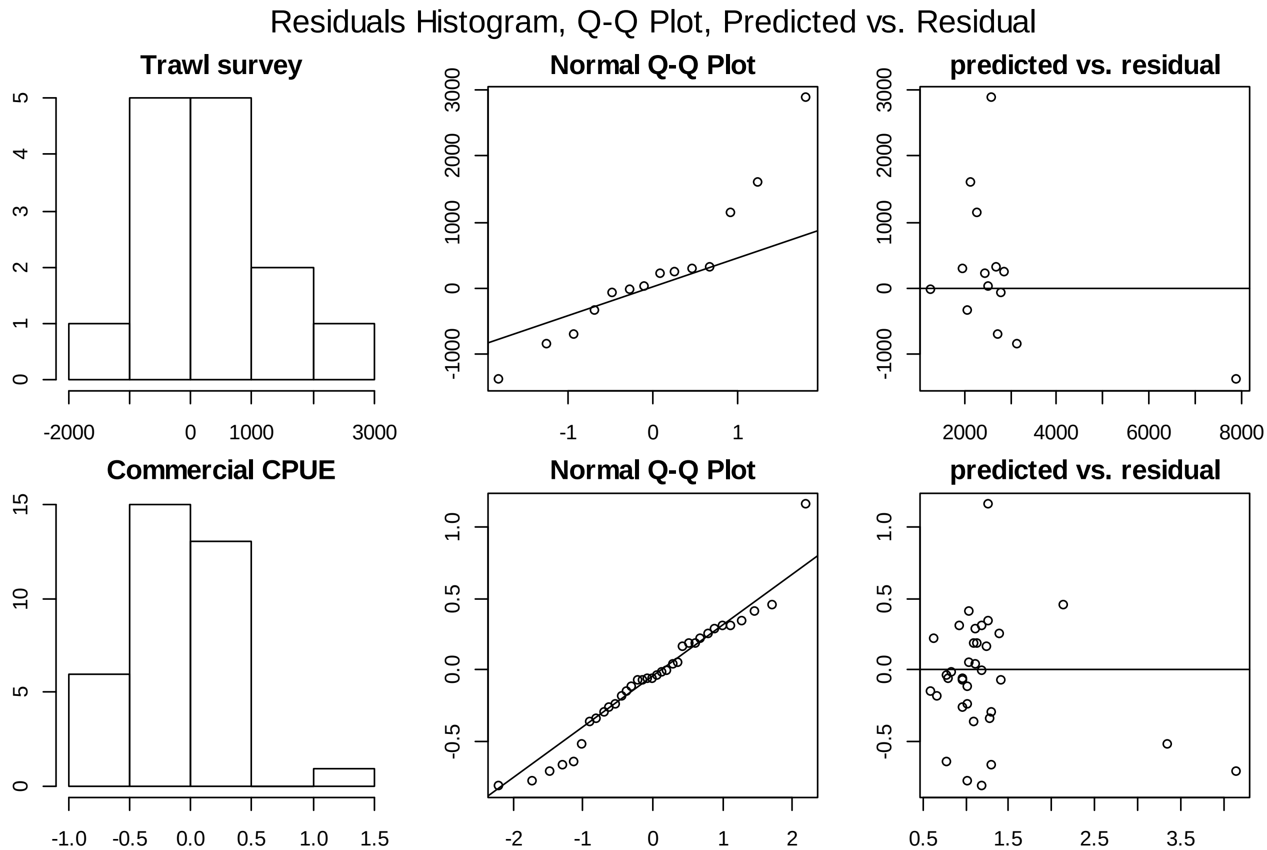
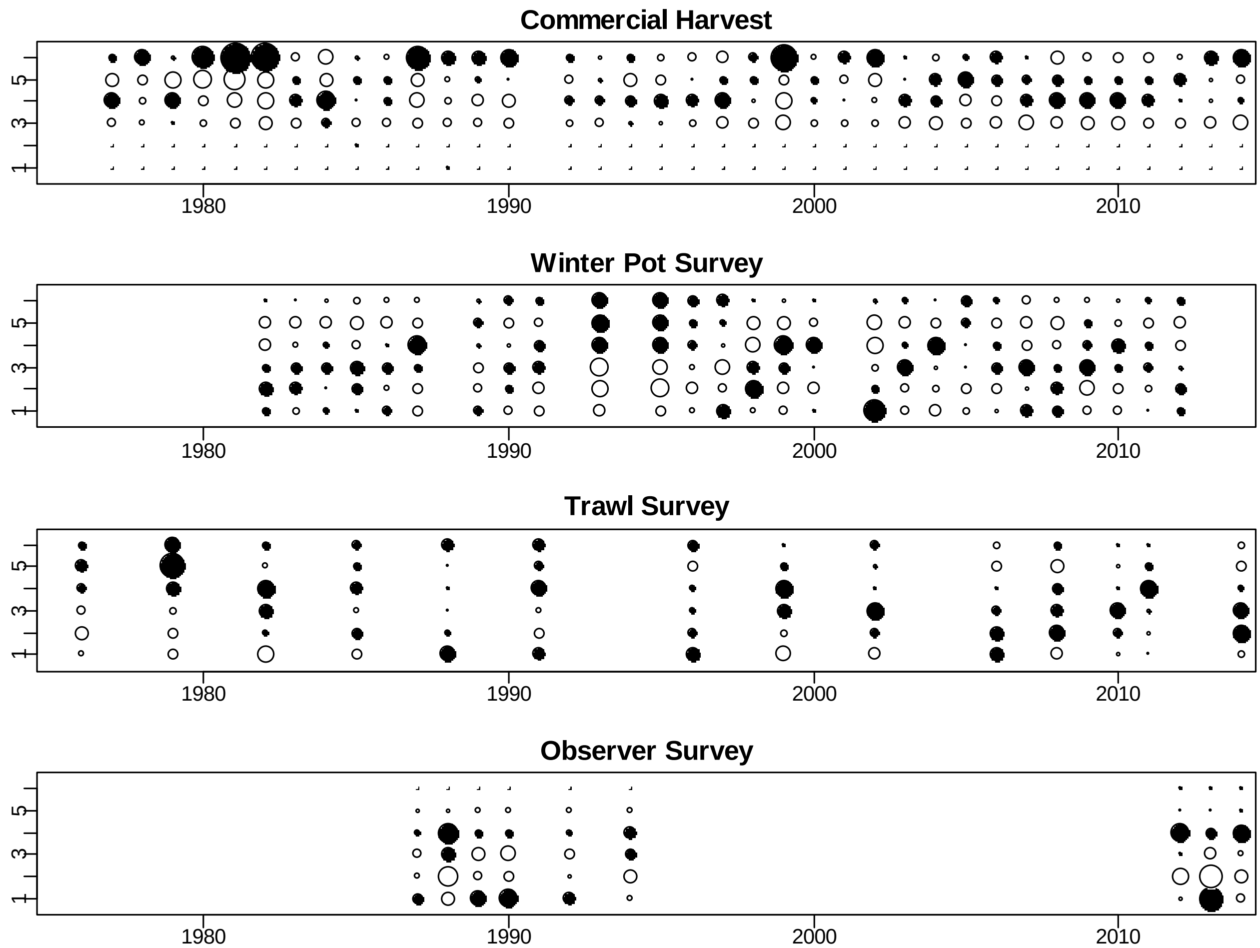


Figure 11. Residual and QQ plot.



1: 74-83, 2: 84-93, 3: 94-103, 4: 104-113, 5: 114-123, 6: >124

Figure 12. Bubble plot of predicted and observed length proportion (Alternative model 0). Black circle indicates model estimates lower than observed, white circle indicates model estimates higher than observed. Size of circle indicate degree of deviance (larger circle = larger deviance).

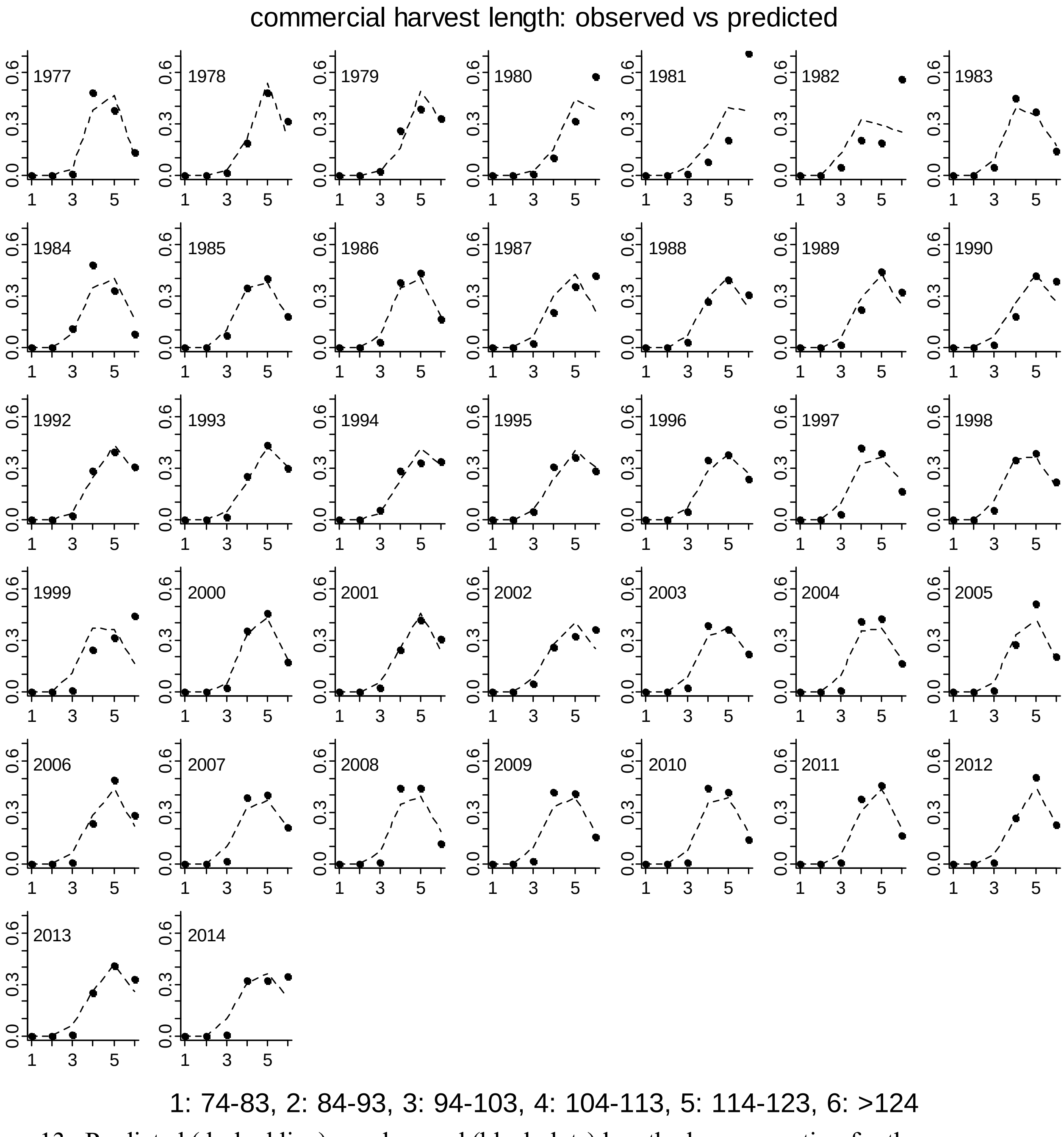
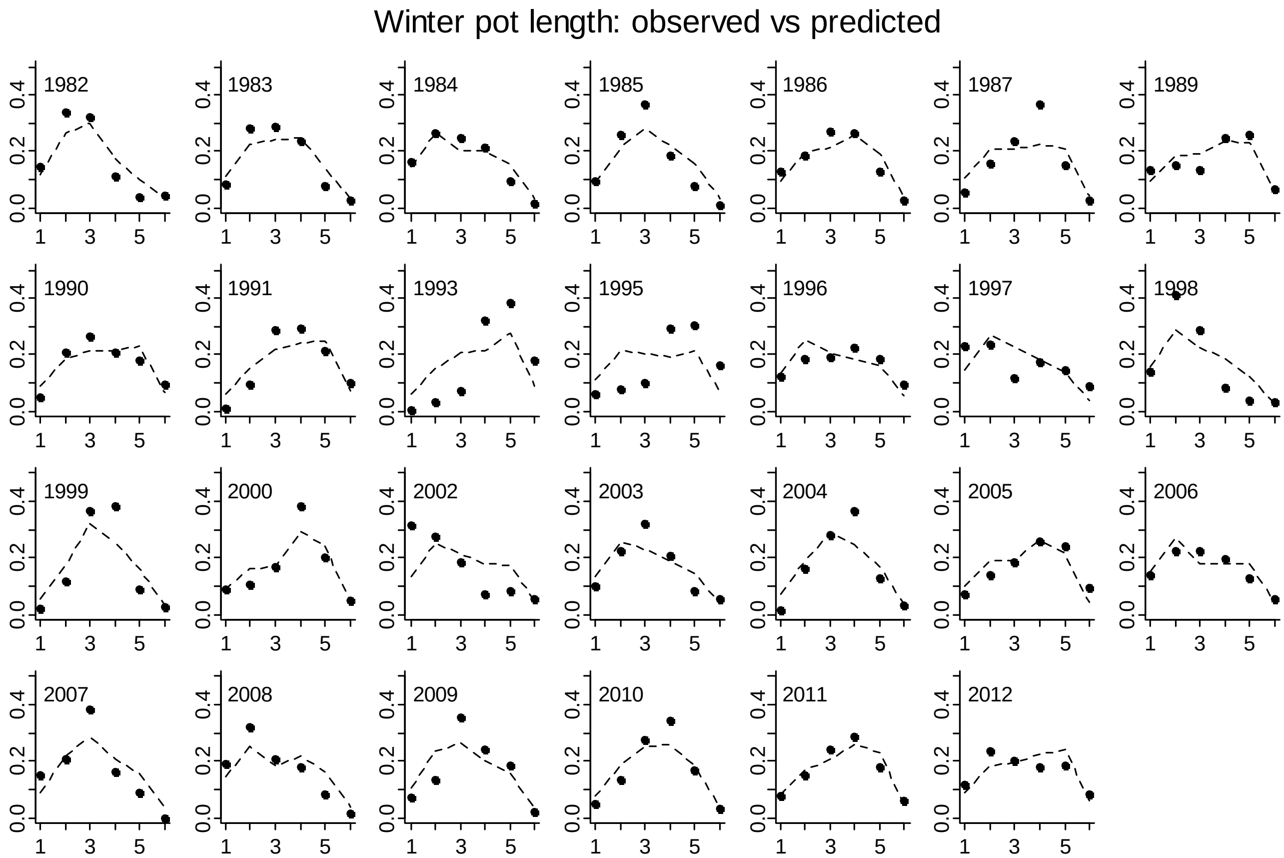
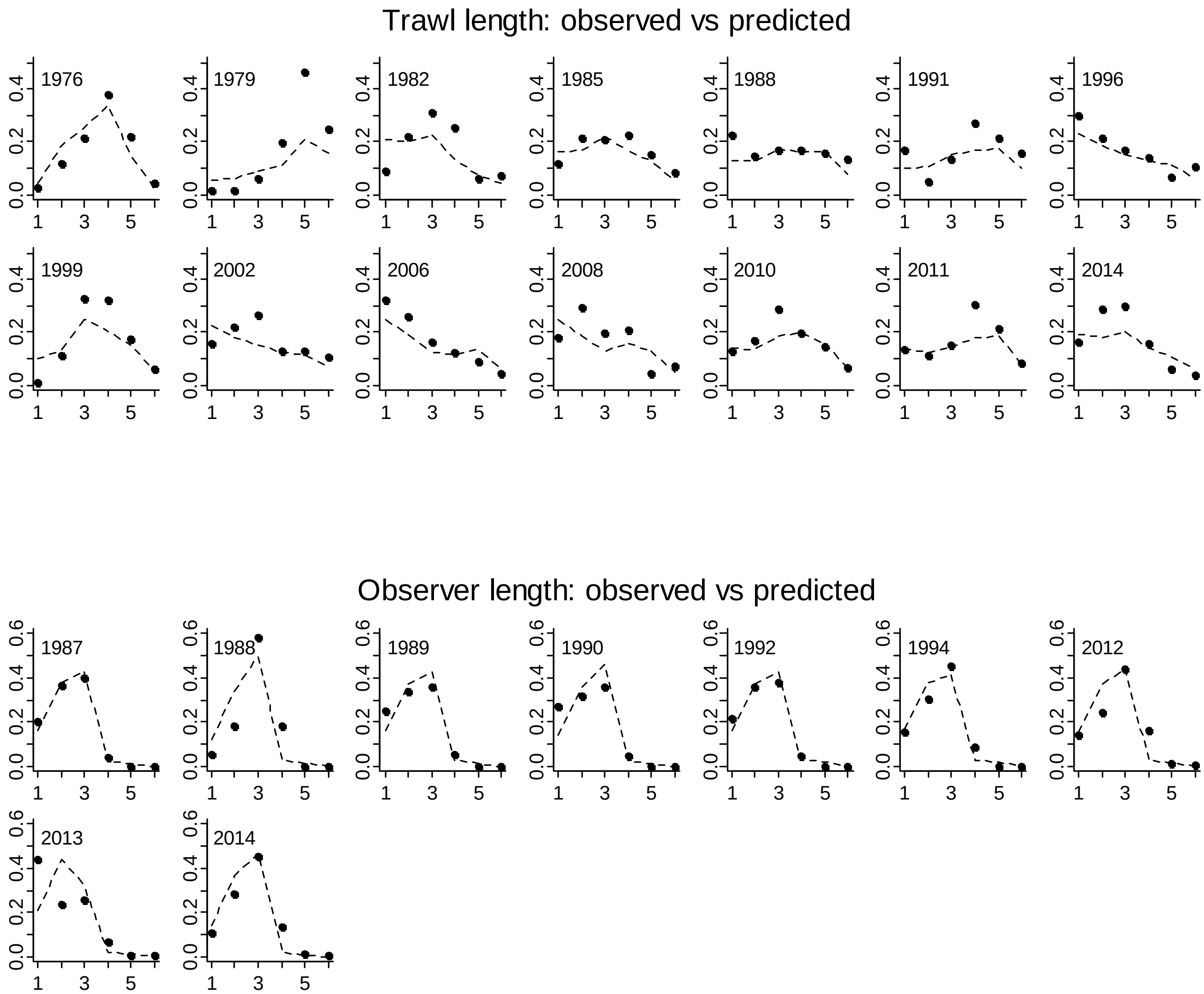


Figure 13. Predicted (dashed line) vs. observed (black dots) length class proportion for the summer commercial catch.



1: 74-83, 2: 84-93, 3: 94-103, 4: 104-113, 5: 114-123, 6: >124

Figure 14. Predicted vs. observed length class proportion for winter pot survey.



1: 74-83, 2: 84-93, 3: 94-103, 4: 104-113, 5: 114-123, 6: >124

Figure 15. Predicted vs. observed length class proportion for trawl survey and commercial observer.

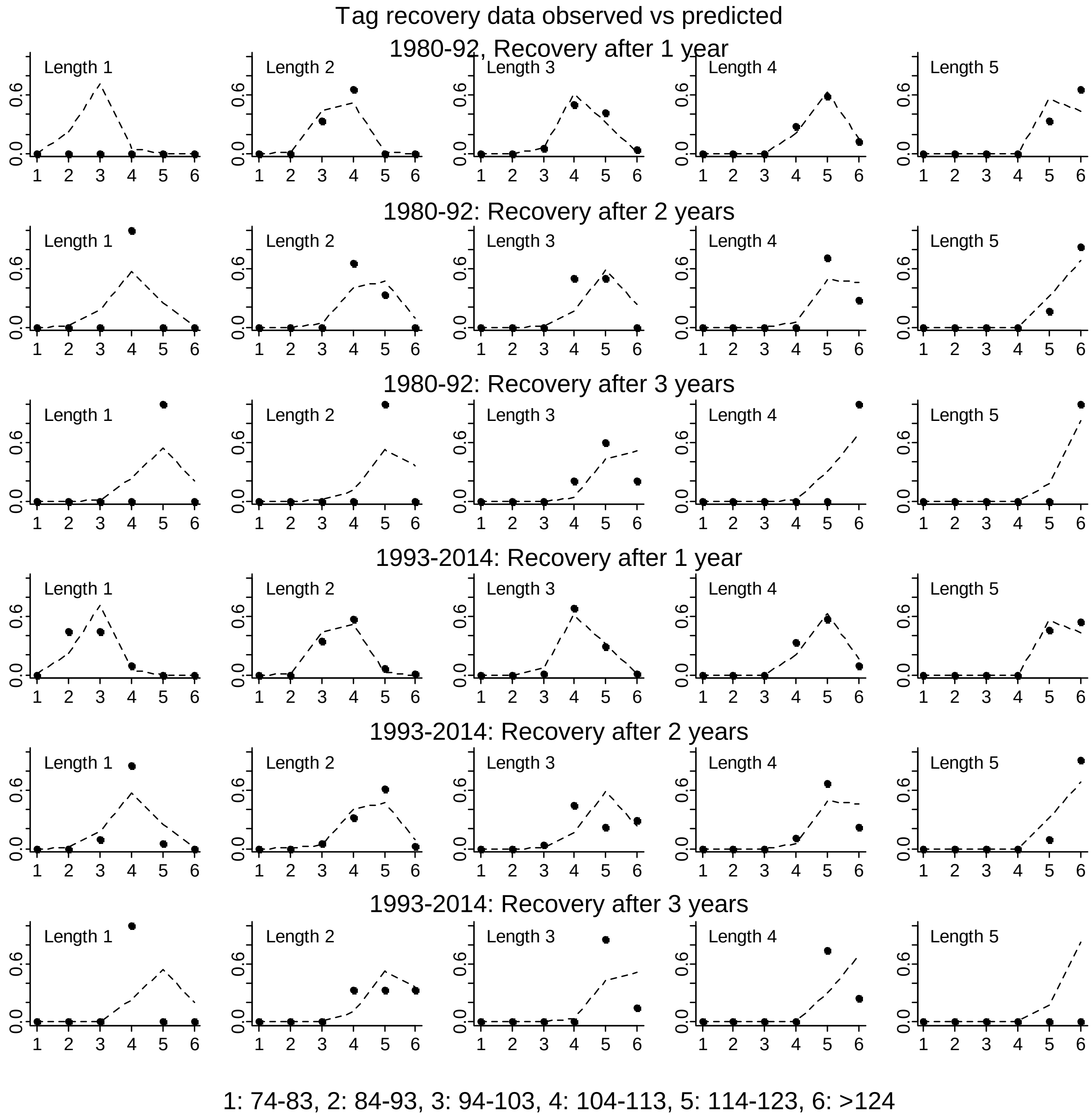


Figure 16. Predicted vs. observed length class proportion for tag recovery data 1980-1992, and 1993-2014.

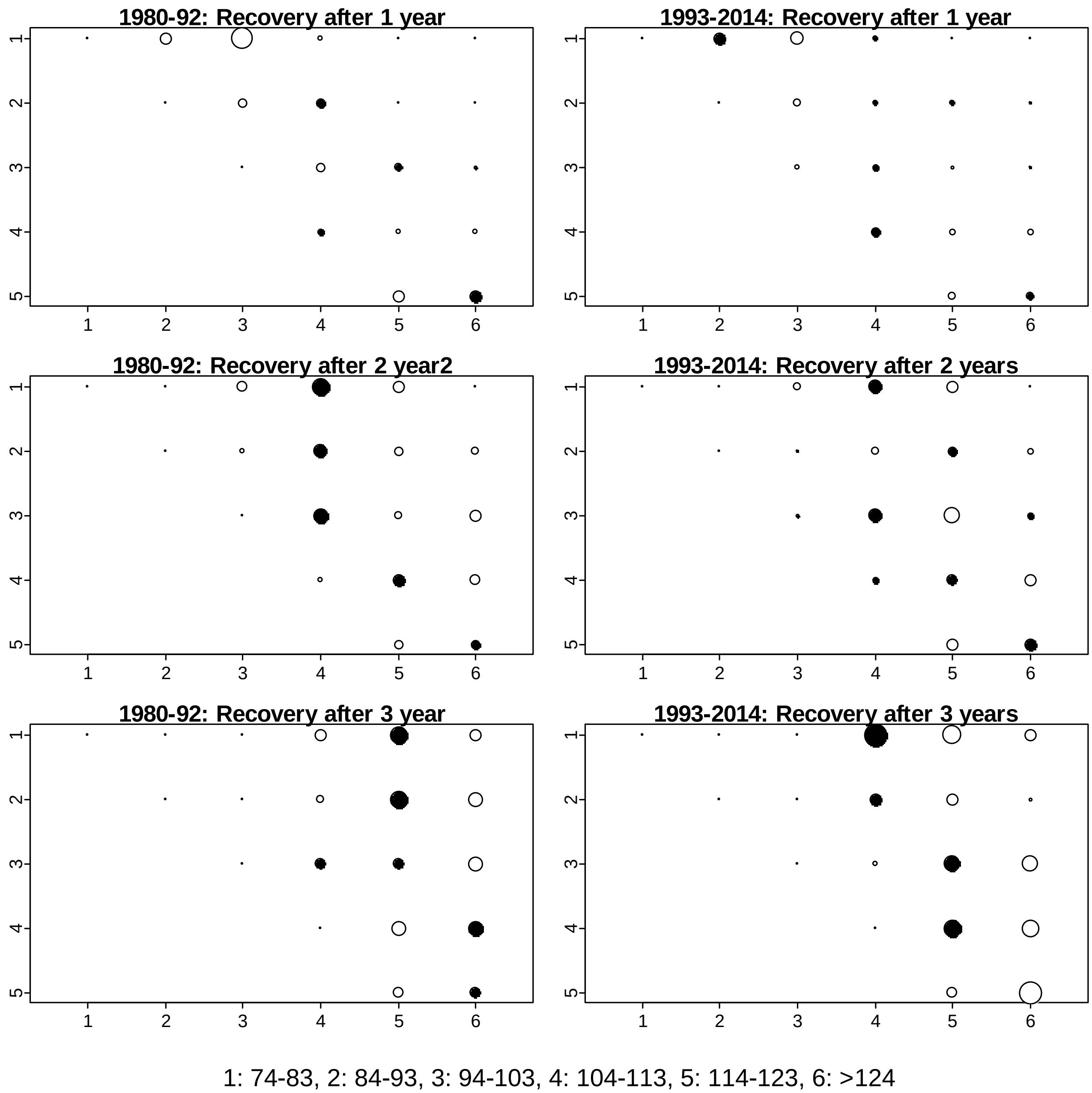


Figure 17. Bubble plot of predicted vs. observed length class proportion for tag recovery data 1980-1992, and 1993-2014.

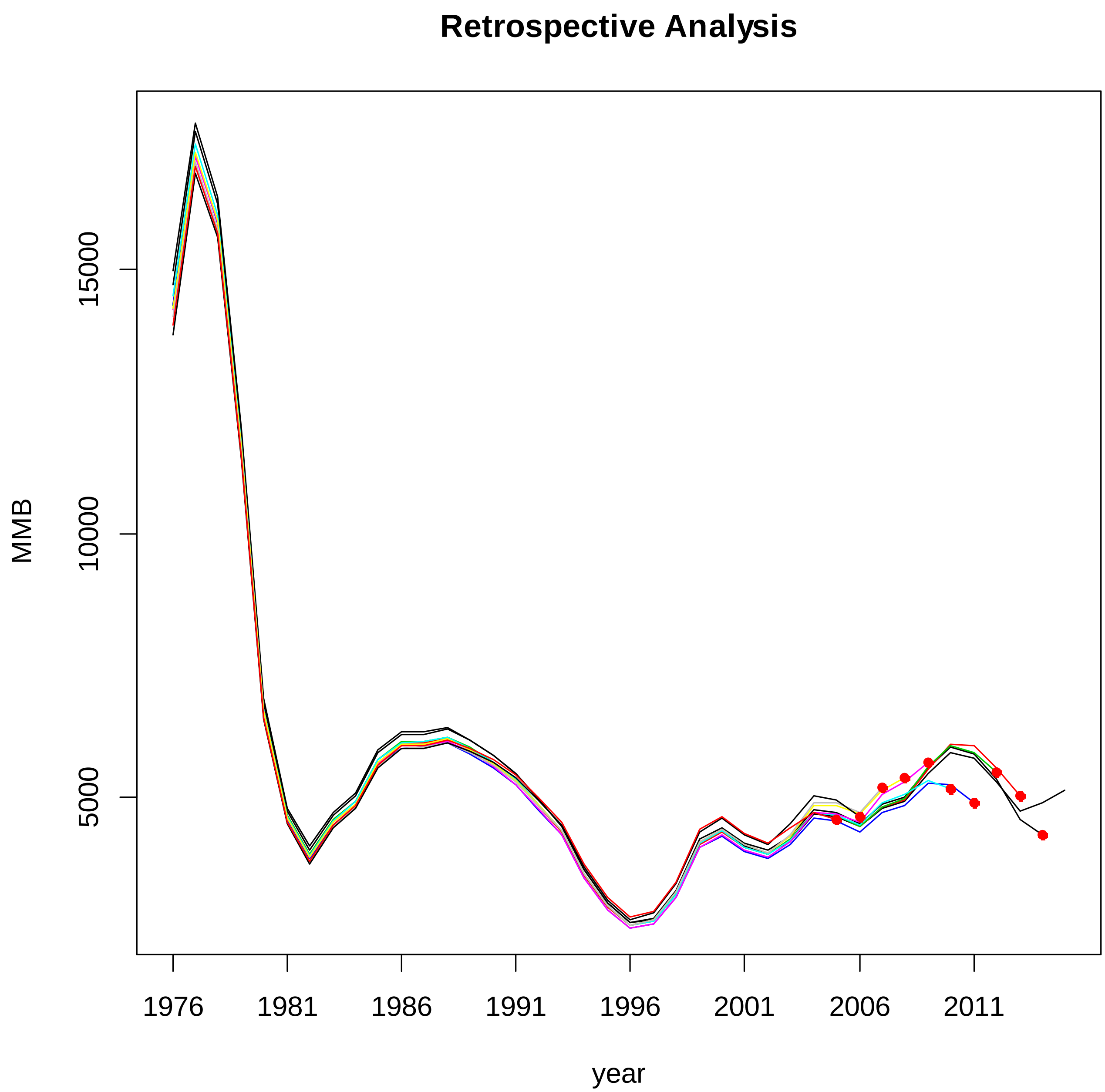


Figure 18. Retrospective analyses. The bold red dot shows retrospectively predicted MMB, and each line shows retrospective MMB.

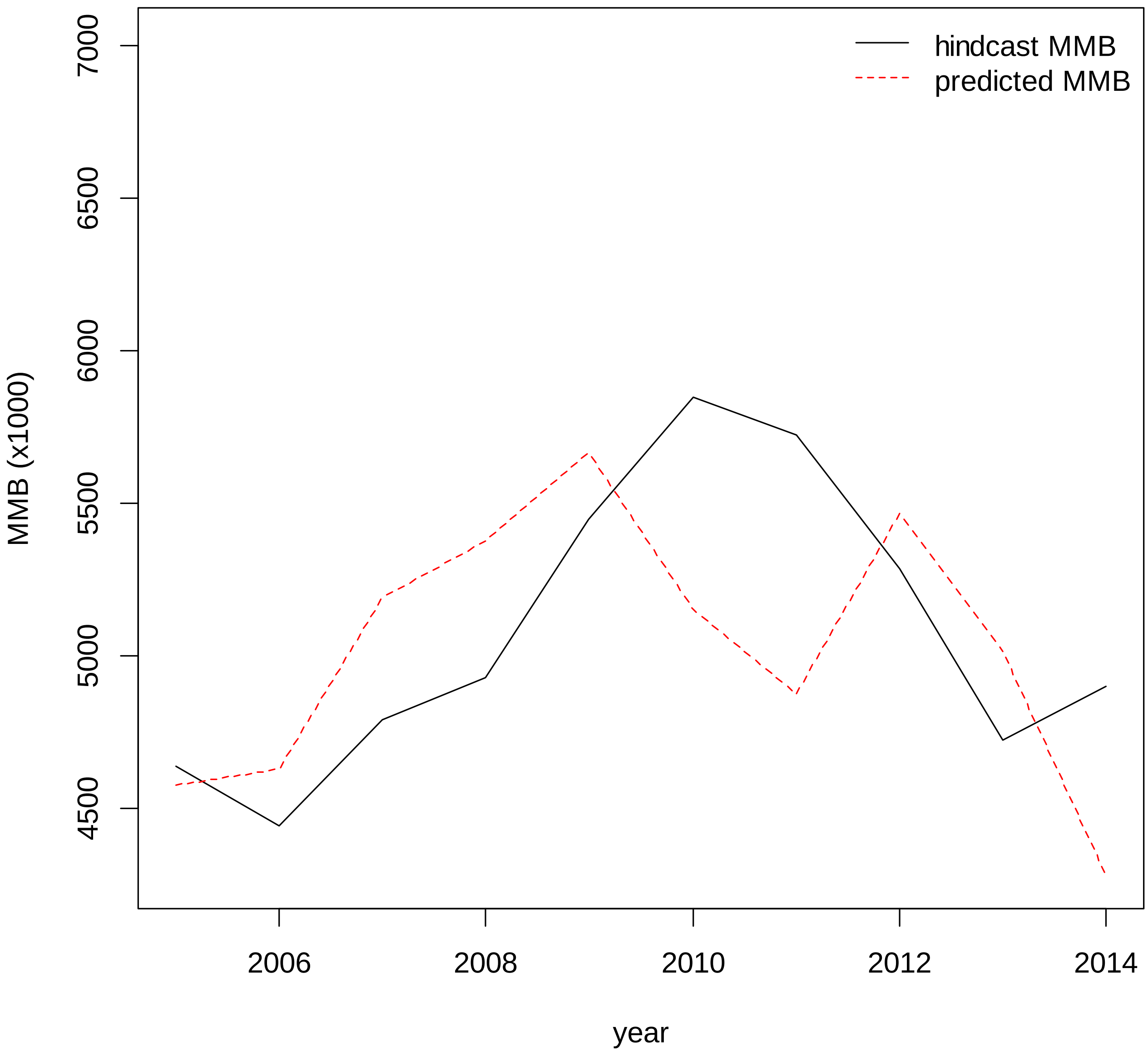
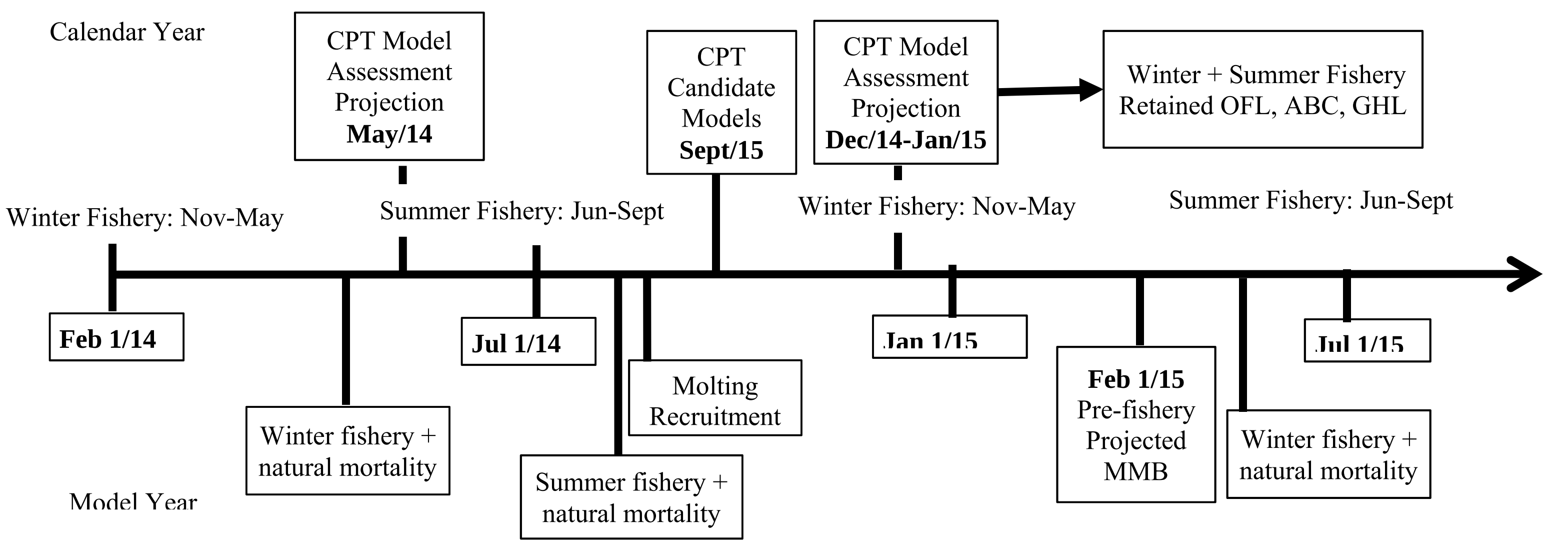


Figure 19. Retrospective analyses 2005-2014. The black line shows retrospective MMB using all (1976-2014) data, and red dash line shows retrospective predicted MMB.

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 6 male length classes with model parameters estimated by the maximum likelihood method. The model estimates abundances of crab with CL ≥74 mm and with 10-mm length intervals (6 length classes) because few crab measuring less than 74 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.



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 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 new and oldshells consists of survivors of winter commercial and subsistence crab fisheries and natural mortality from 01Feb to 01July:

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

where

$N_{s,l,t}$, $O_{s,l,t}$: summer abundances of newshell and oldshell crab in length class *l* in year *t* ,
$N_{w,l,t-1}$, $O_{w,l,t-1}$: winter abundances of newshell and oldshell crab in length class *l* in year *t-1* ,
$C_{w,t-1}$, $C_{p,t-1}$: total winter commercial and subsistence catches in year *t-1*,
$P_{w,n,l,t-1}$, $P_{w,o,l,t-1}$: Proportion of newshell and oldshell length class *l* crab in year *t-1*, harvested by winter commercial fishery,
$P_{p,n,l,t-1}$, $P_{p,o,l,t-1}$: Proportion of newshell and oldshell length class *l* crab in year *t-1*, harvested by winter subsistence fishery,
$D_{w,n,l,t-1}$, $D_{w,o,l,t-1}$: Discard mortality of newshell and oldshell length class *l* crab in winter commercial fishery in year *t-1* ,
$D_{p,n,l,t-1}$, $D_{p,o,l,t-1}$: Discard mortality of newshell and oldshell length class *l* crab in winter subsistence fishery in year *t-1*,
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:

$$P_{w,n,l,t} = N_{w,l,t} S_{w,l} L_l / \sum_{l=1} [(N_{w,l,t} + O_{w,l,t}) S_{w,l} L_l]$$
$$P_{w,o,l,t} = O_{w,l,t} S_{w,l} L_l / \sum_{l=1} [(N_{w,l,t} + O_{w,l,t}) S_{w,l} L_l] \quad (4)$$

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

The 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

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

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 ($R_{l,t}$) .

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

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:

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

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
$P_{s,n,l,t}$, $P_{s,o,l,t}$: proportion of summer catch for newshell and oldshell crabs of length class l in year t,
$D_{l,t}$: summer discard mortality of length class l in year t,
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,
$R_{l,t}$: recruitment into length class l in year t.

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 Catchx(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

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

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

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

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,

Winter subsistence Discards

Discards of winter subsistence fishery is reported in a permit survey ($C_{d,t}$), though its catch 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 come from only length classes 1 and 2 so that

$$\begin{aligned} R_{1,t} &= r\, R_t \\ R_{2,t} &= (1-r)\, R_t \end{aligned} \tag{14}$$

where r is a positive parameter with a value less than or equal to 1. $R_{l,t} = 0$ when $l \geq 3$.

Molting Probability

Molting probability for length class l, m_l, was fitted as a decreasing logistic function of length-class mid carapace length and constrained to equal 0.99 for the smallest length-class (L_1):

$$m_l = \frac{1}{1 + e^{(\alpha(L_1 - L) + \ln(1/0.01 - 1))}} \tag{15}$$

Trawl net and pot selectivity

For efficiency of estimating model parameters, the above equation was modified, so that selectivity reaches 0.999 at the mid-length of the largest lengths class (L_6)

$$S_l = \frac{1}{1 + e^{(\phi(L_6 - L) + \ln(1/0.999 - 1))}} \tag{16}$$

For summer trawl survey, two selectivity curves with parameters (ϕ_{st1}, ϕ_{st2}) were estimated: 1) during NMFS survey 1976-1991, and 2) during ADF&G survey since 1996. Similarly, two selectivity curves with parameters (ϕ_1, ϕ_2) were estimated for the summer commercial fishery: 1) before 1993, and 2) 1933 to present reflecting changes in fisheries, and crab pot configurations.

For winter pot survey and winter harvest parameter (ϕ_w), selectivity ($S_{w,l}$) was assumed to be dome shaped, with $S_{w,5}$ =0.999, and $S_{w,6}$ was directly estimated from the model.

Growth transition matrix

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

Growth matrix was assumed to be normally distributed

$$G_{l',l} = \begin{cases} \dfrac{\int_{lm_l - h}^{lm_l + h} N(L \mid \mu_{l'}, \sigma^2) dL}{\sum_{l=1}^{n} \int_{lm_l - h}^{lm_l + h} N(L \mid \mu_{l'}, \sigma^2) dL} & \text{when } l \geq l' \\ 0 & \text{when } l < l' \end{cases} \tag{17}$$

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 *t-th* year ($B_{st,t}$) is July 1st abundance subtracted by summer commercial fishery harvest occurring from the July 1st to the mid-point of summer trawl survey, multiplied by natural mortality occurring between 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.

$$\hat{B}_{st,t} = \sum_{l}[(N_{s,l,t} + O_{s,l,t})e^{-y_c M_l} - C_{s,t} P_{c,t}(P_{s,n,l,t} + P_{s,o,l,t})]e^{-(y_{st} - y_c)M_l} S_{st,l} \tag{18}$$

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),
$P_{c,t}$: proportion of summer commercial crab harvested before the mid-point of trawl survey date.

Winter pot survey CPUE

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

$$\hat{f}_{wt} = q_w \sum_{l}[(N_{w,l,t} + O_{w,l,t})S_{w,l}] \tag{19}$$

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.

$$\hat{f}_t = q_i(A_t - 0.5C_t) \tag{20}$$

Because 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

$$A_t = \sum_{l}[(N_{s,l,t} + O_{s,l,t})S_{s,l}L_l] \tag{21}$$

Summer pot survey abundance (Removed from likelihood components)
Abundance of t-th year pot survey was estimated as

$$\hat{B}_{p,t} = \sum_{l}[(N_{s,l,t} + O_{s,l,t})e^{-y_p M_l}]S_{p,l} \tag{22}$$

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:

$$\hat{P}_{s,n,l,t} = N_{s,l,t} S_{s,l} L_l / A_t$$
$$\hat{P}_{s,o,l,t} = O_{s,l,t} S_{s,l} L_l / A_t \tag{23}$$

Summer commercial fishery discards

Length/shell compositions of observer discards were modeled as

$$\hat{P}_{b,n,l,t} = N_{s,l,t} S_{s,l} (1 - L_l) / \sum_l [(N_{s,l,t} + O_{s,l,t}) S_{s,l} (1 - L_l)]$$
$$\hat{P}_{b,o,l,t} = O_{s,l,t} S_{s,l} (1 - L_l) / \sum_l [(N_{s,l,t} + O_{s,l,t}) S_{s,l} (1 - L_l)] \tag{24}$$

Summer trawl survey

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

$$\hat{P}_{st,n,l,t} = \frac{[N_{s,l,t} e^{-y_c M_l} - C_{s,t} P_{c,t} \hat{P}_{s,n,l',t}] e^{-(y_{st} - y_c) M_l} S_{st,l}}{\sum_l [(N_{s,l,t} + O_{s,l,t}) e^{-y_c M_l} - C_{s,t} P_{c,t} (\hat{P}_{s,n,l',t} + \hat{P}_{s,o,l',t})] e^{-(y_{st} - y_c) M_l} S_{st,l}}$$
$$\hat{P}_{st,o,l,t} = \frac{[O_{s,l,t} e^{-y_c M_l} - C_{s,t} \hat{P}_{s,o,l',t} P_{c,t}] e^{-(y_{st} - y_c) M_l} S_{st,l}}{\sum_l [(N_{s,l,t} + O_{s,l,t}) e^{-y_c M_l} - C_{s,t} P_{c,t} (\hat{P}_{s,n,l,t} + \hat{P}_{s,o,l,t})] e^{-(y_{st} - y_c) M_l} S_{st,l}} \tag{25}$$

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

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

Summer pre-season survey (1976) (Removed from likelihood due to only 1 year of survey)

The same selectivity for the summer commercial fishery was applied to the summer pre-season survey, resulting in estimated length compositions for both newshell and oldshell crab as:

$$\hat{P}_{sf,n,l,t} = N_{s,l,t} S_{s,l} / \sum_{l} [(N_{s,l,t} + O_{s,l,t}) S_{s,l}]$$
$$\hat{P}_{sf,o,l,t} = O_{s,l,t} S_{s,l} / \sum_{l} [(N_{s,l,t} + O_{s,l,t}) S_{s,l}] \tag{27}$$

This was not incorporated into likelihood calculation because of one year data.

Summer pot survey (1980-82, 85) (Removed from likelihood with failure to locate original data)

The length/shell condition compositions of summer pot survey were estimated as

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

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 proportional to the growth matrix, catch selectivity, and molting probability (m_l) as

$$\hat{P}_{l',l,t,s} = \frac{S_l \cdot [X^t]_{l',l}}{\sum_{l=1}^{n} S_l \cdot [X^t]_{l',l}} \tag{29}$$

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

$$X_{l',l} = \begin{cases} m_{l'} \cdot G_{l',l} & \text{when } l' \neq l \\ m_l \cdot G_{l',l} + (1\text{-}m_i) & \text{when } l' = l \end{cases} \tag{30}$$

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

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:

$$\sum_{i=1}^{i=4}\sum_{t=1}^{t=n_i} K_{i,t}\left[\sum_{l=1}^{l=6} P_{i,l,t}\ln(\hat{P}_{i,l,t}+\kappa) - \sum_{l=1}^{l=6} P_{i,l,t}\ln(P_{i,l,t}+\kappa)\right]$$
$$-\sum_{t=1}^{t=n_i}\frac{[\ln(q\cdot\hat{B}_{i,t}+\kappa)-\ln(B_{i,t}+\kappa)]^2}{2\cdot ln(CV_{i,t}^2+1)}$$
$$-\sum_{t=1}^{t=n_i}\left[\frac{\ln\left[\ln(CV_t^2+1)+w_t\right]}{2}+\frac{[\ln(\hat{f}_t+\kappa)-\ln(f_t+\kappa)]^2}{2\cdot\left[\ln(CV_t^2+1)+w_t\right]}\right] \tag{31}$$
$$-\sum_{t=1}\frac{\tau_t^2}{2\cdot SDR^2}$$
$$+W\sum_{s=1}^{s=2}\sum_{t=1}^{t=3}\sum_{l'=1}^{l'=6} K_{l',t,s}\left[\sum_{l=1}^{l=6} P_{l',l,t}\ln(\hat{P}_{l',l,t,s}+\kappa) - \sum_{l=1}^{l=6} P_{l',l,t}\ln(P_{l',l,t,s}+\kappa)\right]$$

where

i: length/shell compositions of :

1 triennial summer trawl survey,
2 annual winter pot survey,
3 summer commercial fishery,
4 observer discards during the summer fishery.

n_i: the number of years in which data set *i* is available,
$K_{i,t}$: 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.*
In this, while observation and estimation were made for oldshell and newshell separately, both were combined for likelihood calculations.
κ : a constant equal to 0.001,
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_w : Standard deviation of winter survey CPUE = 0.3,
SDR : Standard deviation of recruitment = 0.5,
$K_{l',t}$: the effective sample size of length class *l'* released and recovered after *t-th* in year,
$K_{l',t}$: the effective 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*,
s: fishery selectivity (1) 1976-1992, (2) 1993- present,
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.

e. 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

f. 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 of 3 to 6

$$MMB = \sum_{l=3} (N_{s,l,} + O_{s,l,}) wm_l$$

wm_l: mean weight of each length class (Table 11).

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

$$Legal\_B = \sum_{l} (N_{s,l,} + O_{s,l,}) S_{s,l} L_l wm_l$$

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

Appendix B1. Likelihood profile for weights: Using model 0

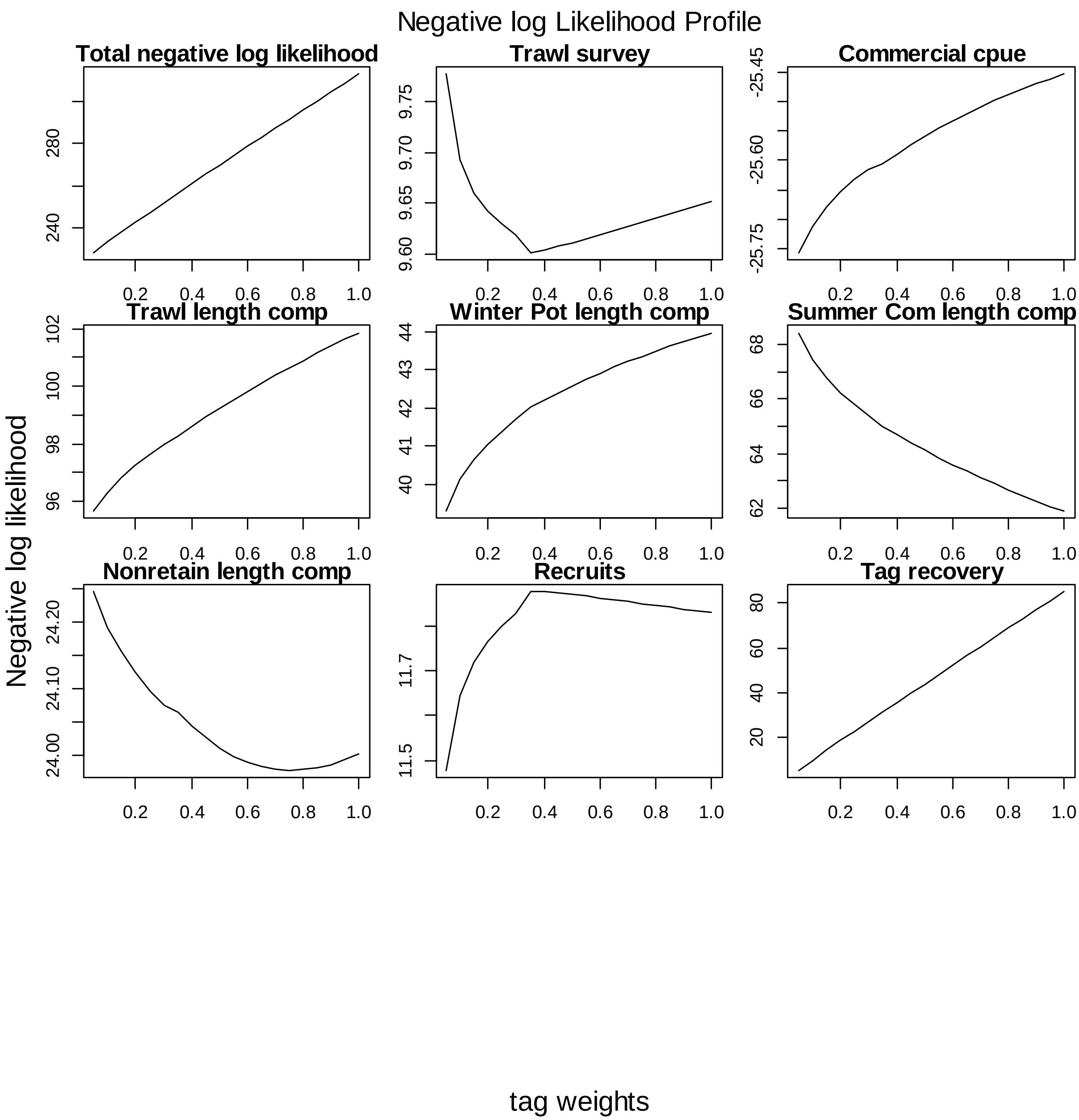


Figure B1-1. Negative log-likelihood.

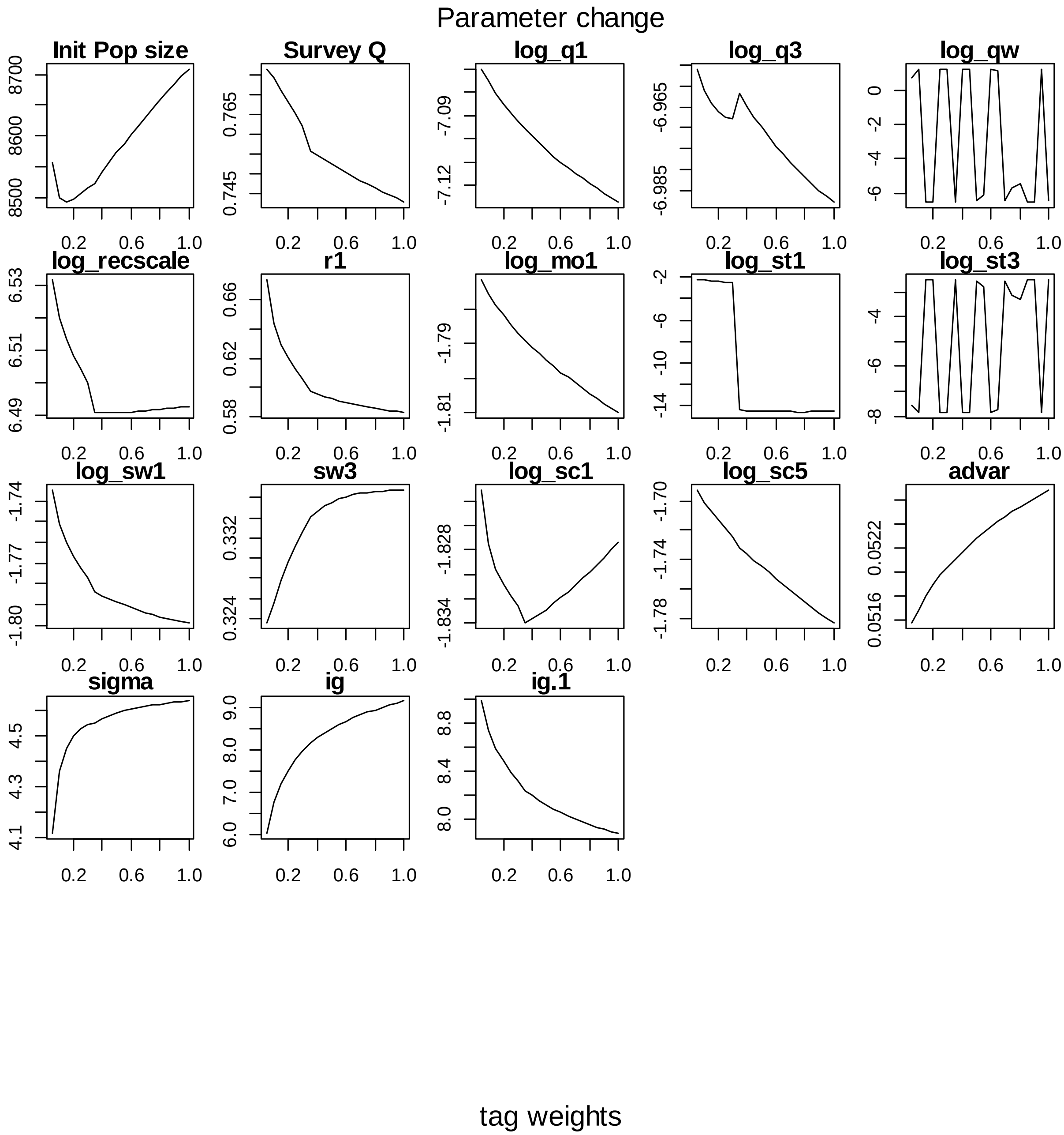


Figure B1-2. Changes in Parameter value.

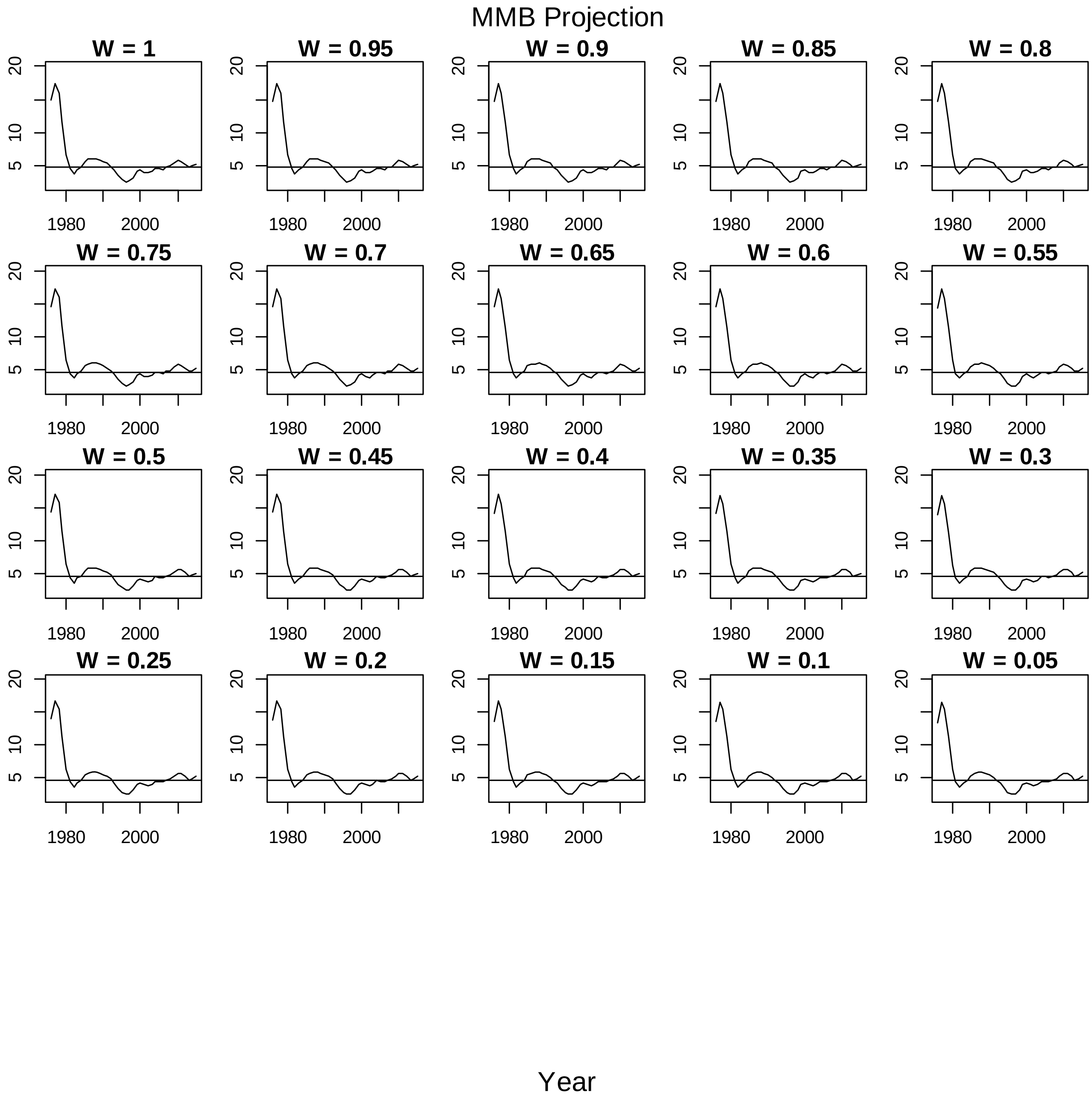


Figure B1-3. MMB projection changes.

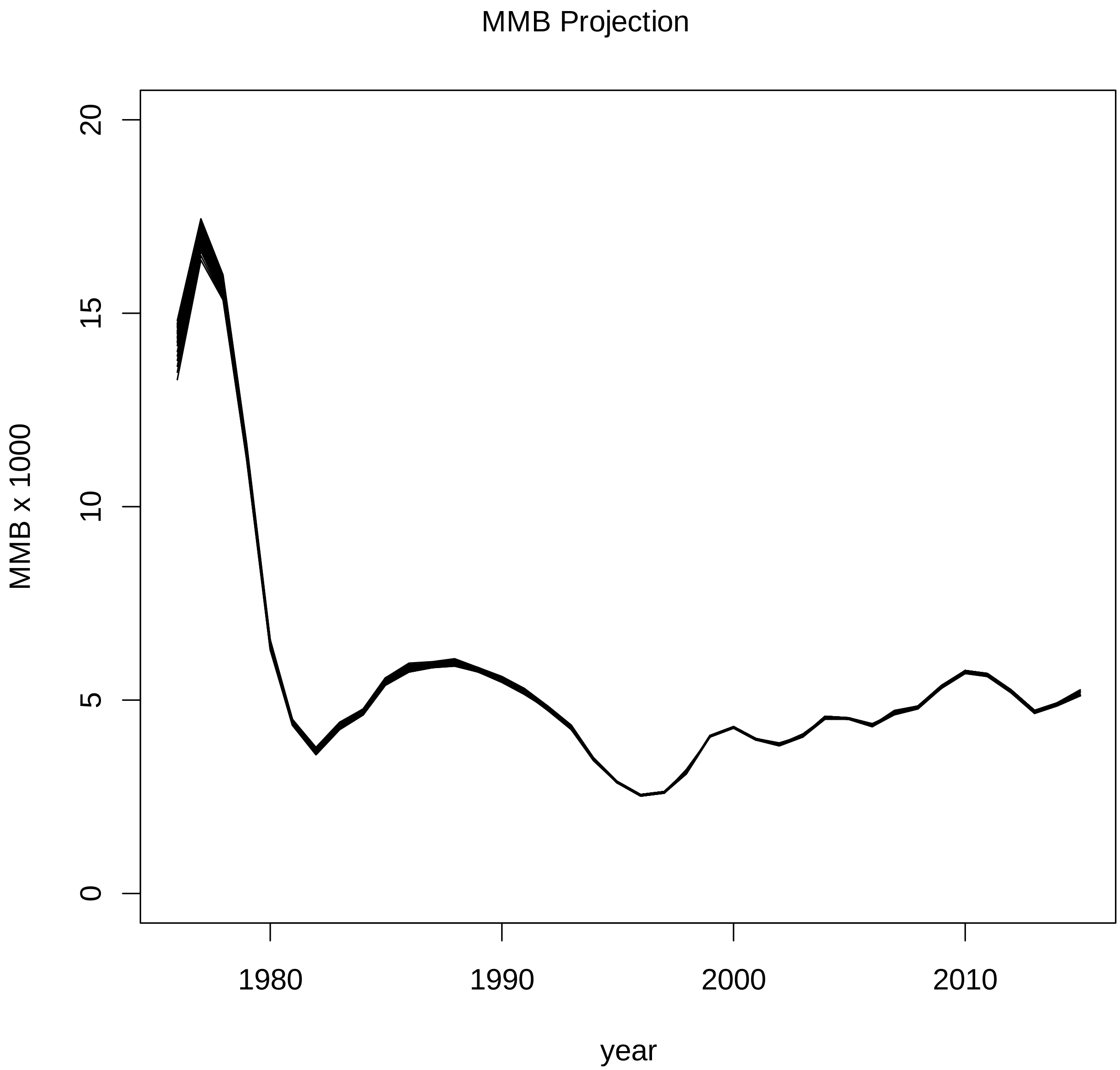


Figure B1-4. MMB projection.

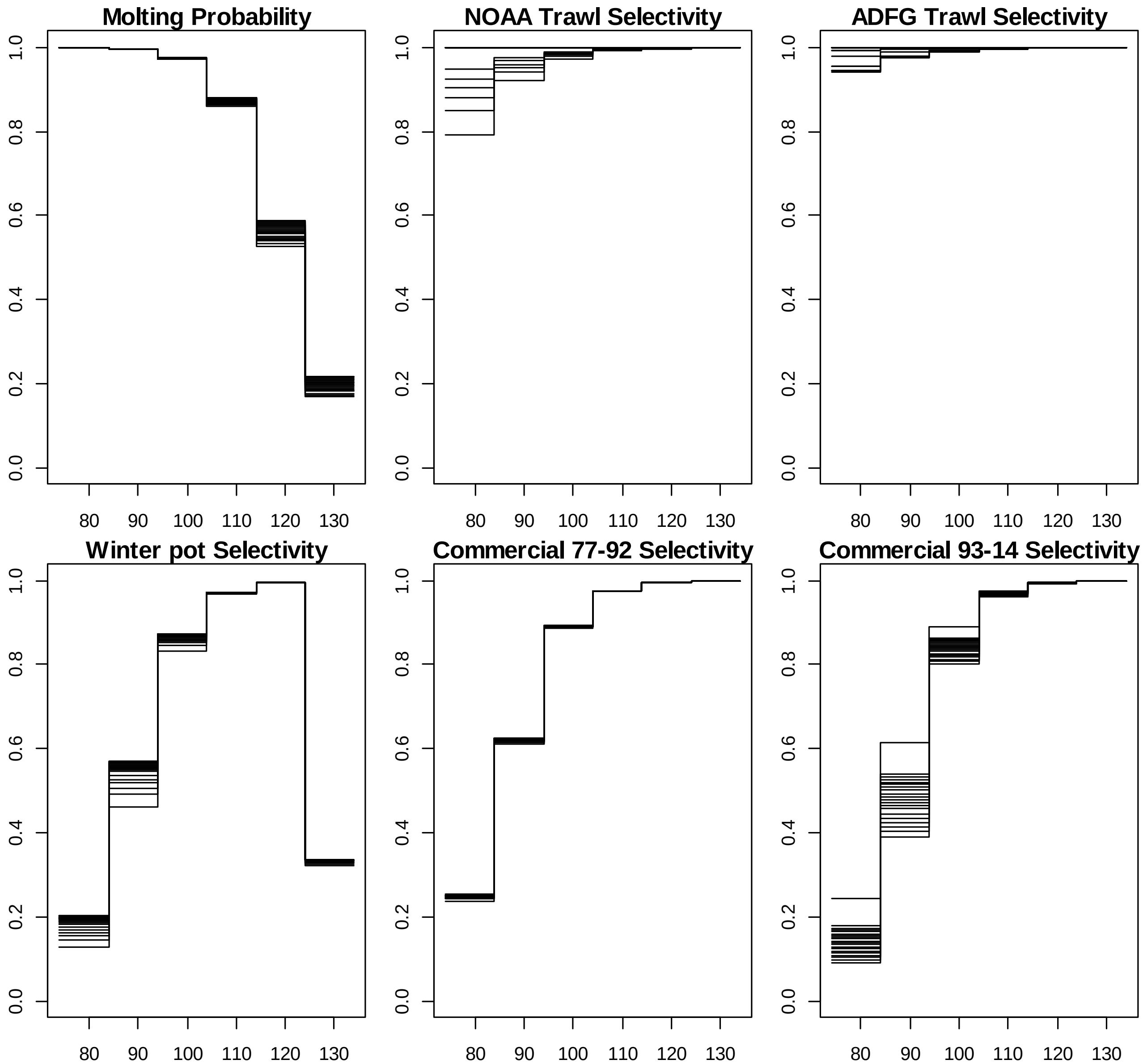


Figure B1-5. Changes of selectivities and molting probability combined.

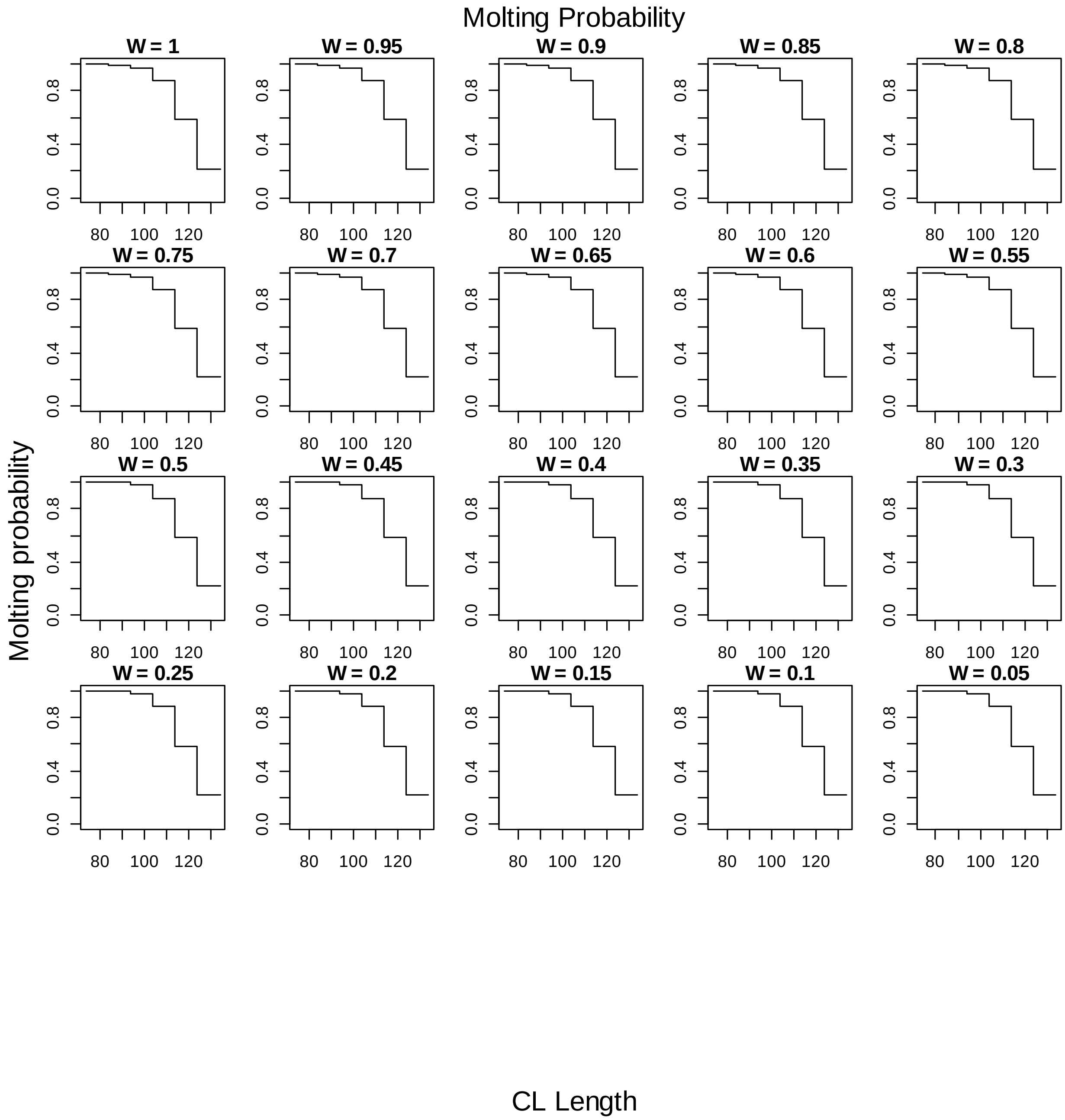


Figure B1-6. Changes of molting probability by different weights

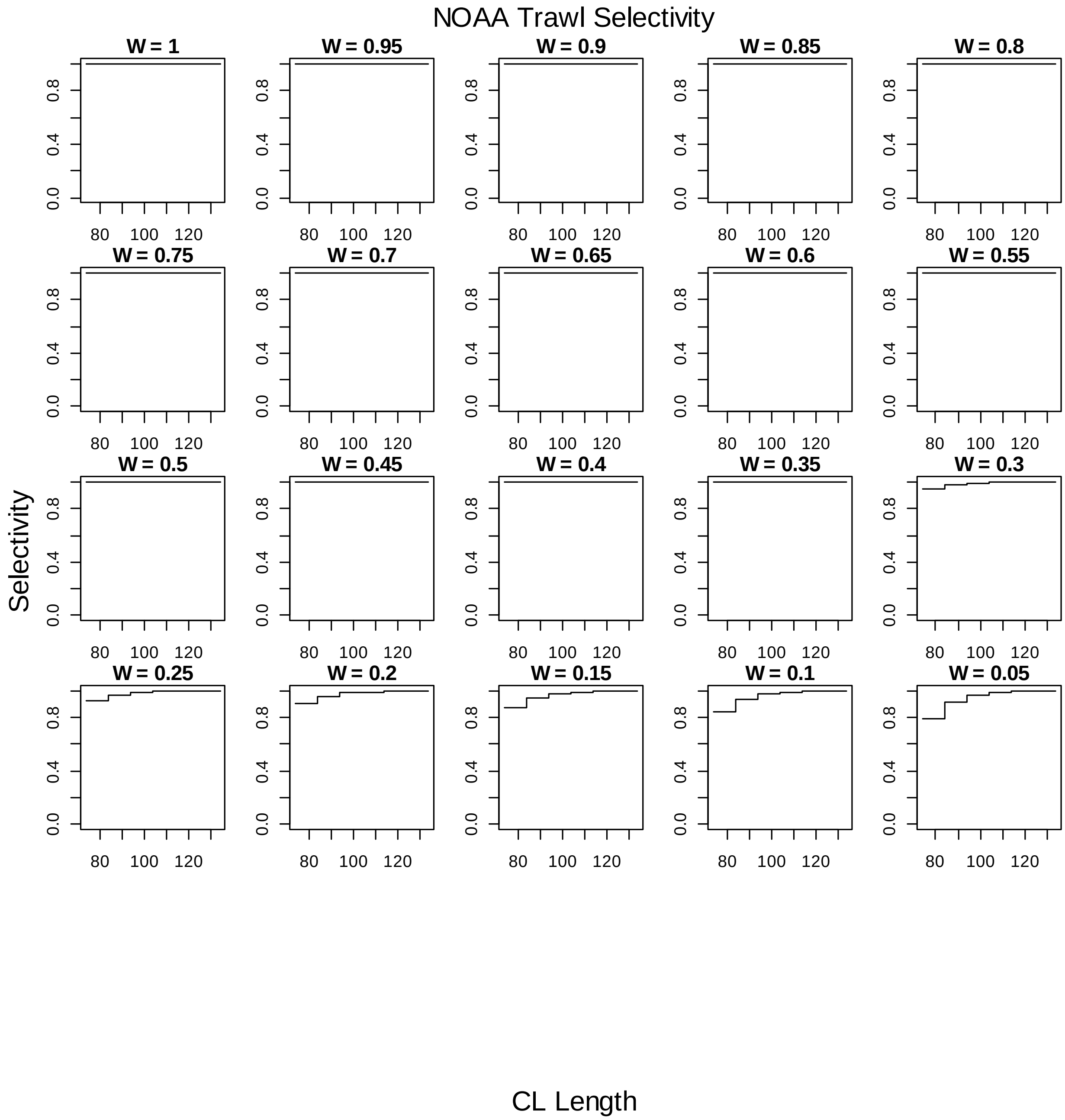


Figure B1-7. Changes of NMFS trawl selectivity by different weights

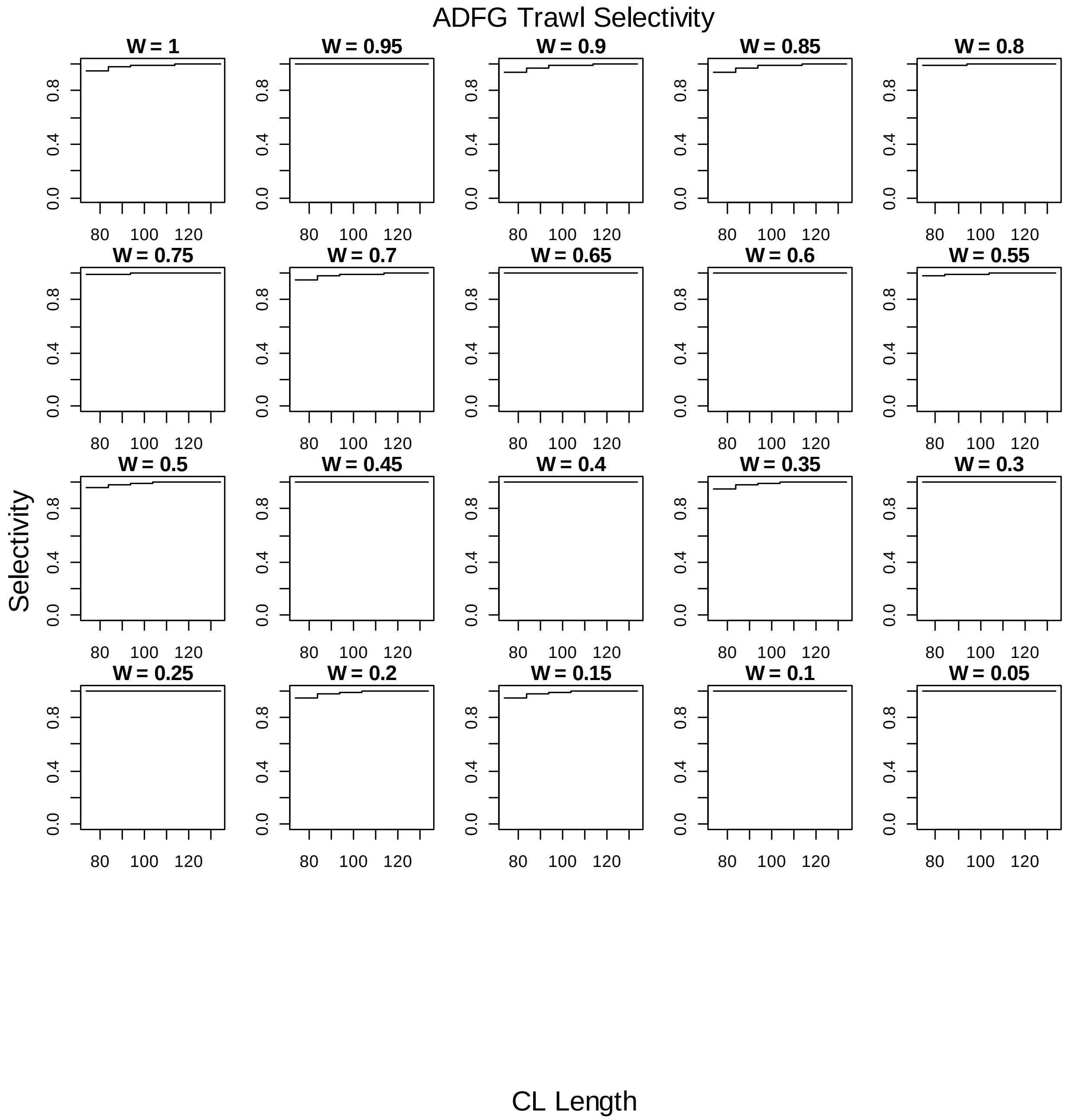


Figure B1-8: Changes of ADF&G Trawl selectivity by different weights

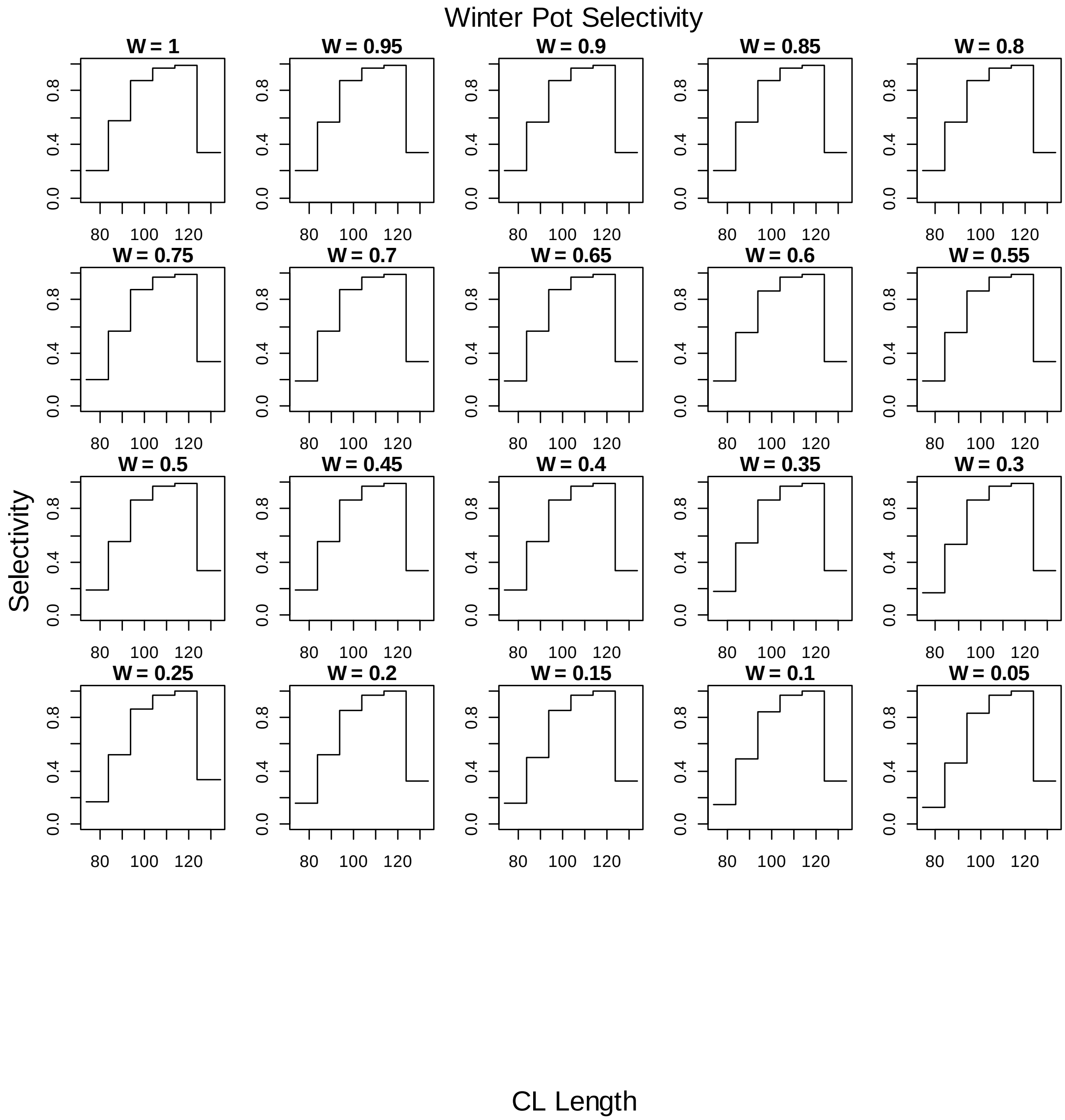


Figure B1-9. Changes of Winter pot selectivity by different weights

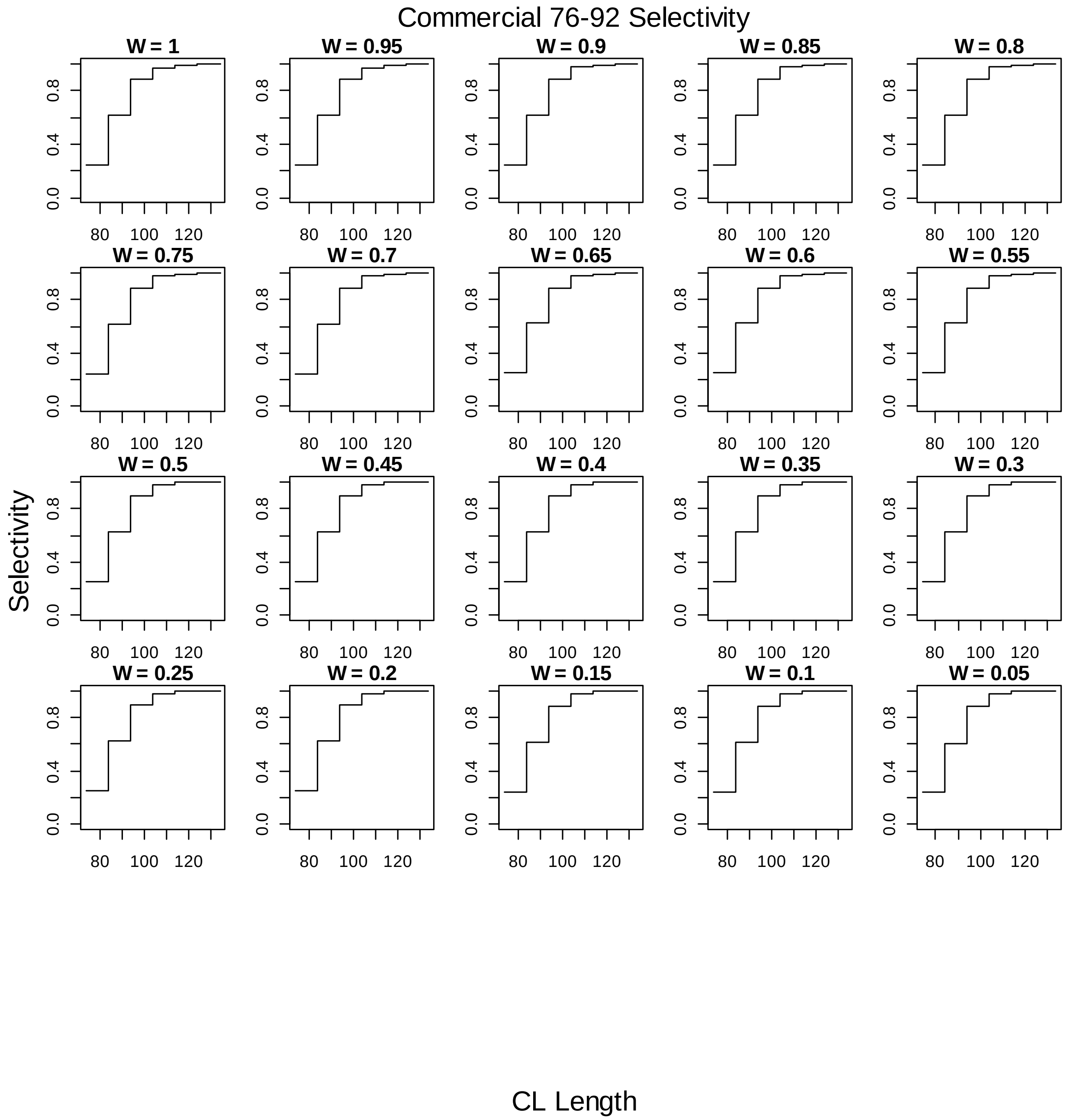


Figure B1-10. Changes of 1976-1992 Commercial Catch selectivity by different weights

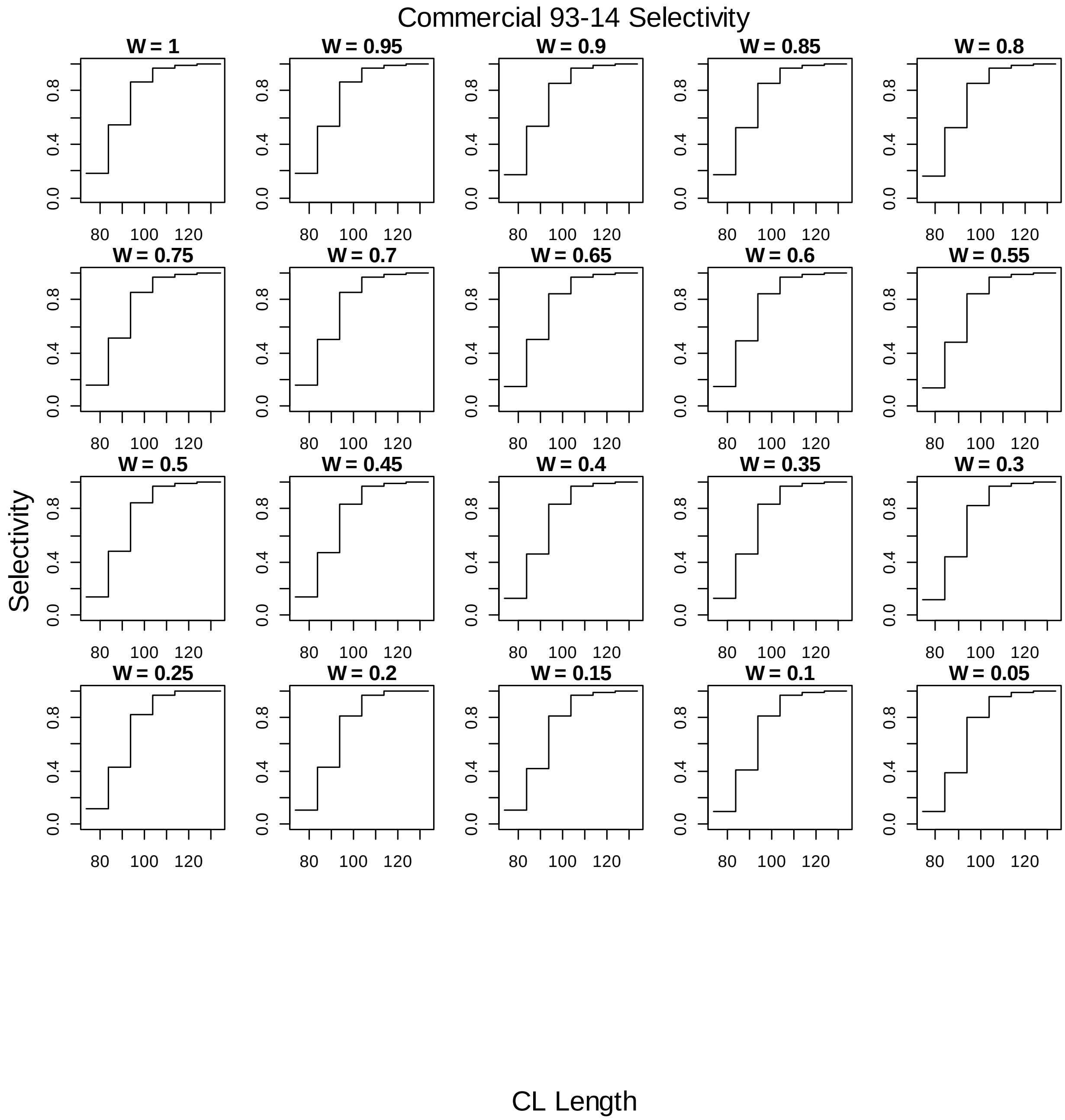


Figure B1-11. Changes of 1993-2014 Commercial Catch selectivity by different weights

Appendix B2: Likelihood profile for M: using model 4

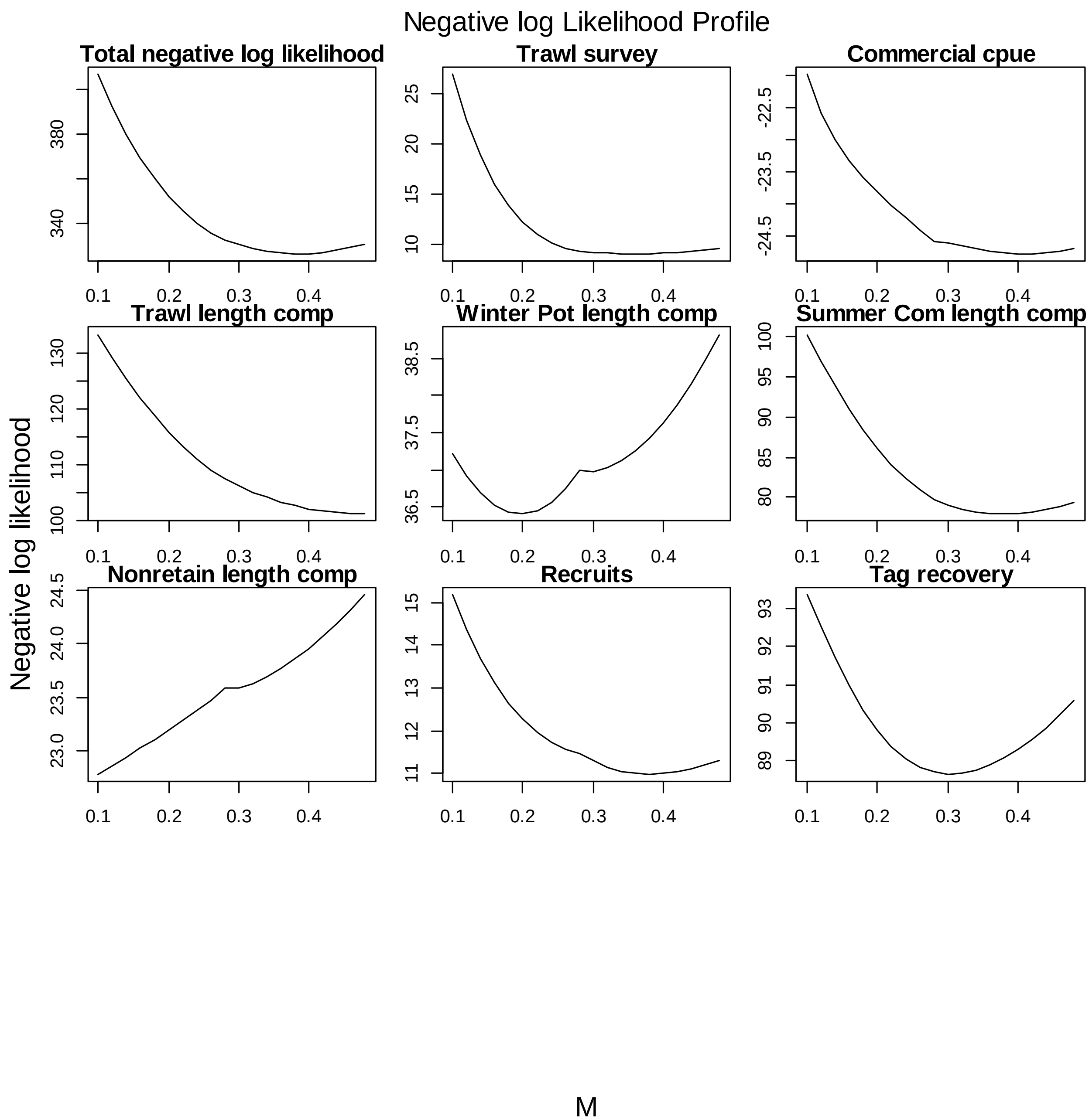


Figure B2-1: Negative log-likelihood

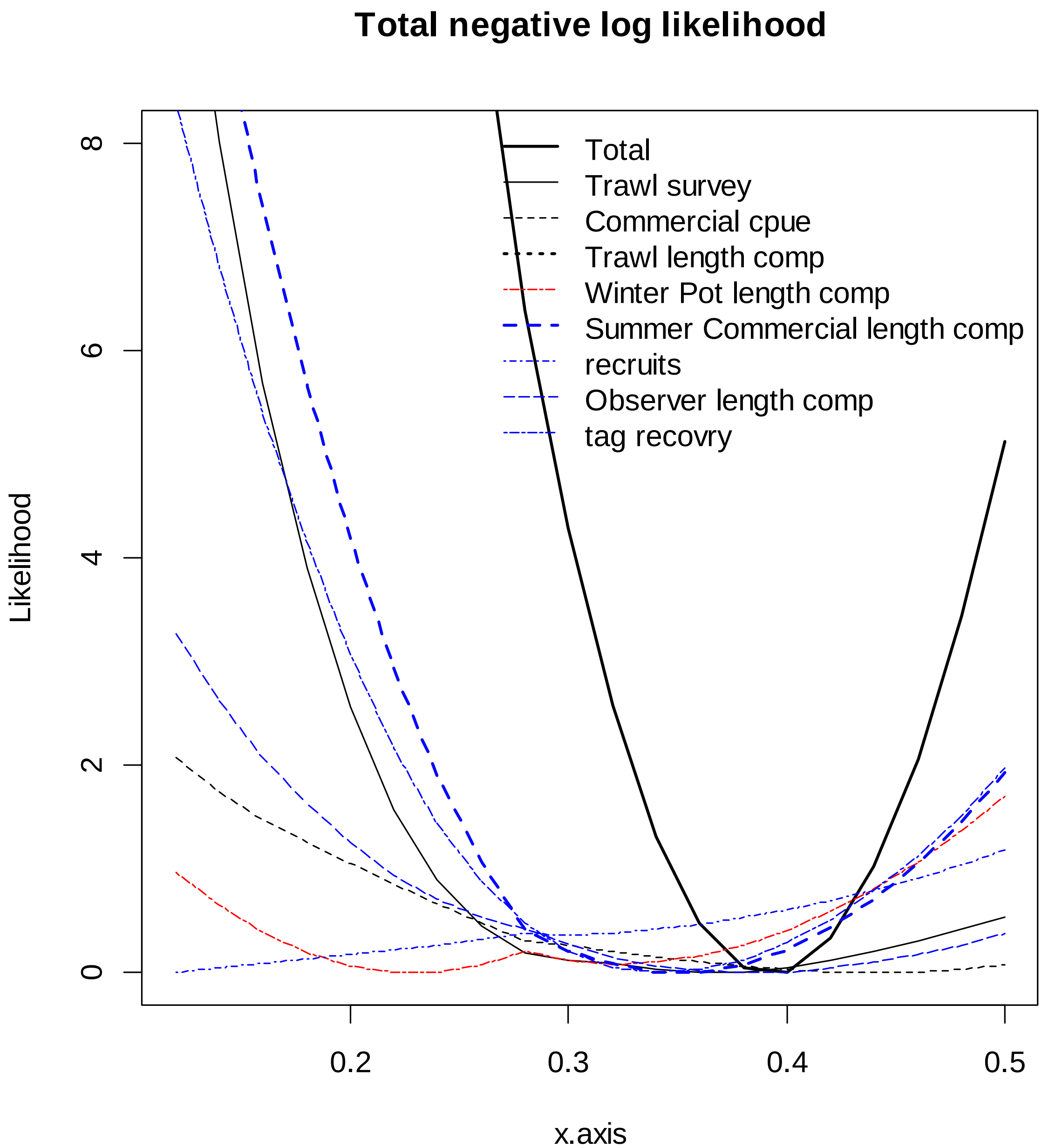


Figure B2-1.1: Negative log-likelihood profile combined

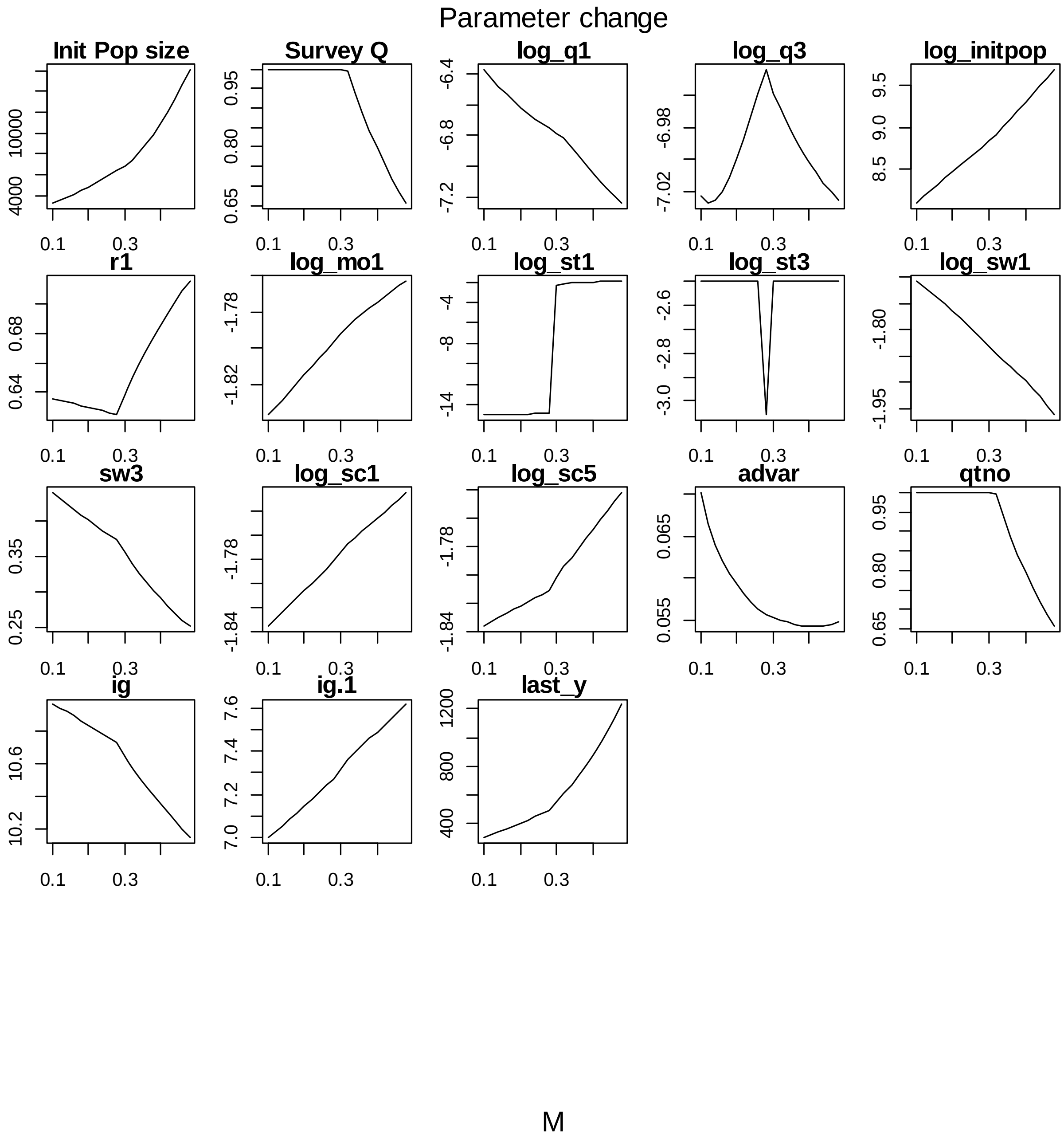


Figure B2-2. Change in Parameter value in different *M*

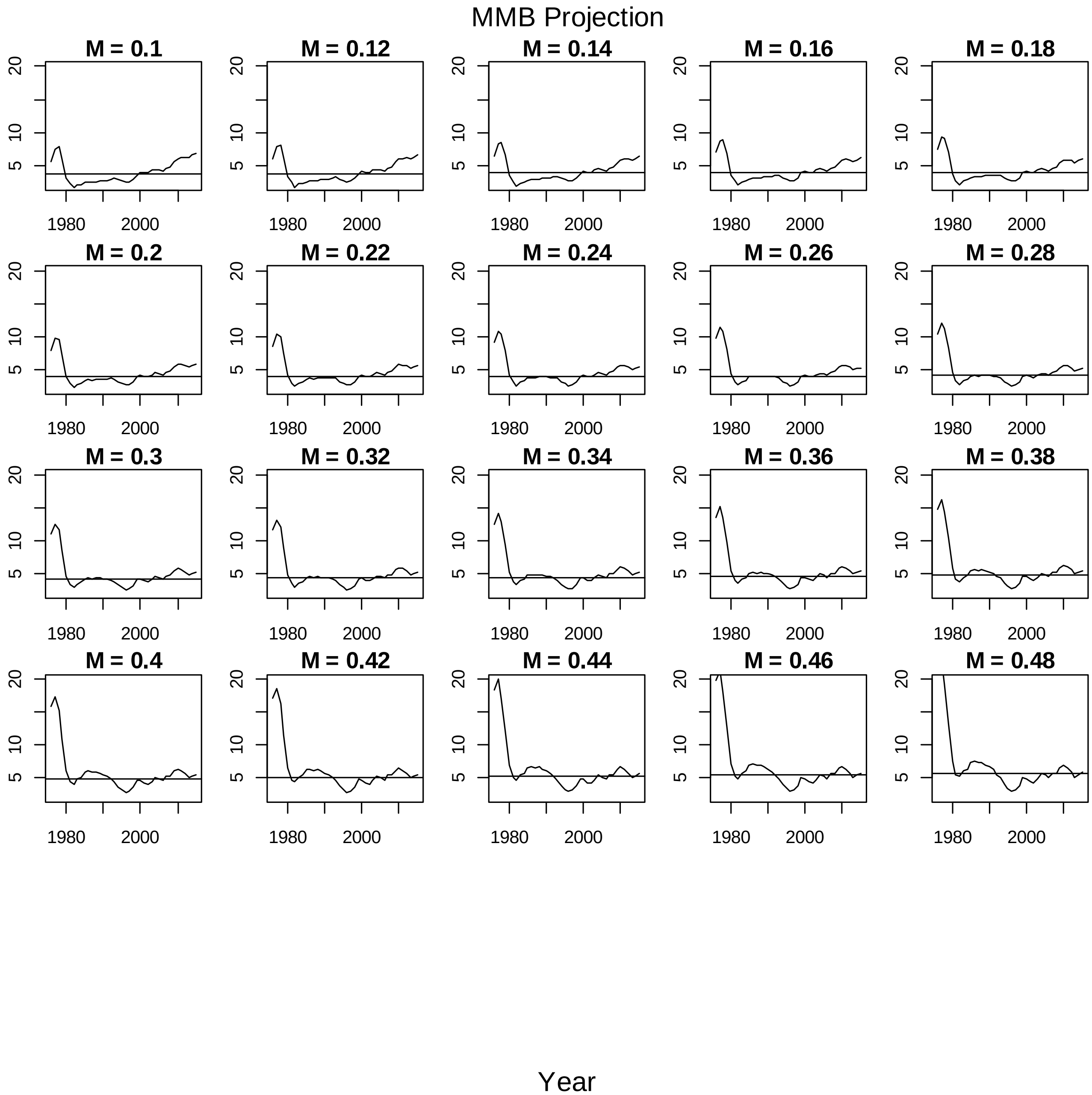


Figure B2-3. Change of MMB projection in different *M*

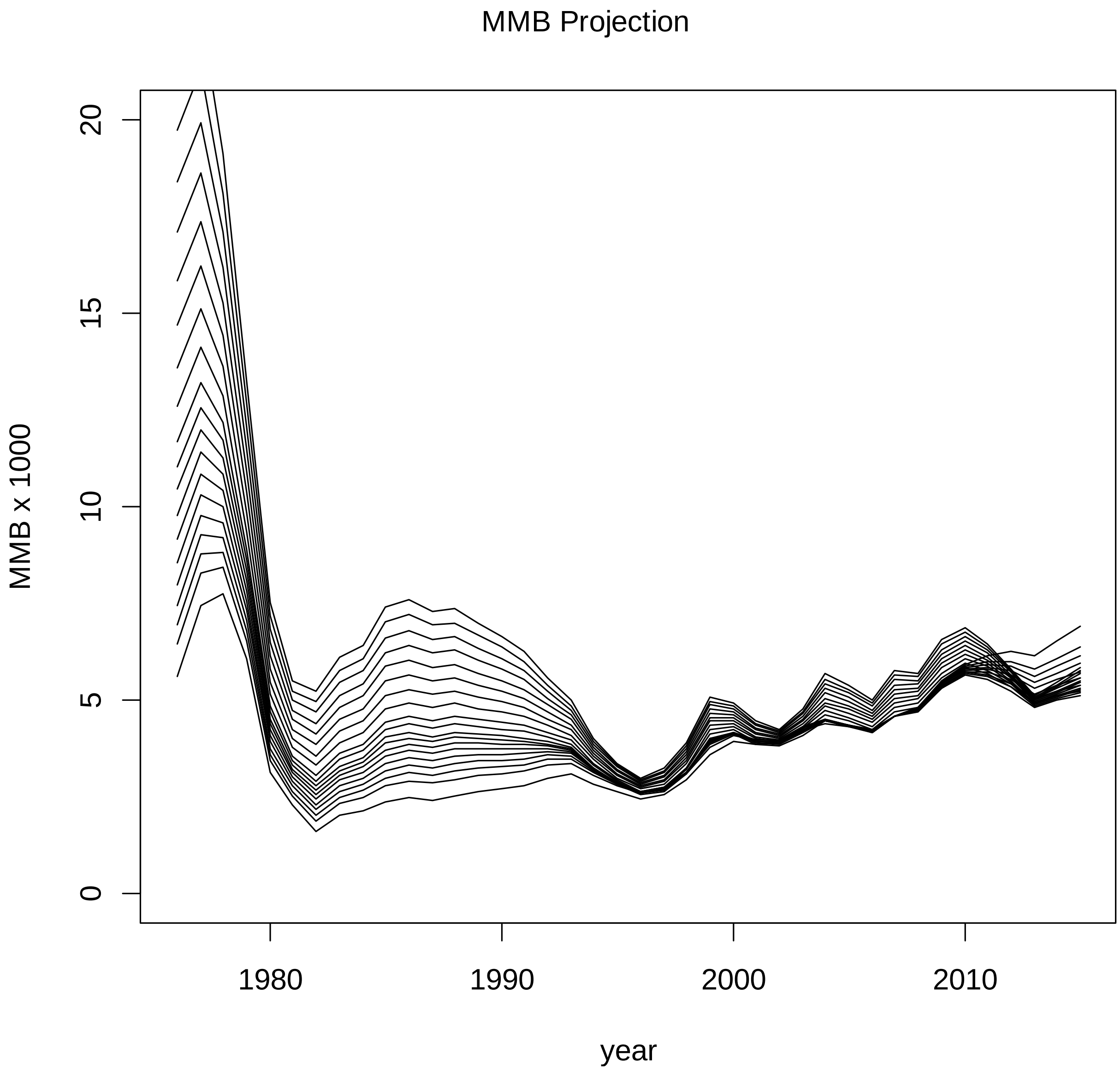


Figure B2-4. Change of MMB projection in different *M* combined

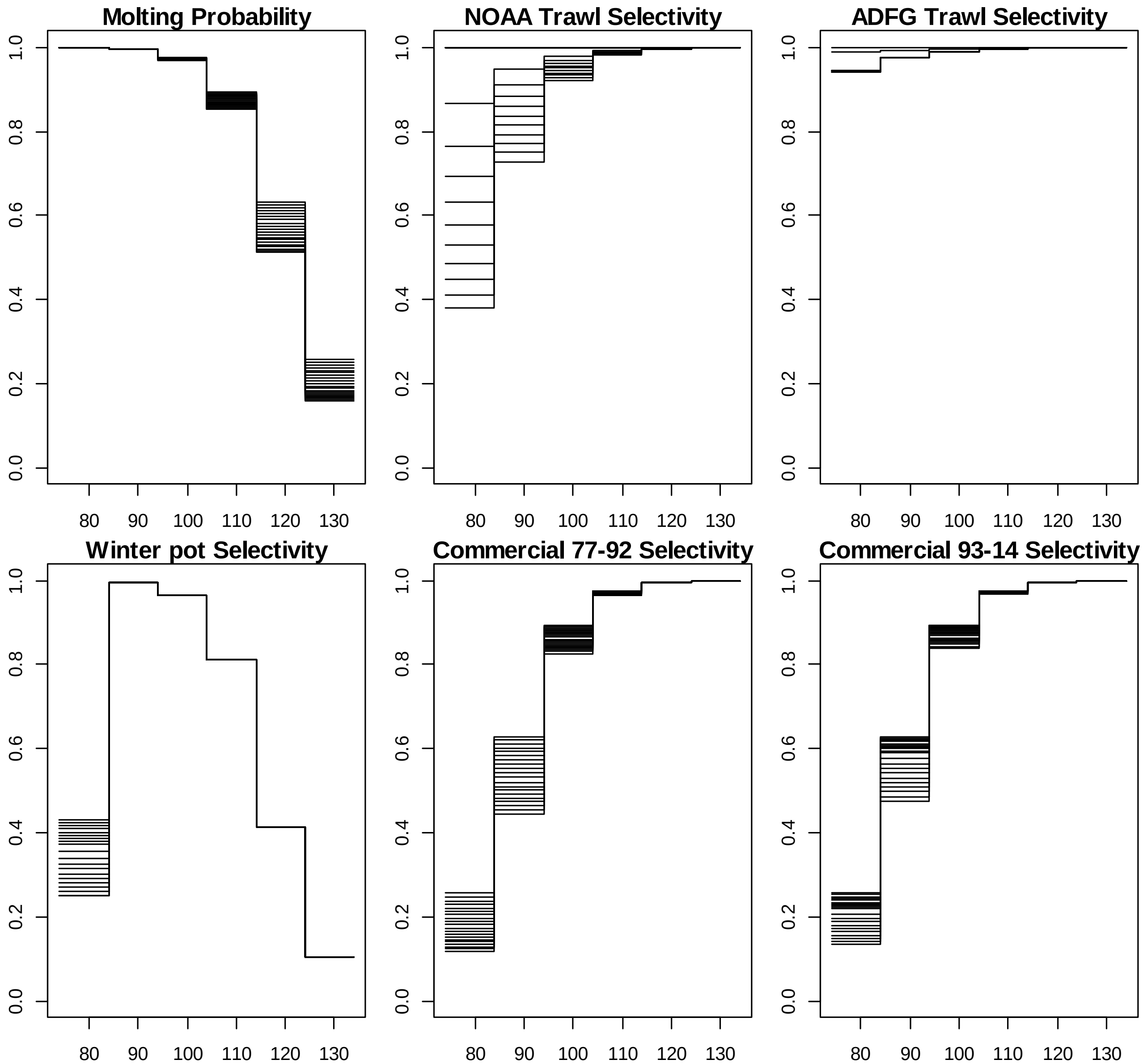


Figure B2-5. Change of selectivities and molting probability in different *M* (combined)

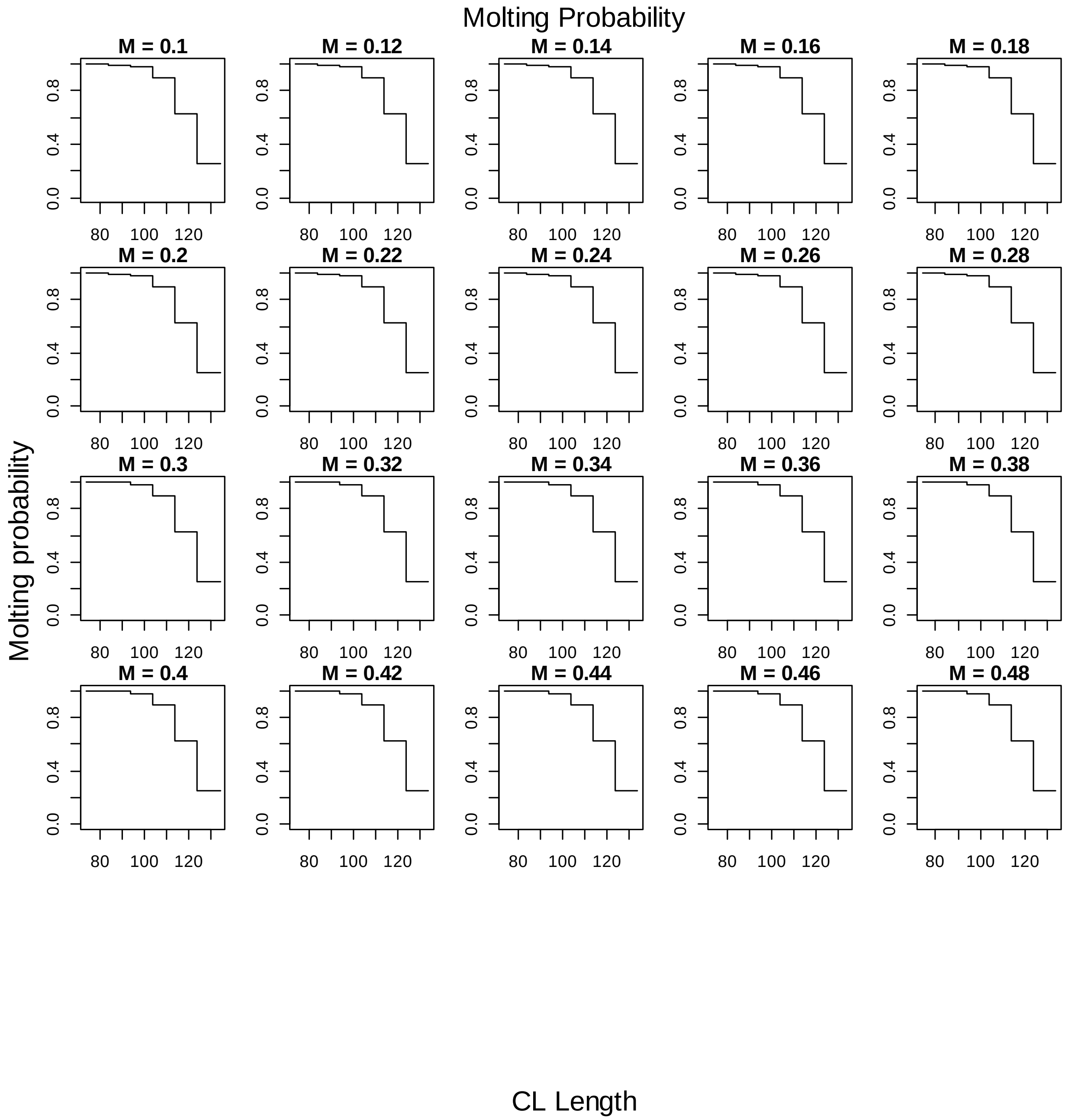


Figure B2-6. Change of molting probability in different *M*

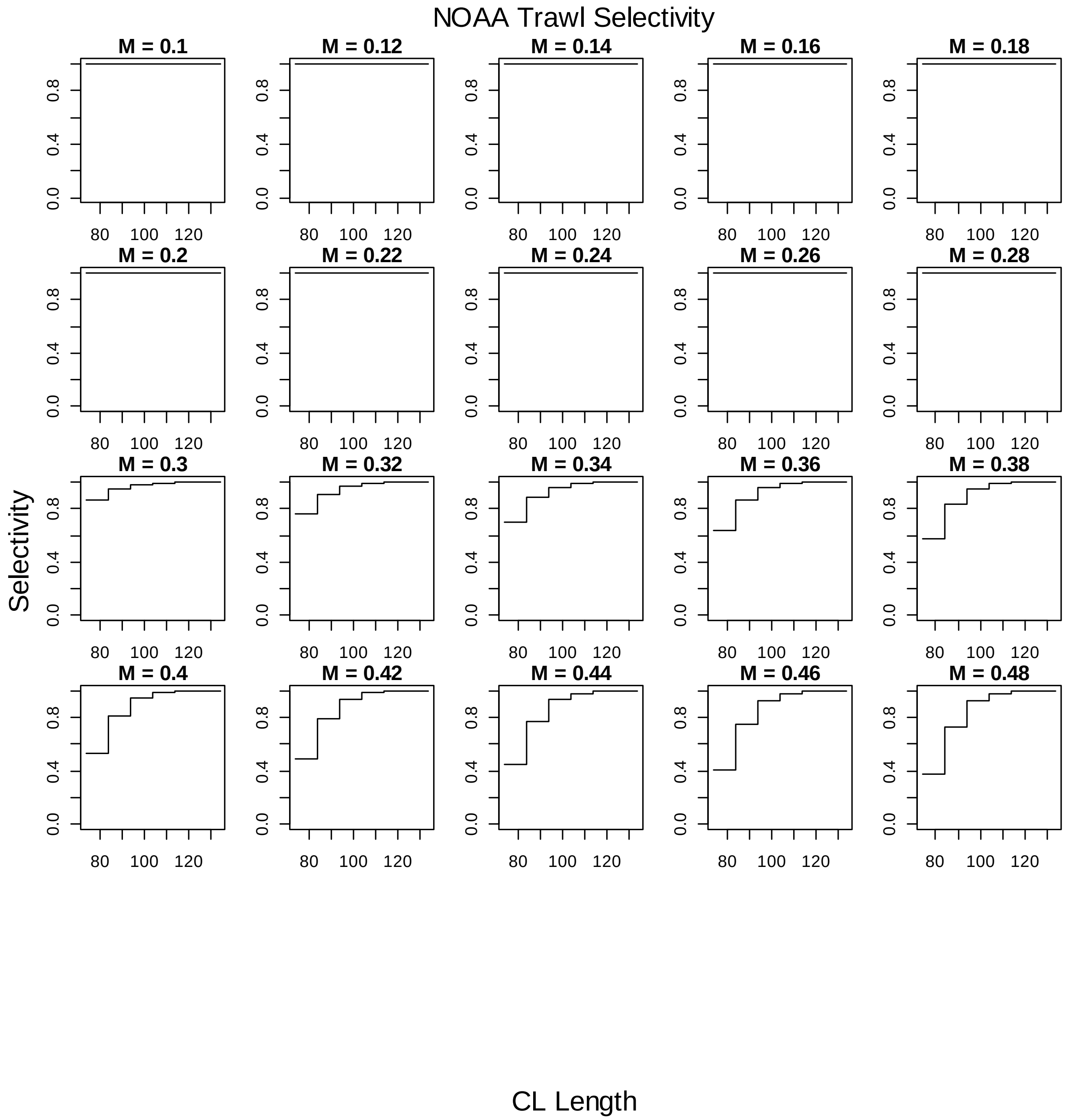


Figure B2-7. Change of NMFS trawl survey selectivity in different *M*

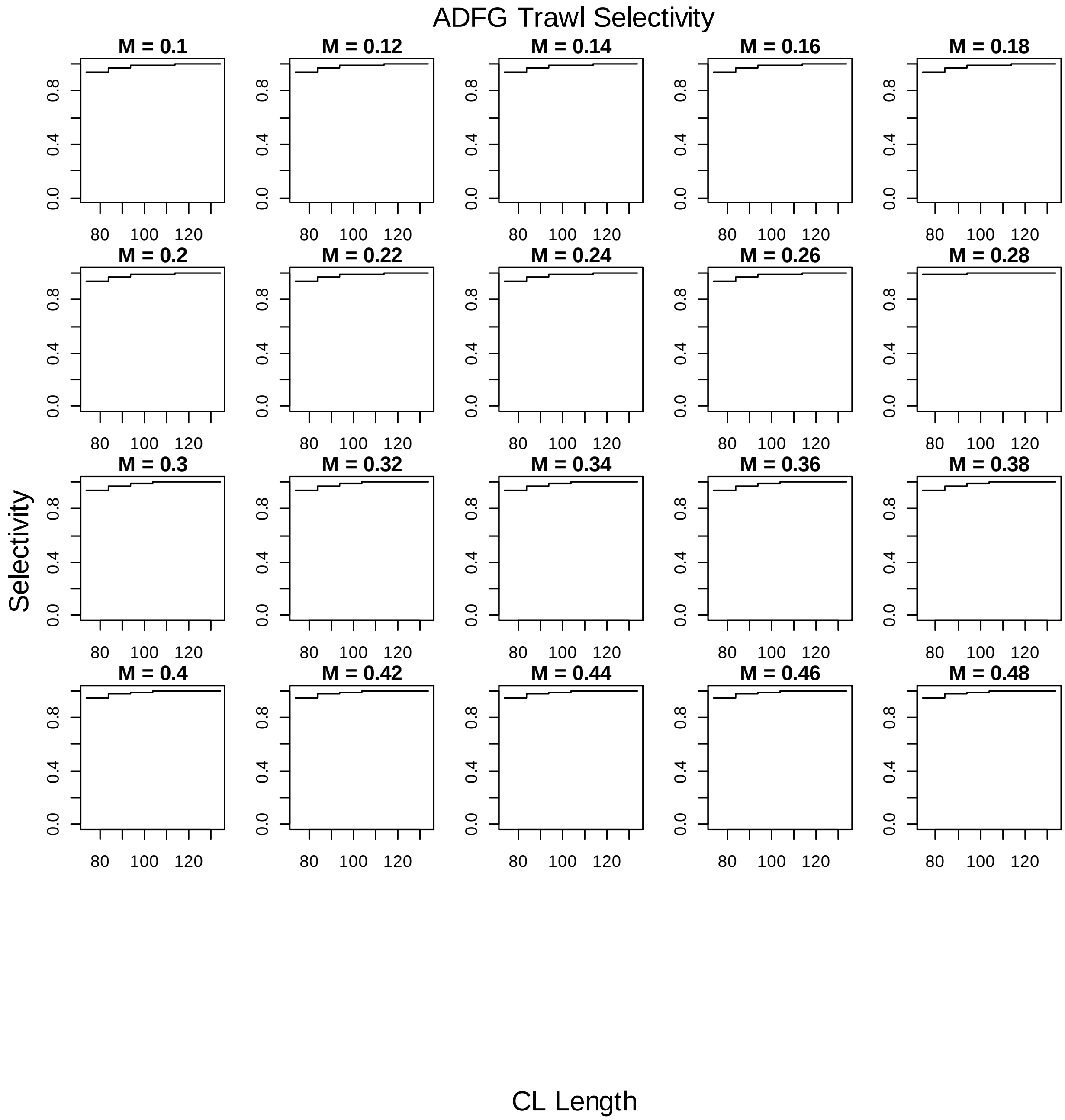


Figure B2-8: Change of ADF&G trawl survey selectivity in different *M*

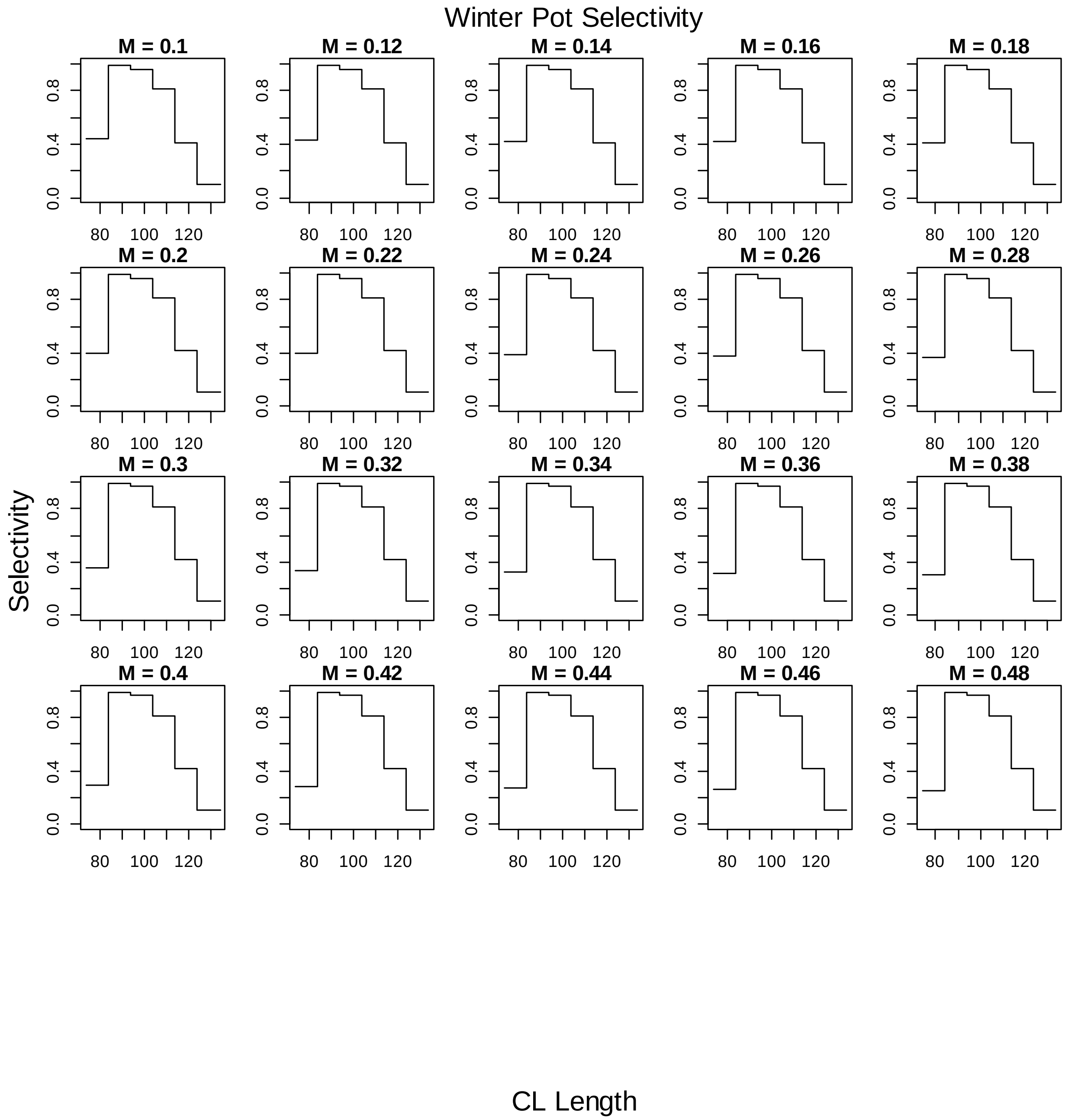


Figure B2-9: Change of Winter pot survey selectivity in different *M*

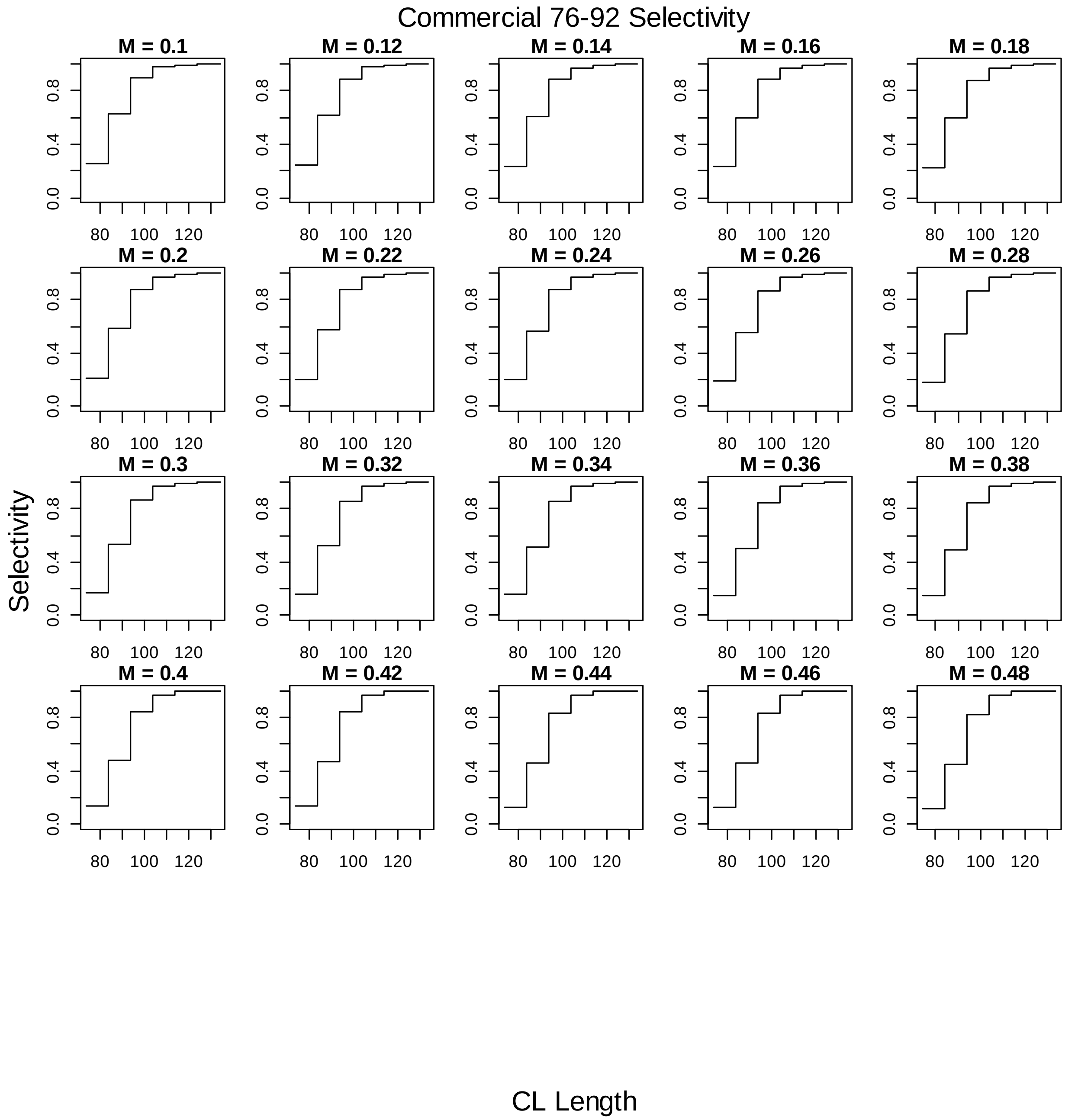


Figure B2-10: Change of 1977-92 commercial catch selectivity in different *M*

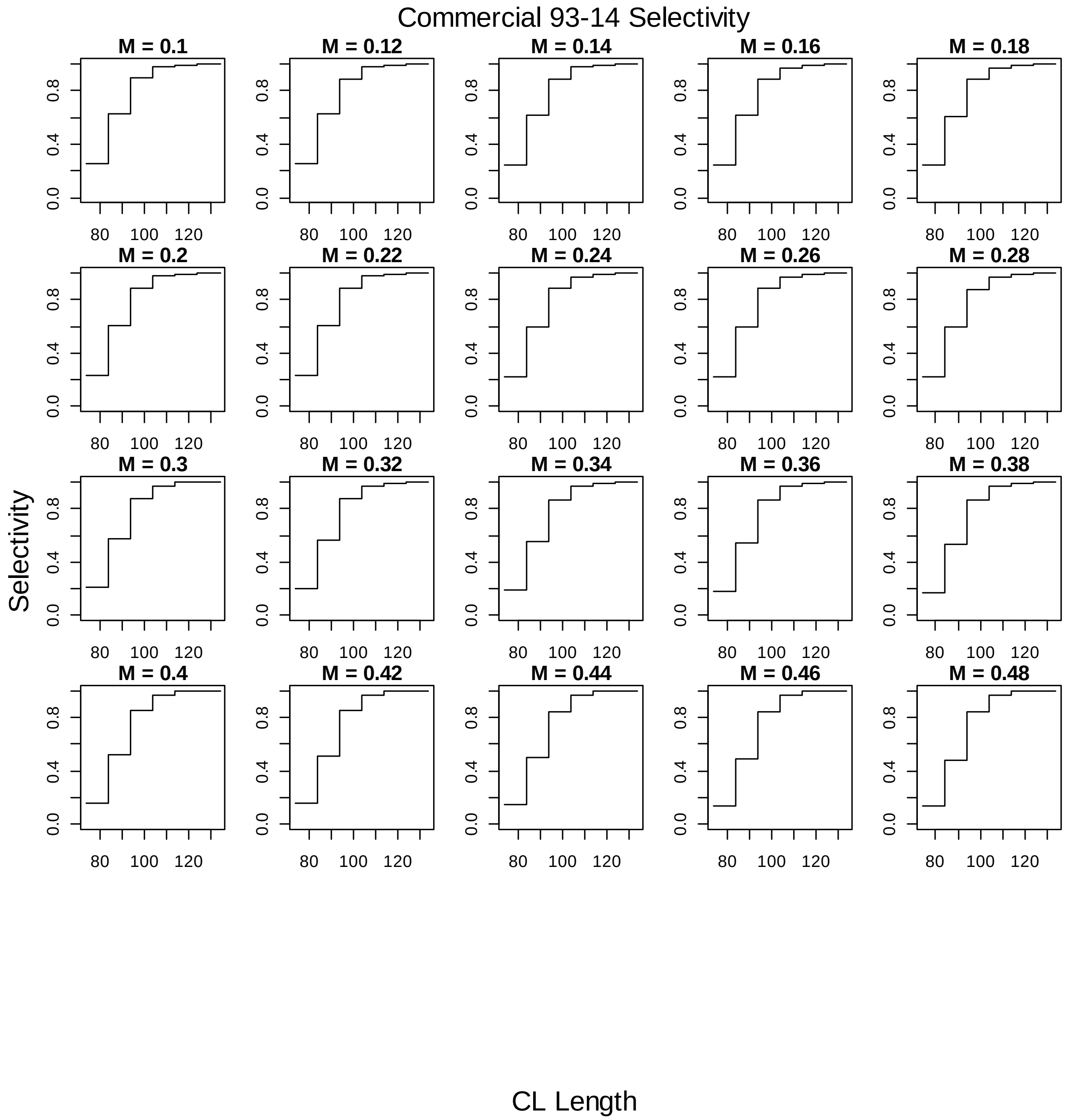


Figure B2-11: Change of 1993-2014 commercial catch selectivity in different *M*

Appendix C1: Results Model 1

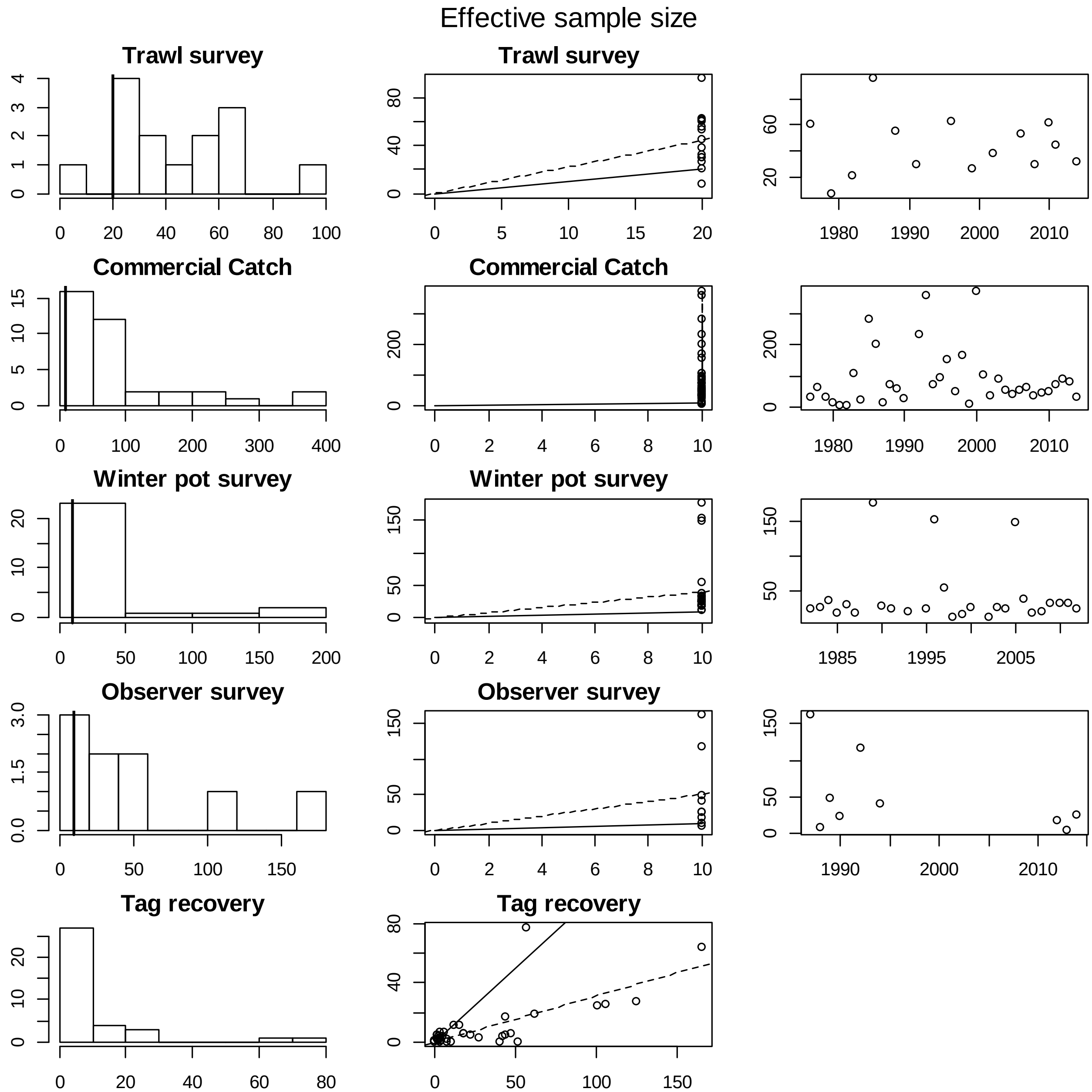


Figure C1-1: Effective sample size vs. implied sample size. Figures in the first column show effective sample size (x-axis) vs. frequency (y-axis). Vertical solid line is the implied sample size. Figures in the second column show implied sample size (x-axis) vs. effective sample size (y-axis). Dashed line indicates linear regression slope, and solid line is 1:1 line. Figures in the third column show year (x-axis) vs. effective sample size (y-axis).

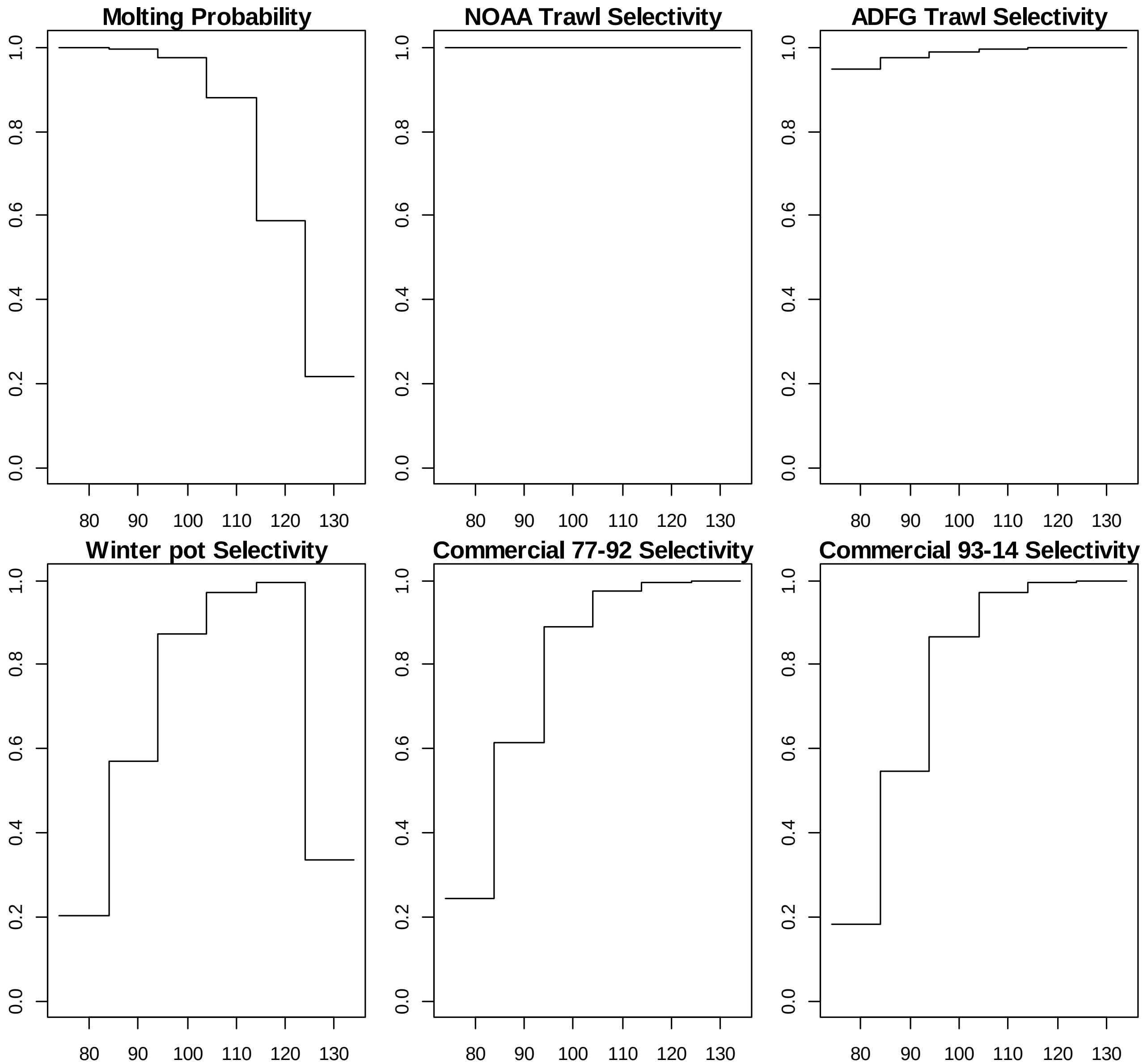


Figure C1-2. Molting probability and trawl/pot selectivities. X-axis is carapace length.

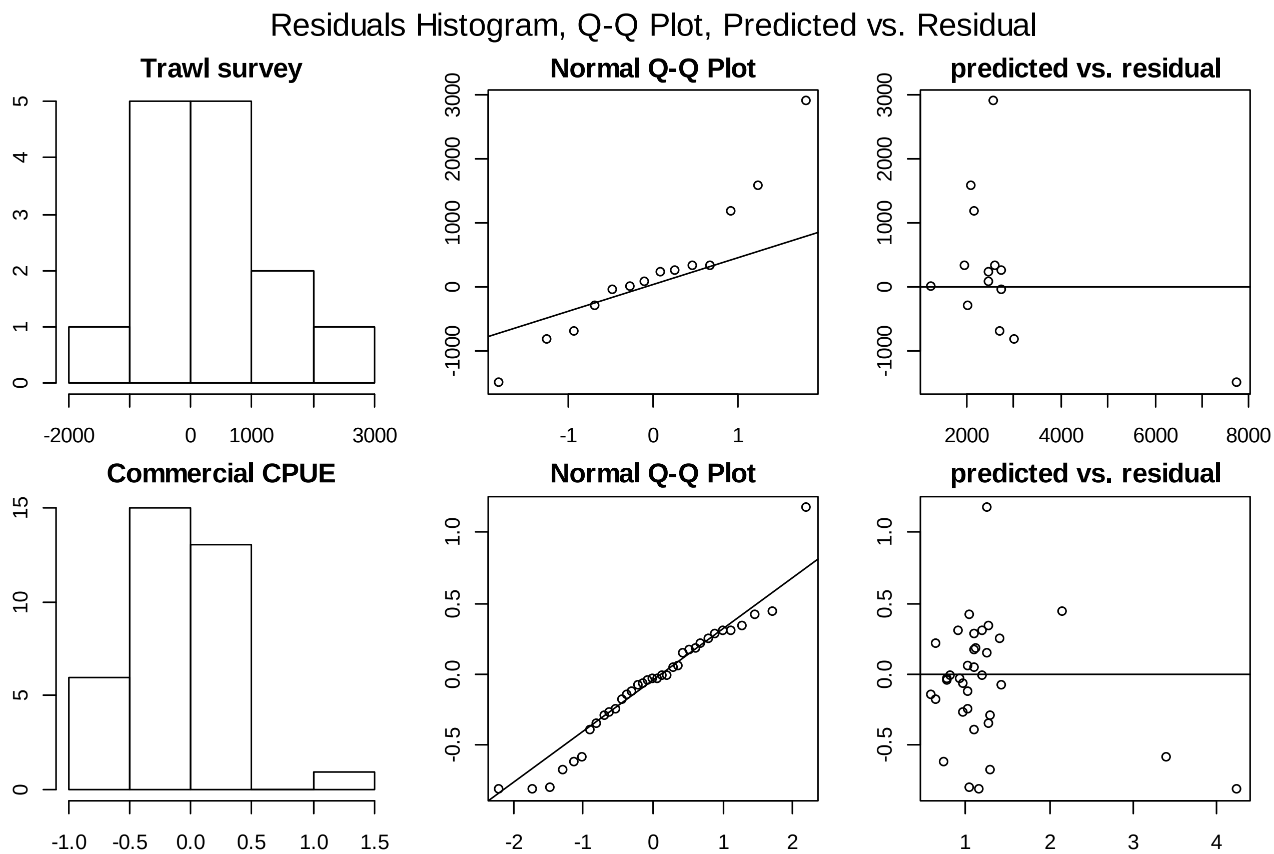


Figure C1-3. QQ Plot of Trawl survey and Commercial CPUE.

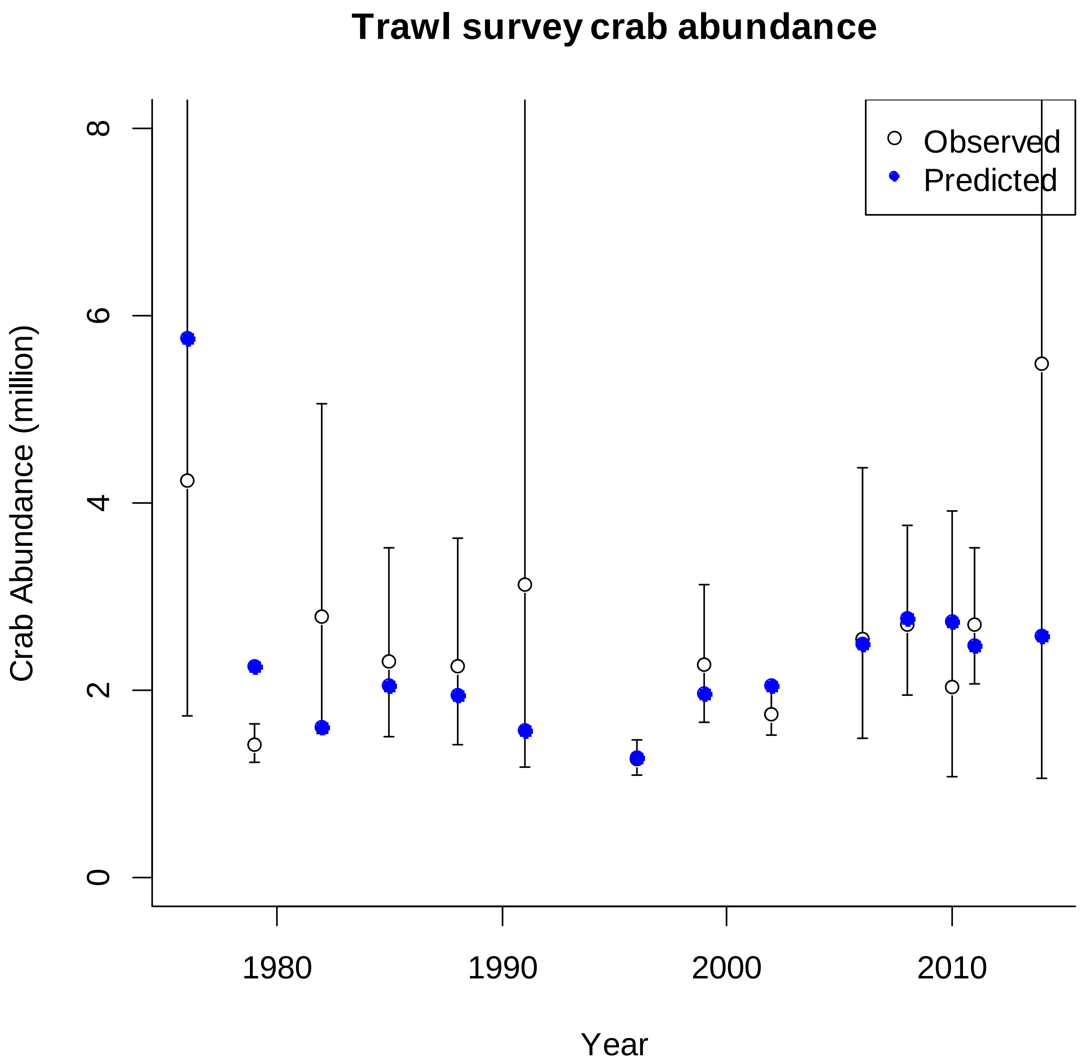


Figure C1-4. Estimated trawl survey male abundance (crab ≥ 74 mm CL).

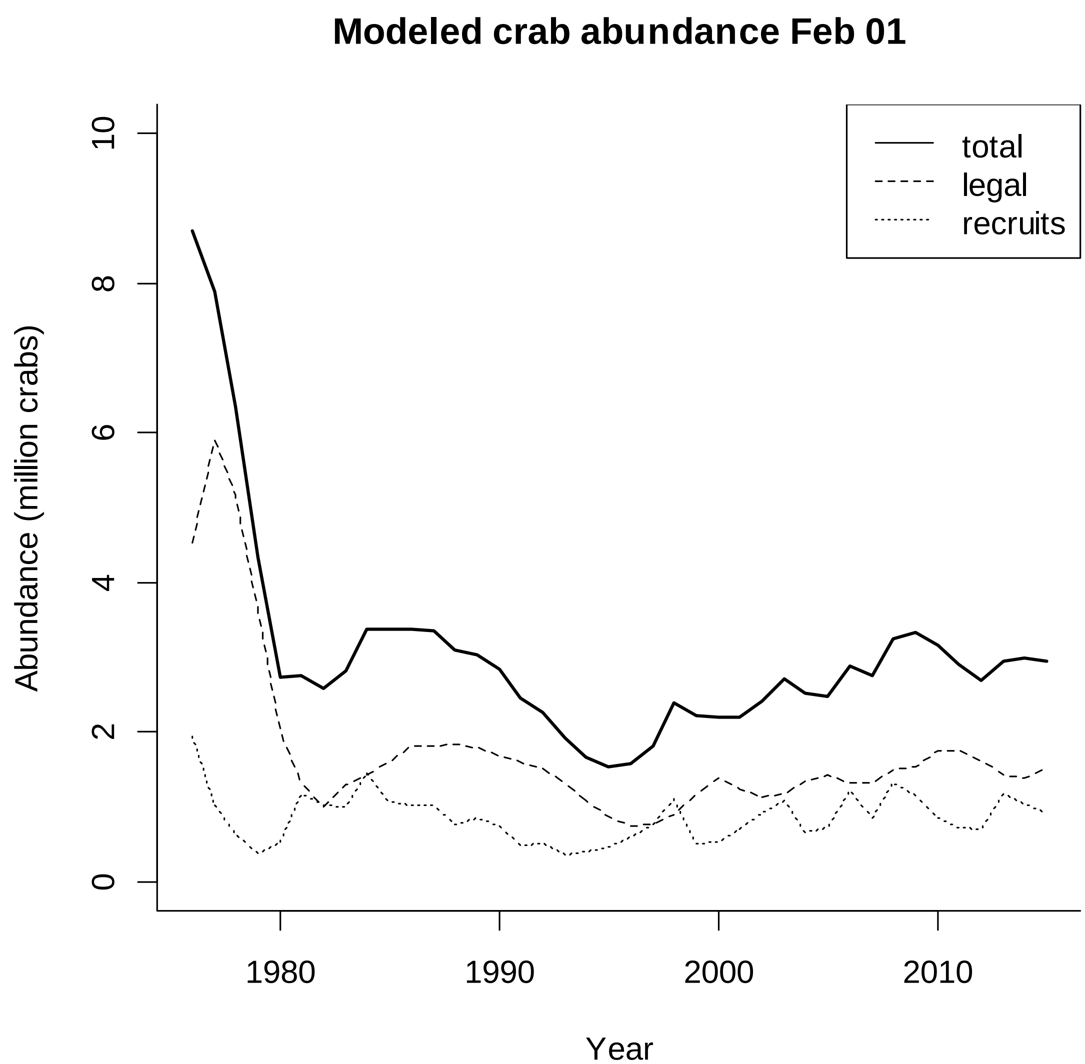


Figure C1-5. Estimated abundance of legal males from 1976-2014.

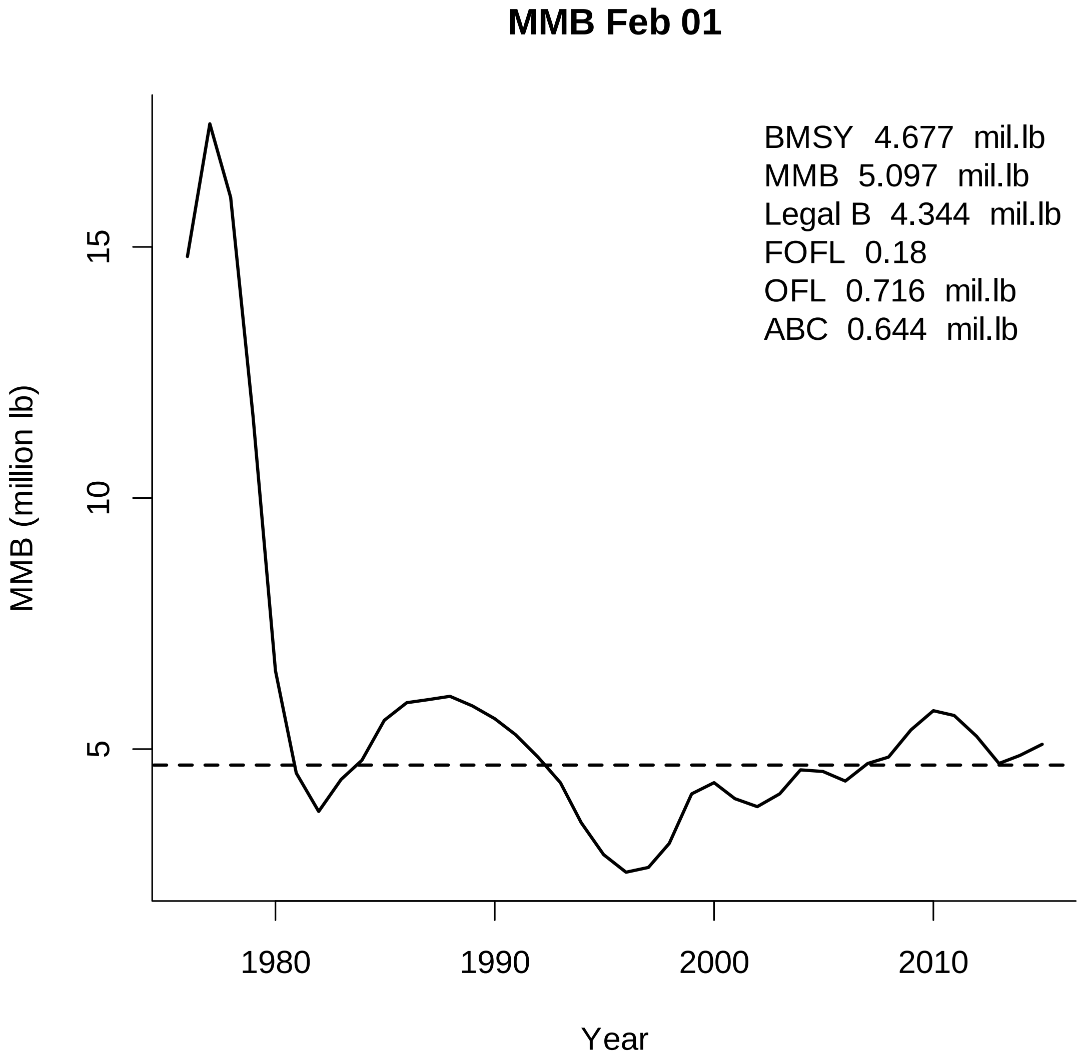


Figure C1-6. Estimated abundance of leg recruits from 1976-2015. Dash line shows Bmsy (Average MMB of 1980-2015).

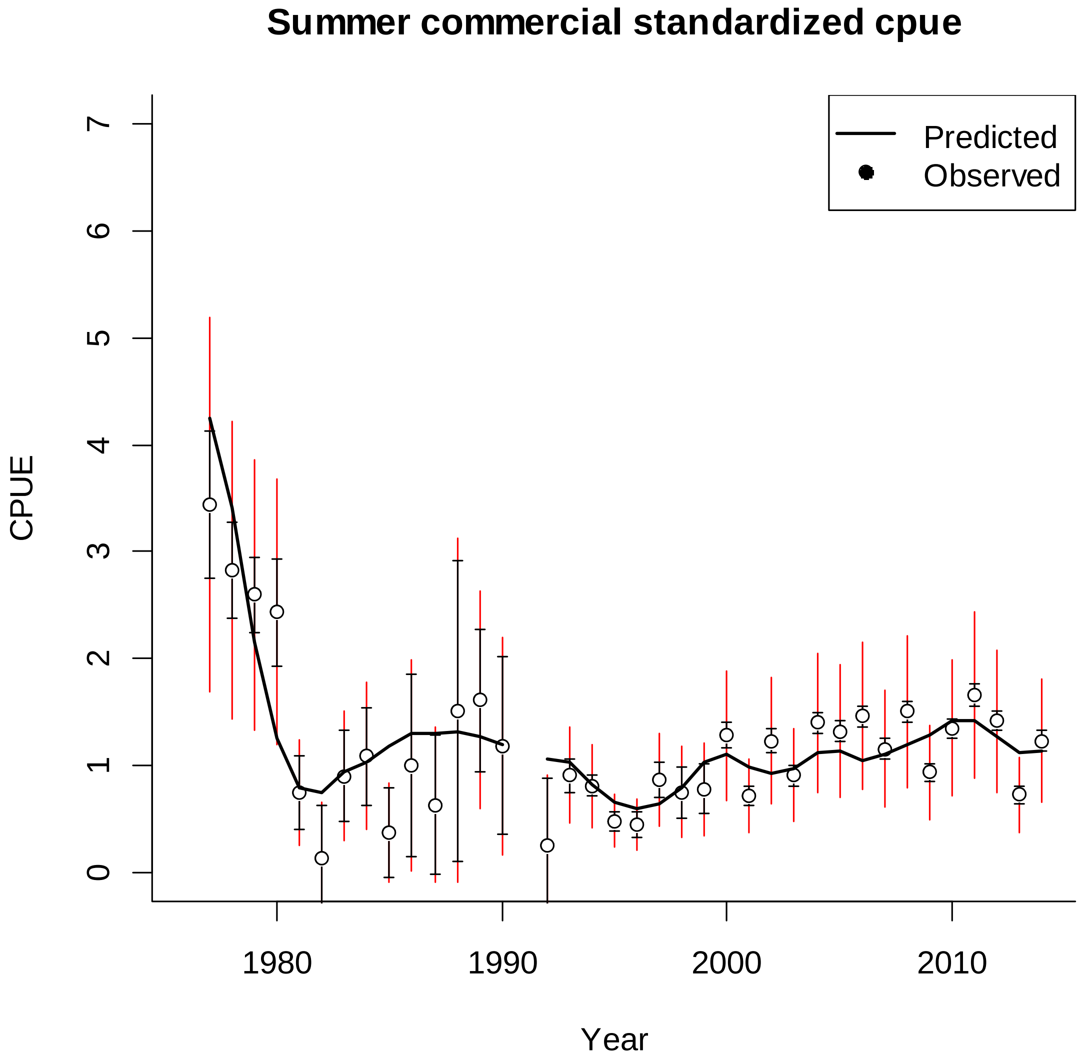


Figure C1-7. Summer commercial standardized cpue (1977-2014).

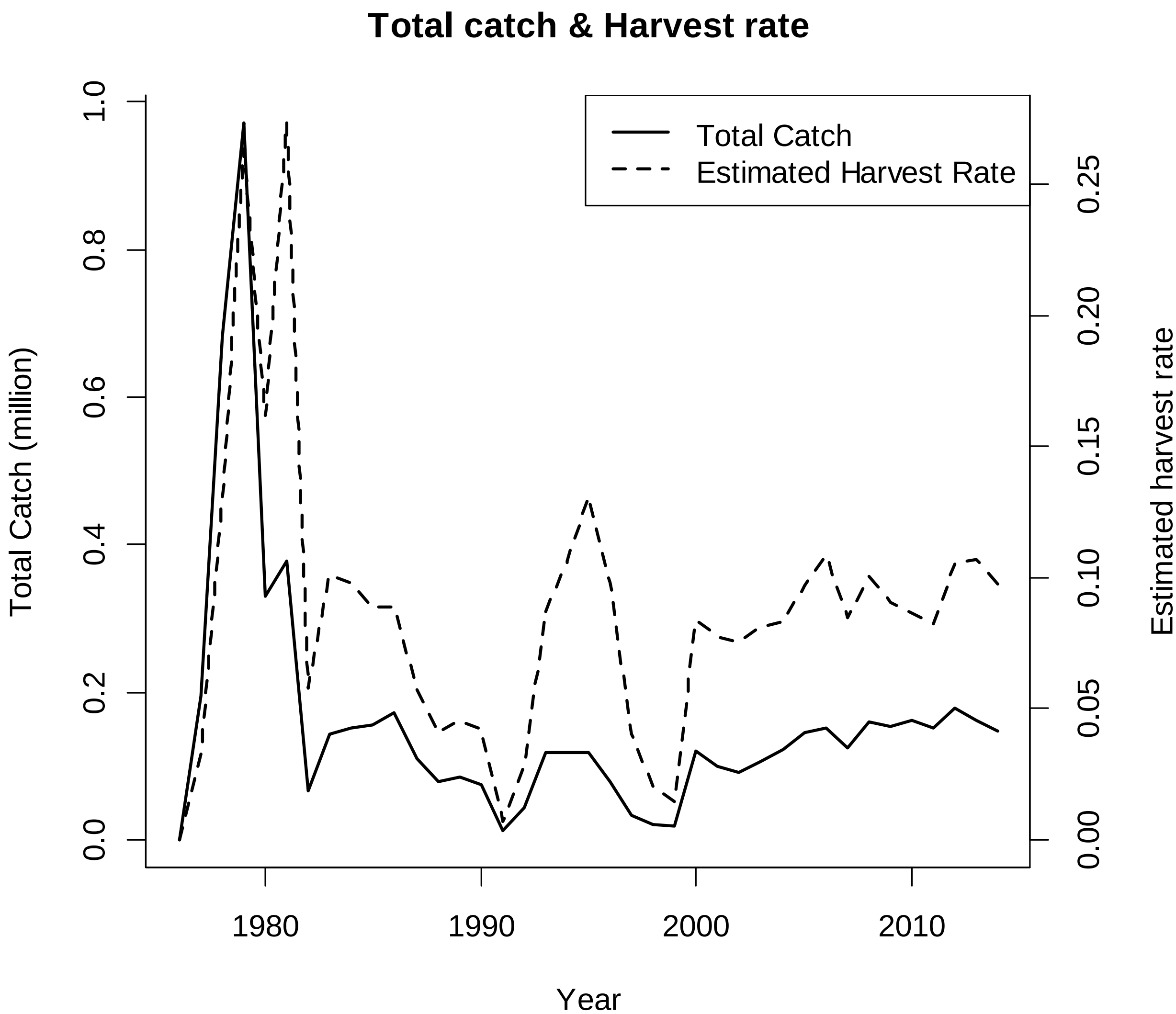


Figure C1-8. Total catch and estimated harvest rate 1976-2014.

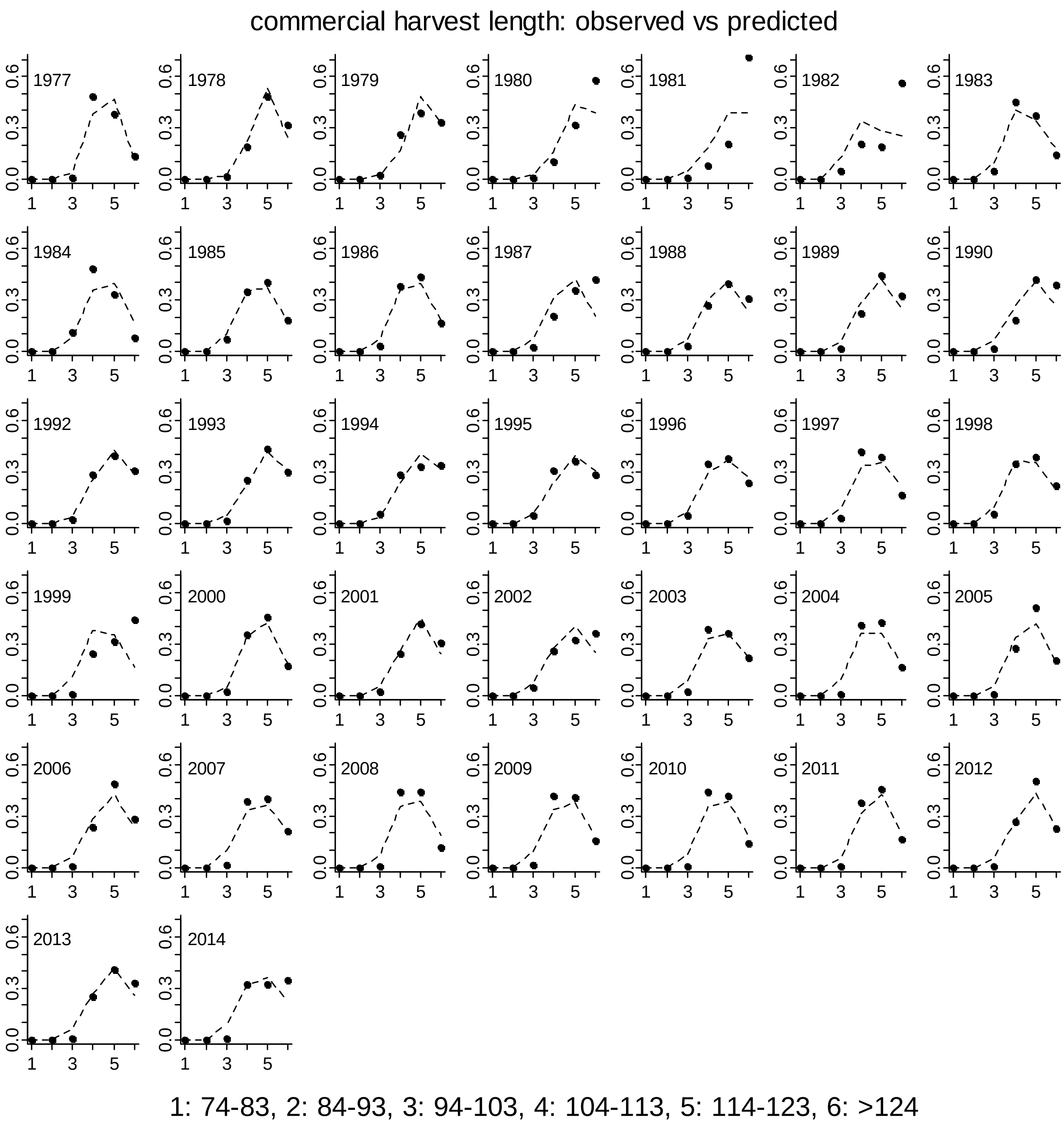
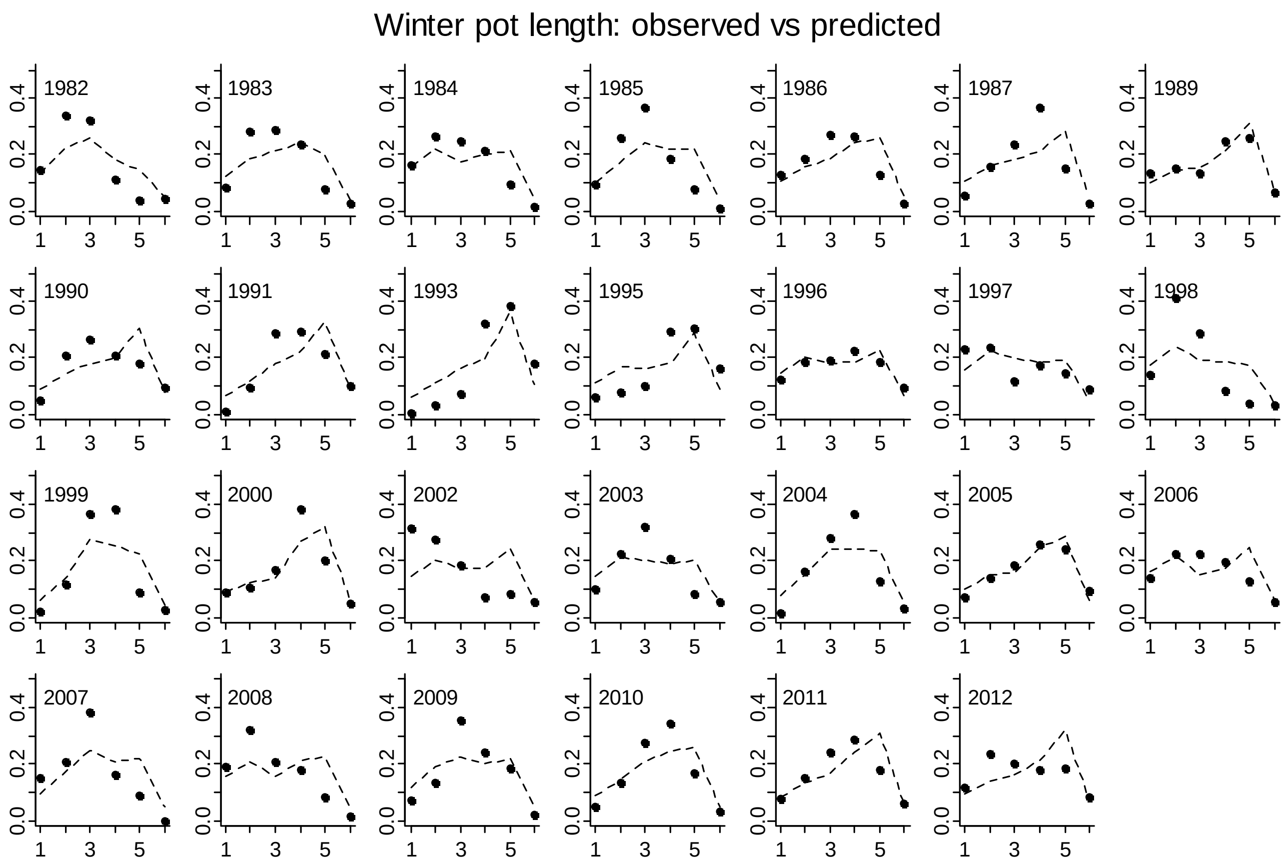
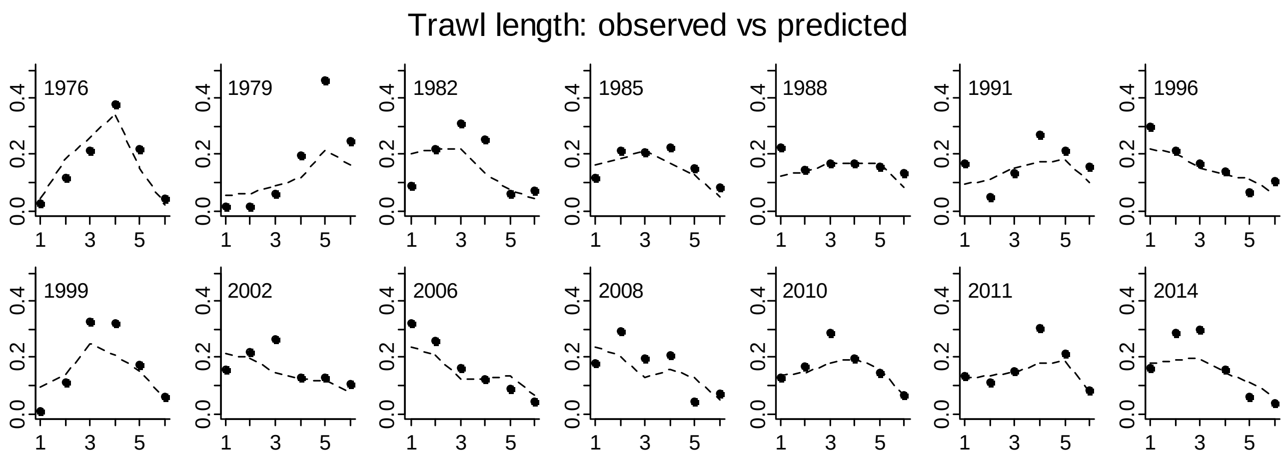


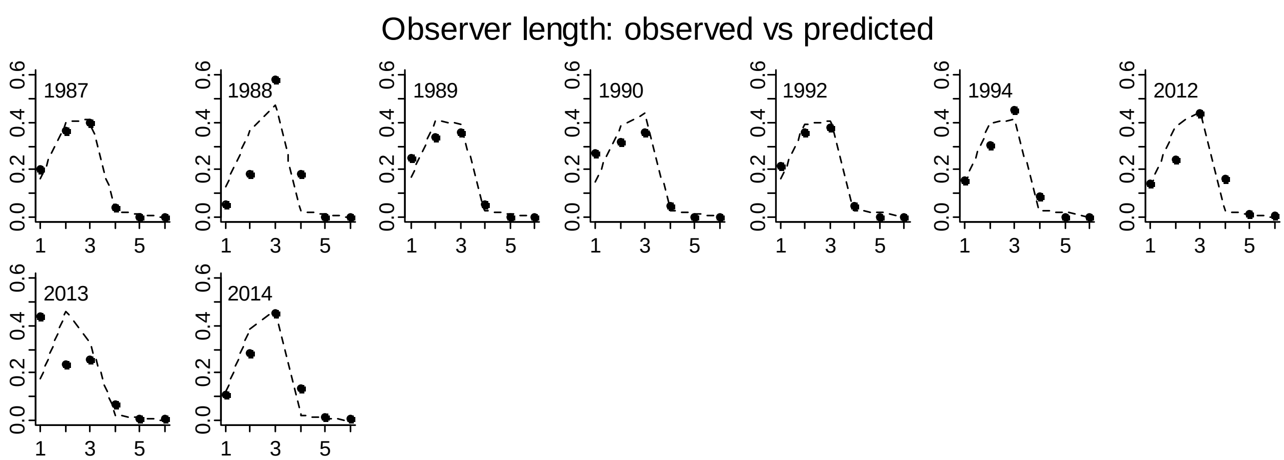
Figure C1-9. Predicted (dashed line) vs. observed (black dots) length class proportions for commercial catch.



1: 74-83, 2: 84-93, 3: 94-103, 4: 104-113, 5: 114-123, 6: >124

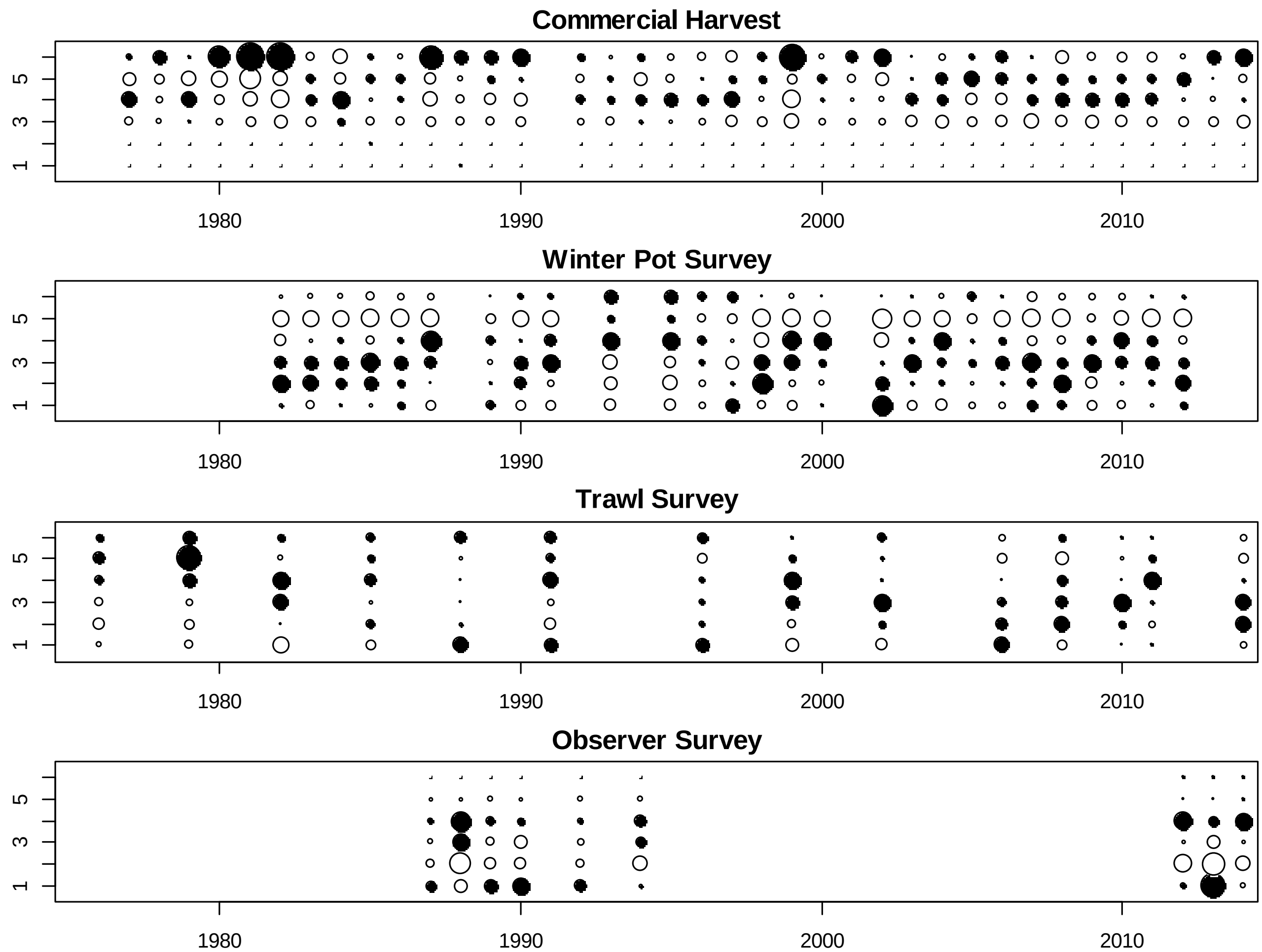
Figure C1-10. Predicted (dashed line) vs. observed (black dots) length class proportions for the winter pot survey.





1: 74-83, 2: 84-93, 3: 94-103, 4: 104-113, 5: 114-123, 6: >124

Figure C1-11. Predicted (dashed line) vs. observed (black dots) length class proportions for the trawl survey and observer survey.



1: 74-83, 2: 84-93, 3: 94-103, 4: 104-113, 5: 114-123, 6: >124

Figure C1-12. 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).

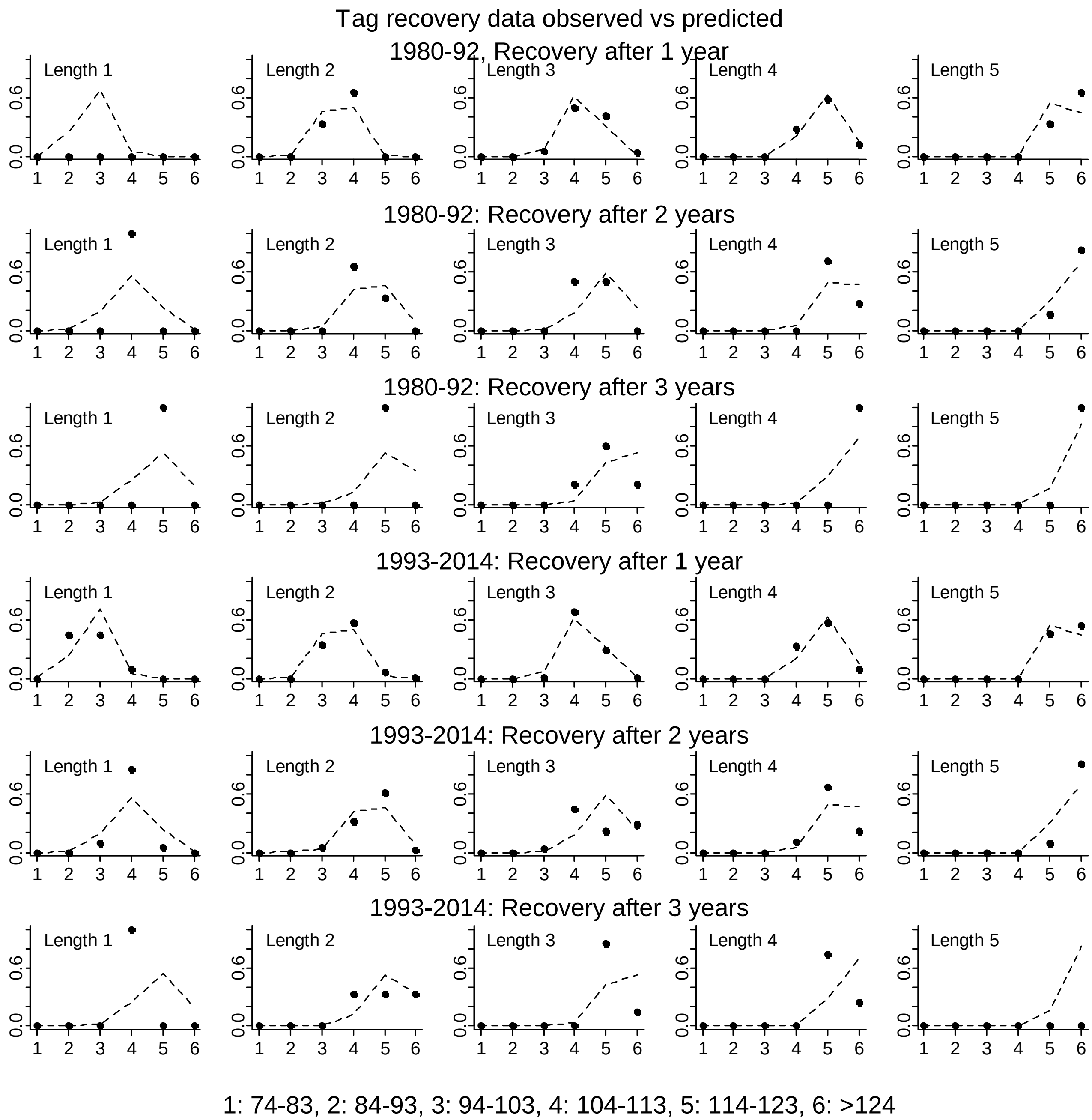
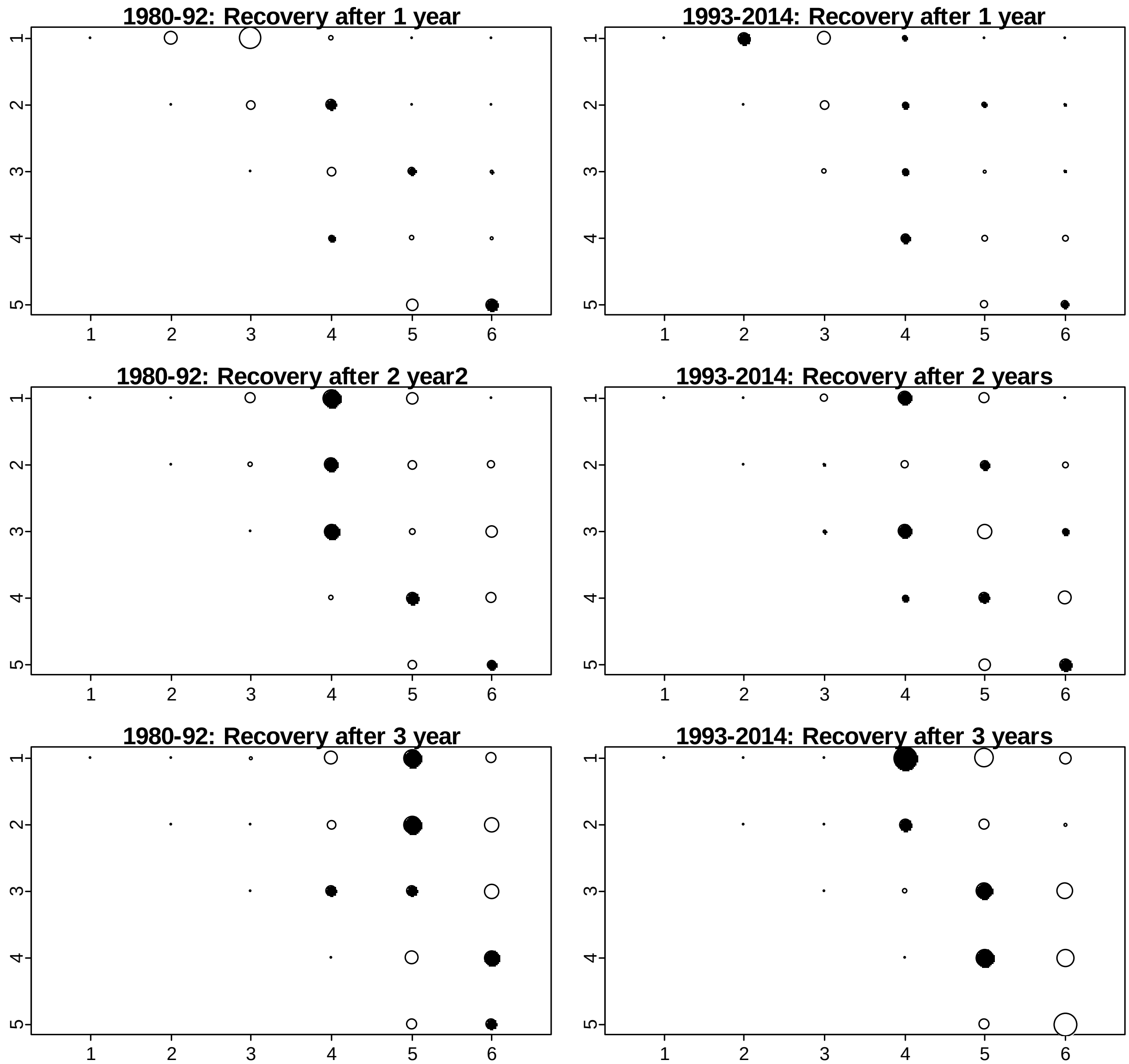


Figure C1-13. Predicted vs. observed length class proportions for tag recovery data 1980-1992, and 1993-2014.



1: 74-83, 2: 84-93, 3: 94-103, 4: 104-113, 5: 114-123, 6: >124

Figure C1-14. Bubble plots of predicted vs. observed length class proportions for tag recovery data 1980-1992 and 1993-2014.

Table C1-1 . 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	-7.127	0.17656
log_q_2	-6.9878	0.094566
log_N_{76}	9.0721	0.1535
R_0	6.4929	0.069105
$log\_\sigma_R^2$	0.30948	0.4562
log_R_{77}	-0.31725	0.38802
log_R_{78}	-0.76475	0.35056
log_R_{79}	-0.34097	0.37631
log_R_{80}	0.5063	0.26909
log_R_{81}	0.2481	0.28528
log_R_{82}	0.25407	0.326
log_R_{83}	0.67982	0.27011
log_R_{84}	0.25391	0.30368
log_R_{85}	0.2811	0.31083
log_R_{86}	0.28163	0.27041
log_R_{87}	-0.05958	0.27581
log_R_{88}	0.11129	0.26565
log_R_{89}	-0.06254	0.27019
log_R_{90}	-0.54924	0.29976
log_R_{91}	-0.39701	0.28092
log_R_{92}	-0.87032	0.32178
log_R_{93}	-0.6006	0.28479
log_R_{94}	-0.49694	0.27573
log_R_{95}	-0.21499	0.23842
log_R_{96}	0.030493	0.27535
log_R_{97}	0.41201	0.21789
log_R_{98}	-0.65183	0.3258
log_R_{99}	-0.32476	0.31115
log_R_{00}	-0.06076	0.29164
log_R_{01}	0.21447	0.22834
log_R_{02}	0.36023	0.27723
log_R_{03}	-0.27403	0.34387
log_R_{04}	-0.05466	0.29202
log_R_{05}	0.51508	0.20307
log_R_{06}	-0.01012	0.30701
log_R_{07}	0.60996	0.20771
log_R_{08}	0.36358	0.26953
log_R_{09}	0.029118	0.27672
log_R_{10}	-0.07926	0.26879
log_R_{11}	-0.09526	0.29552
log_R_{12}	0.48873	0.30875
log_R_{13}	0.27551	0.35564
a_1	0.36358	1.8991
a_2	1.8521	1.3711
a_3	2.188	1.3278
a_4	2.481	1.3052
a_5	1.6617	1.3594

r1	0.58293	0.052011
log_ α	-1.8099	0.018035
log_ ϕ_{st1}	-14.548	1430.8
log_ ϕ_{st2}	-2.525	15547
log_ ϕ_{w}	-1.7991	0.078231
Sw_6	0.33674	0.09315
log_ ϕ_{1}	-1.8274	0.085364
log_ ϕ_{2}	-1.7831	0.091305
w^2_t	0.052679	0.017827
q	0.74288	0.12989
σ	4.6363	0.21147
β_1	9.1501	0.67711
β_2	7.8816	0.21291

Appendix C2: Results Model 2

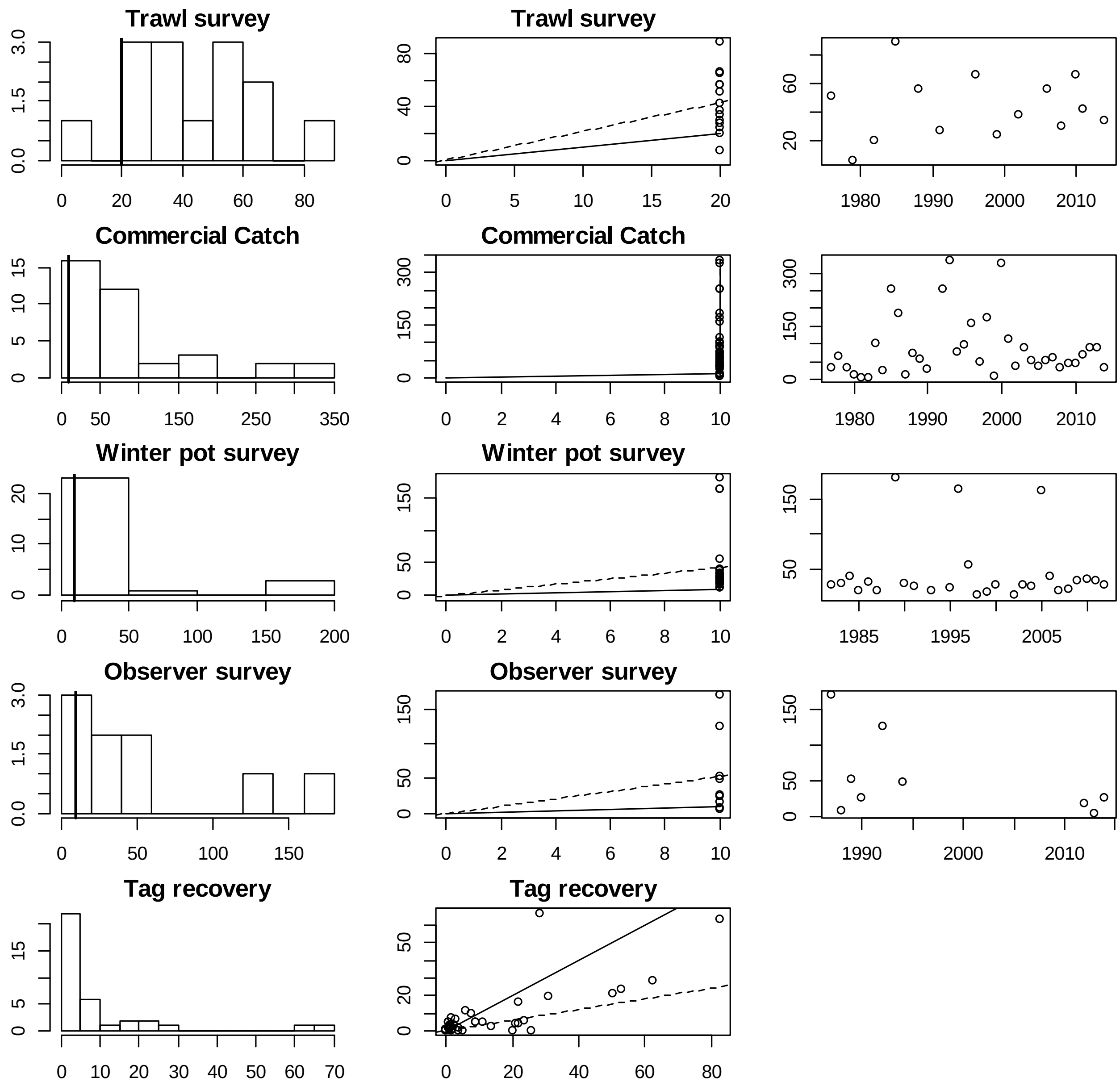


Figure C2-1: Effective sample size vs. implied sample size. Figures in the first column show effective sample size (x-axis) vs. frequency (y-axis). Vertical solid line is the implied sample size. Figures in the second column show implied sample size (x-axis) vs. effective sample size (y-axis). Dashed line indicates linear regression slope, and solid line is 1:1 line. Figures in the third column show year (x-axis) vs. effective sample size (y-axis).

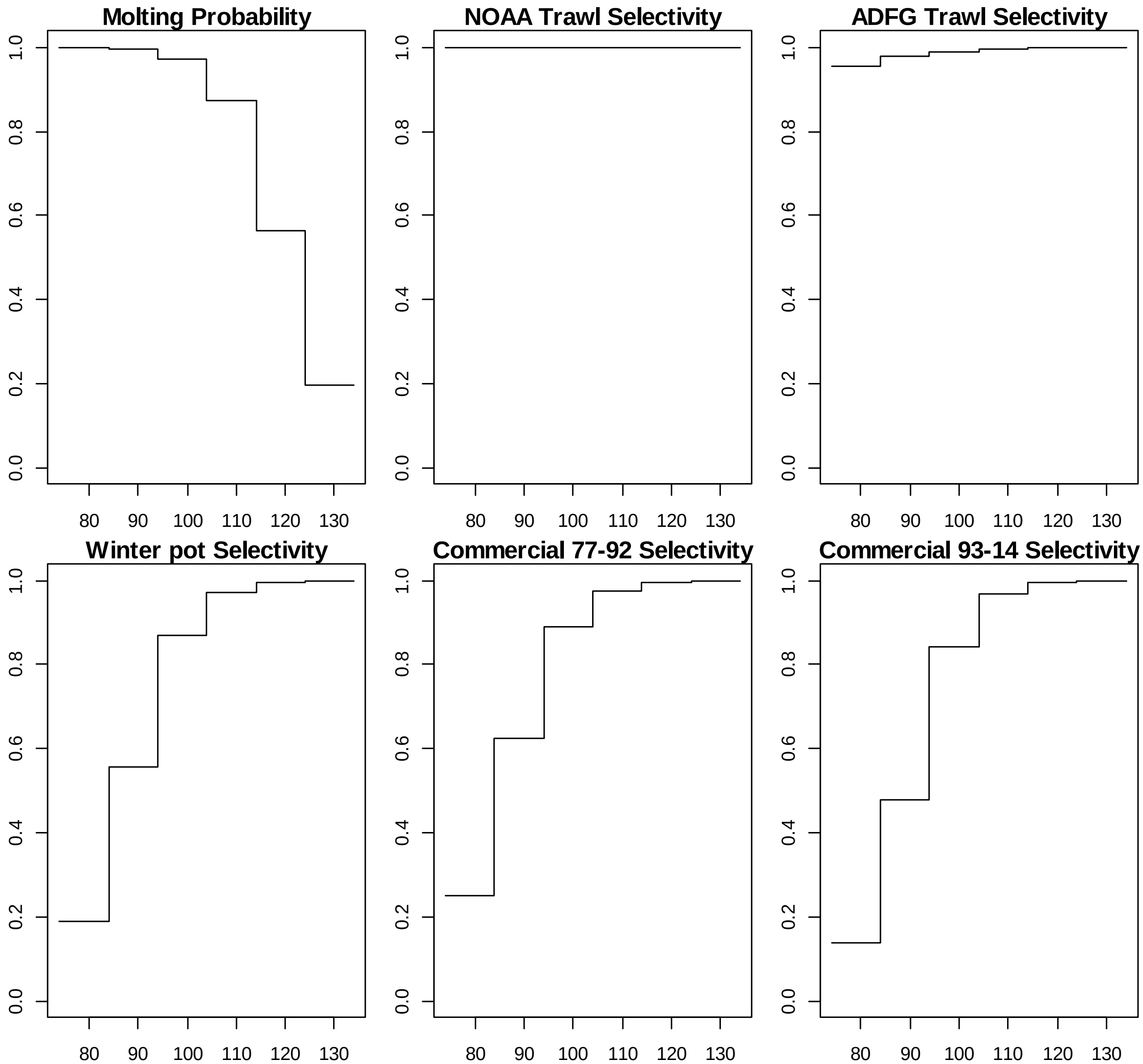


Figure C2-2. Molting probability and trawl/pot selectivities. X-axis is carapace length.

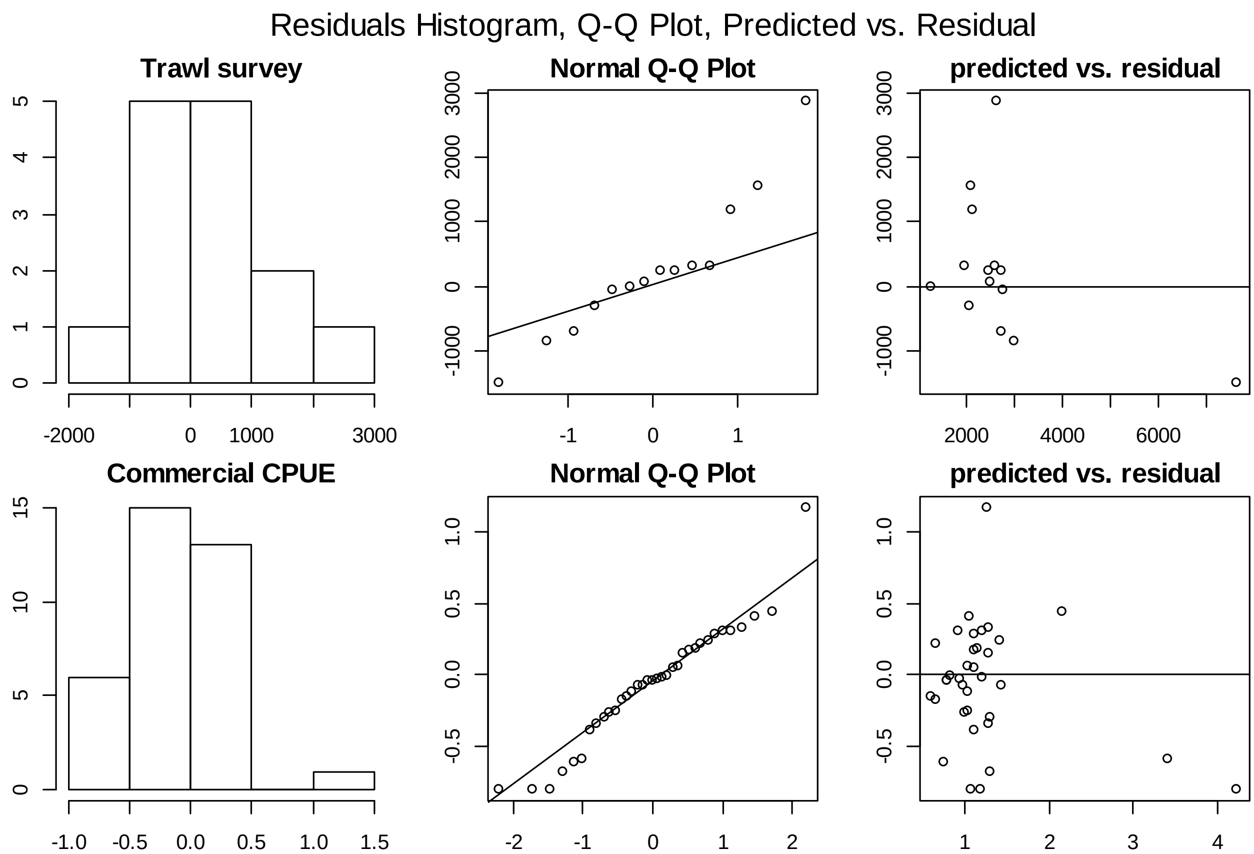


Figure C2-3. QQ Plot of Trawl survey and Commercial CPUE

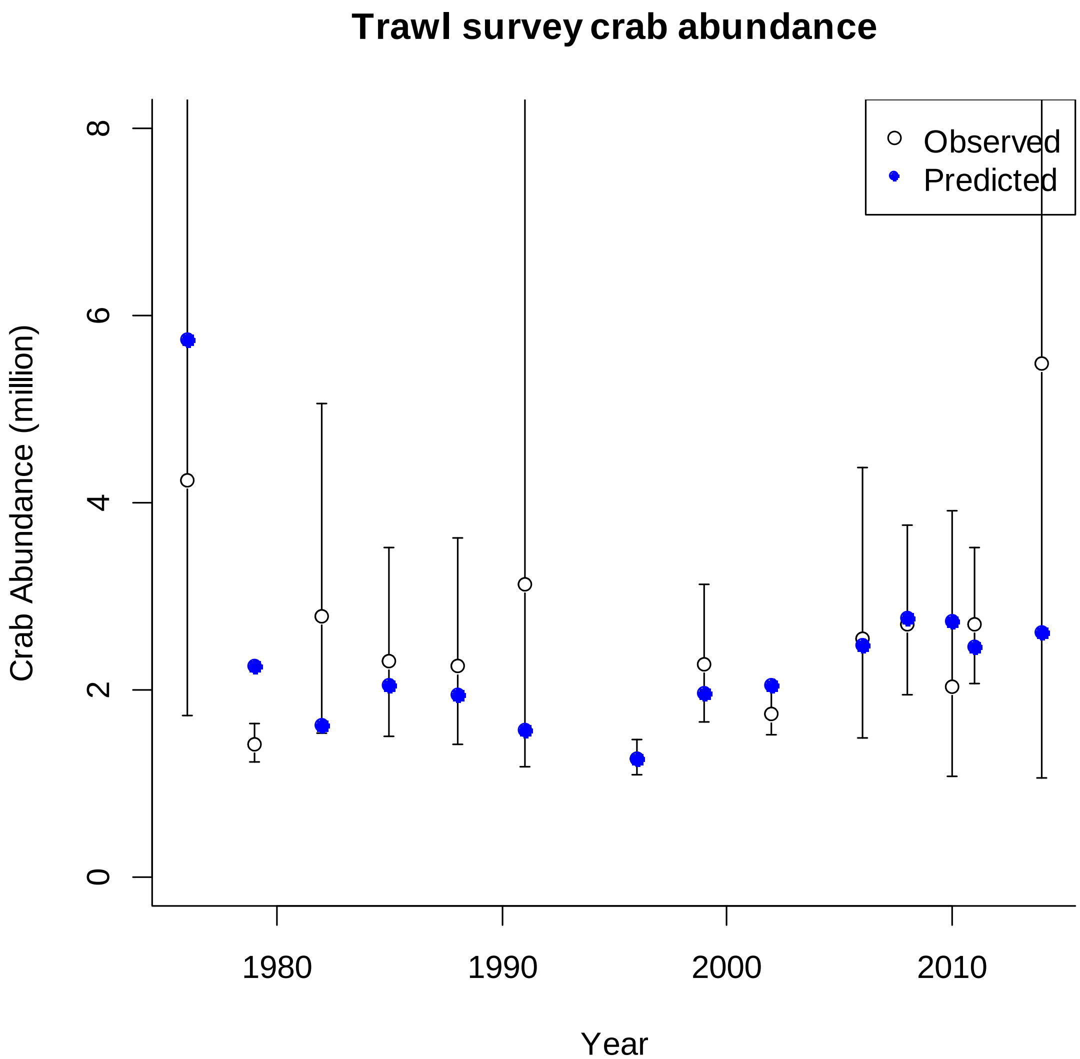


Figure C2-4. Estimated trawl survey abundance (crabs ≥ 74 mm CL) male

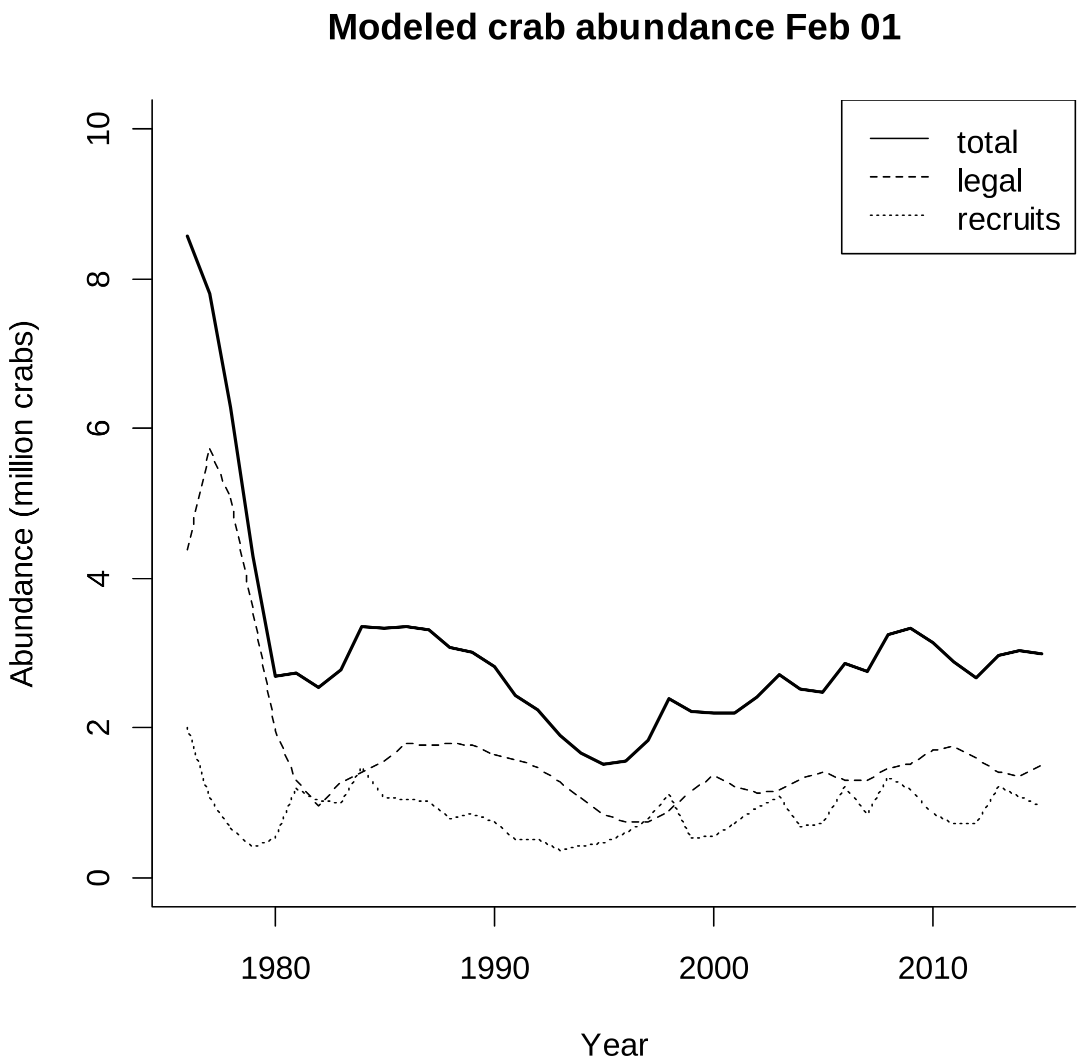


Figure C2-5. Estimated abundance of legal male from 1976-2014

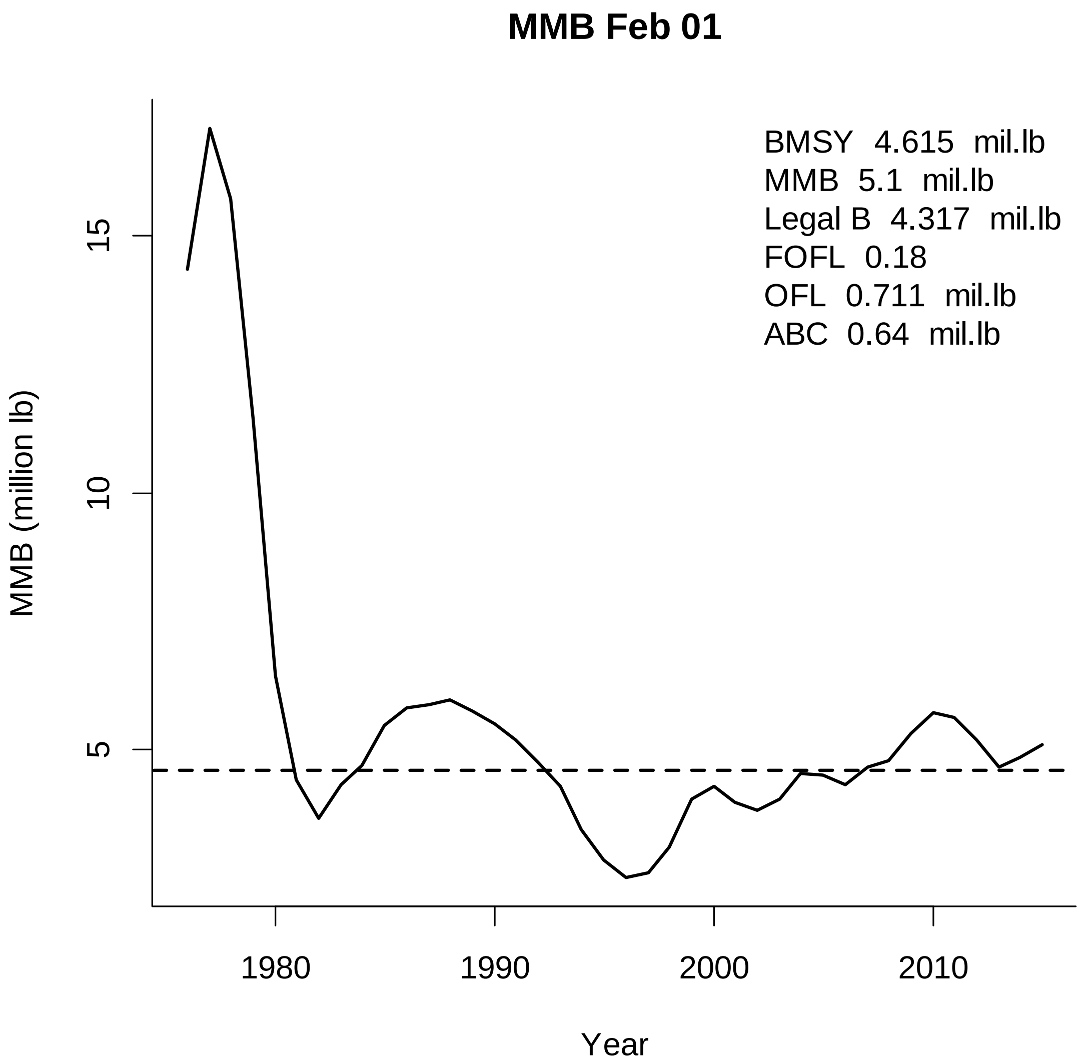


Figure C2-6. Estimated abundance of leg recruits from 1976-2015. Dash line shows Bmsy (Average MMB of 1980-2015)

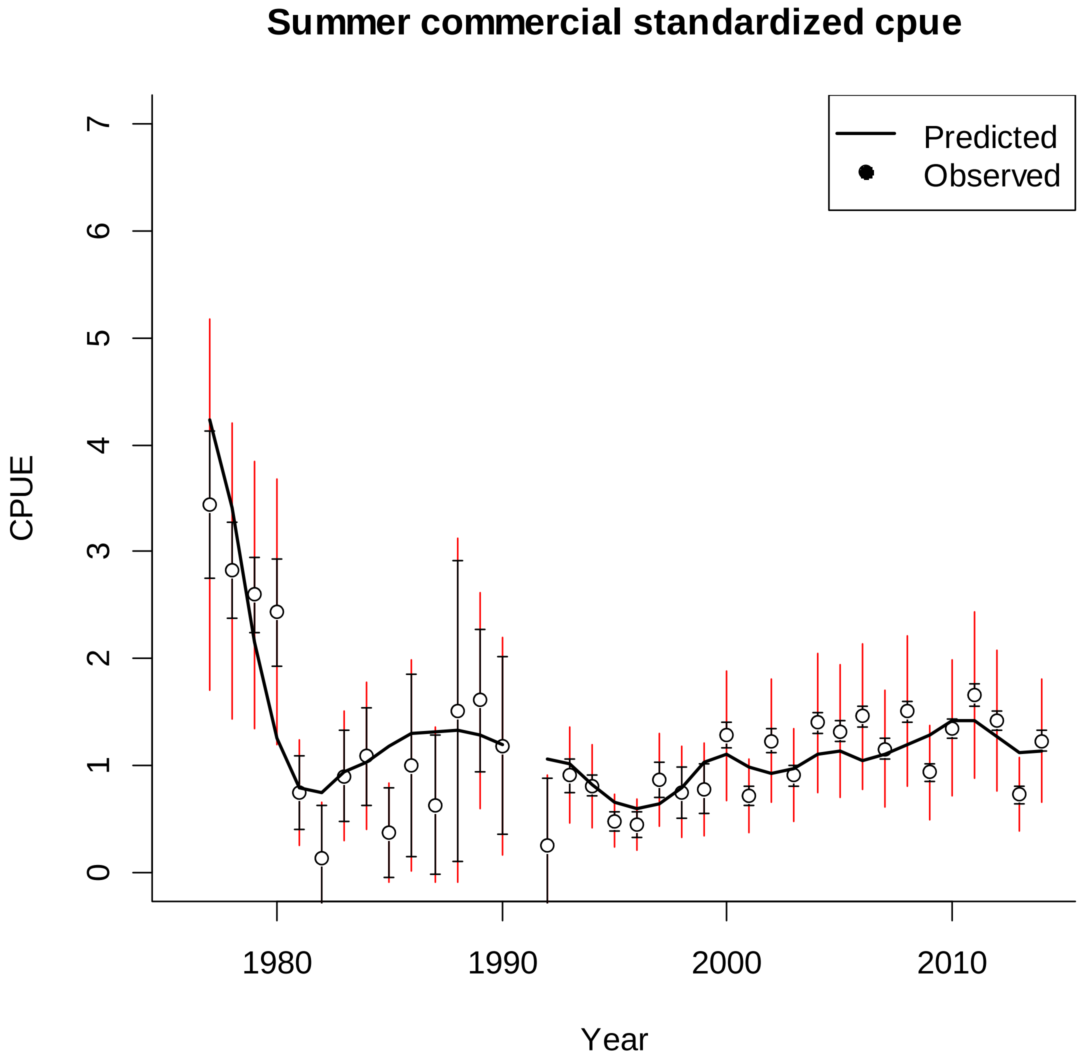


Figure C2-7. Summer commercial standardized cpue (1977-2014)

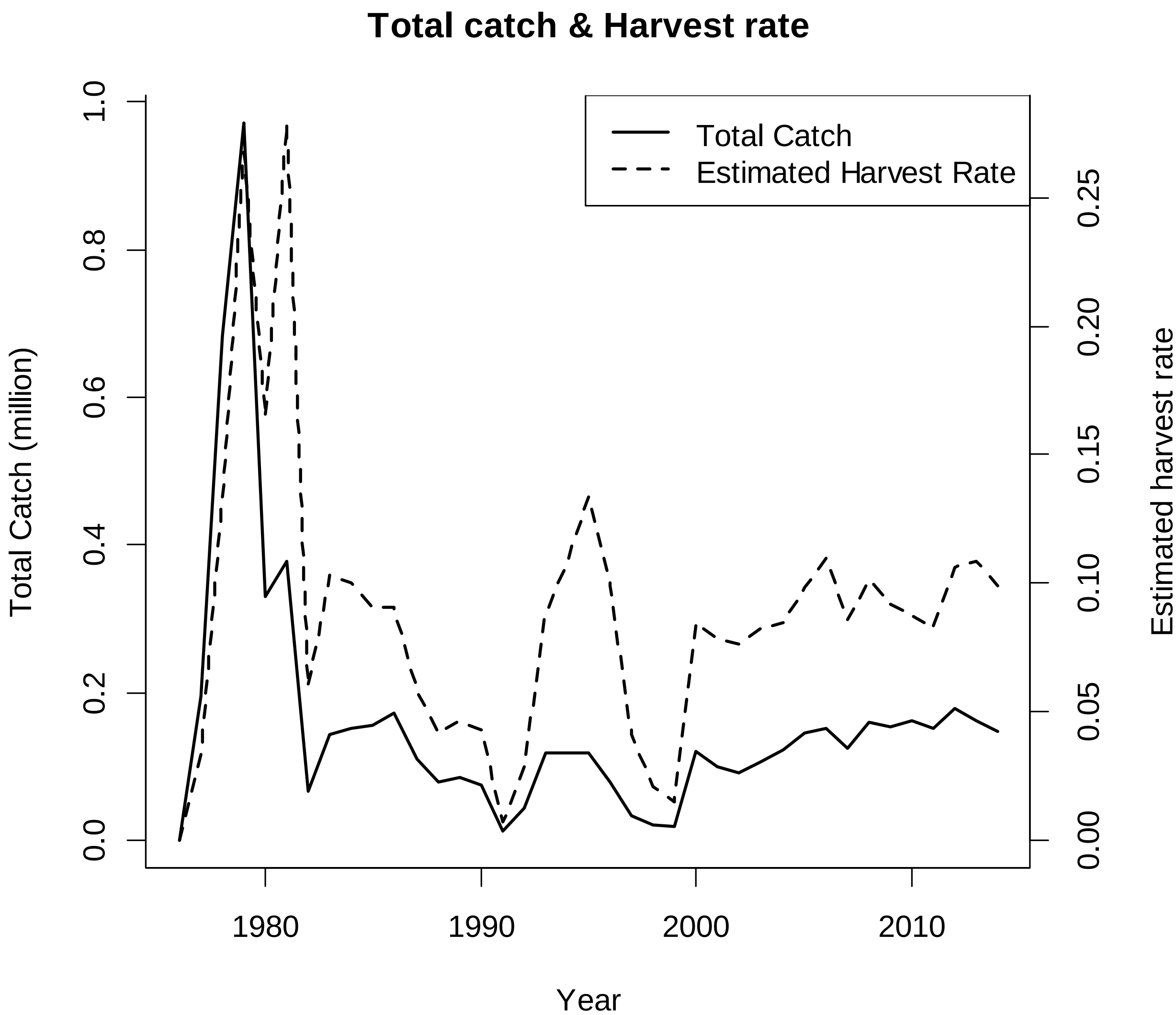
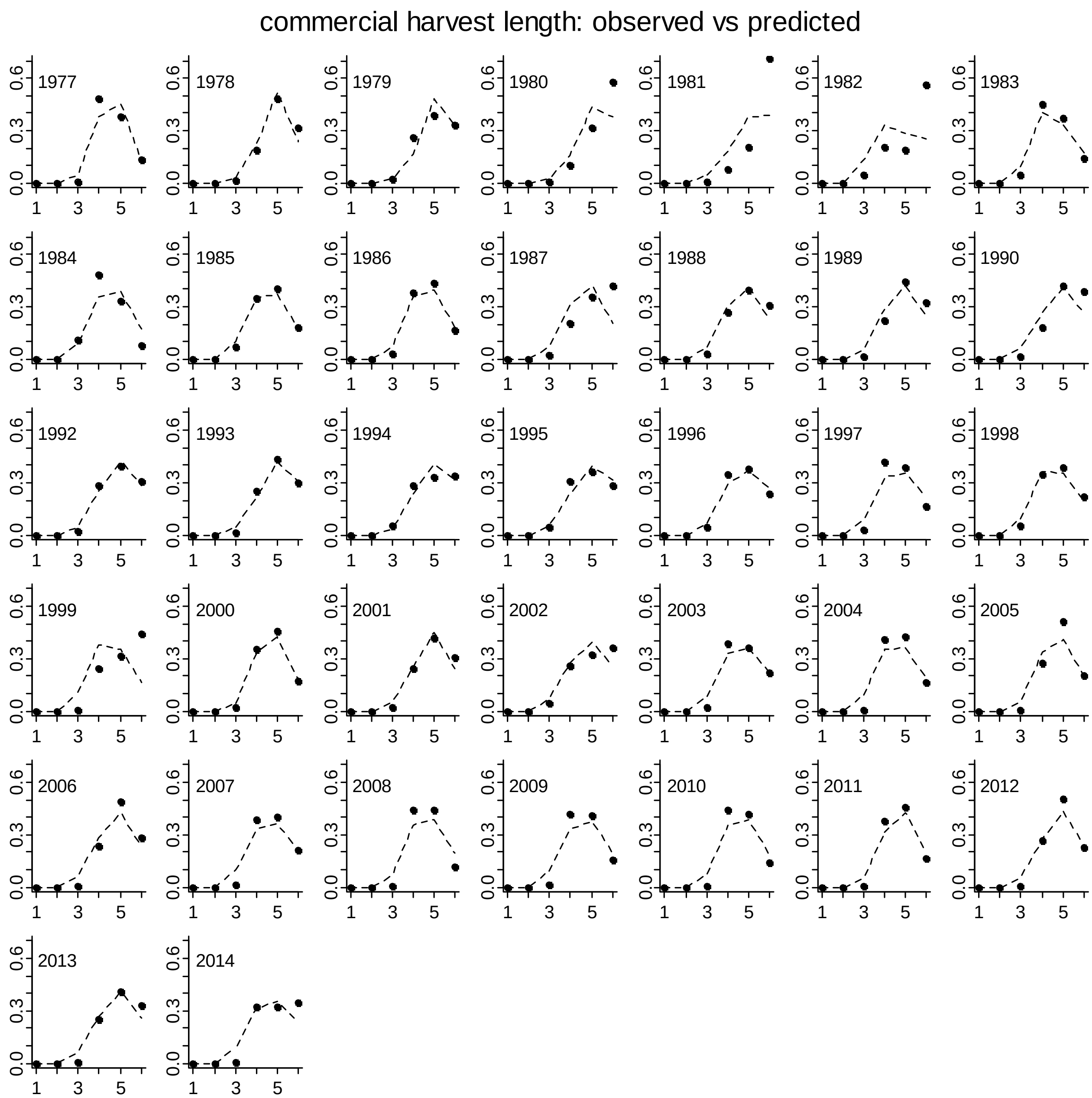
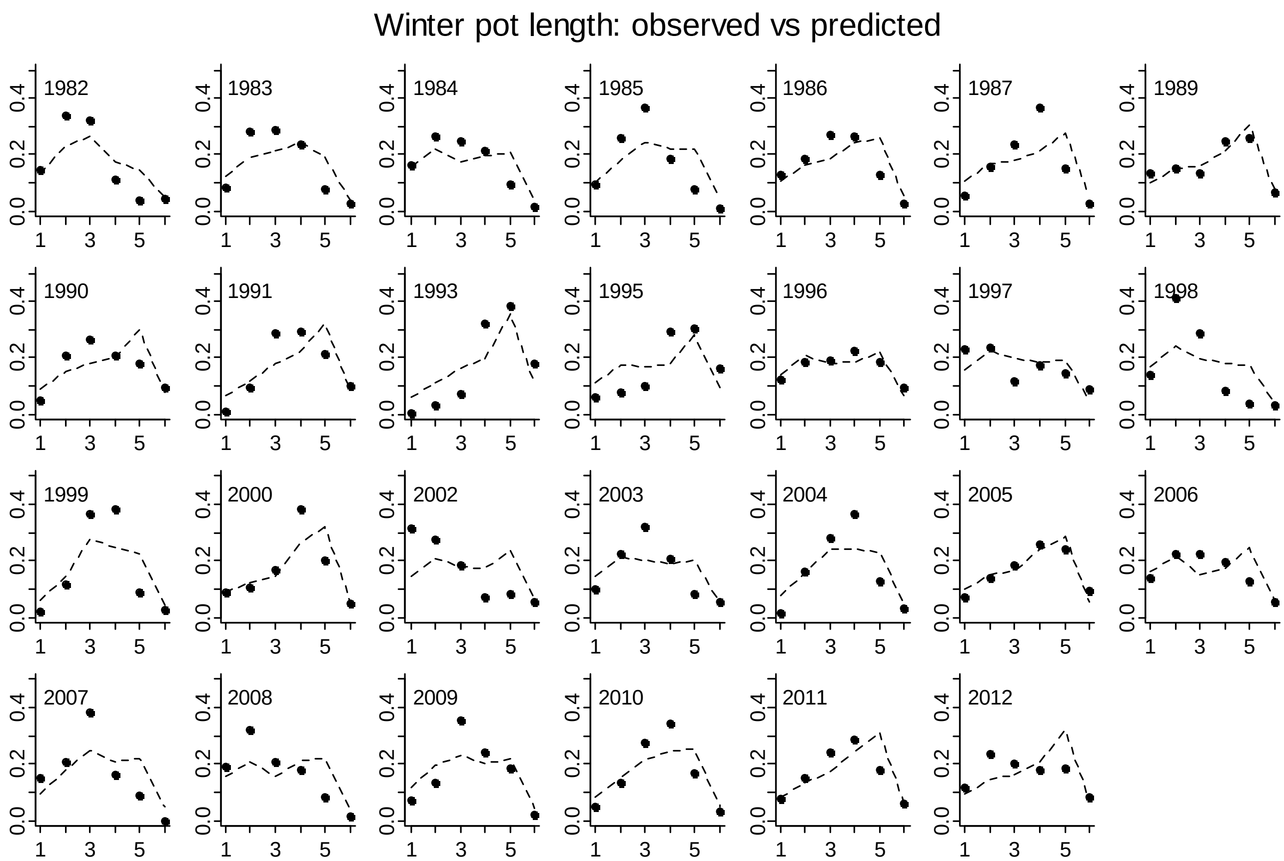


Figure C2-8: Total catch and estimated harvest rate 1976-2014



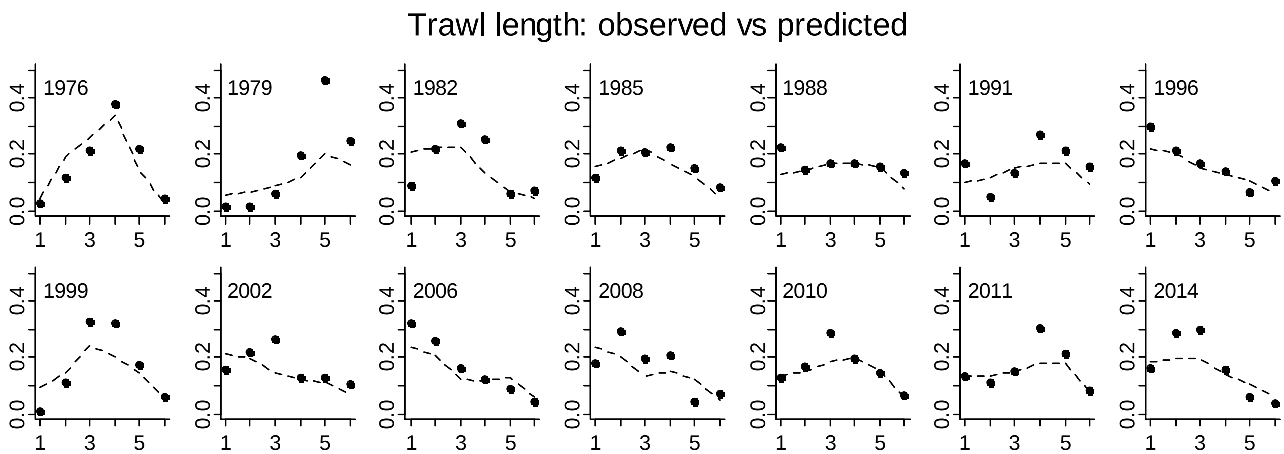
1: 74-83, 2: 84-93, 3: 94-103, 4: 104-113, 5: 114-123, 6: >124

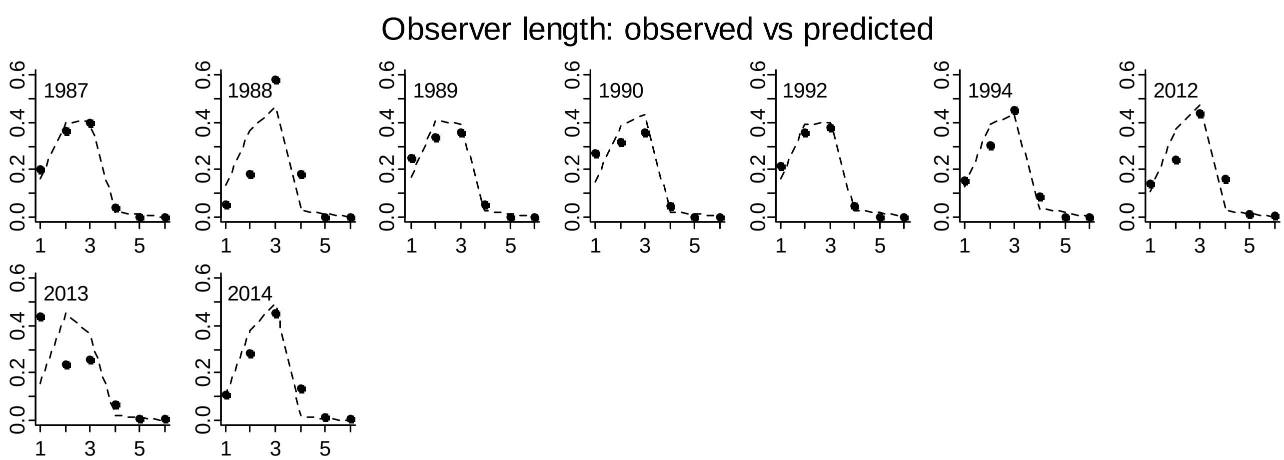
Figure C2-9: Predicted (dashed line) vs. observed (black dots) length class proportion for commercial catch:



1: 74-83, 2: 84-93, 3: 94-103, 4: 104-113, 5: 114-123, 6: >124

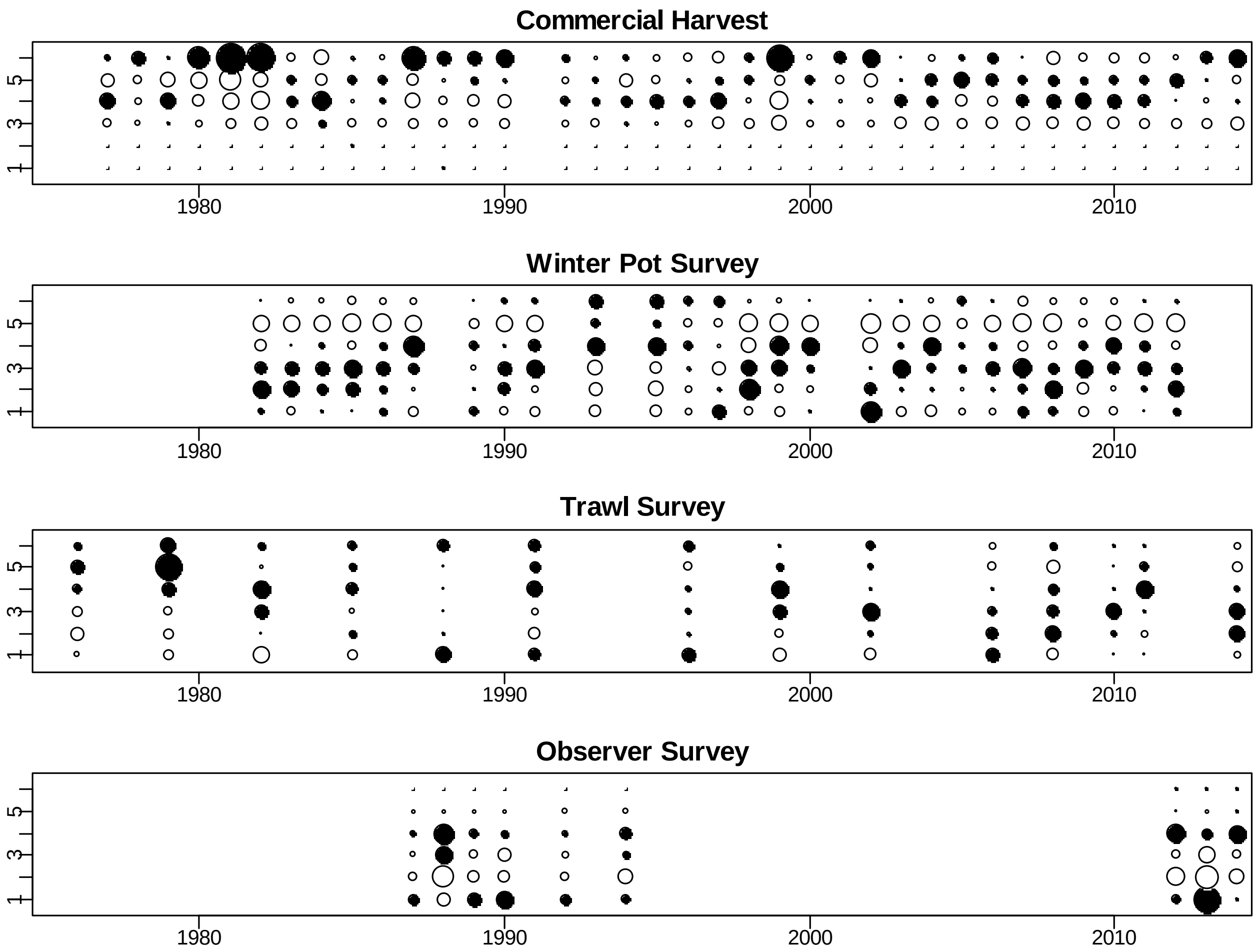
Figure C2-10: Predicted (dashed line) vs. observed (black dots) length class proportion for winter pot survey





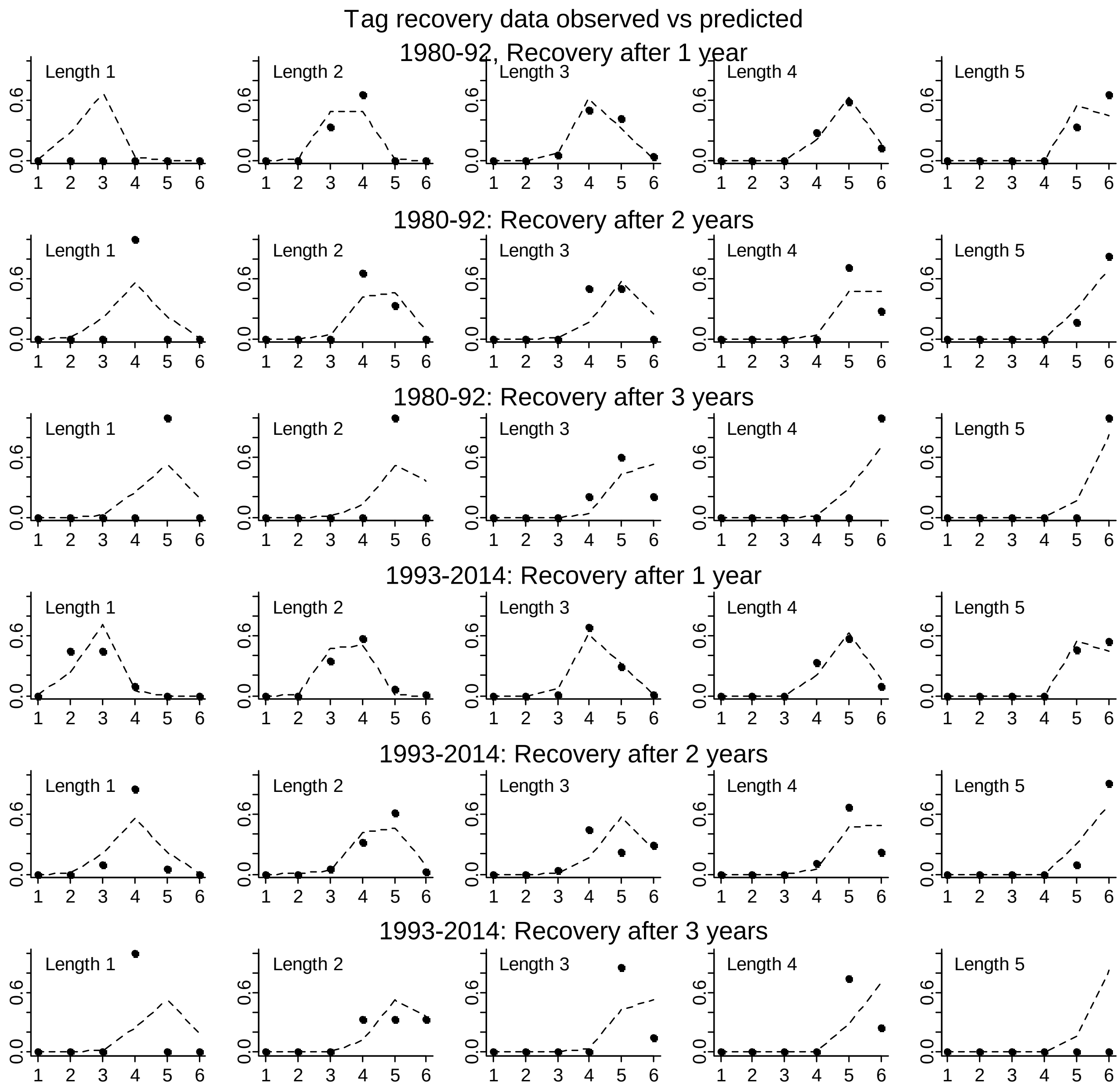
1: 74-83, 2: 84-93, 3: 94-103, 4: 104-113, 5: 114-123, 6: >124

Figure C2-11: Predicted (dashed line) vs. observed (black dots) length class proportion for trawl survey and observer survey



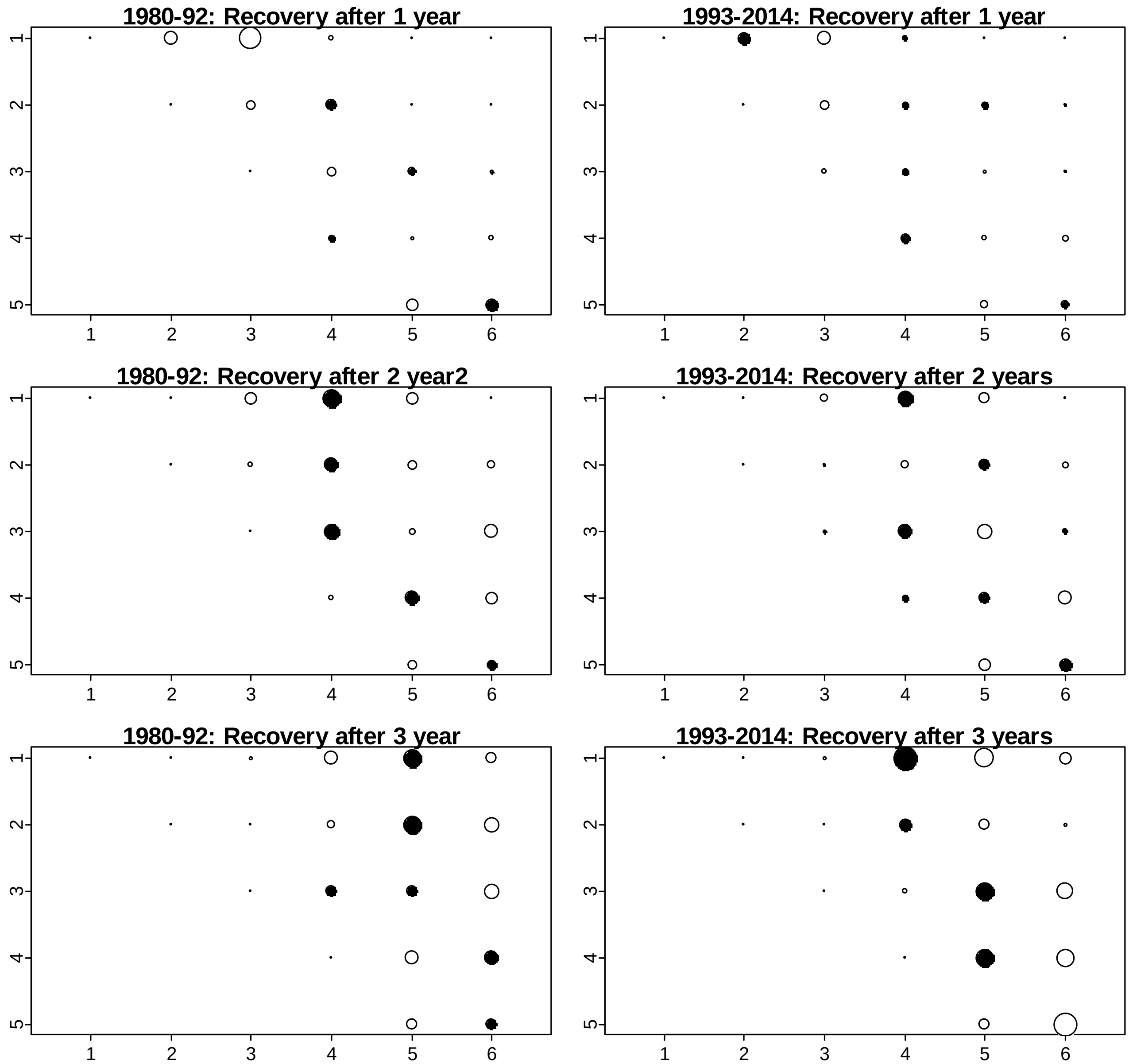
1: 74-83, 2: 84-93, 3: 94-103, 4: 104-113, 5: 114-123, 6: >124

Figure C2-12: Bubble plot 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 indicate degree of deviance (larger circle = larger deviance).



1: 74-83, 2: 84-93, 3: 94-103, 4: 104-113, 5: 114-123, 6: >124

Figure C2-13: Predicted vs. observed length class proportion for tag recovery data 1980-1992, and 1993-2014:



1: 74-83, 2: 84-93, 3: 94-103, 4: 104-113, 5: 114-123, 6: >124

Figure C2-14: Bubble plot of predicted vs. observed length class proportion for tag recovery data 1980-1992, and 1993-2014:

Table C2-1 . 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	-7.1048	0.17662
log_q_2	-6.97	0.095744
log_N_{76}	9.0563	0.15446
R_0	6.491	0.069347
$log\_\sigma_R^2$	0.33714	0.45763
log_R_{77}	-0.3232	0.38865
log_R_{78}	-0.76706	0.3502
log_R_{79}	-0.32615	0.37662
log_R_{80}	0.50643	0.27111
log_R_{81}	0.22724	0.28926
log_R_{82}	0.25405	0.32796
log_R_{83}	0.68092	0.27108
log_R_{84}	0.2244	0.30905
log_R_{85}	0.29406	0.31167
log_R_{86}	0.26992	0.2736
log_R_{87}	-0.06733	0.27727
log_R_{88}	0.10828	0.26692
log_R_{89}	-0.07751	0.2724
log_R_{90}	-0.54716	0.30018
log_R_{91}	-0.41064	0.28191
log_R_{92}	-0.8815	0.32382
log_R_{93}	-0.57371	0.28374
log_R_{94}	-0.49641	0.27707
log_R_{95}	-0.2247	0.24044
log_R_{96}	0.049319	0.27676
log_R_{97}	0.40068	0.22156
log_R_{98}	-0.66152	0.32784
log_R_{99}	-0.31458	0.31108
log_R_{00}	-0.05404	0.29304
log_R_{01}	0.21408	0.23024
log_R_{02}	0.3549	0.27847
log_R_{03}	-0.27601	0.34569
log_R_{04}	-0.04466	0.29359
log_R_{05}	0.50884	0.20501
log_R_{06}	-0.00859	0.30991
log_R_{07}	0.61182	0.20922
log_R_{08}	0.36676	0.27064
log_R_{09}	0.018401	0.28083
log_R_{10}	-0.09418	0.2731
log_R_{11}	-0.08166	0.29694
log_R_{12}	0.51037	0.31218
log_R_{13}	0.293	0.35983
a_1	0.45931	1.8886
a_2	1.913	1.3704
a_3	2.2159	1.3292
a_4	2.4852	1.3068
a_5	1.6554	1.3603

r1	0.59245	0.055077
log_ α	-1.7948	0.018979
log_ ϕ_{st1}	-14.505	1533.7
log_ ϕ_{st2}	-2.569	15686
log_ ϕ_W	-1.789	0.07563
Sw_6	0.33555	0.093222
log_ ϕ_1	-1.8329	0.085933
log_ ϕ_2	-1.7446	0.094652
w^2_t	0.052278	0.017716
q	0.75234	0.13156
σ	4.5884	0.29558
β_1	8.5014	0.87056
β_2	8.121	0.27127

Appendix C3: Results Model 3

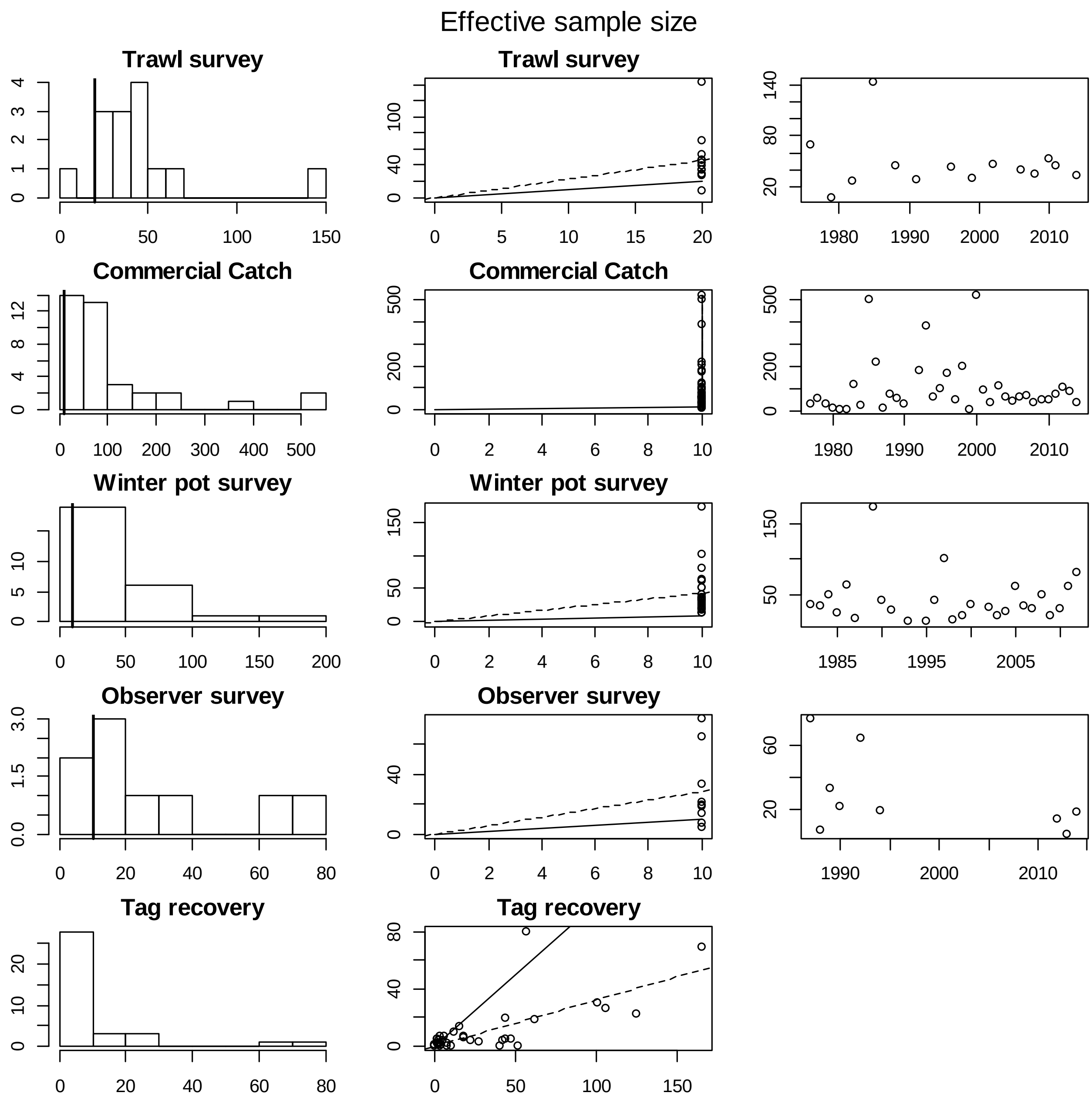


Figure C3-1: Effective sample size vs. implied sample size. Figures in the first column show effective sample size (x-axis) vs. frequency (y-axis). Vertical solid line is the implied sample size. Figures in the second column show implied sample size (x-axis) vs. effective sample size (y-axis). Dashed line indicates linear regression slope, and solid line is 1:1 line. Figures in the third column show year (x-axis) vs. effective sample size (y-axis).

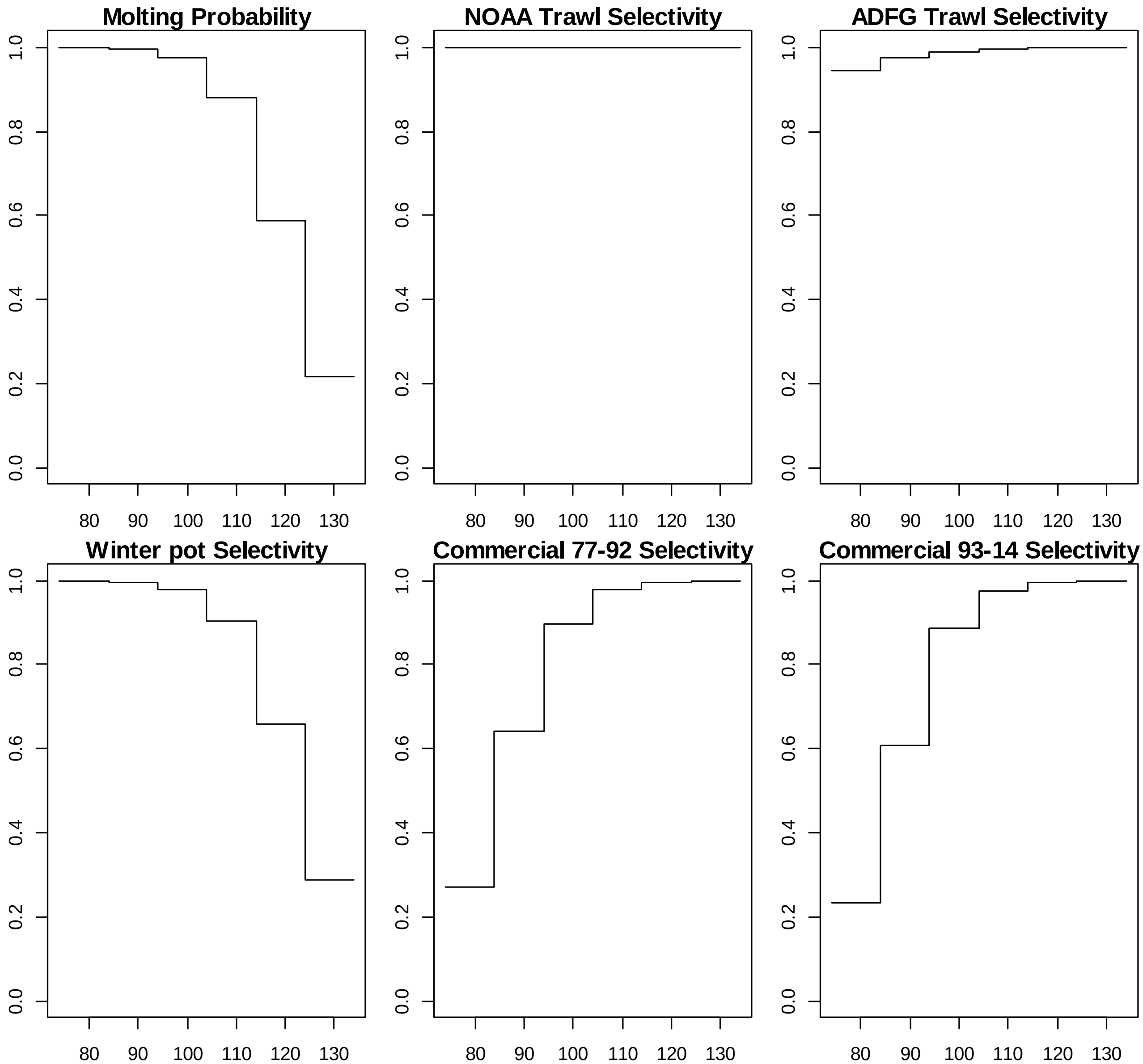


Figure C3-2. Molting probability and trawl/pot selectivities. X-axis is carapace length.

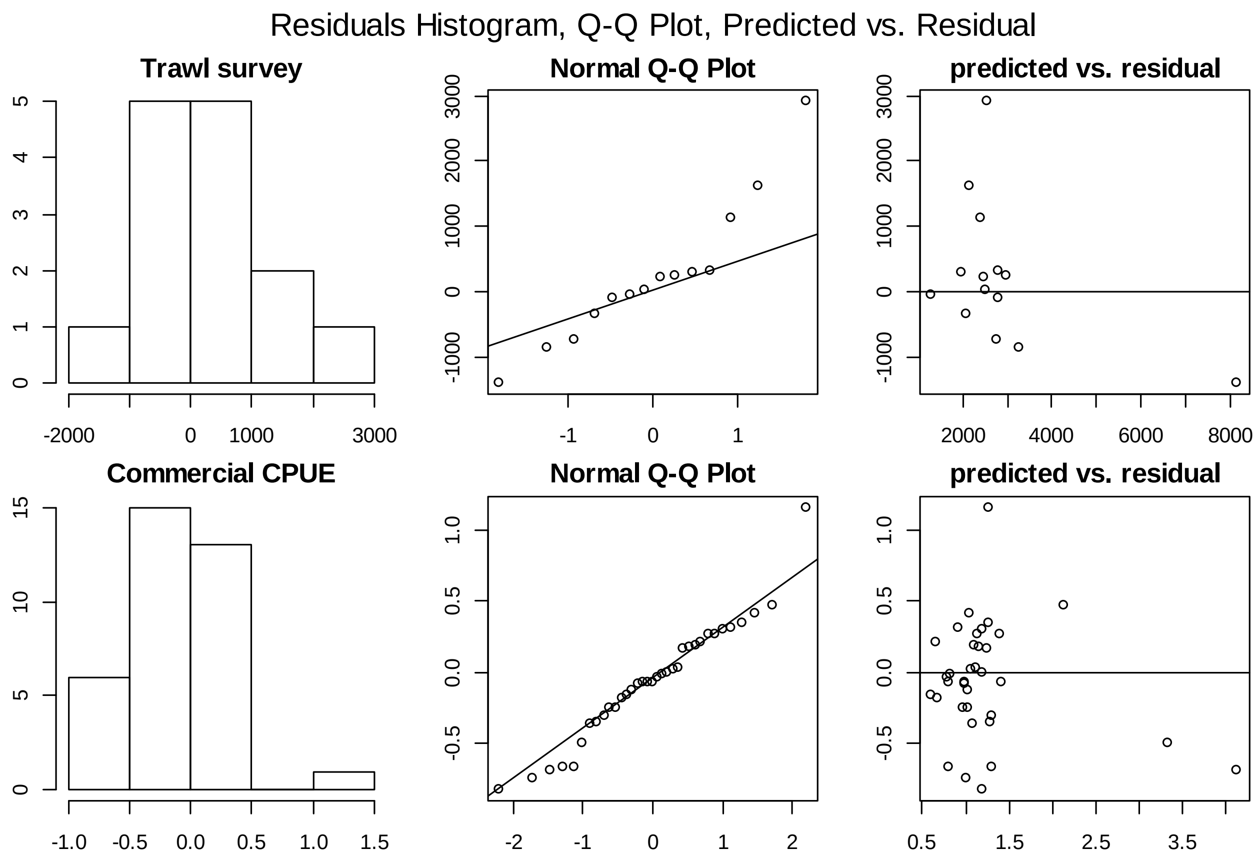


Figure C3-3. QQ Plot of Trawl survey and Commercial CPUE

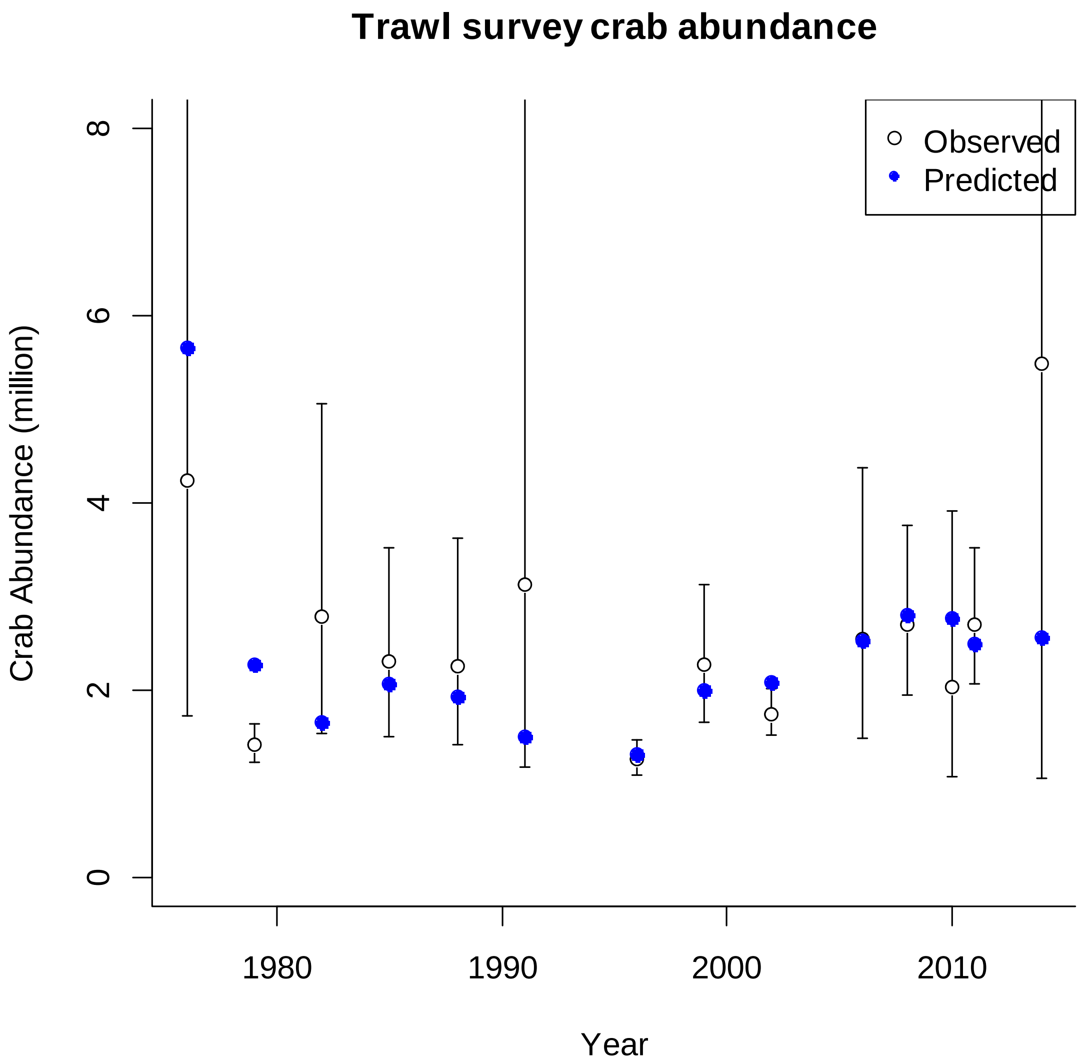


Figure C3-4. Estimated trawl survey abundance (crabs ≥ 74 mm CL) male

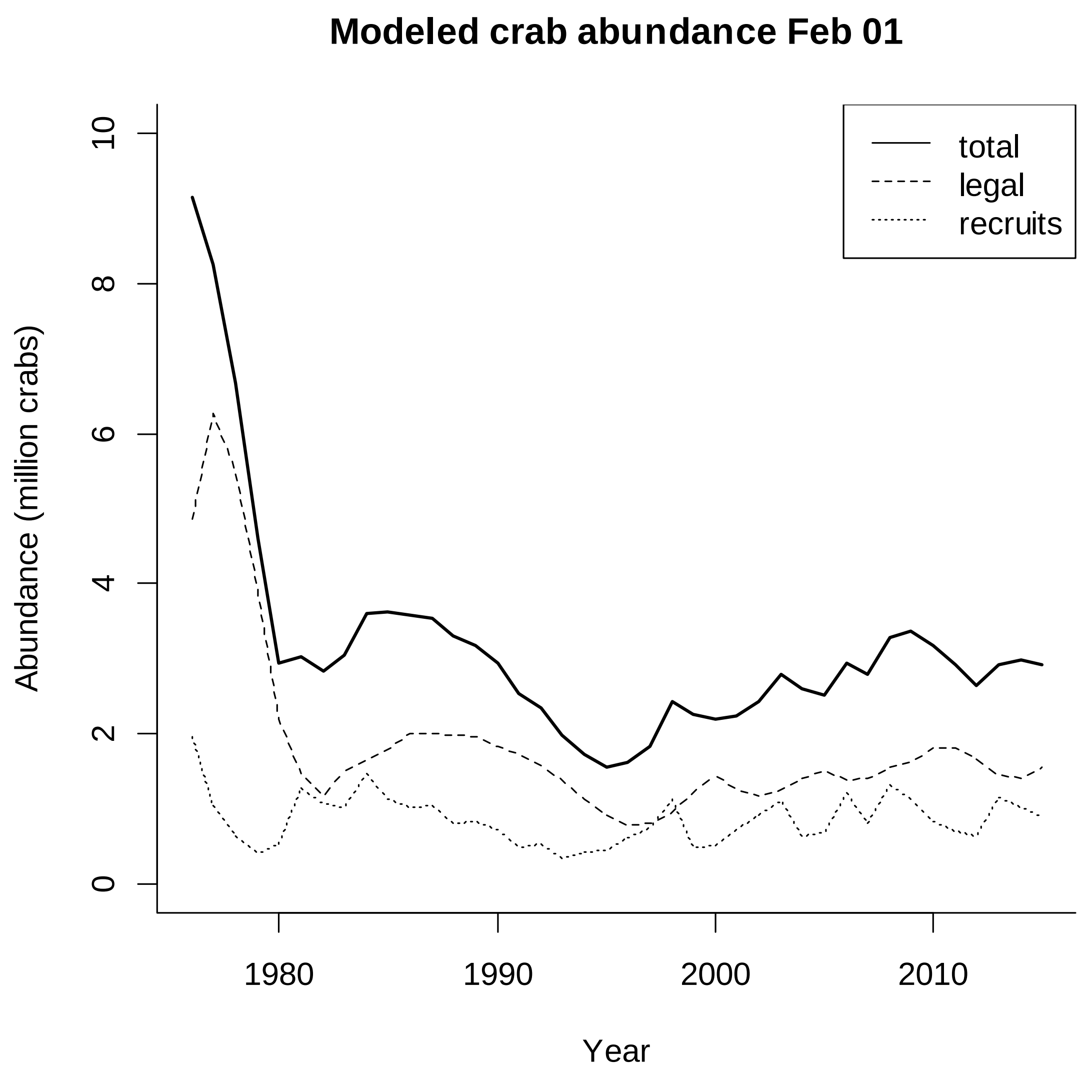


Figure C3-5. Estimated abundance of legal male from 1976-2014

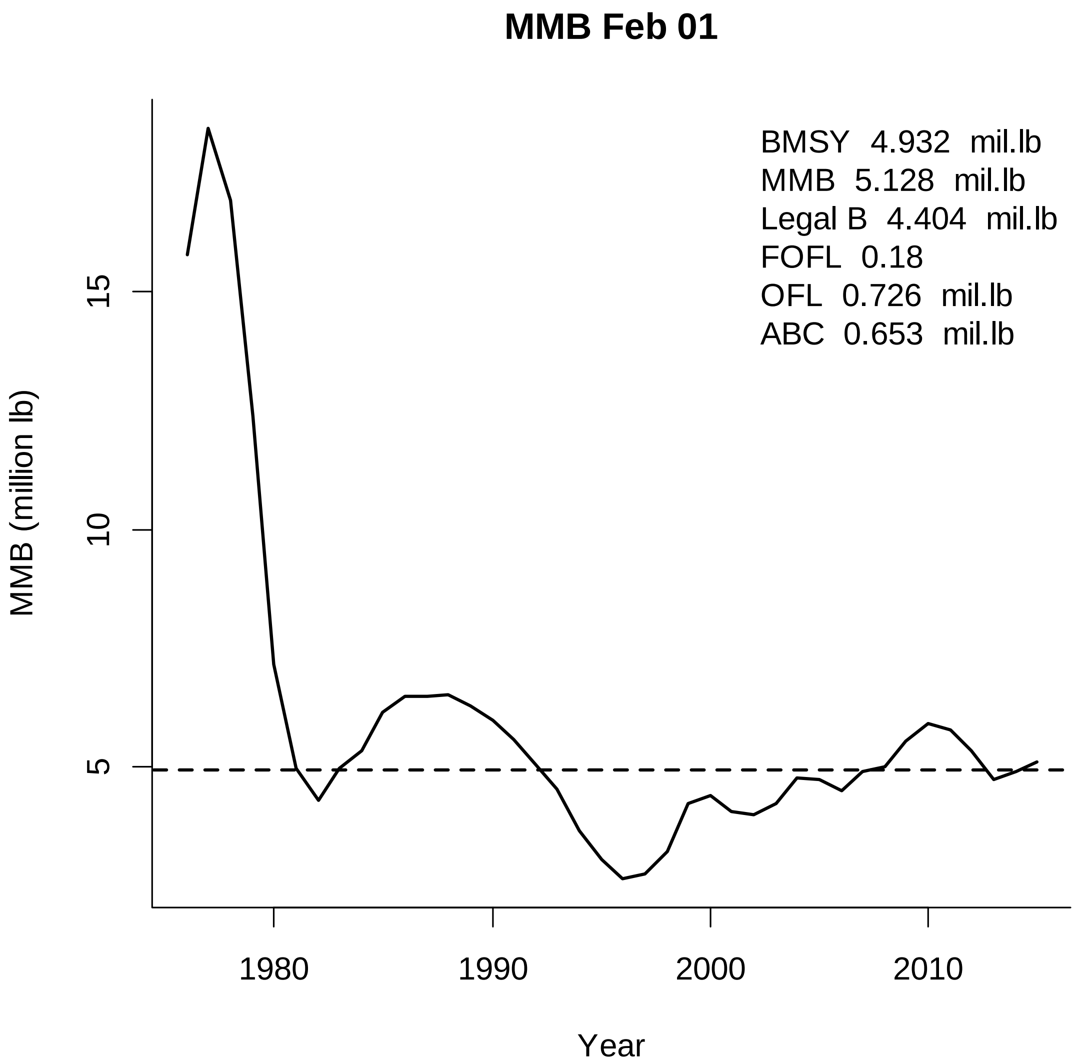


Figure C3-6. Estimated abundance of leg recruits from 1976-2015. Dash line shows Bmsy (Average MMB of 1980-2015)

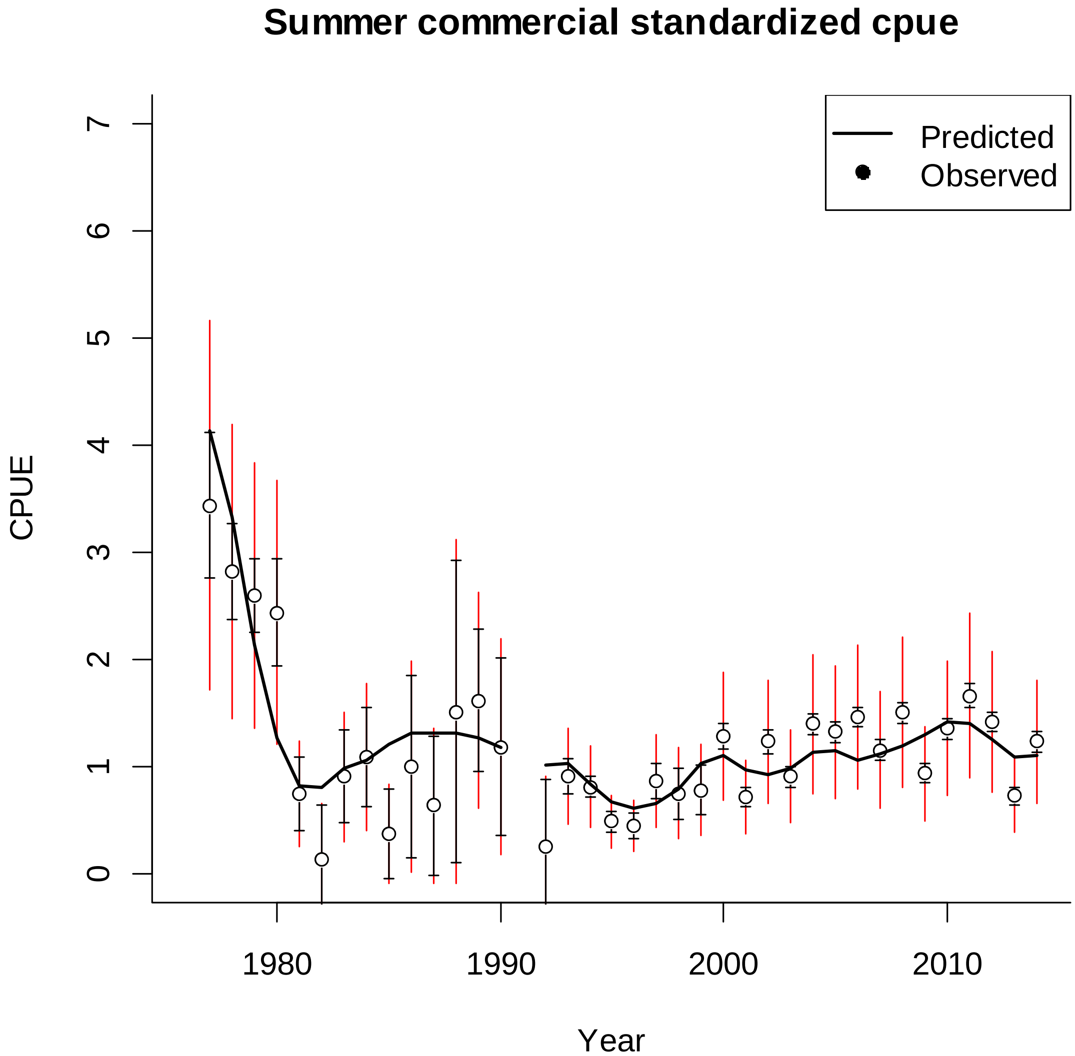


Figure C3-7. Summer commercial standardized cpue (1977-2014)

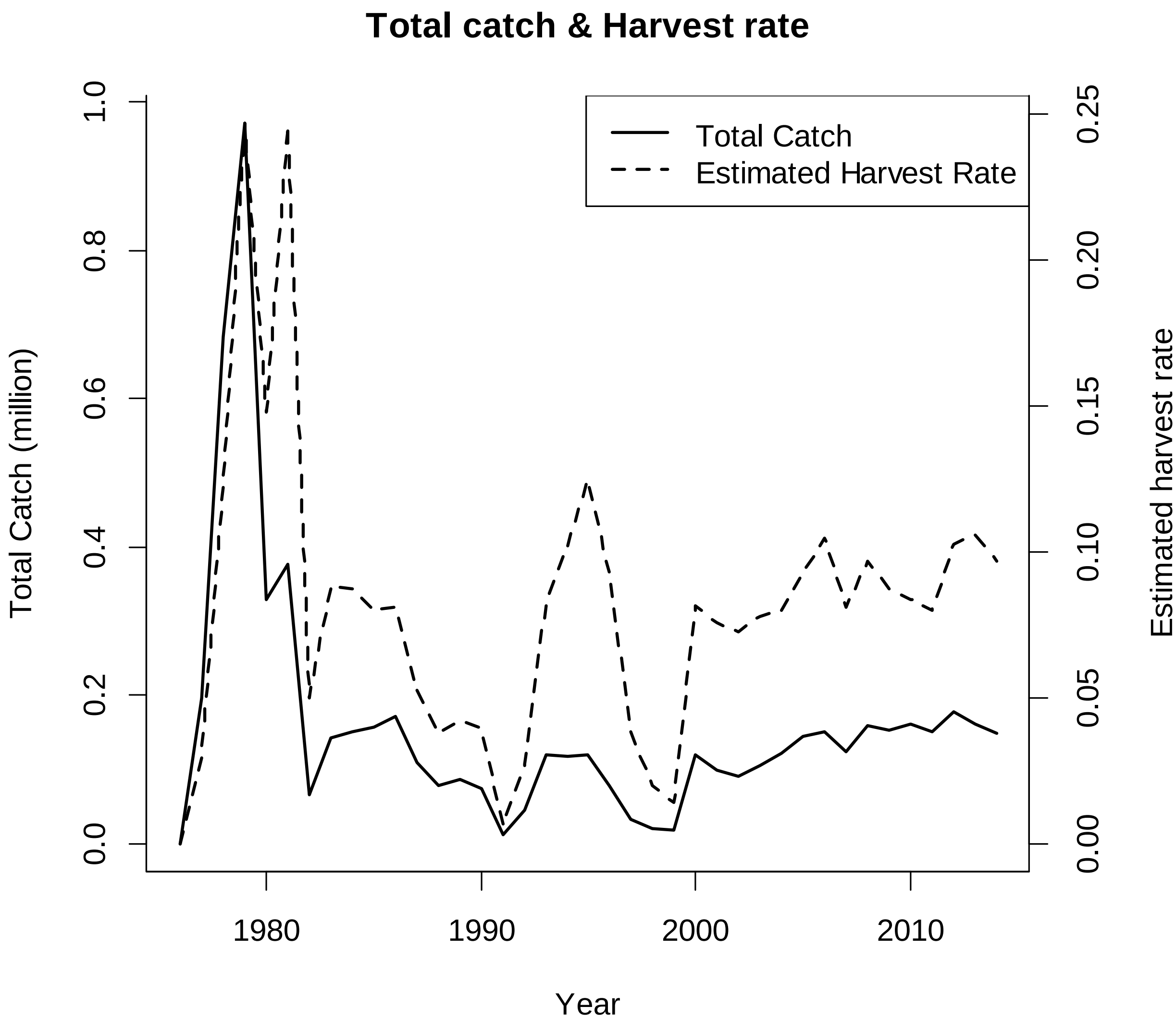


Figure C3-8: Total catch and estimated harvest rate 1976-2014

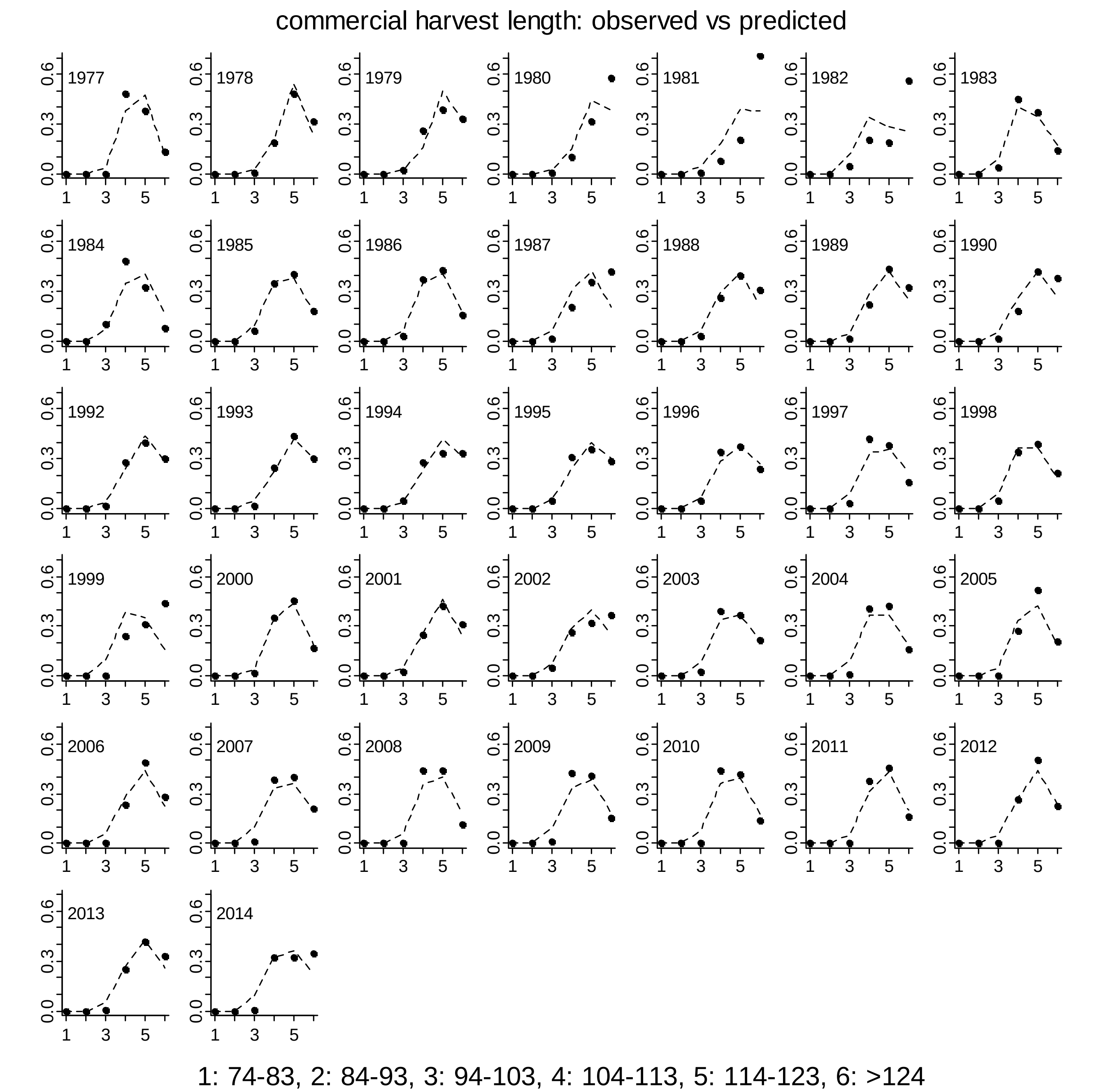
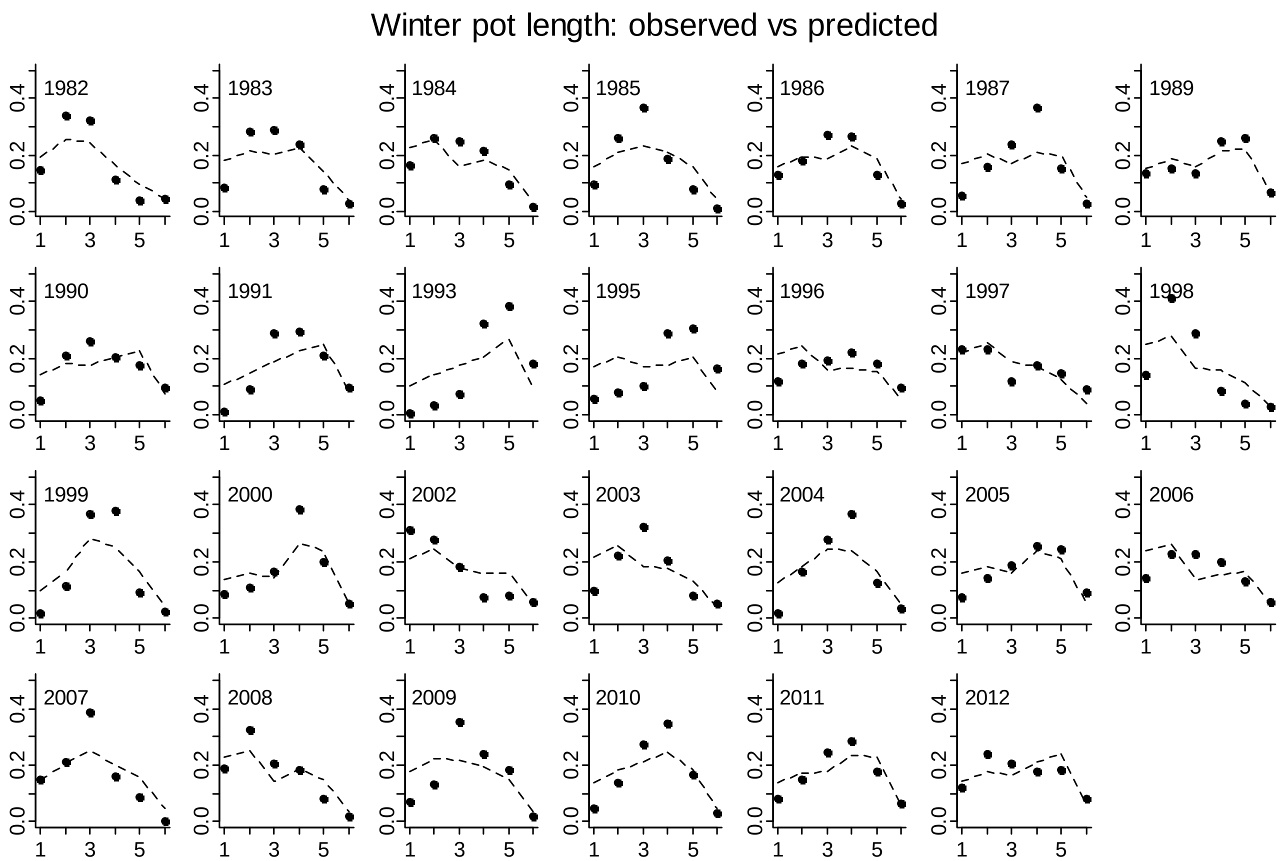
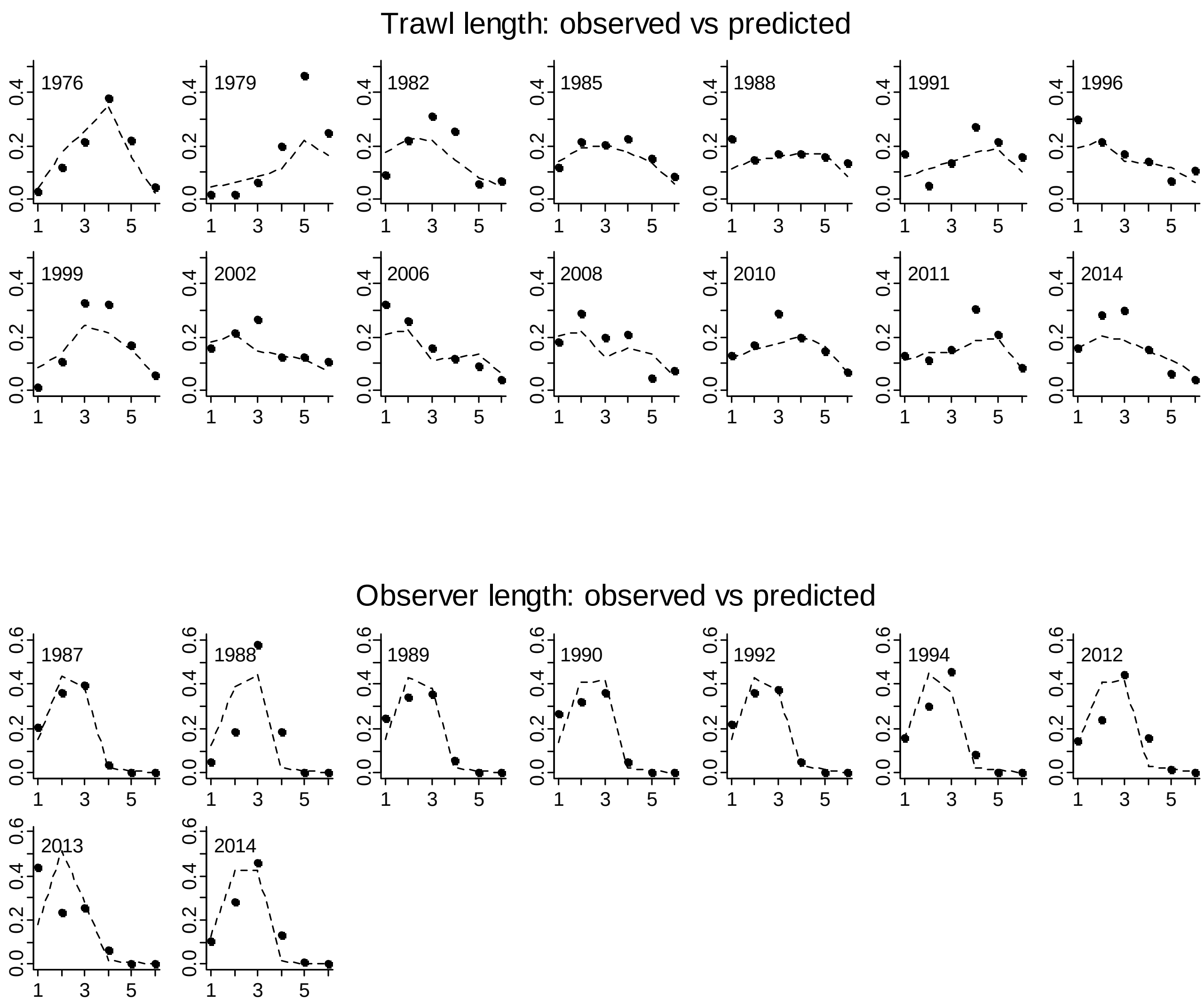


Figure C3-9: Predicted (dashed line) vs. observed (black dots) length class proportion for commercial catch:



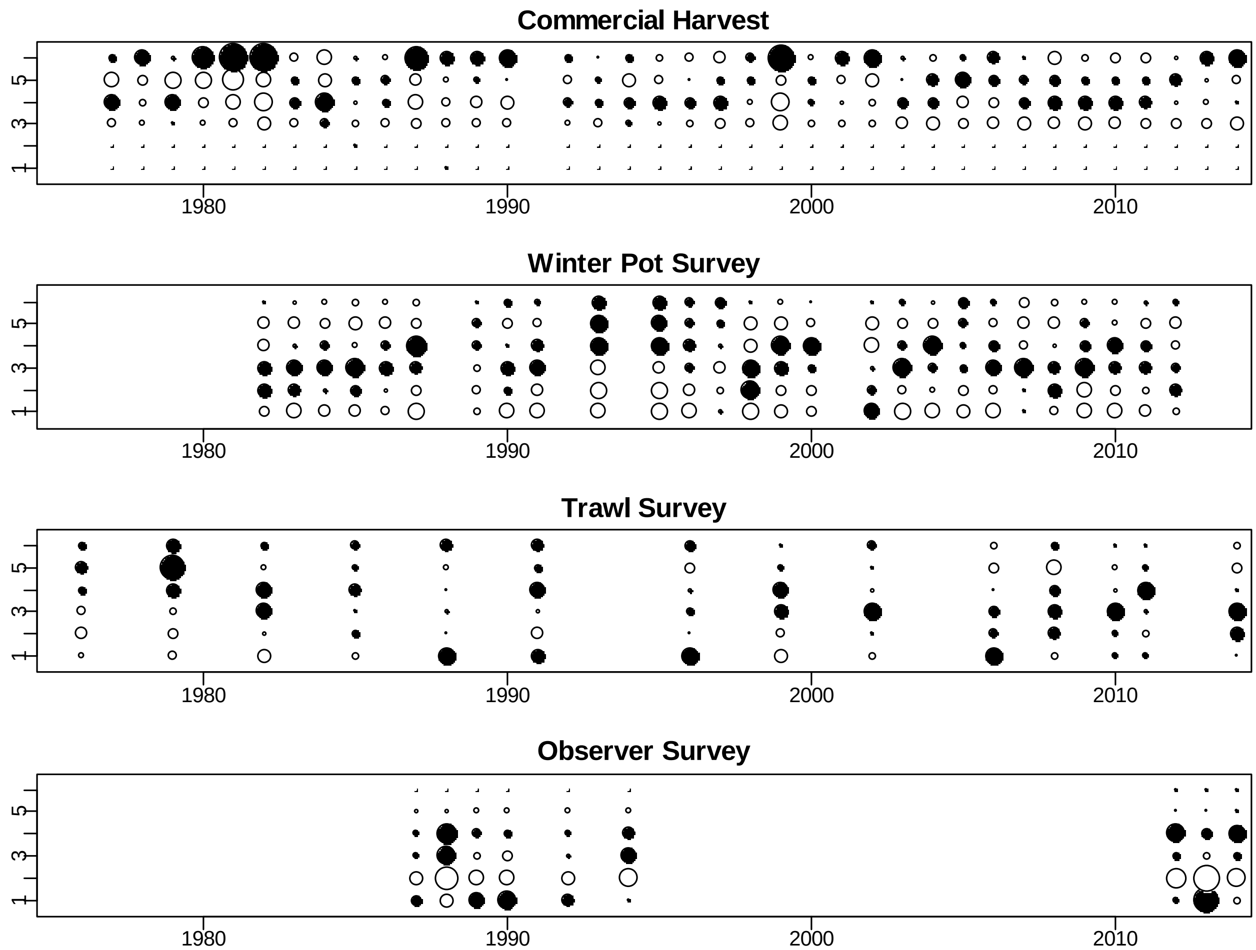
1: 74-83, 2: 84-93, 3: 94-103, 4: 104-113, 5: 114-123, 6: >124

Figure C3-10: Predicted (dashed line) vs. observed (black dots) length class proportion for winter pot survey



1: 74-83, 2: 84-93, 3: 94-103, 4: 104-113, 5: 114-123, 6: >124

Figure C3-11: Predicted (dashed line) vs. observed (black dots) length class proportion for trawl survey and observer survey



1: 74-83, 2: 84-93, 3: 94-103, 4: 104-113, 5: 114-123, 6: >124

Figure C3-12: Bubble plot of predicted and observed length proportion . Black circle indicates model estimates lower than observed, white circle indicates model estimates higher than observed. Size of circle indicate degree of deviance (larger circle = larger deviance).

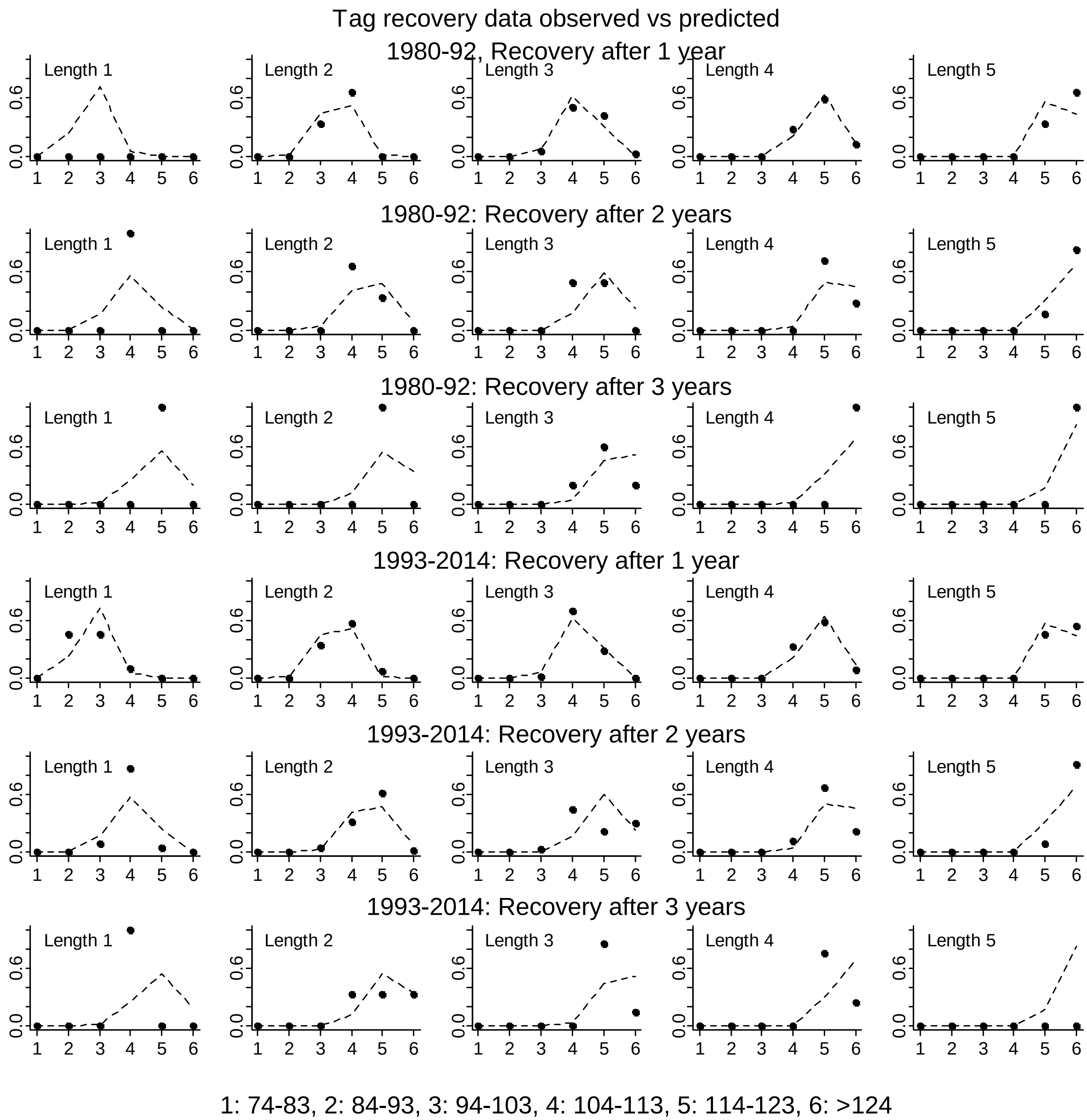


Figure C3-13: Predicted vs. observed length class proportion for tag recovery data 1980-1992, and 1993-2014:

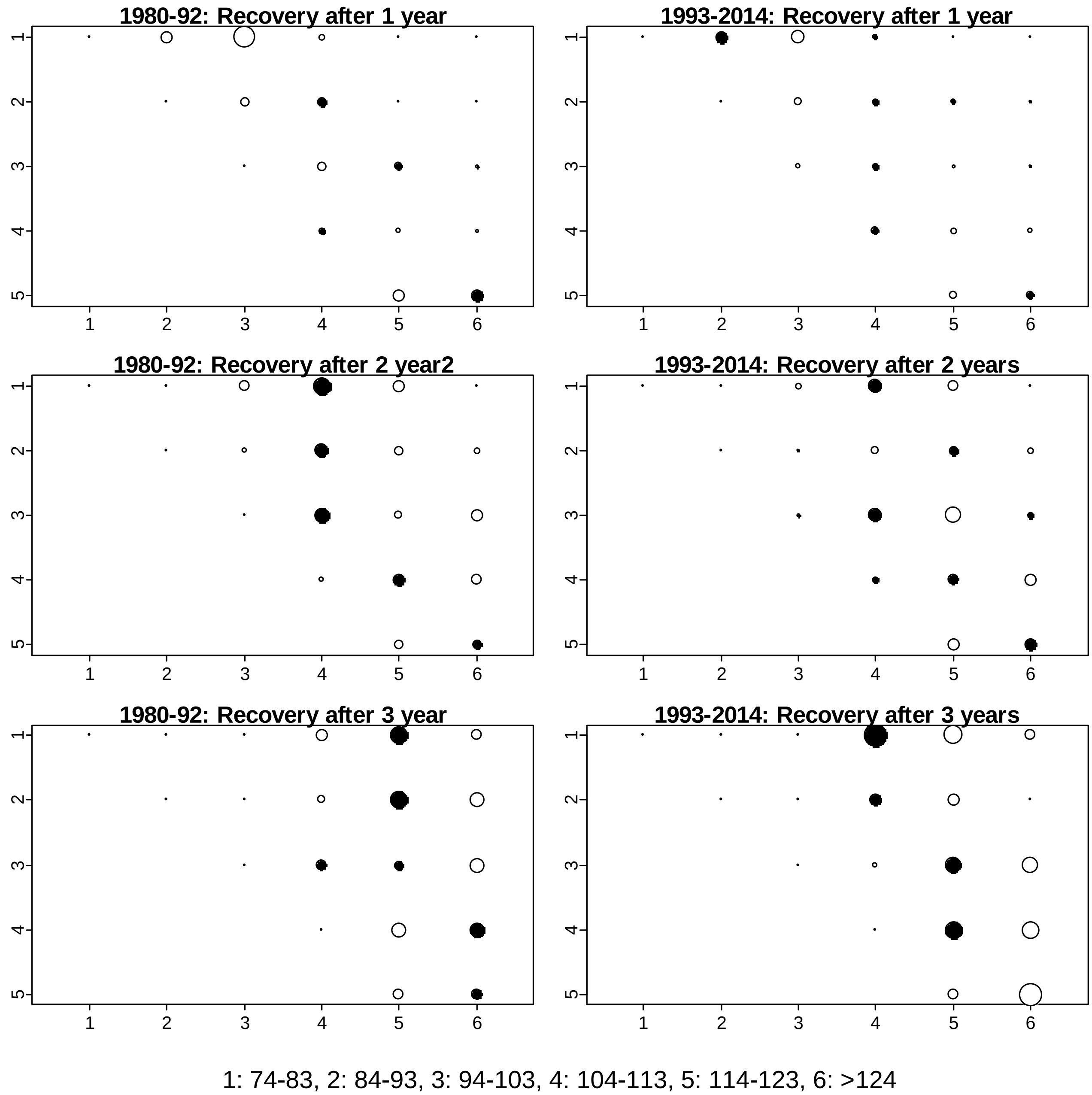


Figure C3-14: Bubble plot of predicted vs. observed length class proportion for tag recovery data 1980-1992, and 1993-2014:

Table C3-1 . 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	-7.2176	0.1805
log_q_2	-7.0309	0.093333
log_N_{76}	9.1211	0.15957
R_0	6.5171	0.070141
log_σ_R^2	0.30409	0.46236
log_R_{77}	-0.26608	0.39184
log_R_{78}	-0.72726	0.35463
log_R_{79}	-0.31435	0.38272
log_R_{80}	0.58792	0.26648
log_R_{81}	0.2934	0.28261
log_R_{82}	0.2703	0.32665
log_R_{83}	0.68811	0.27189
log_R_{84}	0.32209	0.29393
log_R_{85}	0.26882	0.31001
log_R_{86}	0.31723	0.26586
log_R_{87}	0.004382	0.2714
log_R_{88}	0.077068	0.26439
log_R_{89}	-0.08253	0.26903
log_R_{90}	-0.54831	0.29556
log_R_{91}	-0.37248	0.28053
log_R_{92}	-0.88449	0.32019
log_R_{93}	-0.58086	0.28374
log_R_{94}	-0.54005	0.27747
log_R_{95}	-0.20784	0.23538
log_R_{96}	-0.02517	0.27768
log_R_{97}	0.41586	0.21341
log_R_{98}	-0.65499	0.31988
log_R_{99}	-0.37687	0.31366
log_R_{00}	-0.01518	0.28277
log_R_{01}	0.18113	0.22872
log_R_{02}	0.38636	0.27371
log_R_{03}	-0.28422	0.34102
log_R_{04}	-0.10123	0.29073
log_R_{05}	0.51816	0.1996
log_R_{06}	-0.03695	0.30198
log_R_{07}	0.59517	0.20504
log_R_{08}	0.34852	0.2666
log_R_{09}	0.021378	0.2684
log_R_{10}	-0.11698	0.26211
log_R_{11}	-0.18468	0.2909
log_R_{12}	0.45683	0.30116
log_R_{13}	0.26369	0.34828
a_1	0.26973	1.9082
a_2	1.7902	1.3712
a_3	2.1566	1.3255
a_4	2.4659	1.3028
a_5	1.6572	1.3575
r1	0.51166	0.04434
log_α	-1.8095	0.018184
log_ϕ_{st1}	-14.633	1218.6
log_ϕ_{st2}	-2.5079	15493

$\log\_\phi_w$	-1.8572	0.048906
Sw_6		
$\log\_\phi_1$	-1.8451	0.093991
$\log\_\phi_2$	-1.8208	0.098123
w^2_t	0.051556	0.017566
q	0.69375	0.12407
σ	4.567	0.20487
β_1	9.7	0.63122
β_2	7.7074	0.20045

Appendix C4: Results Model 4

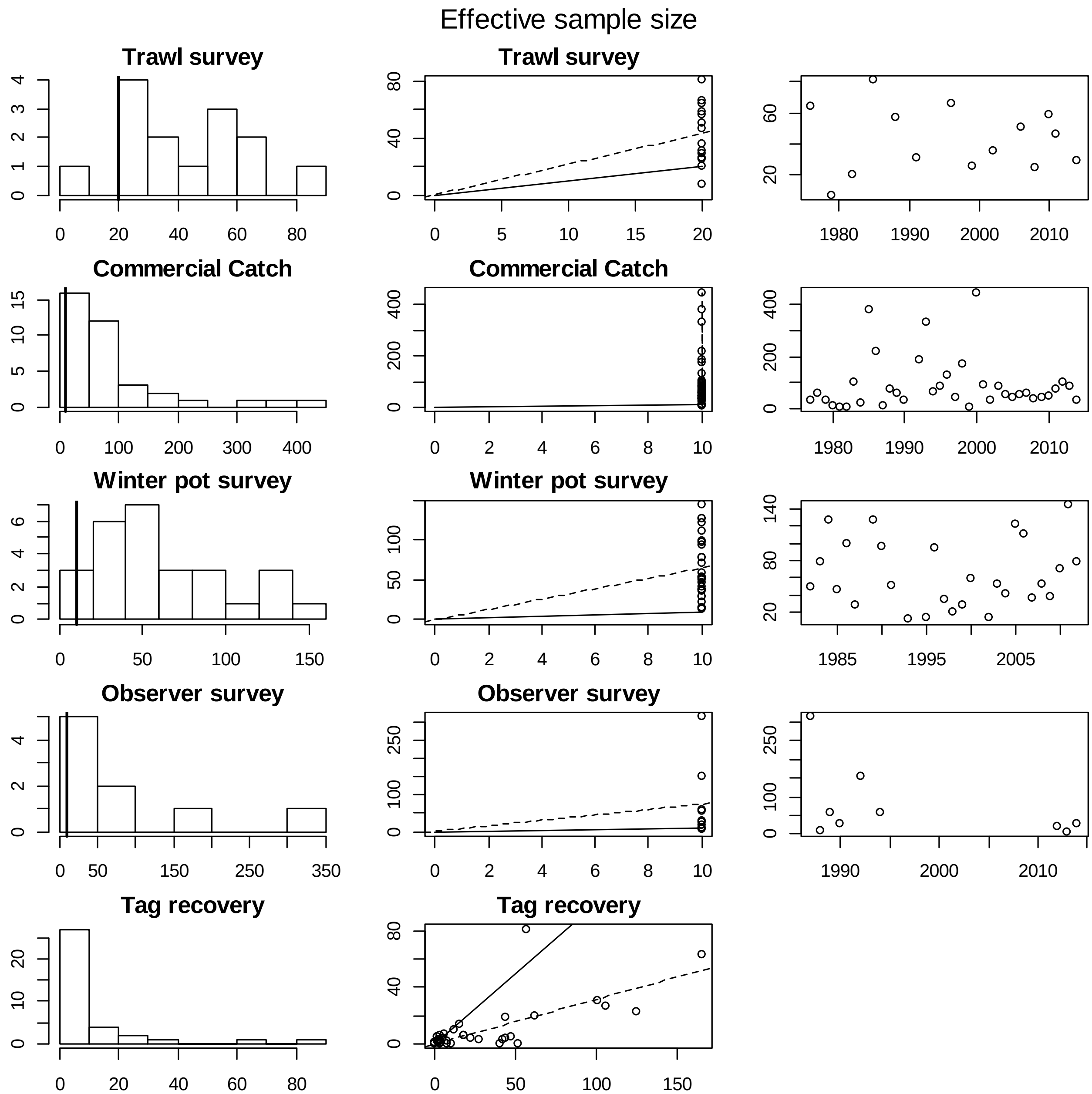


Figure C4-1: Effective sample size vs. implied sample size. Figures in the first column show effective sample size (x-axis) vs. frequency (y-axis). Vertical solid line is the implied sample size. Figures in the second column show implied sample size (x-axis) vs. effective sample size (y-axis). Dashed line indicates linear regression slope, and solid line is 1:1 line. Figures in the third column show year (x-axis) vs. effective sample size (y-axis).

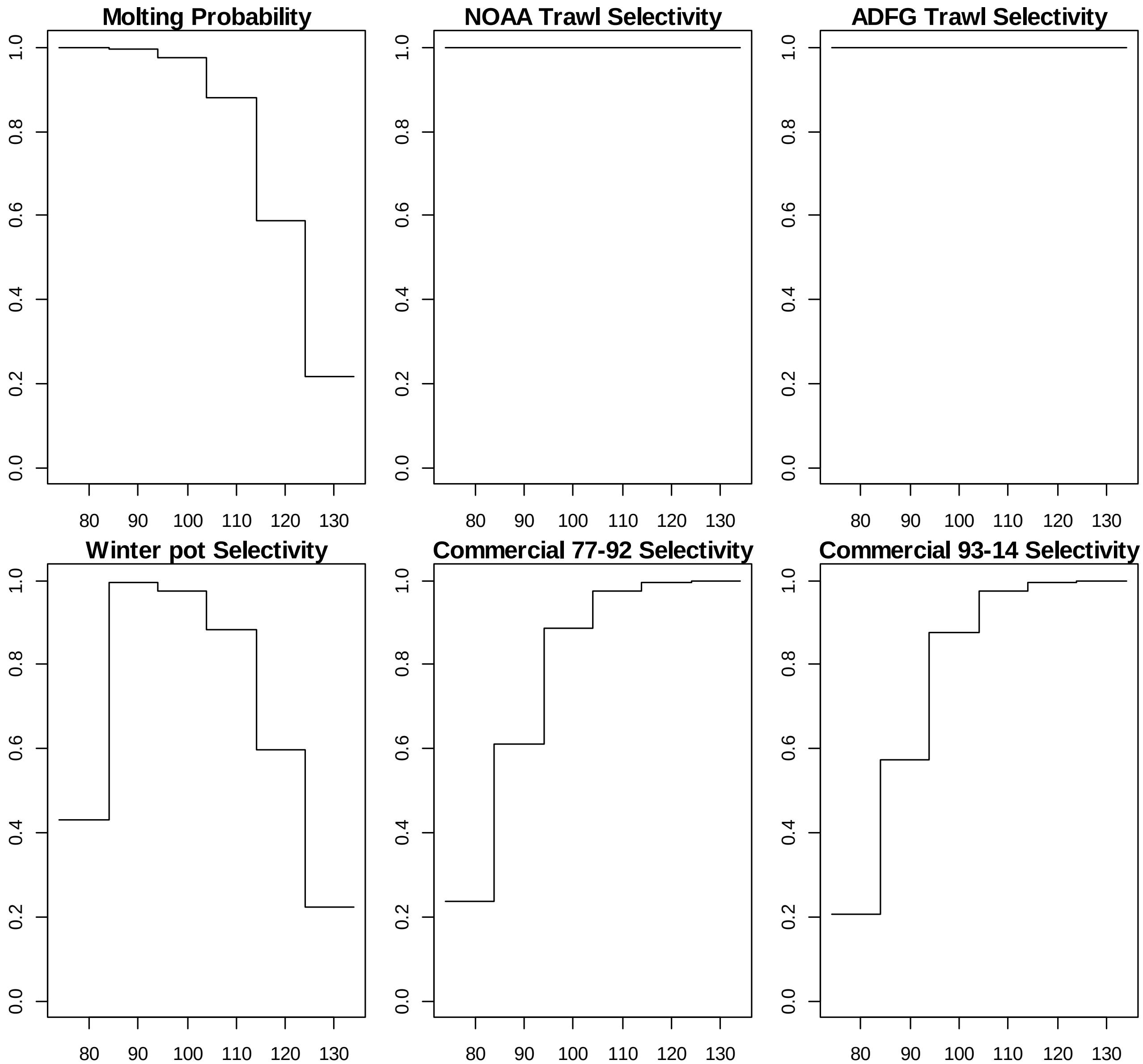


Figure C4-2. Molting probability and trawl/pot selectivities. X-axis is carapace length.

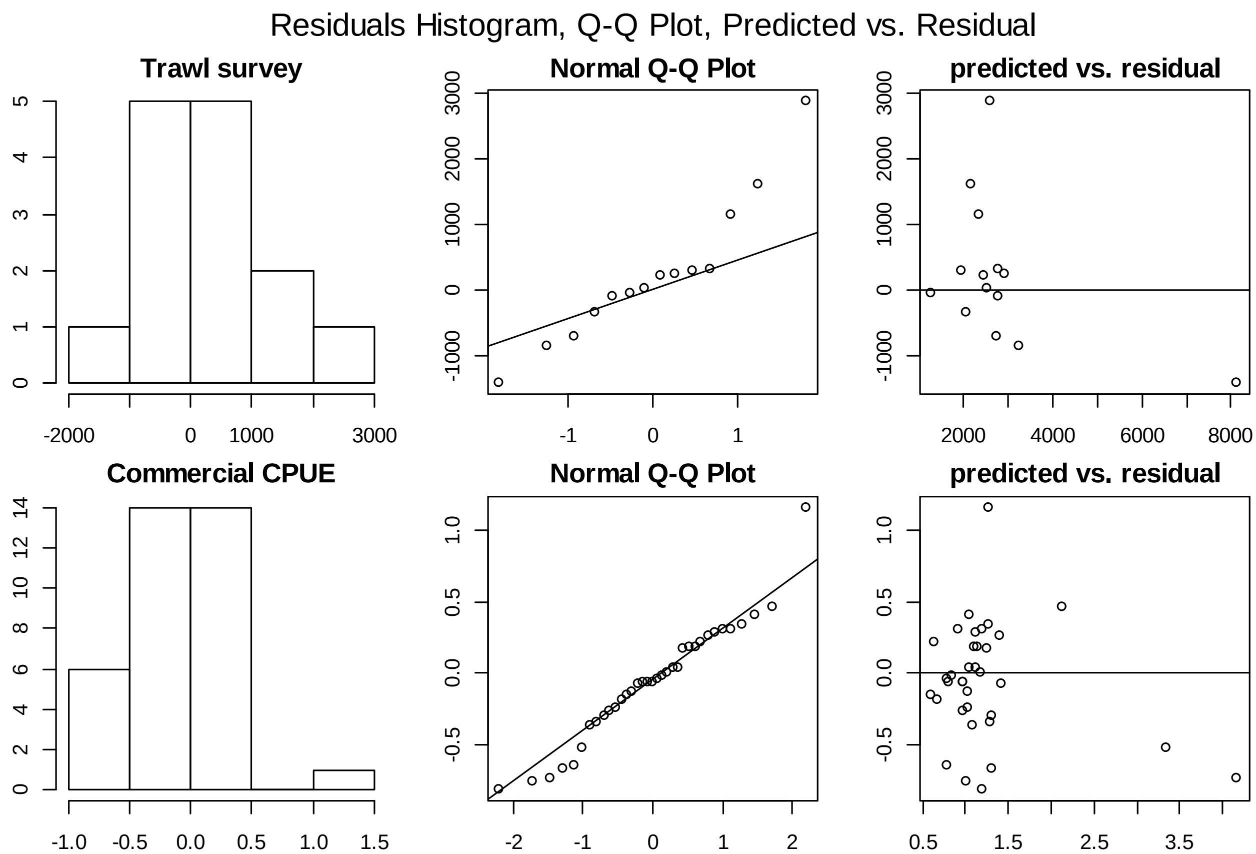


Figure C4-3. QQ Plot of Trawl survey and Commercial CPUE

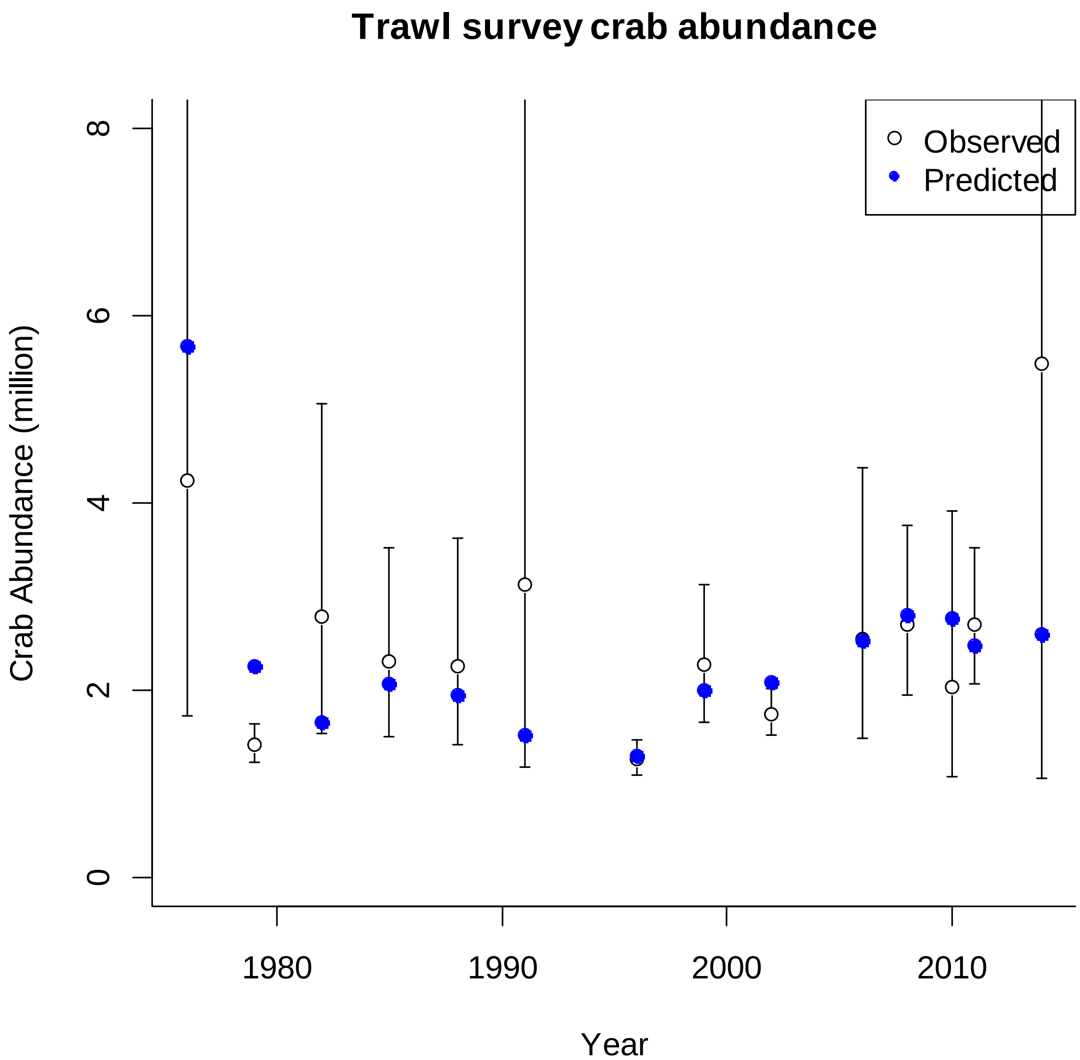


Figure C4-4. Estimated trawl survey abundance (crabs ≥ 74 mm CL) male

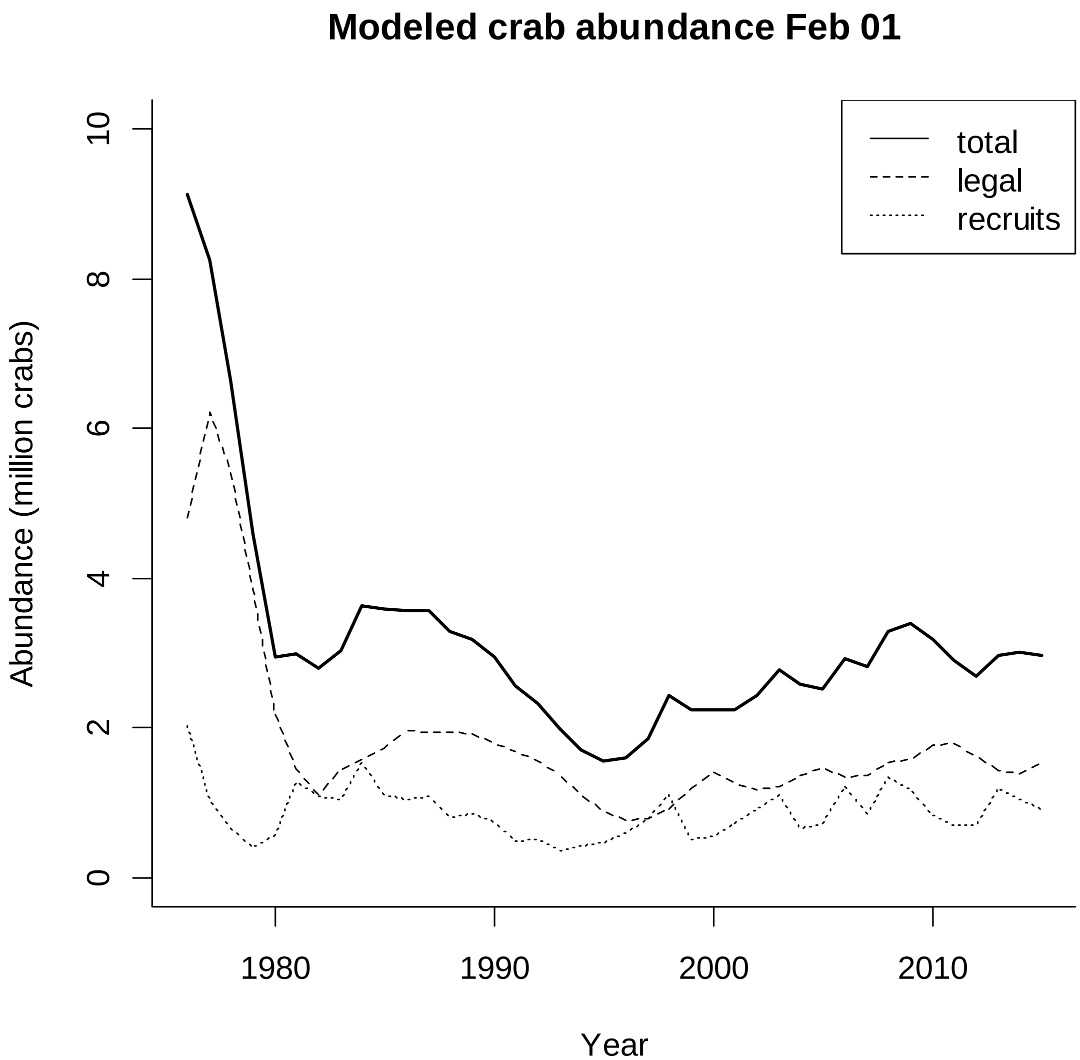


Figure C4-5. Estimated abundance of legal male from 1976-2014

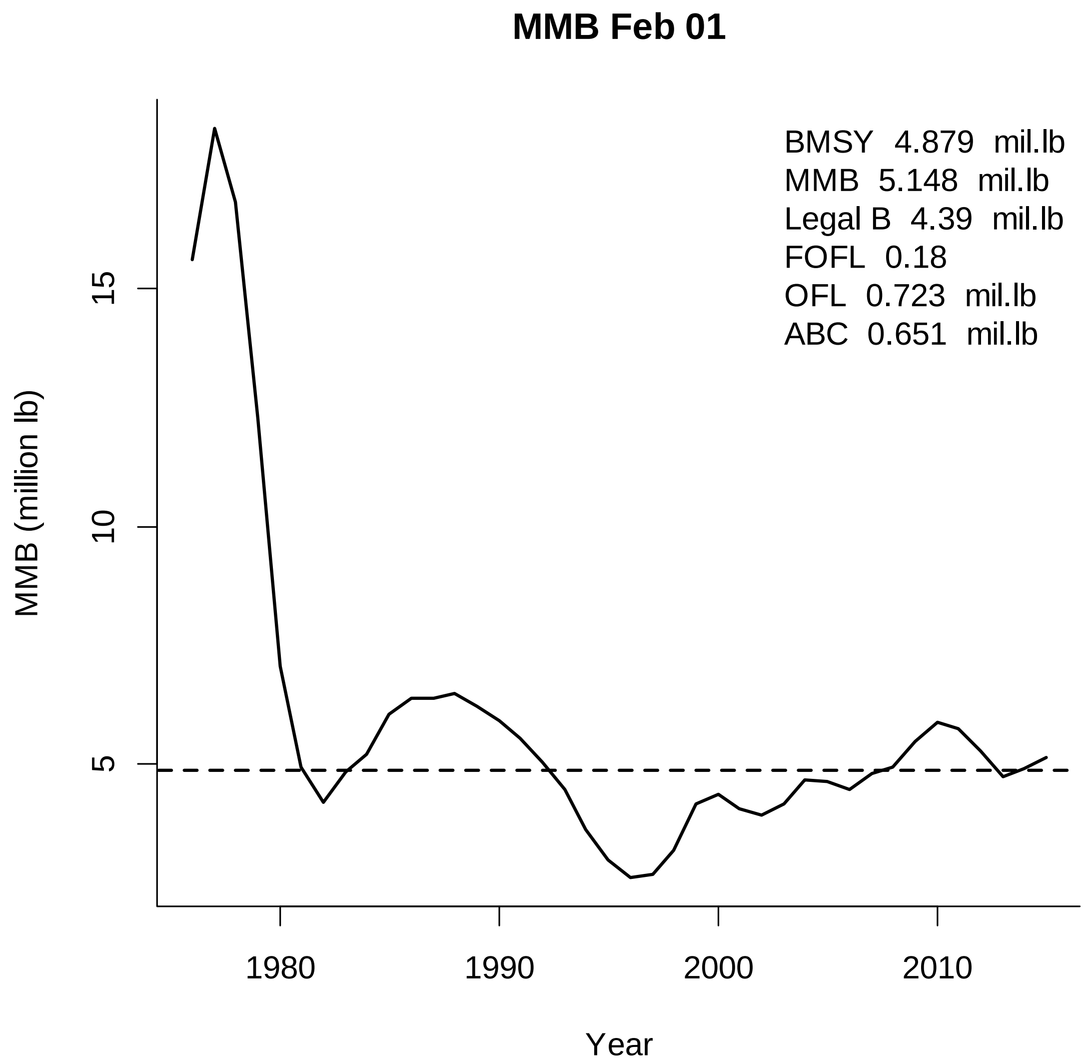


Figure C4-6. Estimated abundance of leg recruits from 1976-2015. Dash line shows Bmsy (Average MMB of 1980-2015)

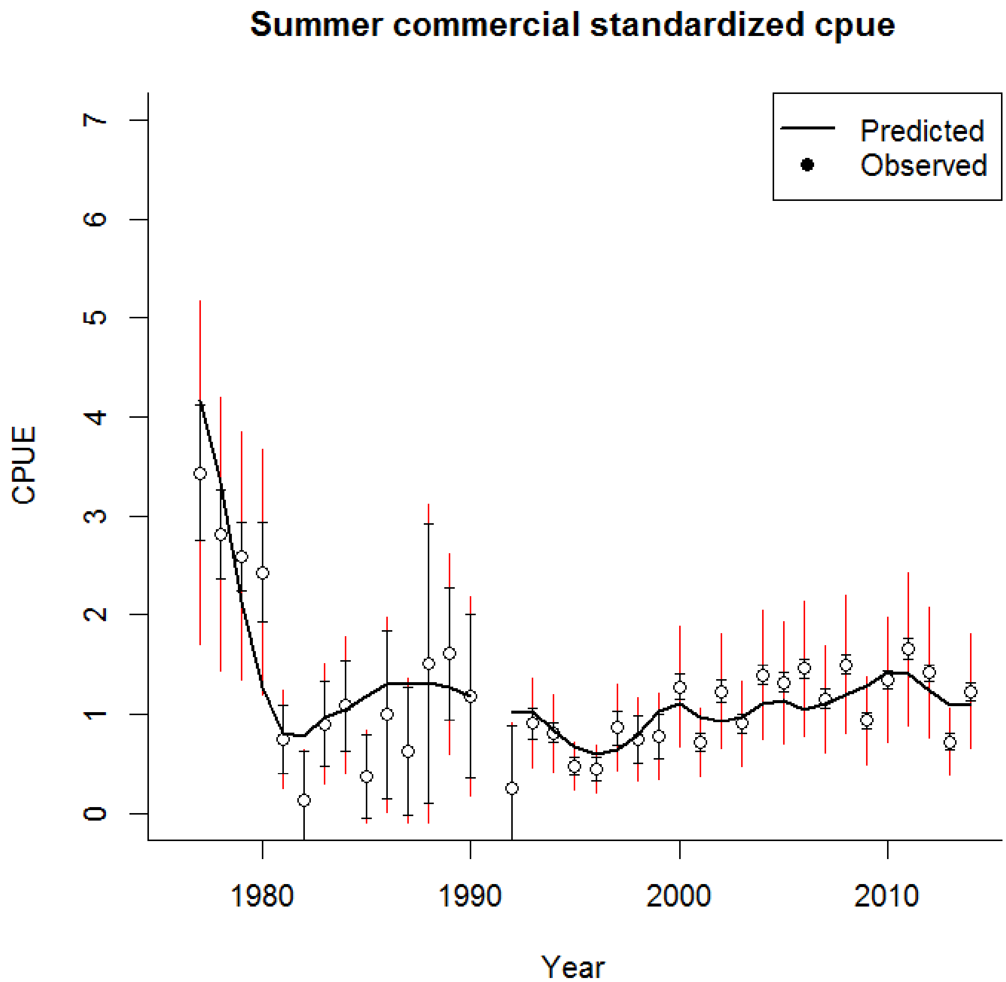


Figure C4-7. Summer commercial standardized cpue (1977-2014)

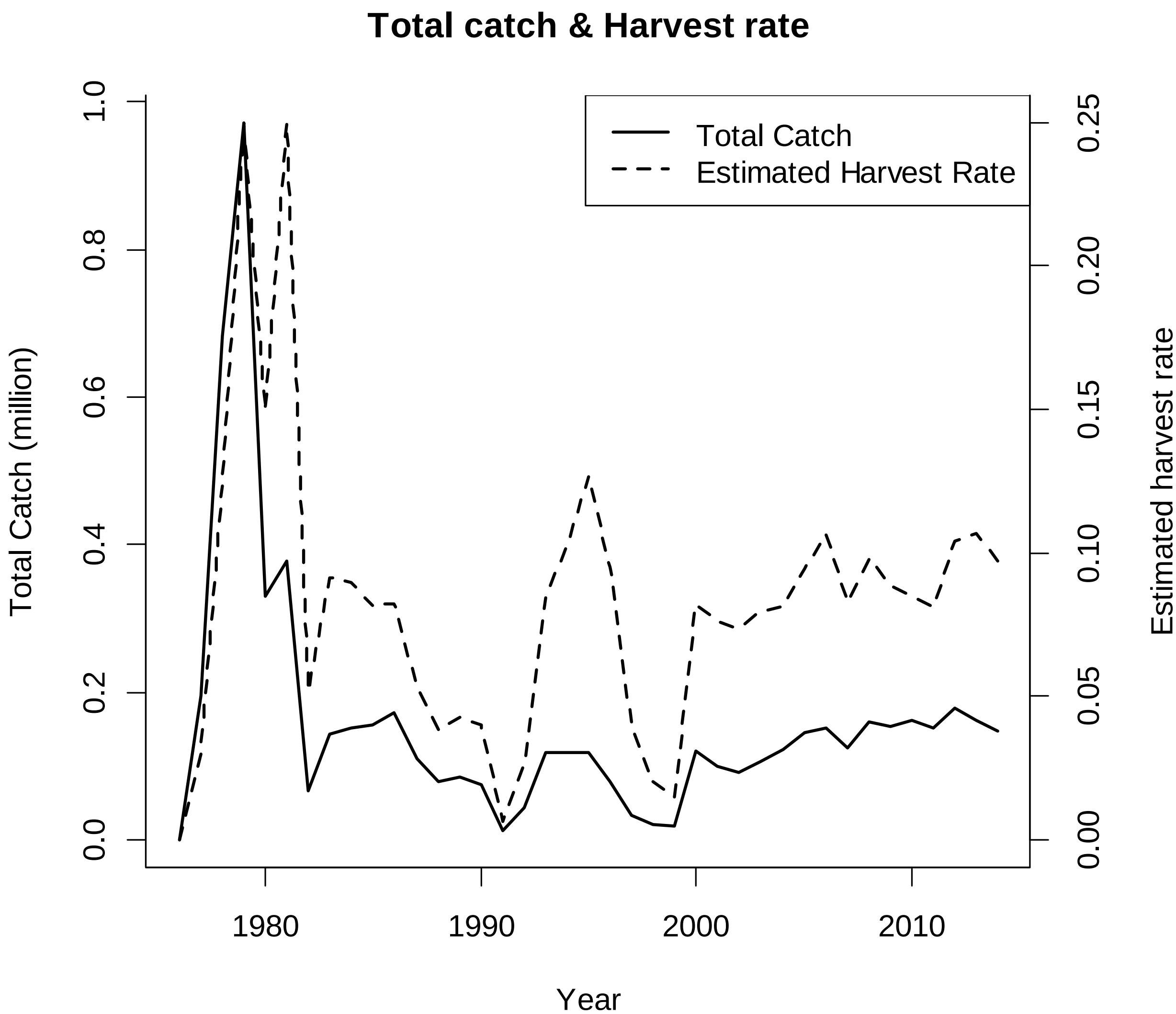
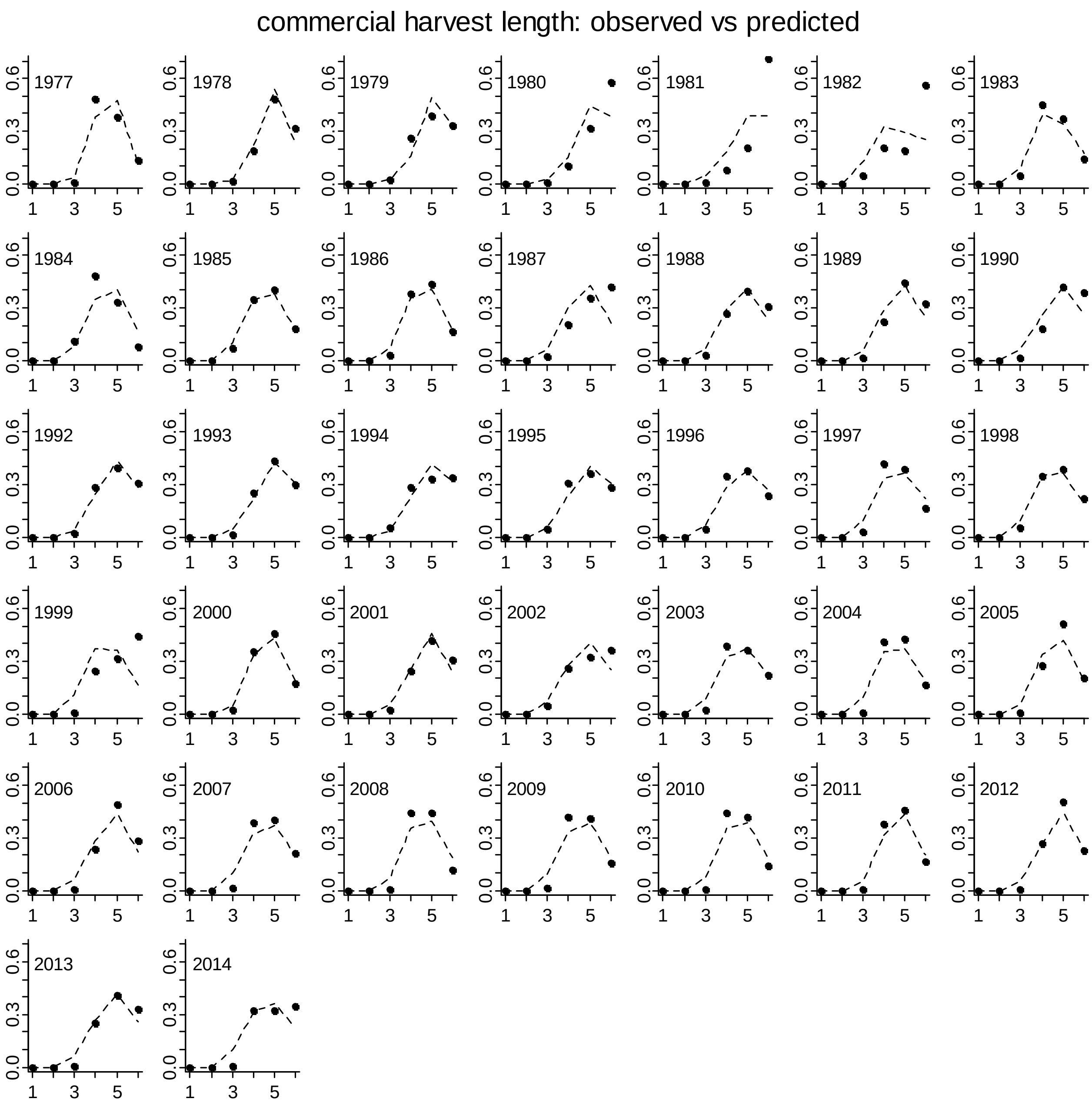
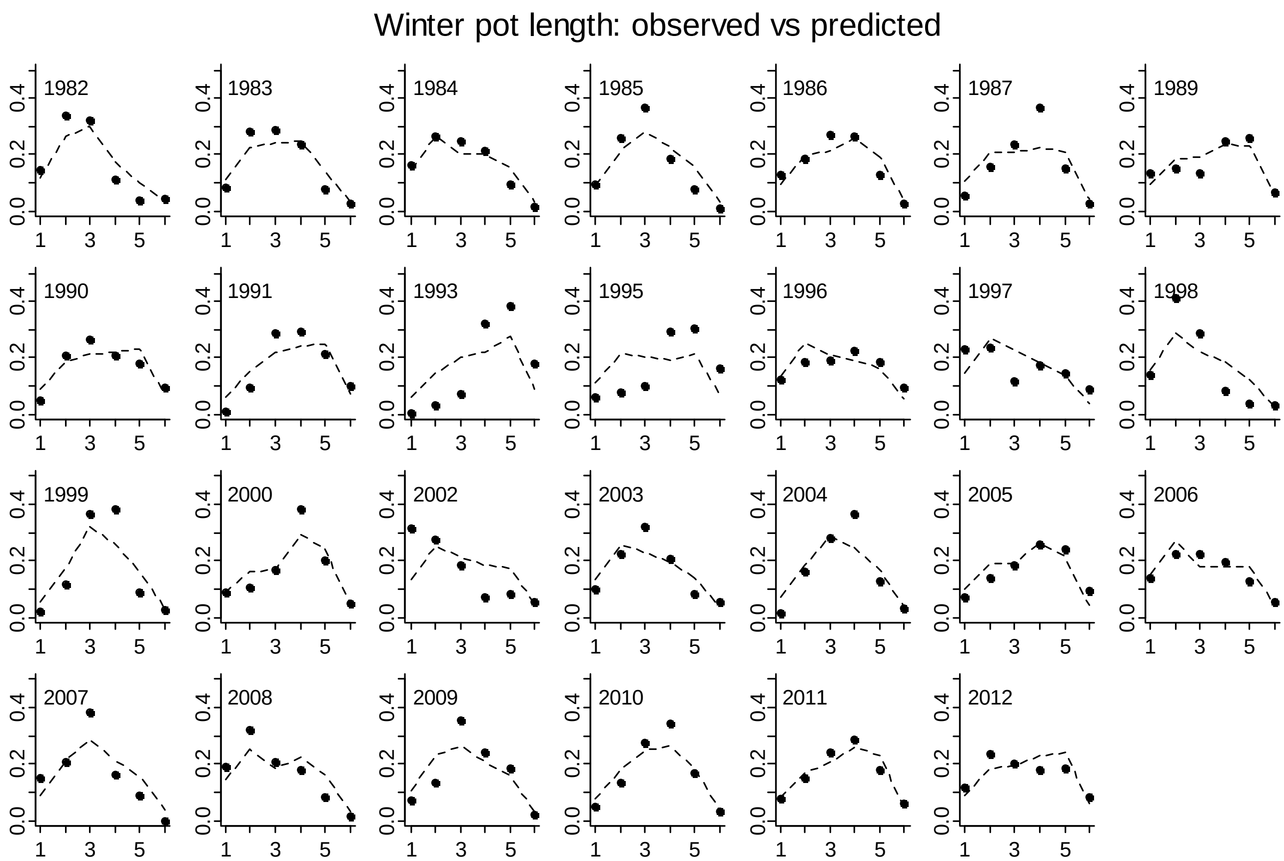


Figure C4-8: Total catch and estimated harvest rate 1976-2014



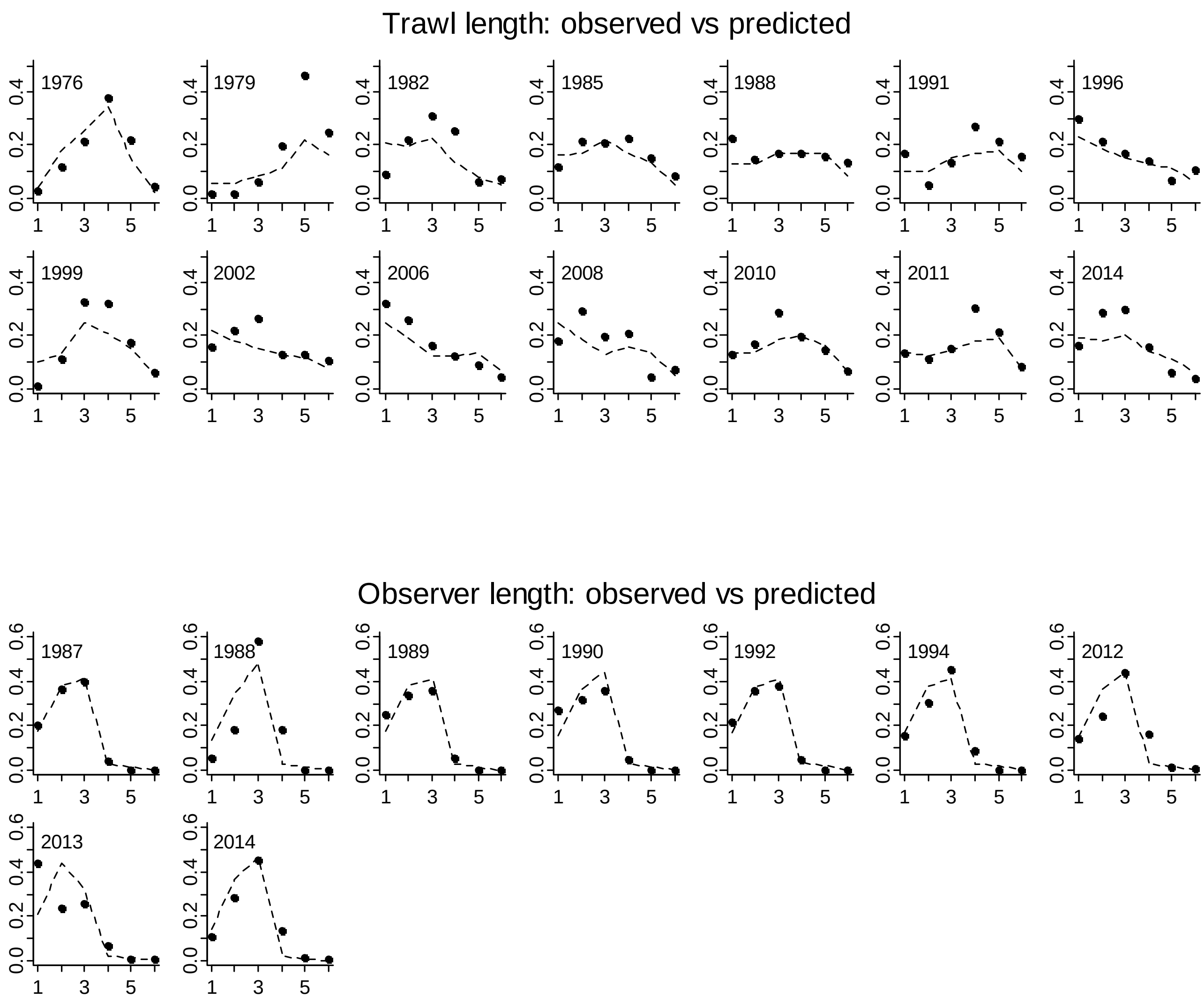
1: 74-83, 2: 84-93, 3: 94-103, 4: 104-113, 5: 114-123, 6: >124

Figure C4-9: Predicted (dashed line) vs. observed (black dots) length class proportion for commercial catch:



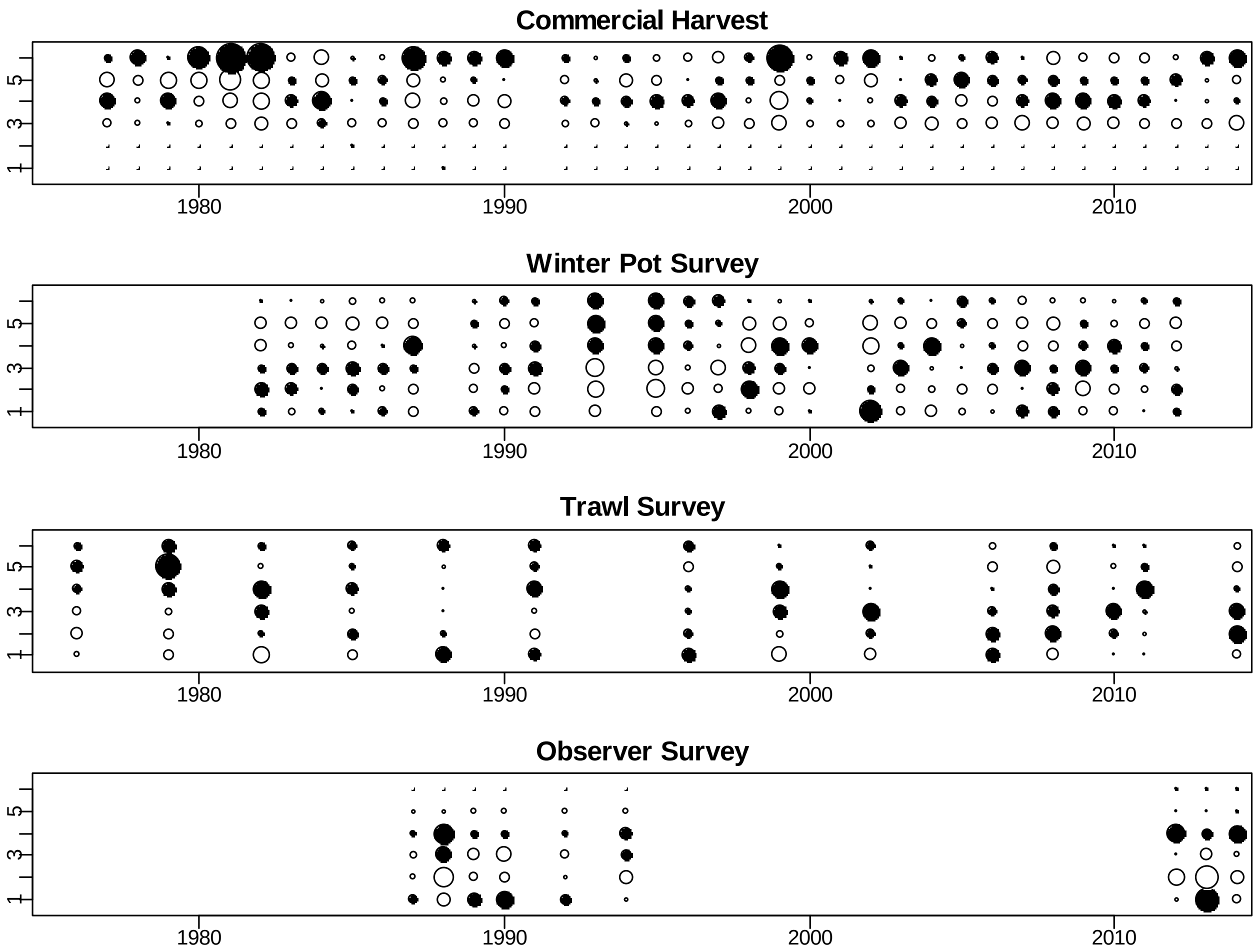
1: 74-83, 2: 84-93, 3: 94-103, 4: 104-113, 5: 114-123, 6: >124

Figure C4-10: Predicted (dashed line) vs. observed (black dots) length class proportion for winter pot survey



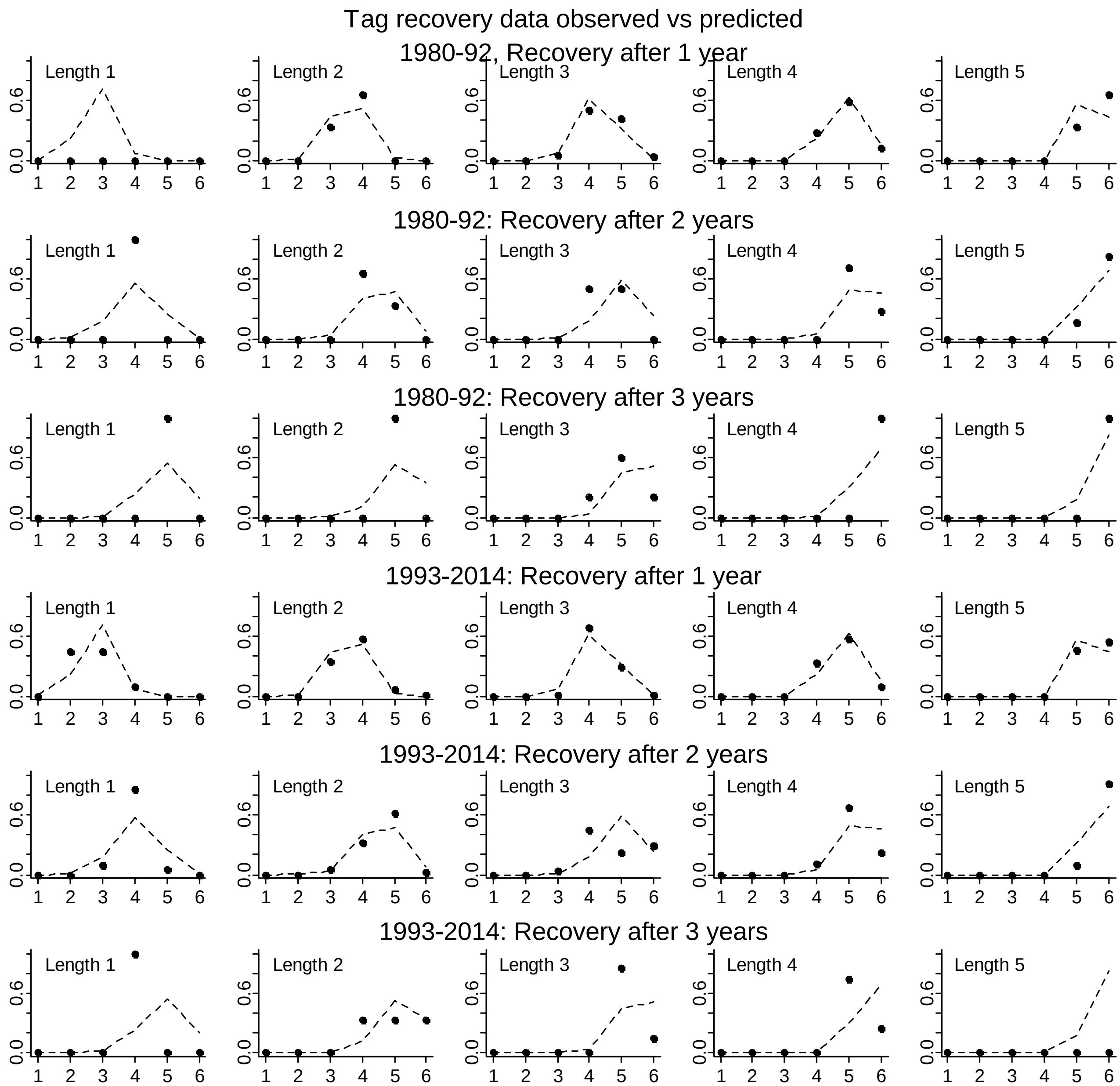
1: 74-83, 2: 84-93, 3: 94-103, 4: 104-113, 5: 114-123, 6: >124

Figure C4-11: Predicted (dashed line) vs. observed (black dots) length class proportion for trawl survey and observer survey



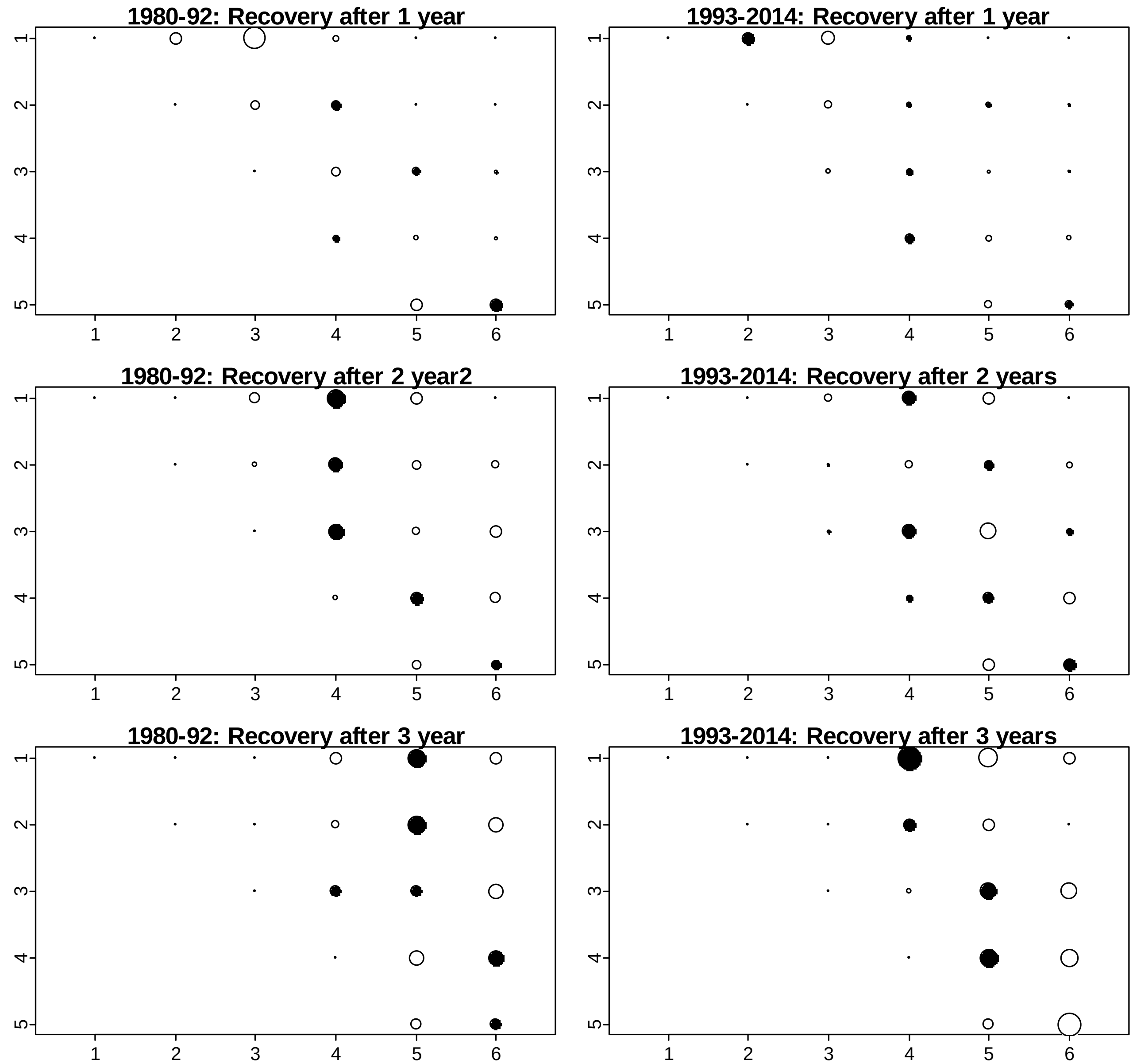
1: 74-83, 2: 84-93, 3: 94-103, 4: 104-113, 5: 114-123, 6: >124

Figure C4-12: Bubble plot of predicted and observed length proportion . Black circle indicates model estimates lower than observed, white circle indicates model estimates higher than observed. Size of circle indicate degree of deviance (larger circle = larger deviance).



1: 74-83, 2: 84-93, 3: 94-103, 4: 104-113, 5: 114-123, 6: >124

Figure C4-13: Predicted vs. observed length class proportion for tag recovery data 1980-1992, and 1993-2014:



1: 74-83, 2: 84-93, 3: 94-103, 4: 104-113, 5: 114-123, 6: >124

Figure C4-14: Bubble plot of predicted vs. observed length class proportion for tag recovery data 1980-1992, and 1993-2014:

Table C4-1 . 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	-7.2007	0.17984
log_q_2	-7.012	0.093943
log_N_{76}	9.12	0.15753
R_0	6.5168	0.069861
log_σ_R^2	0.30721	0.45469
log_R_{77}	-0.30085	0.38974
log_R_{78}	-0.73562	0.35409
log_R_{79}	-0.27985	0.3816
log_R_{80}	0.56302	0.27212
log_R_{81}	0.27521	0.28978
log_R_{82}	0.28151	0.32921
log_R_{83}	0.71707	0.27177
log_R_{84}	0.26055	0.30733
log_R_{85}	0.28923	0.31347
log_R_{86}	0.33146	0.26982
log_R_{87}	-0.04833	0.27741
log_R_{88}	0.088558	0.26734
log_R_{89}	-0.07871	0.27109
log_R_{90}	-0.5462	0.29931
log_R_{91}	-0.40695	0.28289
log_R_{92}	-0.8547	0.32056
log_R_{93}	-0.61636	0.28558
log_R_{94}	-0.50884	0.27609
log_R_{95}	-0.23007	0.24
log_R_{96}	0.034955	0.27414
log_R_{97}	0.38802	0.21982
log_R_{98}	-0.67758	0.32486
log_R_{99}	-0.3138	0.31012
log_R_{00}	-0.05479	0.29043
log_R_{01}	0.19204	0.23028
log_R_{02}	0.36308	0.27723
log_R_{03}	-0.29049	0.34326
log_R_{04}	-0.05957	0.29124
log_R_{05}	0.49961	0.20451
log_R_{06}	-0.00793	0.30527
log_R_{07}	0.59015	0.20861
log_R_{08}	0.3516	0.2665
log_R_{09}	-0.01241	0.27569
log_R_{10}	-0.12878	0.26778
log_R_{11}	-0.12222	0.29413
log_R_{12}	0.48911	0.30812
log_R_{13}	0.25167	0.35643
a_1	0.33834	1.896
a_2	1.825	1.3702
a_3	2.1639	1.3271
a_4	2.4693	1.3038
a_5	1.6571	1.3583
r1	0.61885	0.053389
log_α	-1.8092	0.018122
log_ϕ_{st1}	-14.554	1490.1
log_ϕ_{st2}	-7.0019	22627

log_ϕ_w	-1.8149	0.045224
Sw_6	0.43187	0.10078
log_ϕ_1	-1.8239	0.080854
log_ϕ_2	-1.8009	0.085995
w^2_t	0.051837	0.017658
q	0.697	0.12387
σ	4.6062	0.20796
β_1	9.624	0.65185
β_2	7.741	0.2062

Appendix C5: Results Model 5

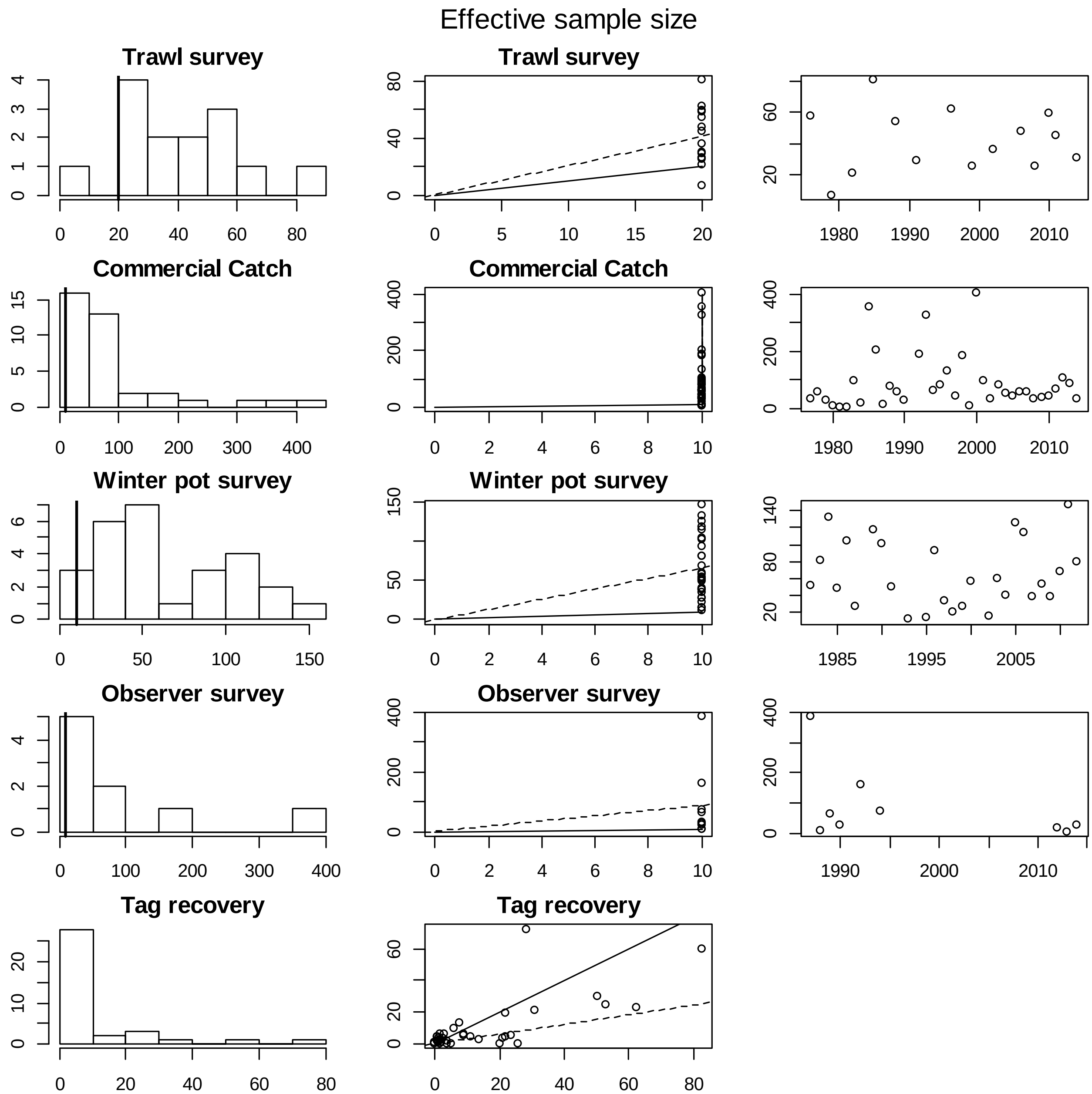


Figure C5-1: Effective sample size vs. implied sample size. Figures in the first column show effective sample size (x-axis) vs. frequency (y-axis). Vertical solid line is the implied sample size. Figures in the second column show implied sample size (x-axis) vs. effective sample size (y-axis). Dashed line indicates linear regression slope, and solid line is 1:1 line. Figures in the third column show year (x-axis) vs. effective sample size (y-axis).

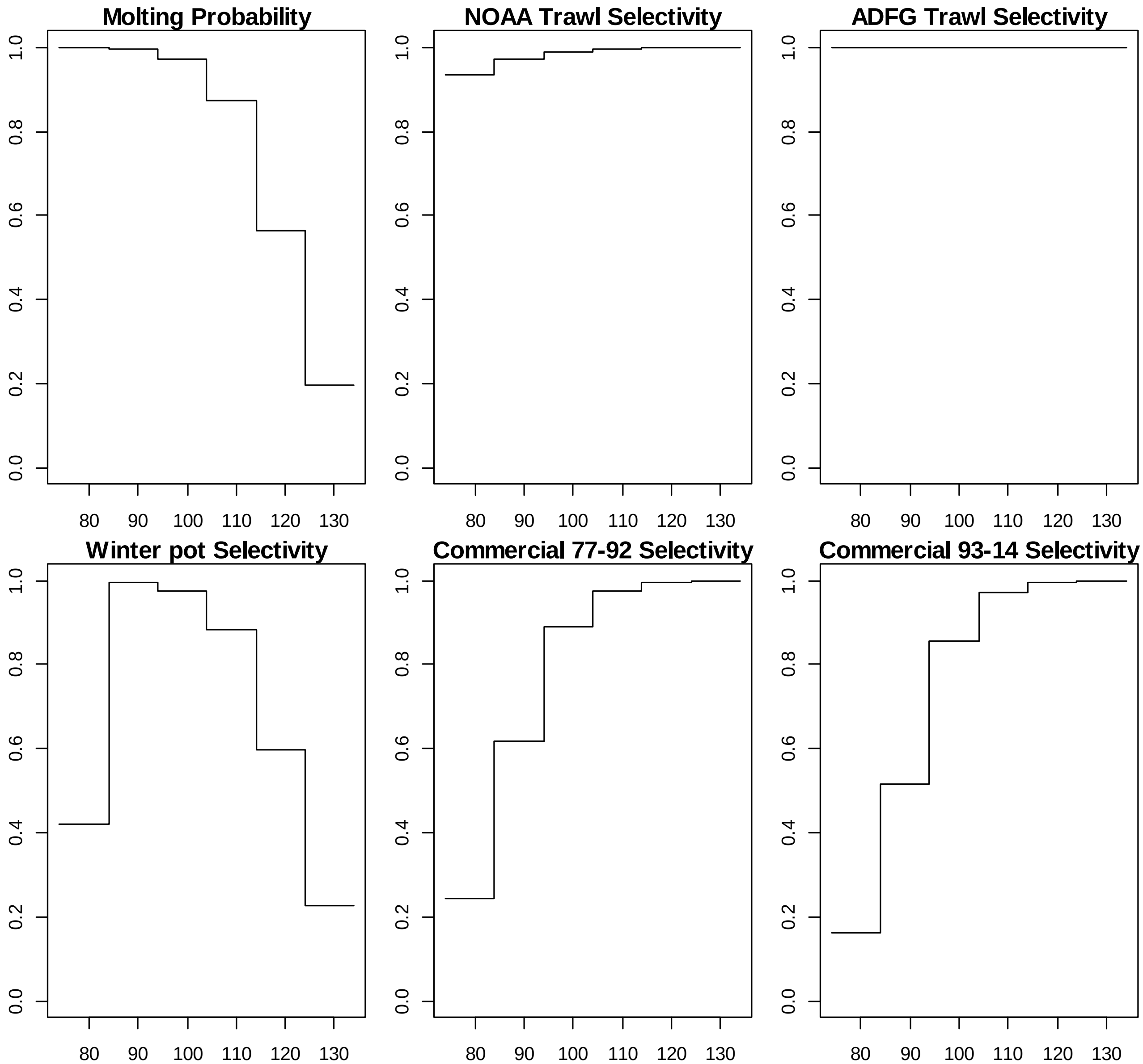


Figure C5-2. Molting probability and trawl/pot selectivities. X-axis is carapace length.

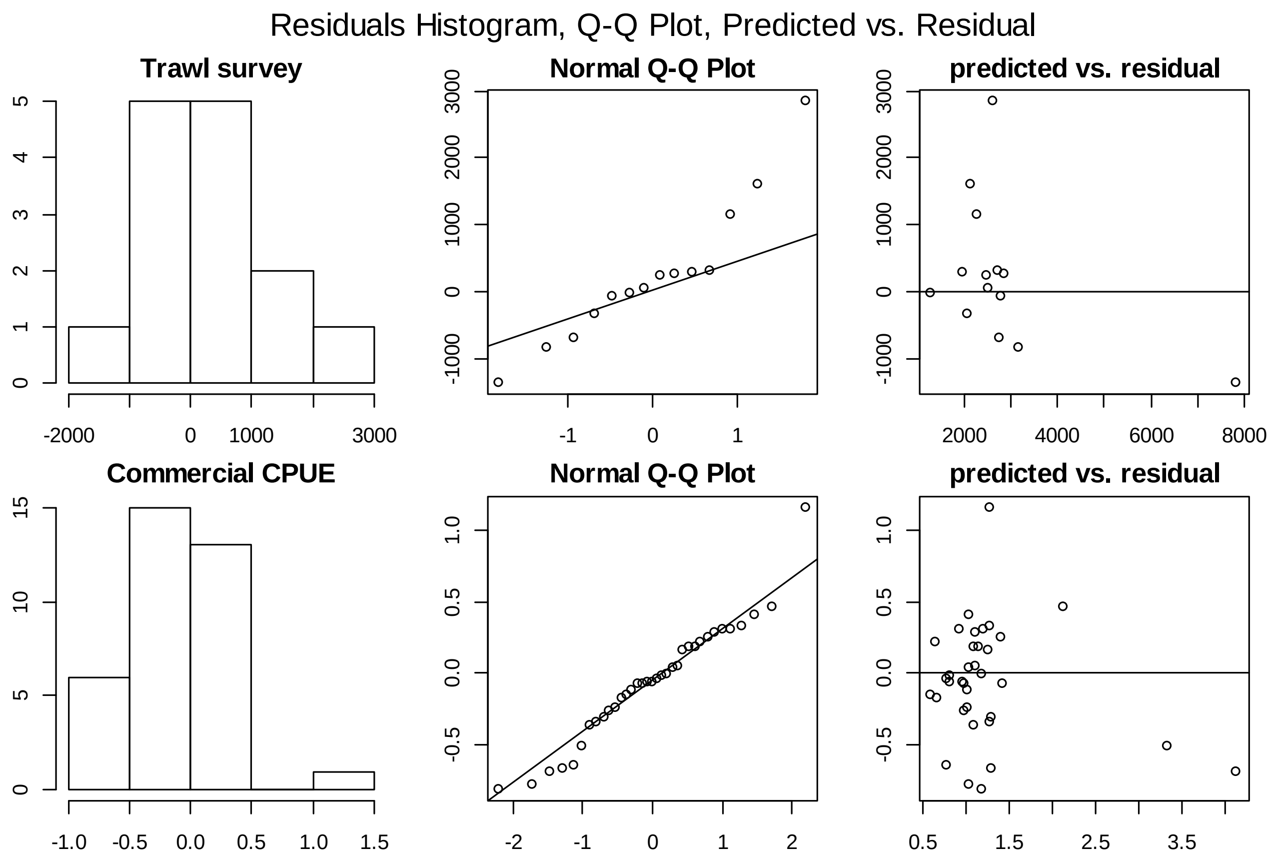


Figure C5-3. QQ Plot of Trawl survey and Commercial CPUE

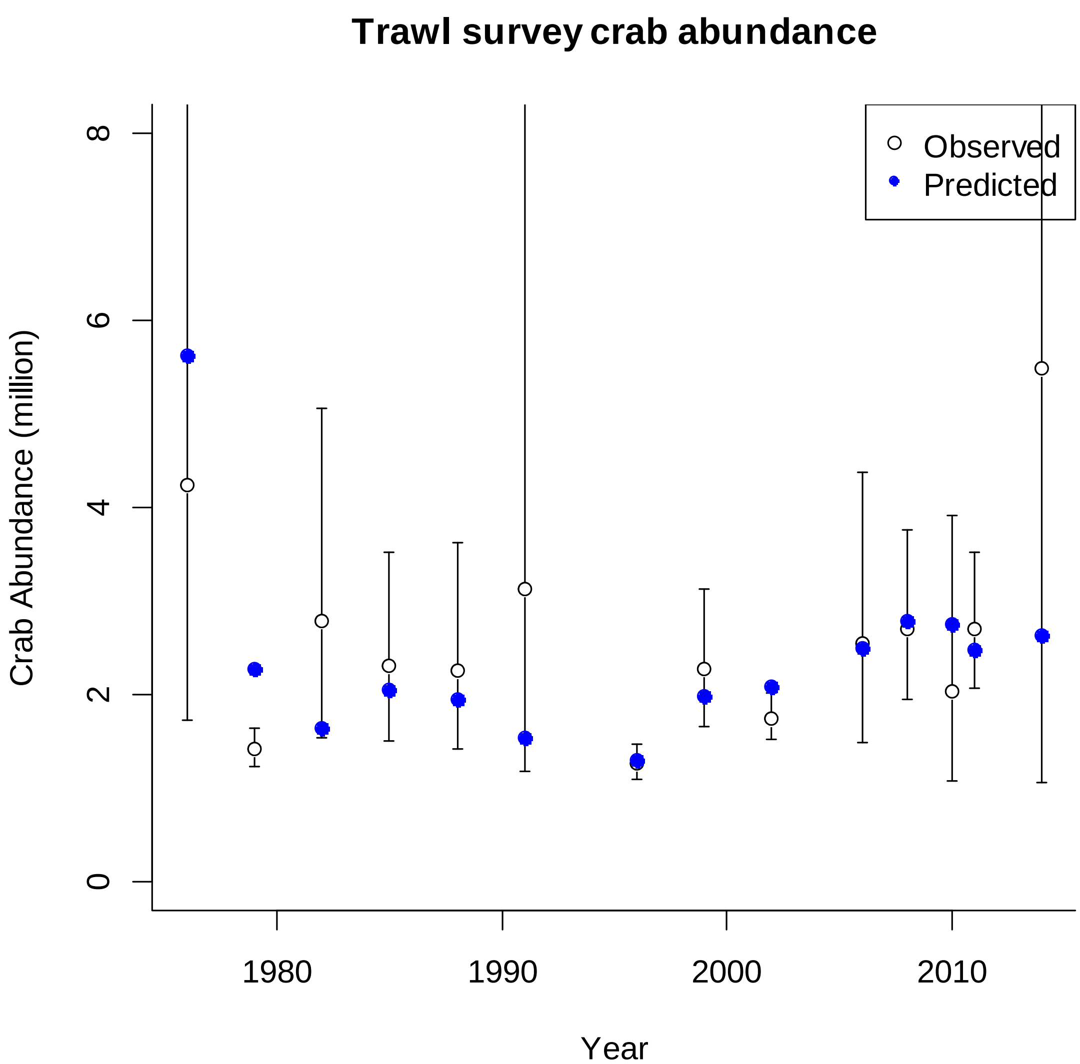


Figure C5-4. Estimated trawl survey abundance (crabs ≥ 74 mm CL) male

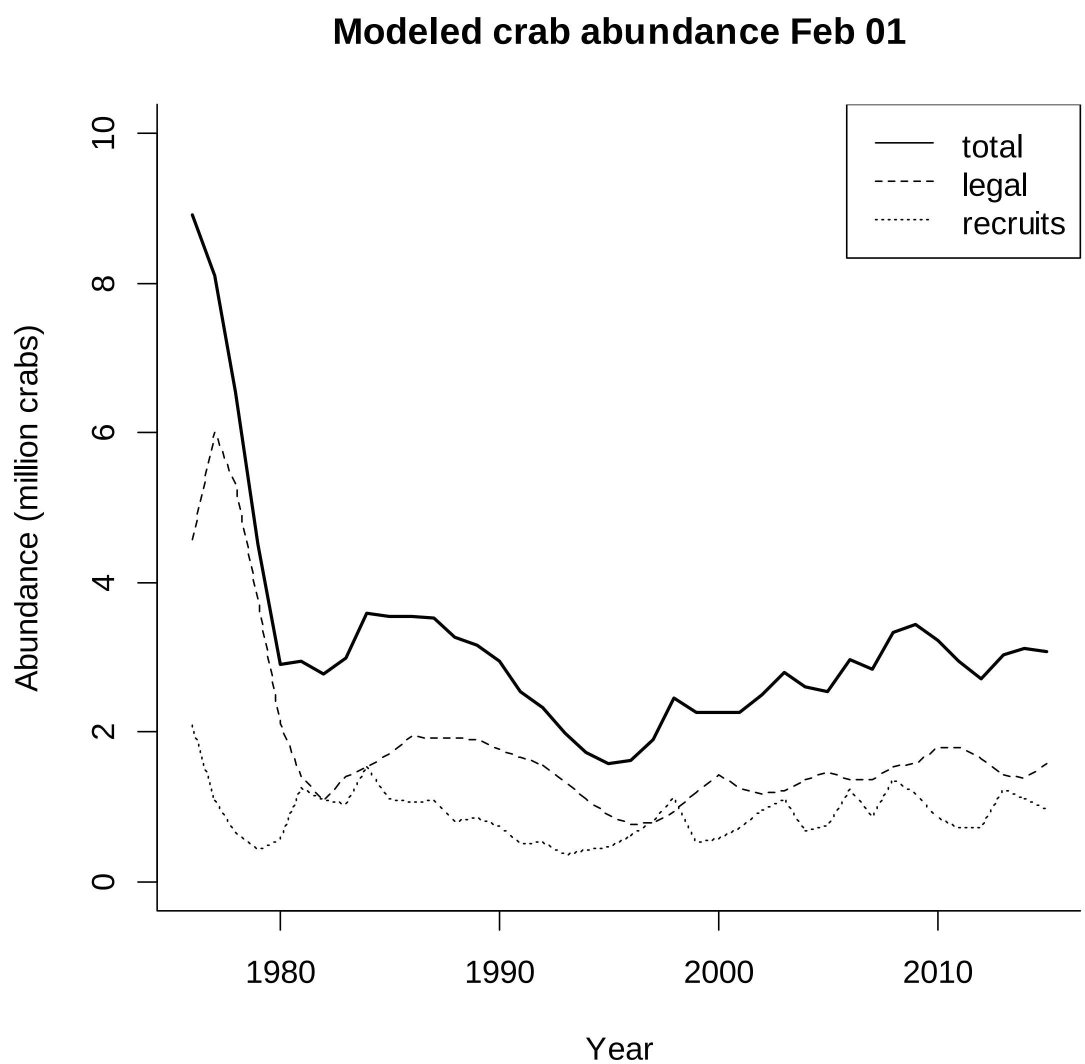


Figure C5-5. Estimated abundance of legal male from 1976-2014

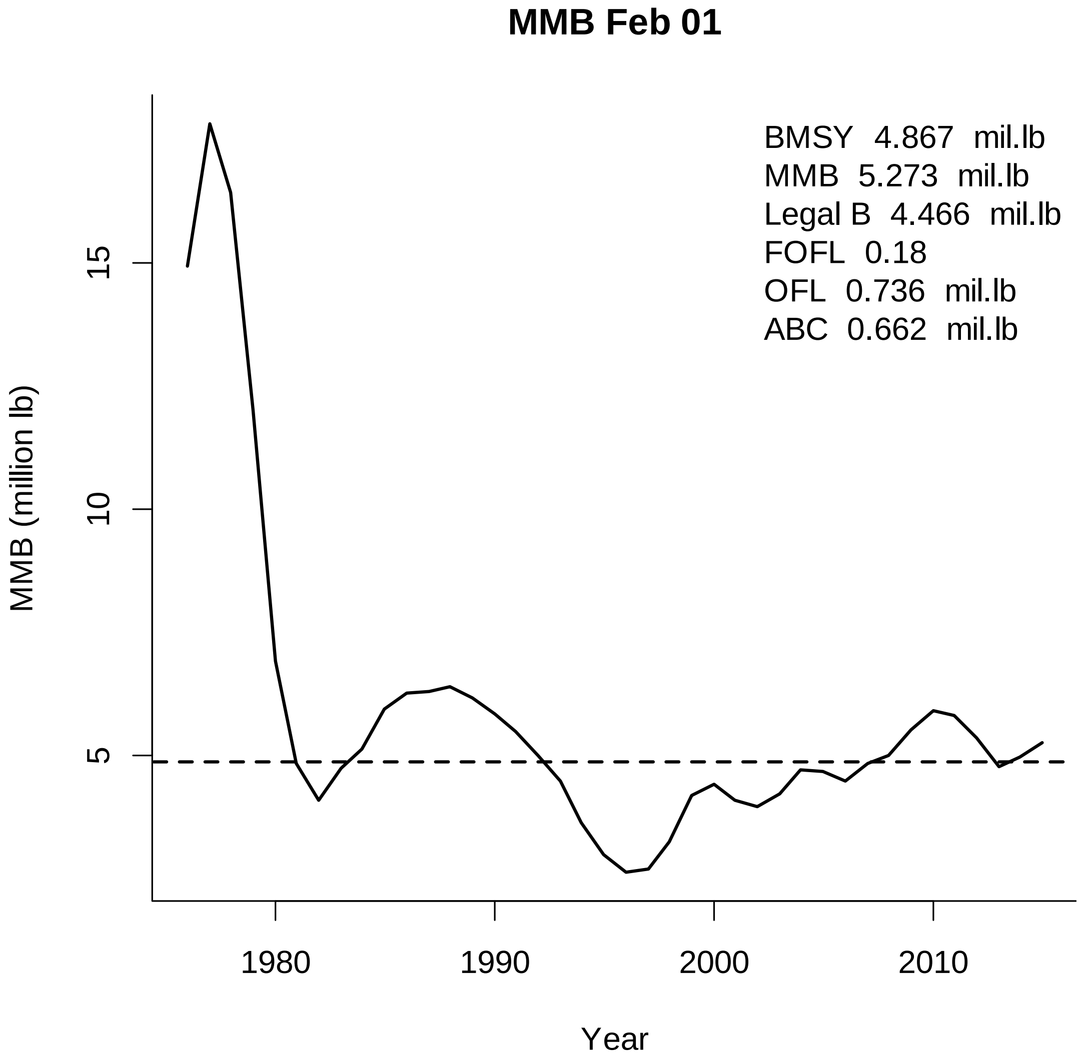


Figure C5-6. Estimated abundance of leg recruits from 1976-2015. Dash line shows Bmsy (Average MMB of 1980-2015)

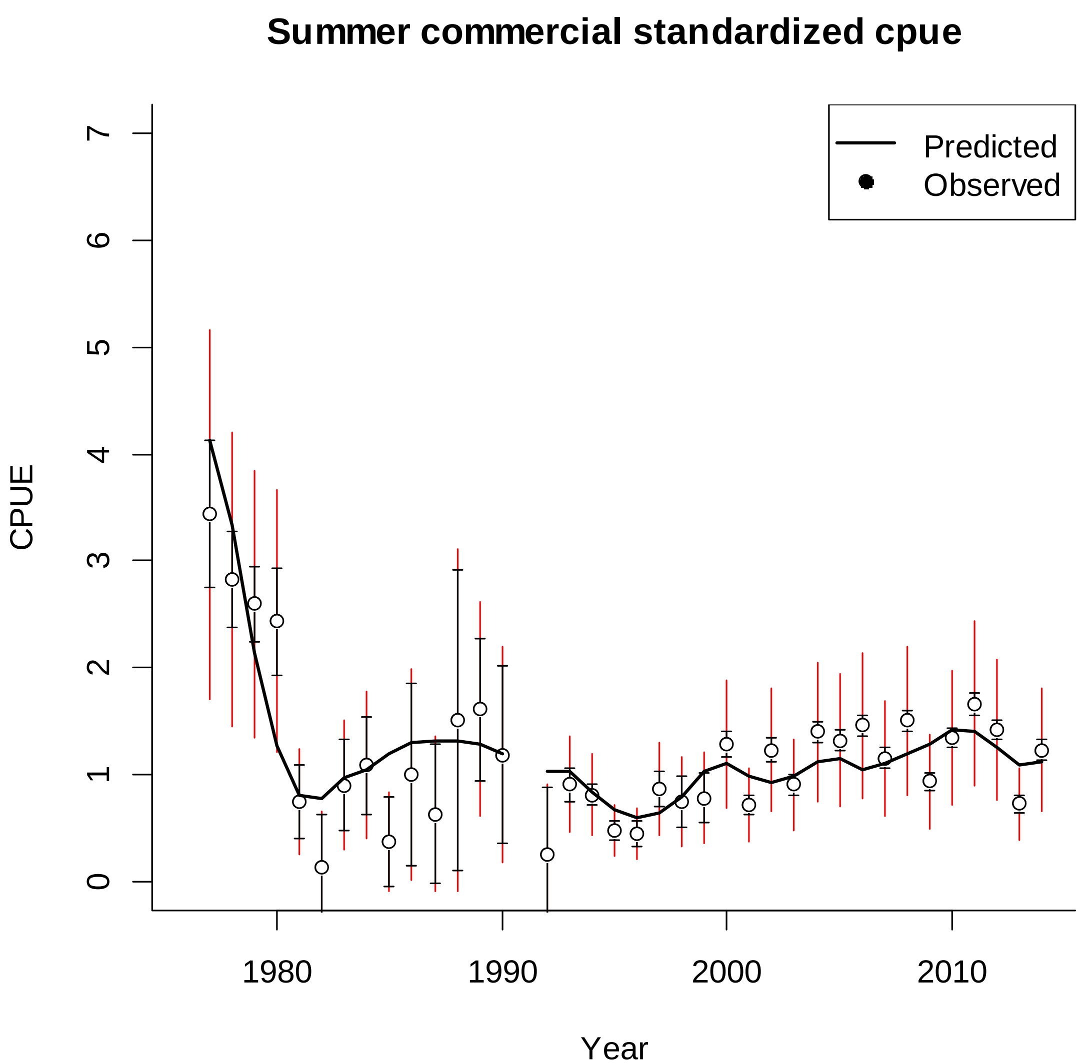


Figure C5-7. Summer commercial standardized cpue (1977-2014)

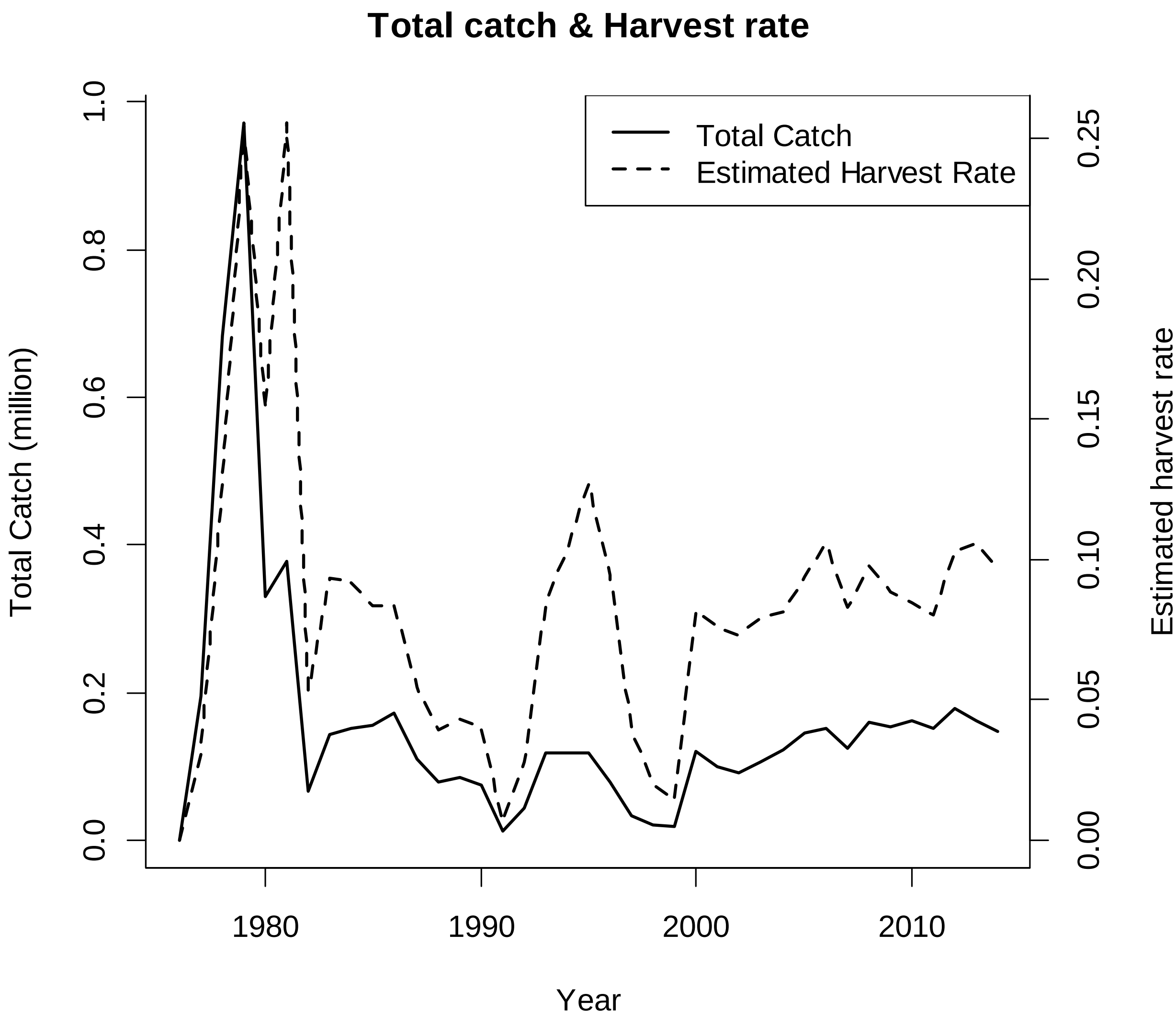


Figure C5-8: Total catch and estimated harvest rate 1976-2014

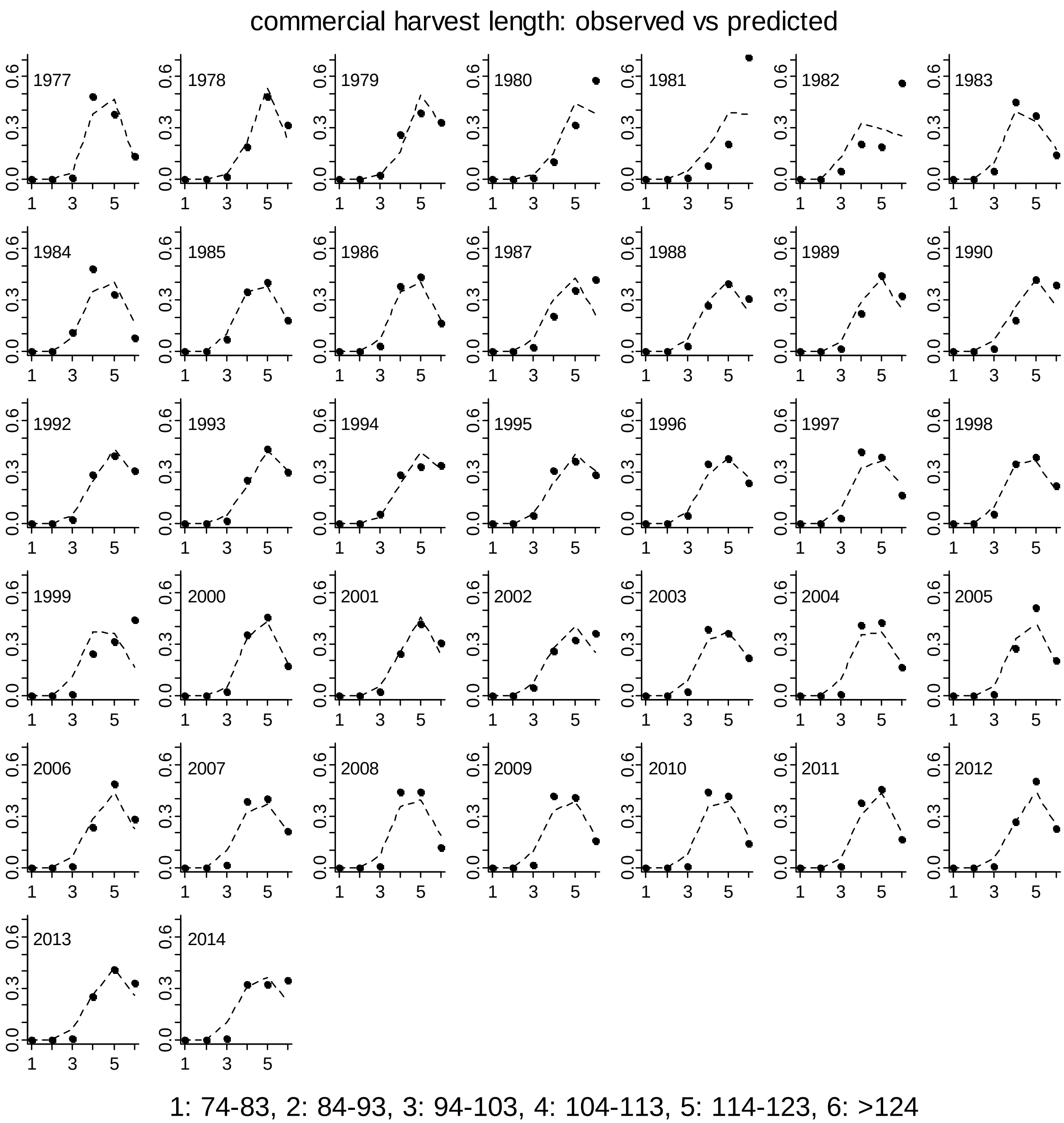
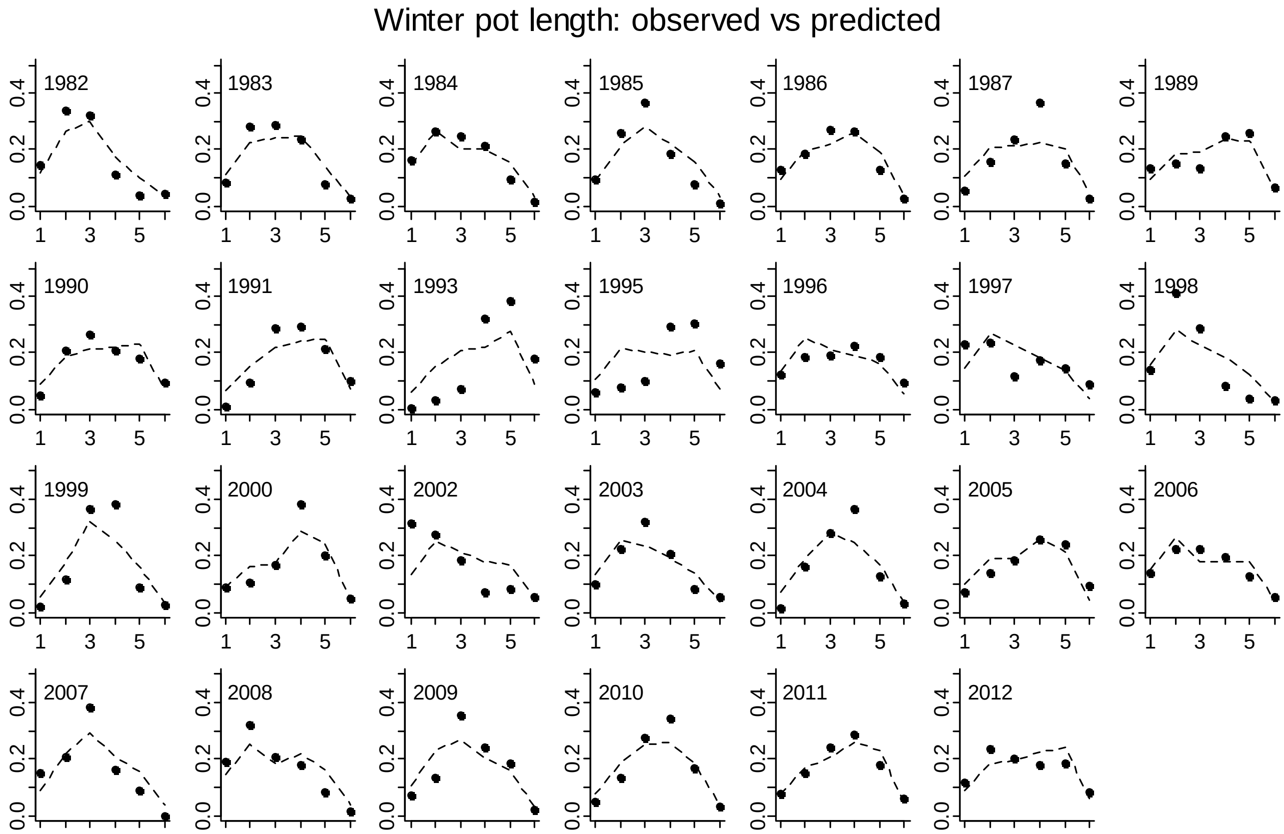
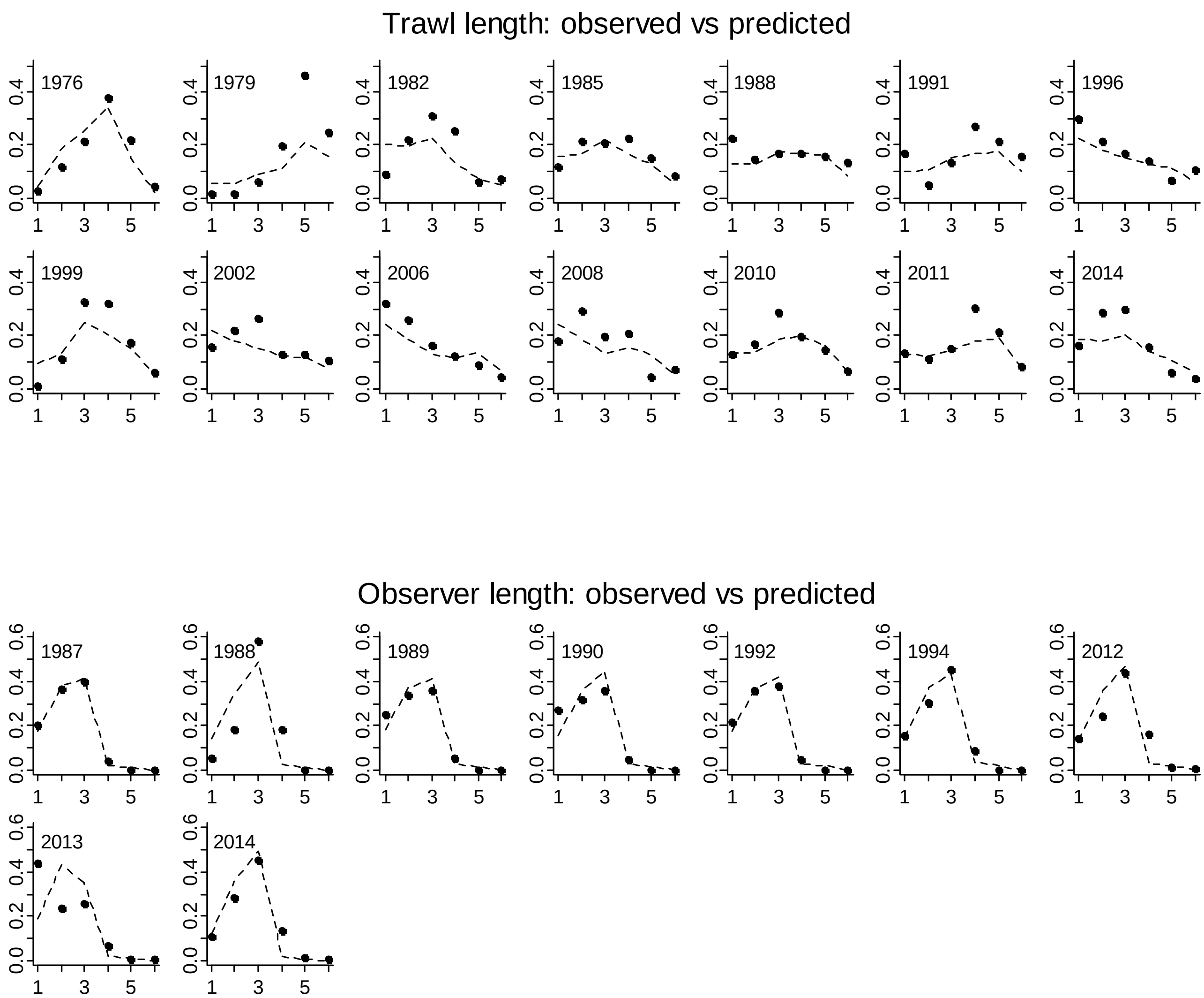


Figure C5-9: Predicted (dashed line) vs. observed (black dots) length class proportion for commercial catch:



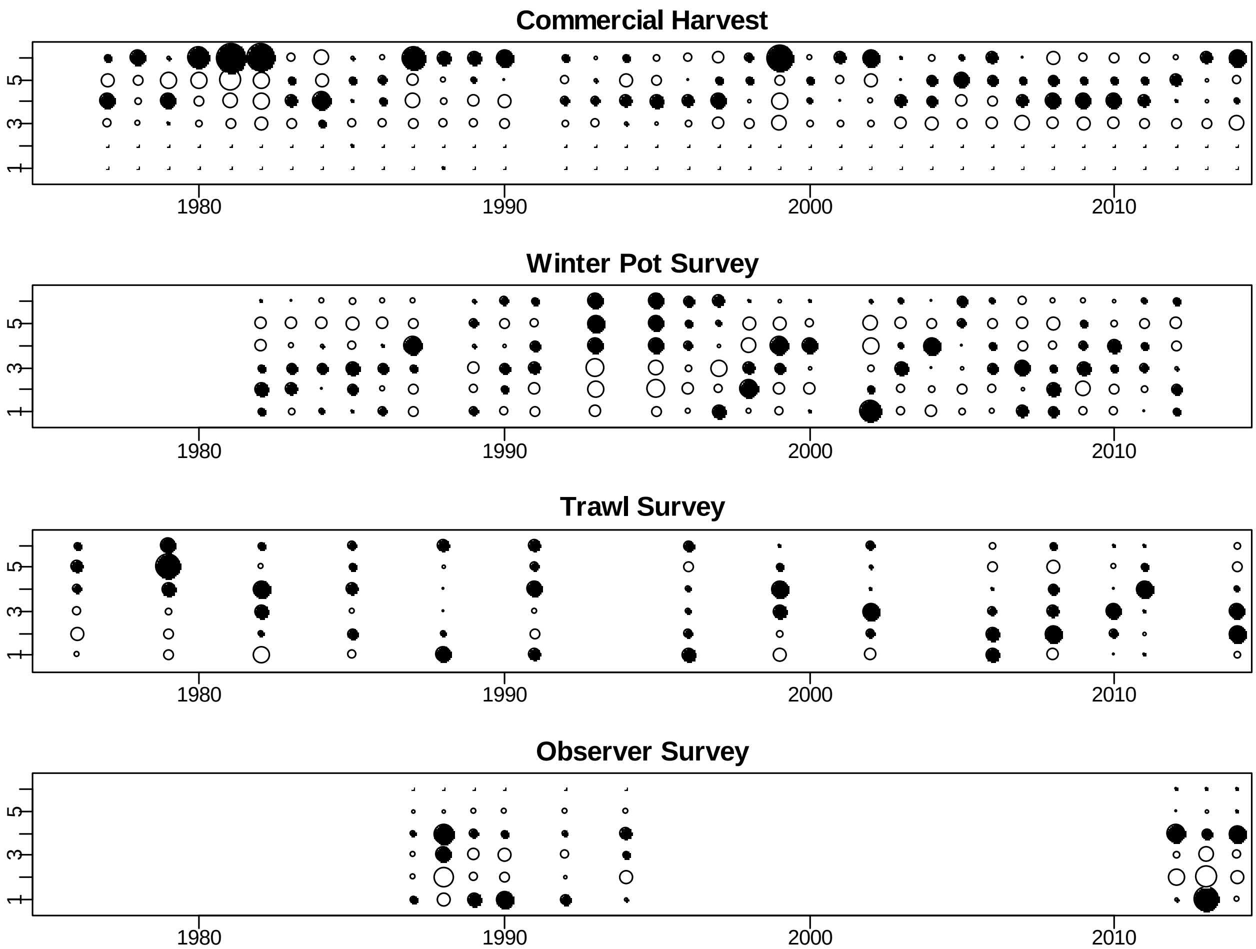
1: 74-83, 2: 84-93, 3: 94-103, 4: 104-113, 5: 114-123, 6: >124

Figure C5-10: Predicted (dashed line) vs. observed (black dots) length class proportion for winter pot survey



1: 74-83, 2: 84-93, 3: 94-103, 4: 104-113, 5: 114-123, 6: >124

Figure C5-11: Predicted (dashed line) vs. observed (black dots) length class proportion for trawl survey and observer survey



1: 74-83, 2: 84-93, 3: 94-103, 4: 104-113, 5: 114-123, 6: >124

Figure C5-12: Bubble plot of predicted and observed length proportion . Black circle indicates model estimates lower than observed, white circle indicates model estimates higher than observed. Size of circle indicate degree of deviance (larger circle = larger deviance).

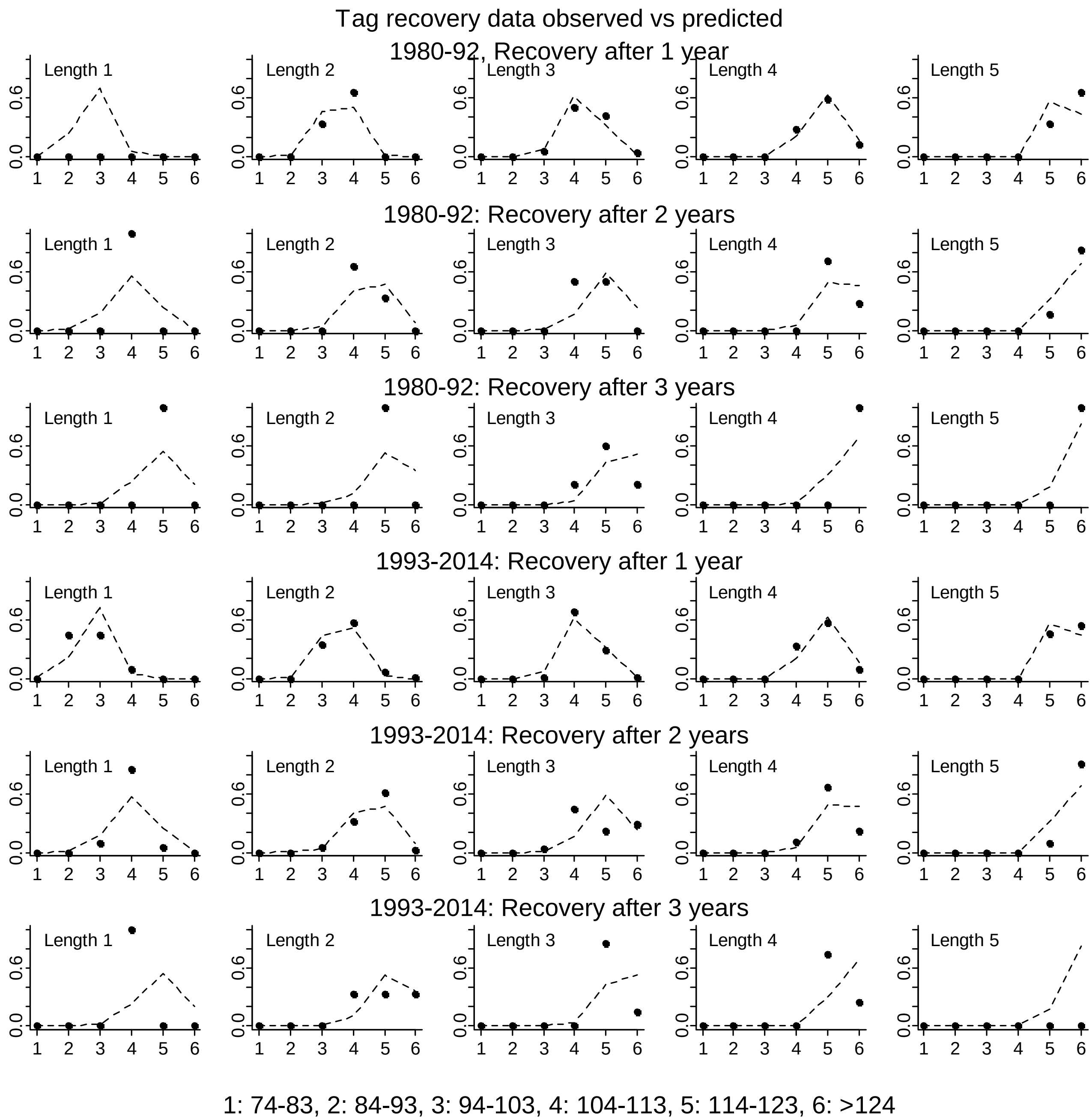
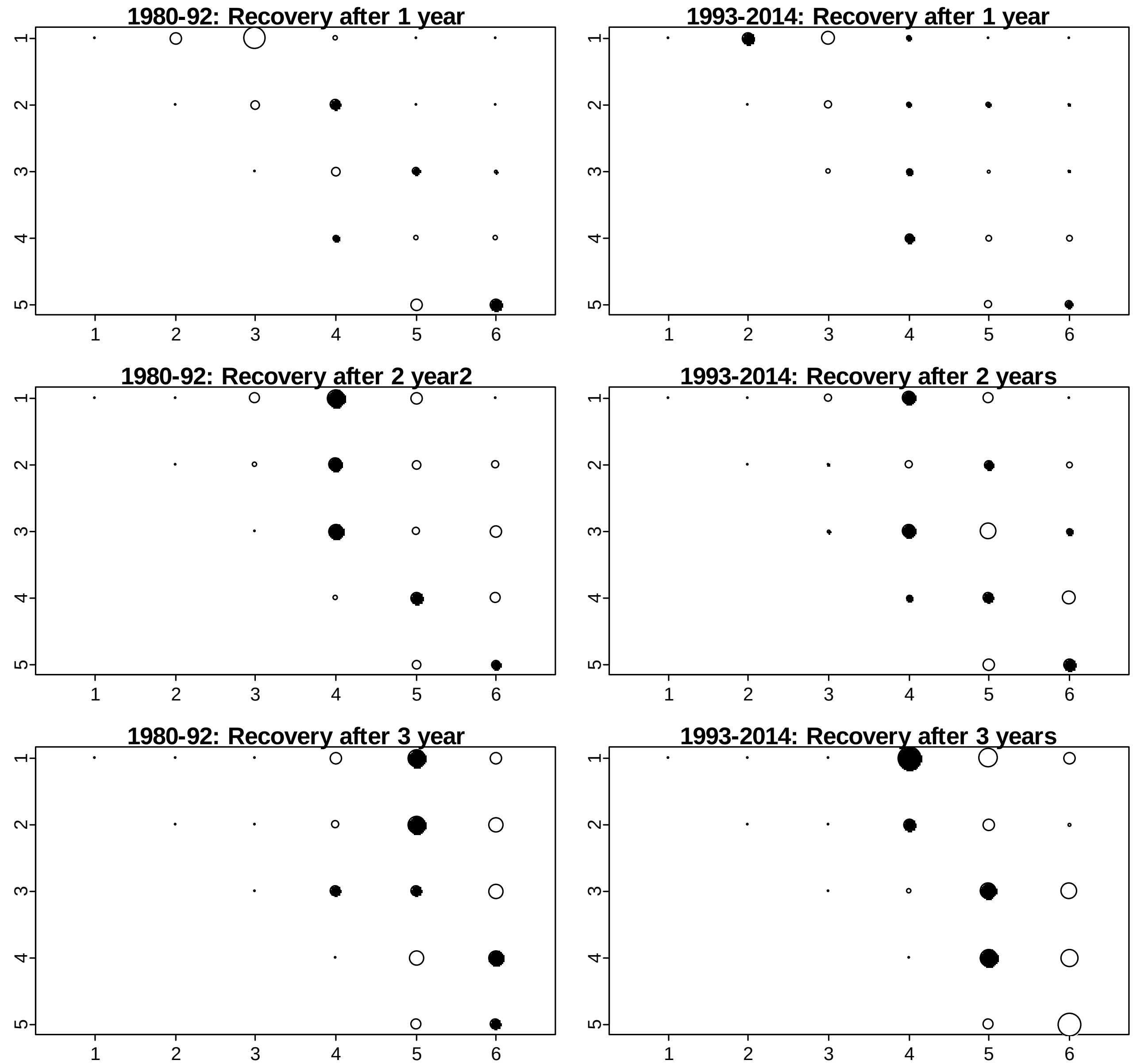


Figure C5-13: Predicted vs. observed length class proportion for tag recovery data 1980-1992, and 1993-2014:



1: 74-83, 2: 84-93, 3: 94-103, 4: 104-113, 5: 114-123, 6: >124

Figure C5-14: Bubble plot of predicted vs. observed length class proportion for tag recovery data 1980-1992, and 1993-2014:

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R_0	6.5239	0.084183
$log\_\sigma_R^2$	0.32119	0.46213
log_R_{77}	-0.30989	0.39151
log_R_{78}	-0.73221	0.35602
log_R_{79}	-0.28266	0.37971
log_R_{80}	0.54195	0.27537
log_R_{81}	0.25807	0.29092
log_R_{82}	0.26419	0.33208
log_R_{83}	0.70234	0.27318
log_R_{84}	0.23998	0.30984
log_R_{85}	0.28344	0.31501
log_R_{86}	0.3154	0.27307
log_R_{87}	-0.0515	0.27872
log_R_{88}	0.081239	0.2679
log_R_{89}	-0.09071	0.27308
log_R_{90}	-0.53588	0.30059
log_R_{91}	-0.41832	0.28358
log_R_{92}	-0.86762	0.32214
log_R_{93}	-0.59476	0.28365
log_R_{94}	-0.50774	0.27655
log_R_{95}	-0.2231	0.24822
log_R_{96}	0.046086	0.27588
log_R_{97}	0.38157	0.2234
log_R_{98}	-0.672	0.32778
log_R_{99}	-0.3073	0.30932
log_R_{00}	-0.0569	0.2924
log_R_{01}	0.21971	0.25843
log_R_{02}	0.34527	0.289
log_R_{03}	-0.29191	0.34332
log_R_{04}	-0.05486	0.29183
log_R_{05}	0.50433	0.20842
log_R_{06}	-0.01536	0.30917
log_R_{07}	0.60502	0.21724
log_R_{08}	0.34547	0.27491
log_R_{09}	-0.00377	0.27913
log_R_{10}	-0.13521	0.27242
log_R_{11}	-0.10872	0.29472
log_R_{12}	0.51081	0.31087
log_R_{13}	0.29438	0.37189
a_1	0.4976	1.9201
a_2	1.8887	1.3711
a_3	2.1849	1.3285
a_4	2.4719	1.3048
a_5	1.6505	1.3585
r1	0.63163	0.069899
log_α	-1.7941	0.019067
log_ϕ_{st1}	-2.459	1.1245
log_ϕ_{st2}	-6.9997	22627

$\log\_\phi_w$	-1.8164	0.045592
Sw_1	0.4214	0.10435
$\log\_\phi_1$	-1.8278	0.080917
$\log\_\phi_2$	-1.765	0.088935
w^2_t	0.051411	0.017522
q	0.71734	0.13061
σ	4.5486	0.29561
β_1	9.2161	0.89774
β_2	7.911	0.27801

Appendix C6: Results Model 6

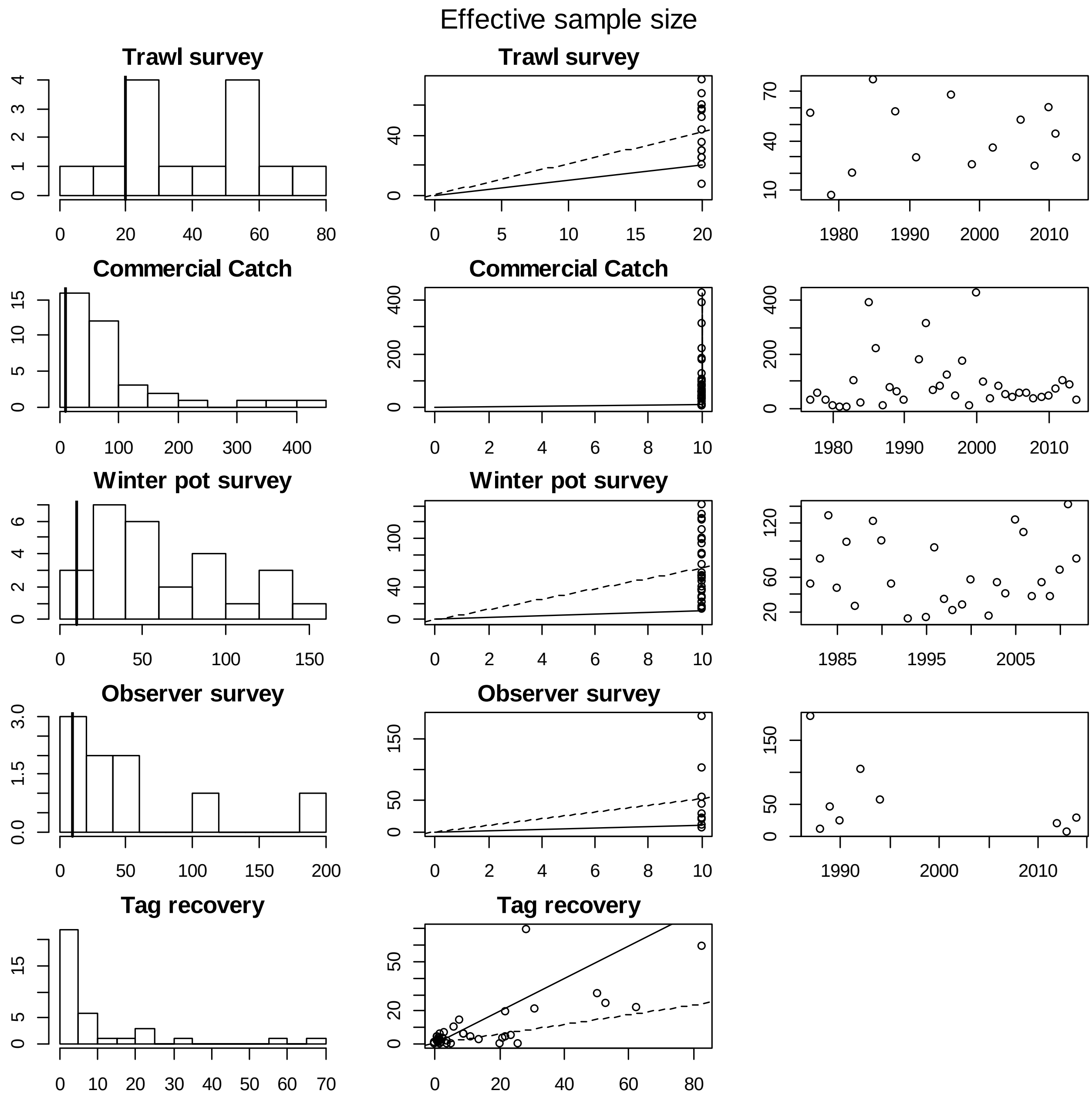


Figure C6-1: Effective sample size vs. implied sample size. Figures in the first column show effective sample size (x-axis) vs. frequency (y-axis). Vertical solid line is the implied sample size. Figures in the second column show implied sample size (x-axis) vs. effective sample size (y-axis). Dashed line indicates linear regression slope, and solid line is 1:1 line. Figures in the third column show year (x-axis) vs. effective sample size (y-axis).

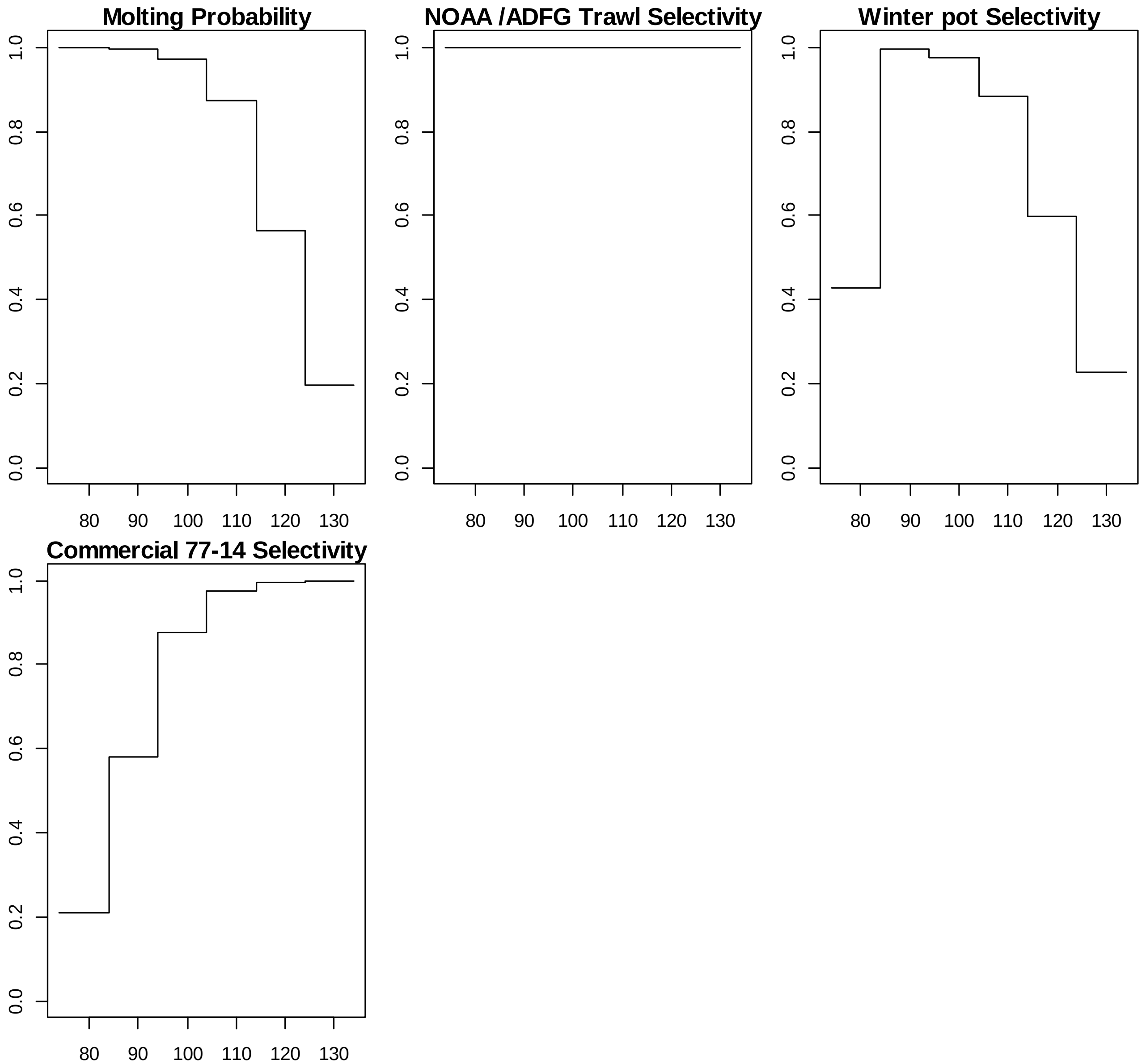


Figure C6-2. Molting probability and trawl/pot selectivities. X-axis is carapace length.

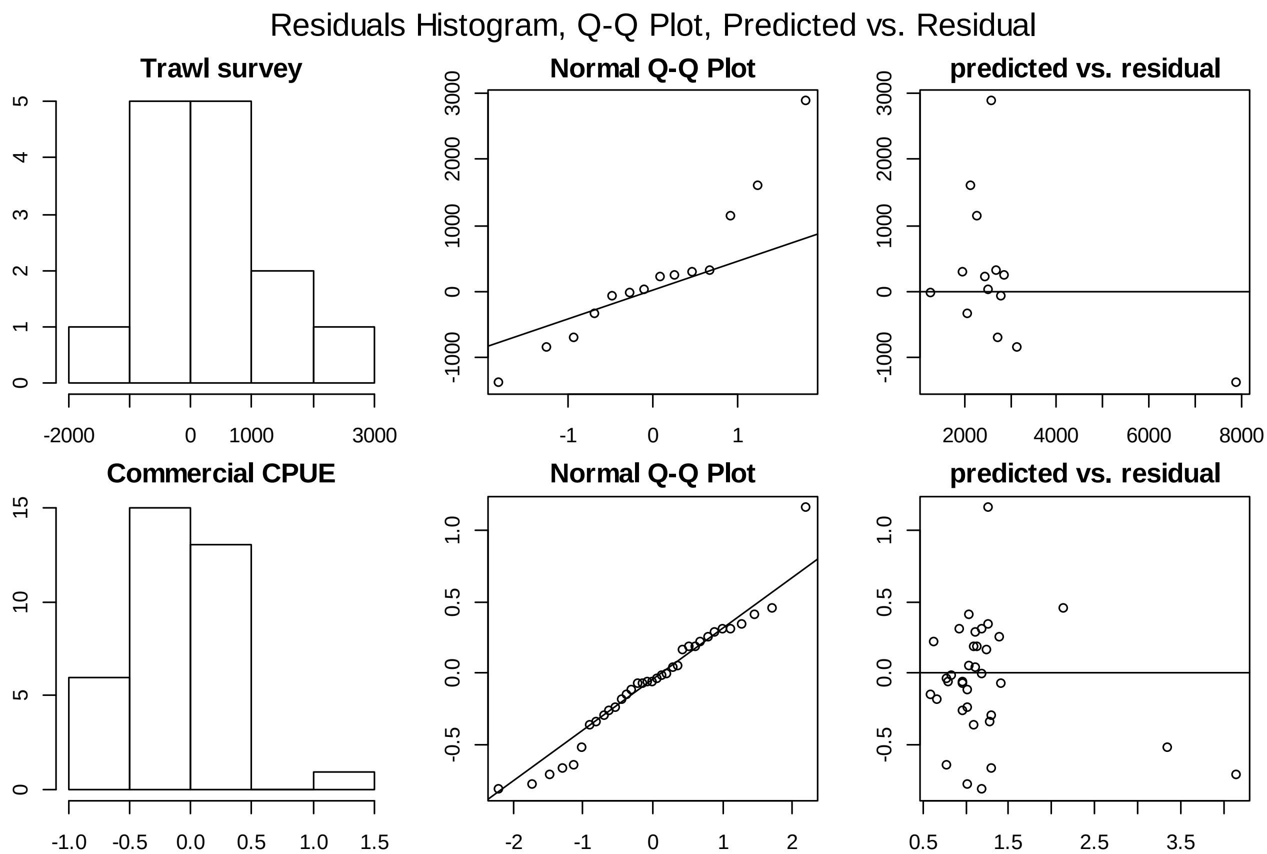


Figure C6-3. QQ Plot of Trawl survey and Commercial CPUE

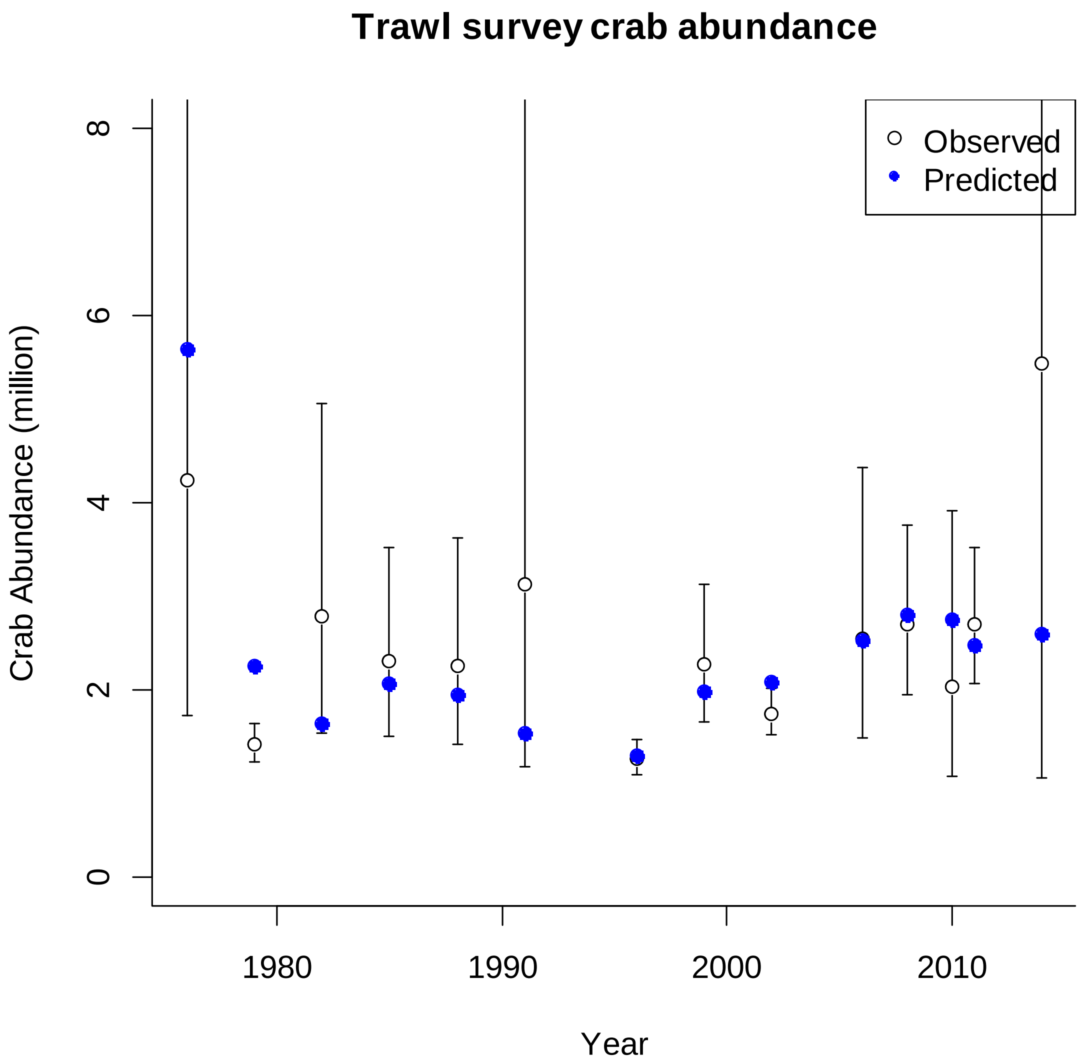


Figure C6-4. Estimated trawl survey abundance (crabs ≥ 74 mm CL) male

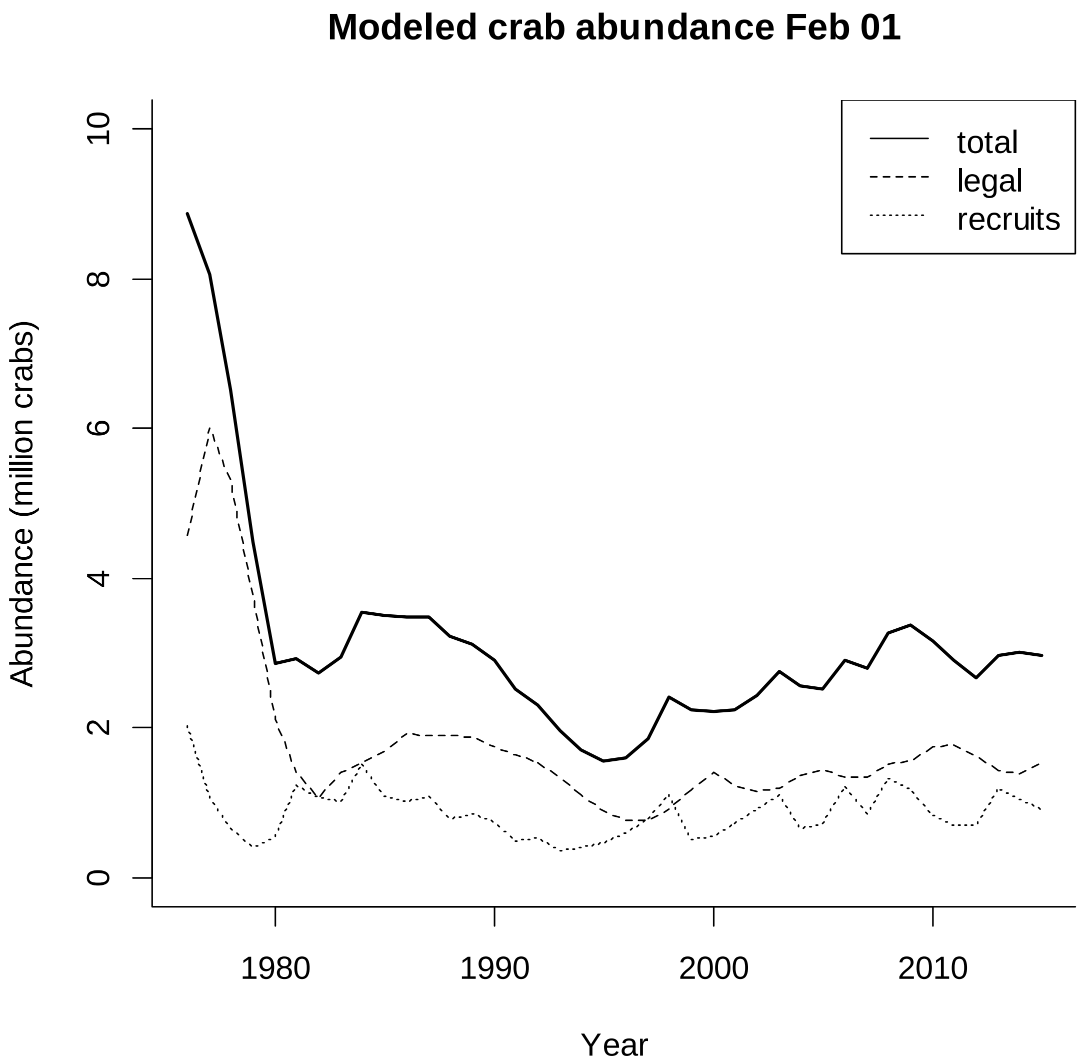


Figure C6-5. Estimated abundance of legal male from 1976-2014

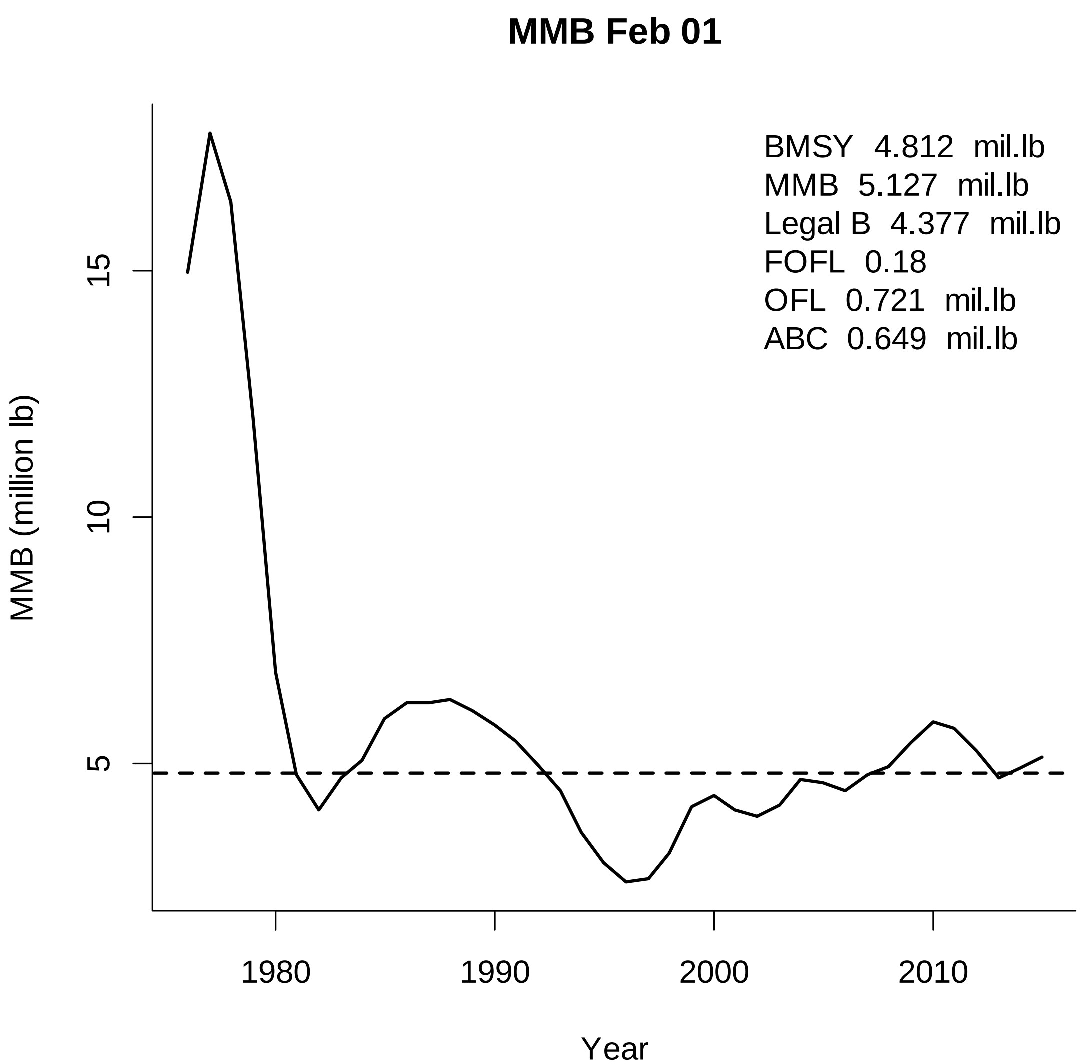


Figure C6-6. Estimated abundance of leg recruits from 1976-2015. Dash line shows Bmsy (Average MMB of 1980-2015)

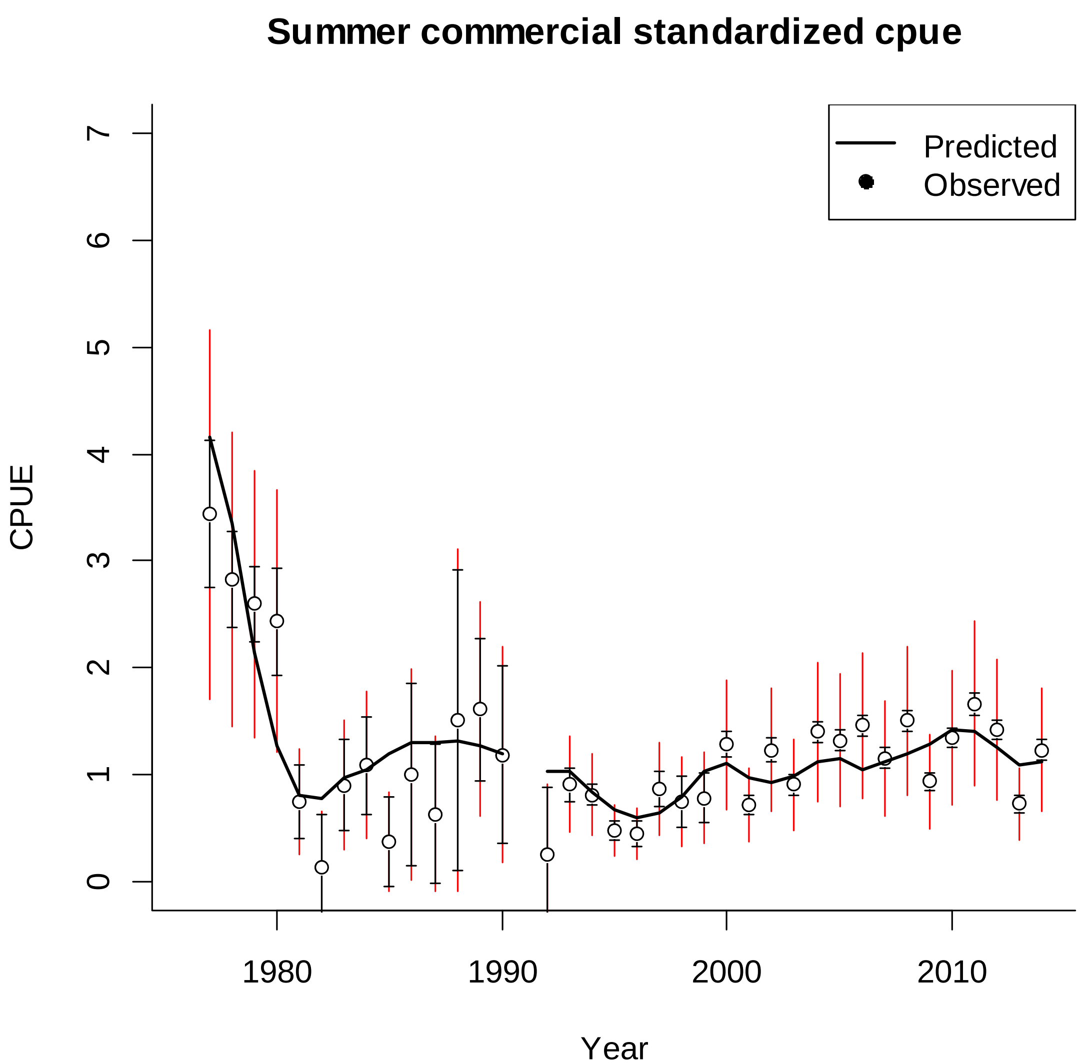


Figure C6-7. Summer commercial standardized cpue (1977-2014)

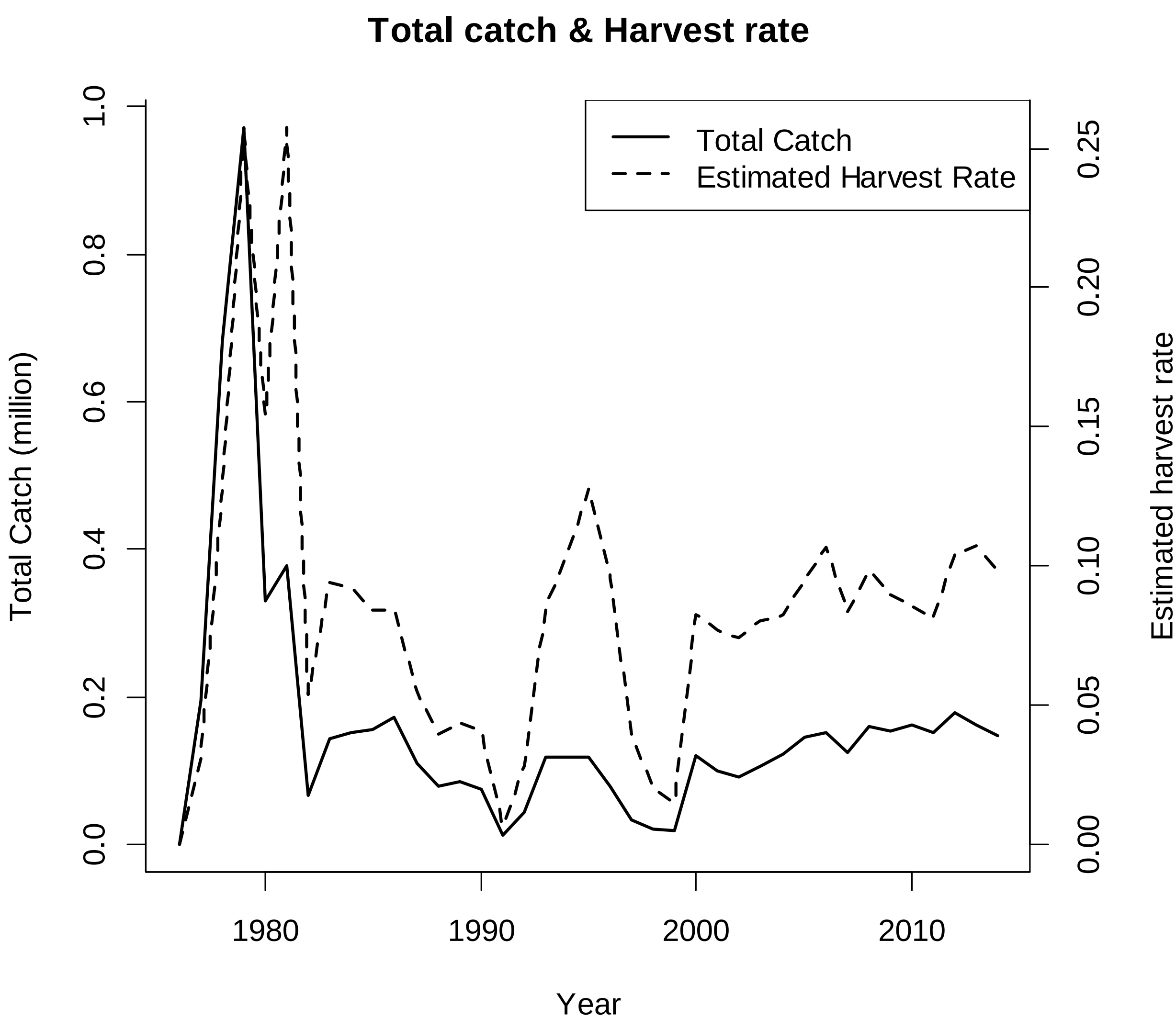


Figure C6-8: Total catch and estimated harvest rate 1976-2014

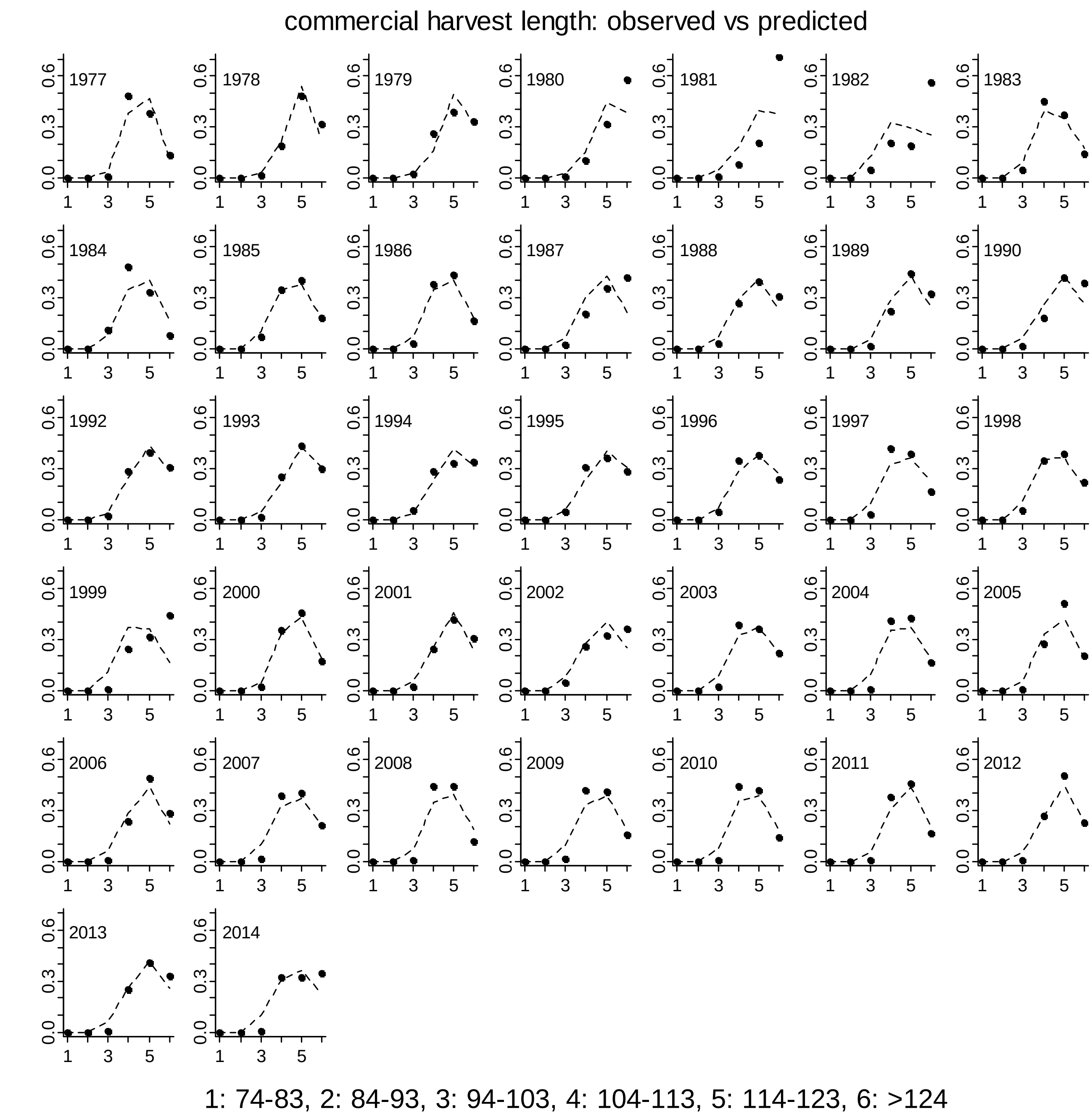
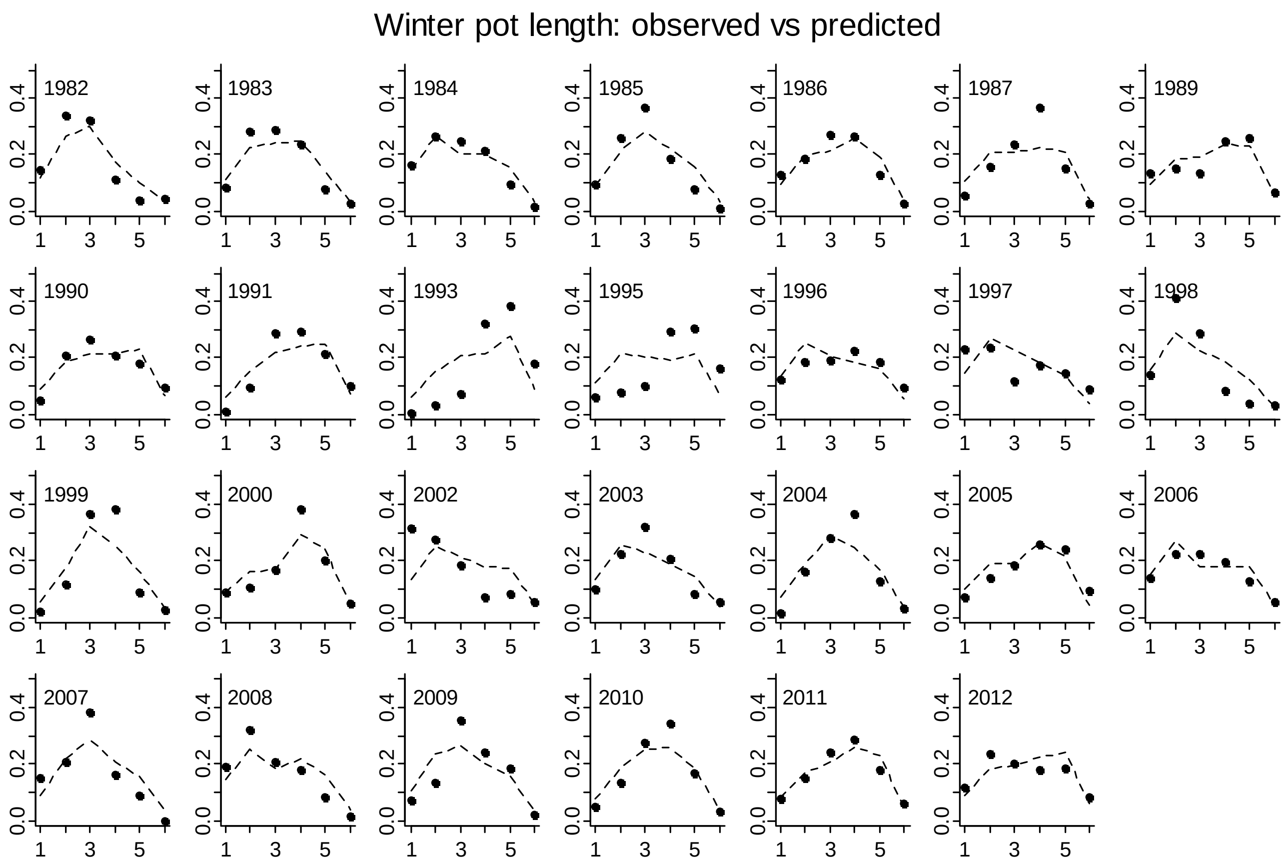
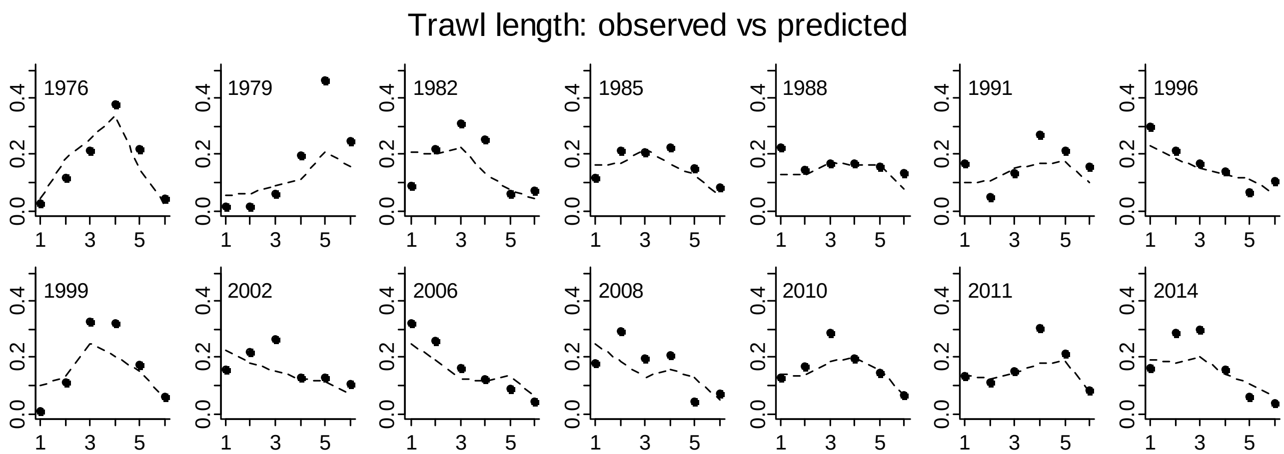


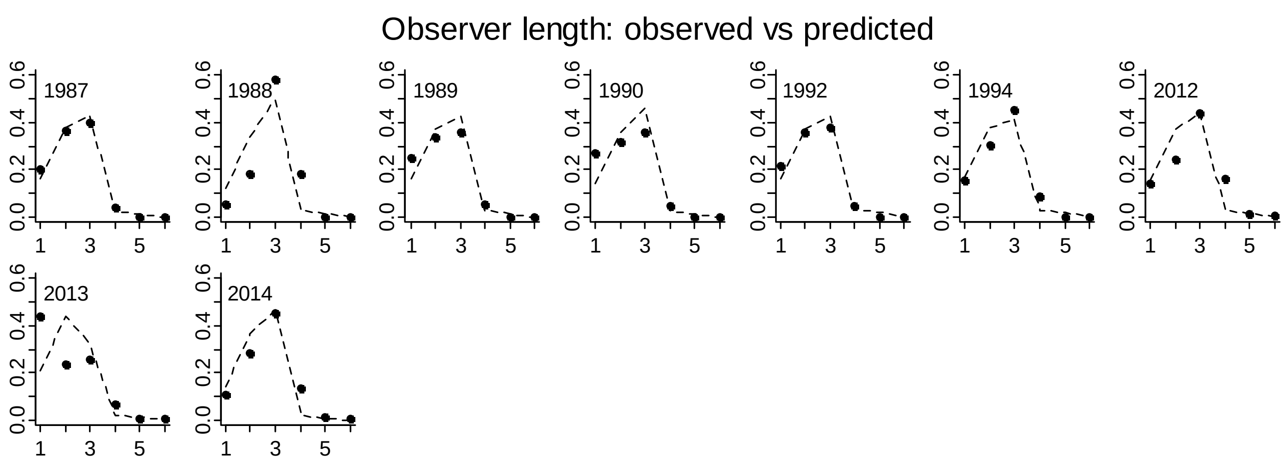
Figure C6-9: Predicted (dashed line) vs. observed (black dots) length class proportion for commercial catch:



1: 74-83, 2: 84-93, 3: 94-103, 4: 104-113, 5: 114-123, 6: >124

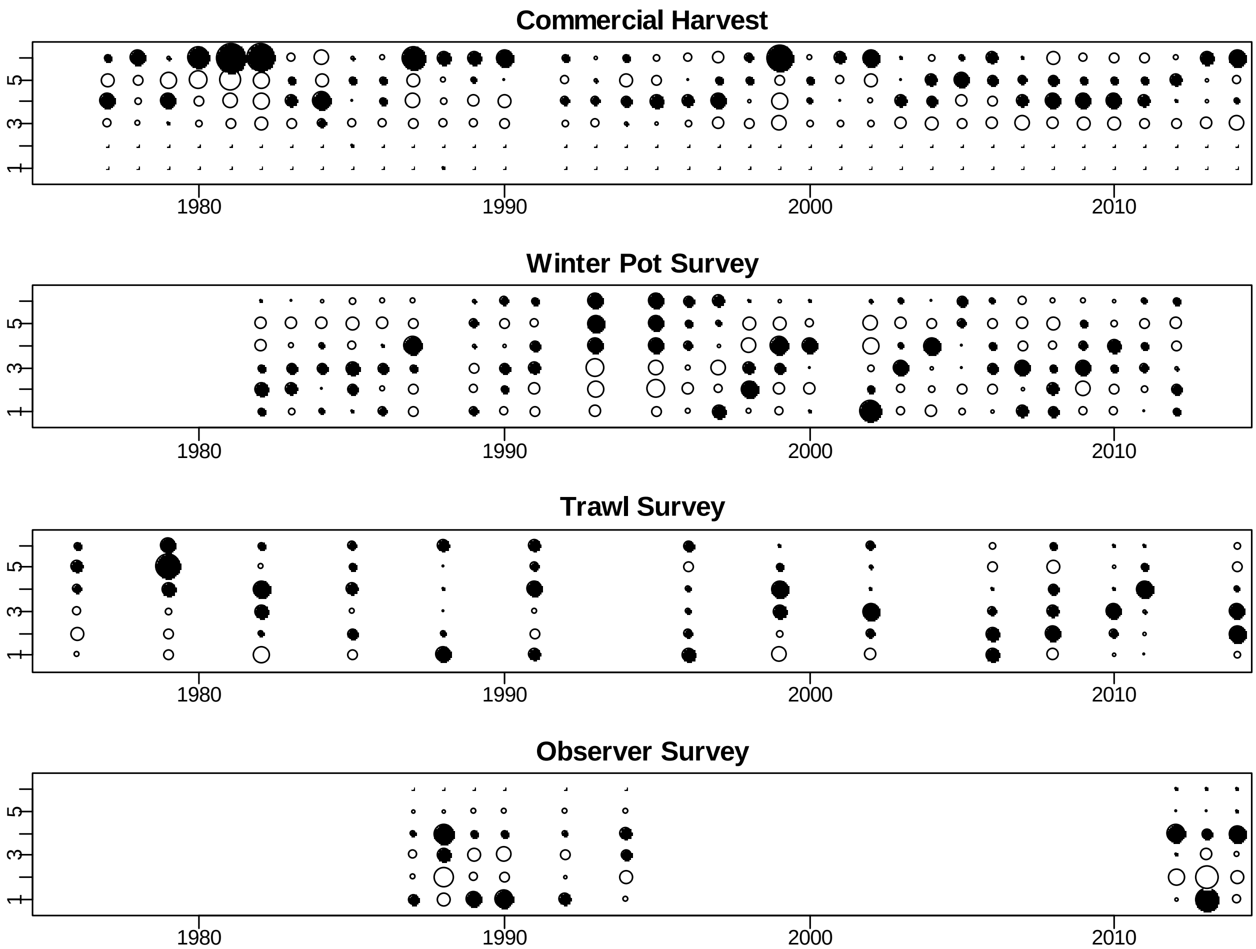
Figure C6-10: Predicted (dashed line) vs. observed (black dots) length class proportion for winter pot survey





1: 74-83, 2: 84-93, 3: 94-103, 4: 104-113, 5: 114-123, 6: >124

Figure C6-11: Predicted (dashed line) vs. observed (black dots) length class proportion for trawl survey and observer survey



1: 74-83, 2: 84-93, 3: 94-103, 4: 104-113, 5: 114-123, 6: >124

Figure C6-12: Bubble plot of predicted and observed length proportion . Black circle indicates model estimates lower than observed, white circle indicates model estimates higher than observed. Size of circle indicate degree of deviance (larger circle = larger deviance).

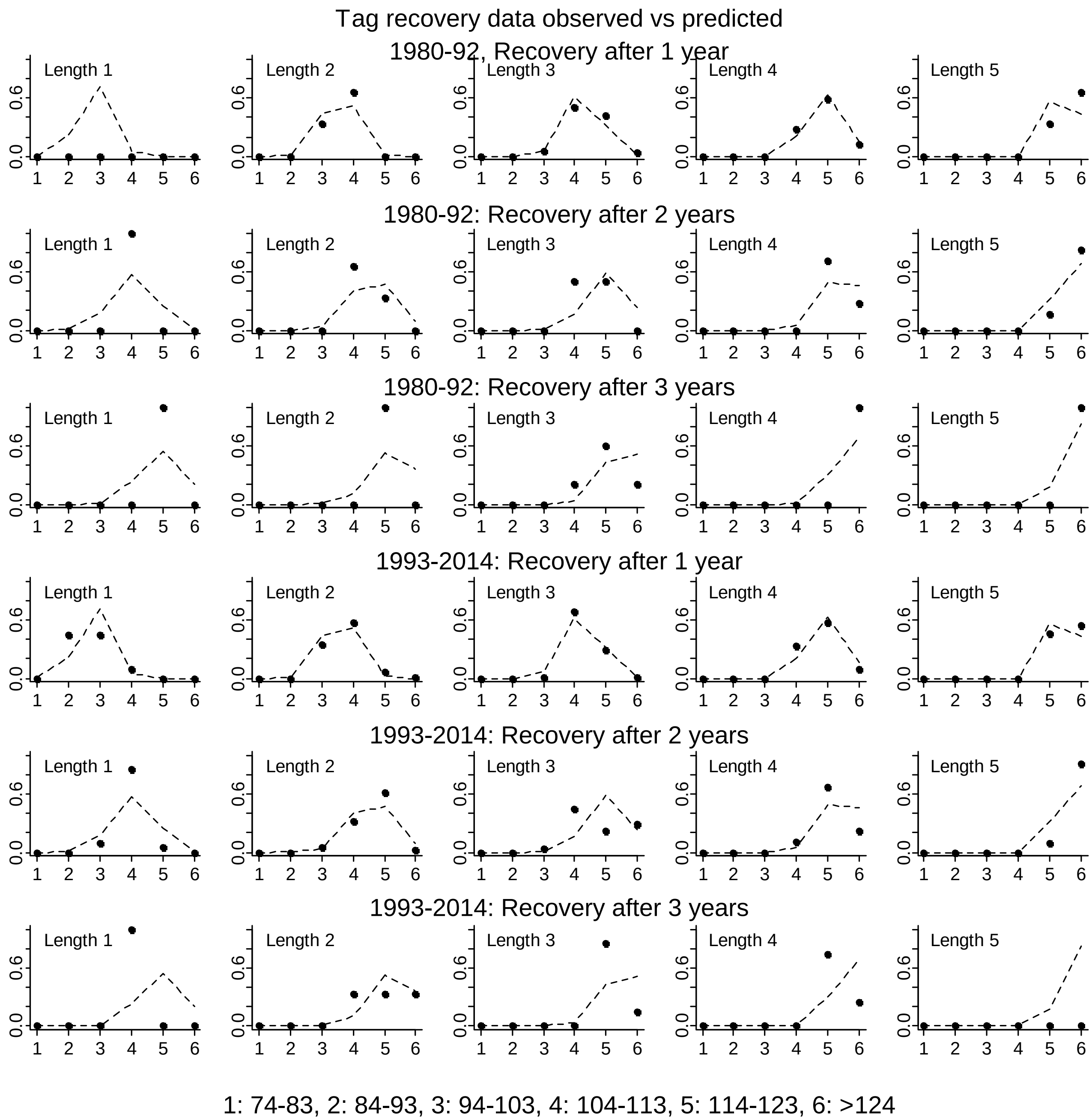
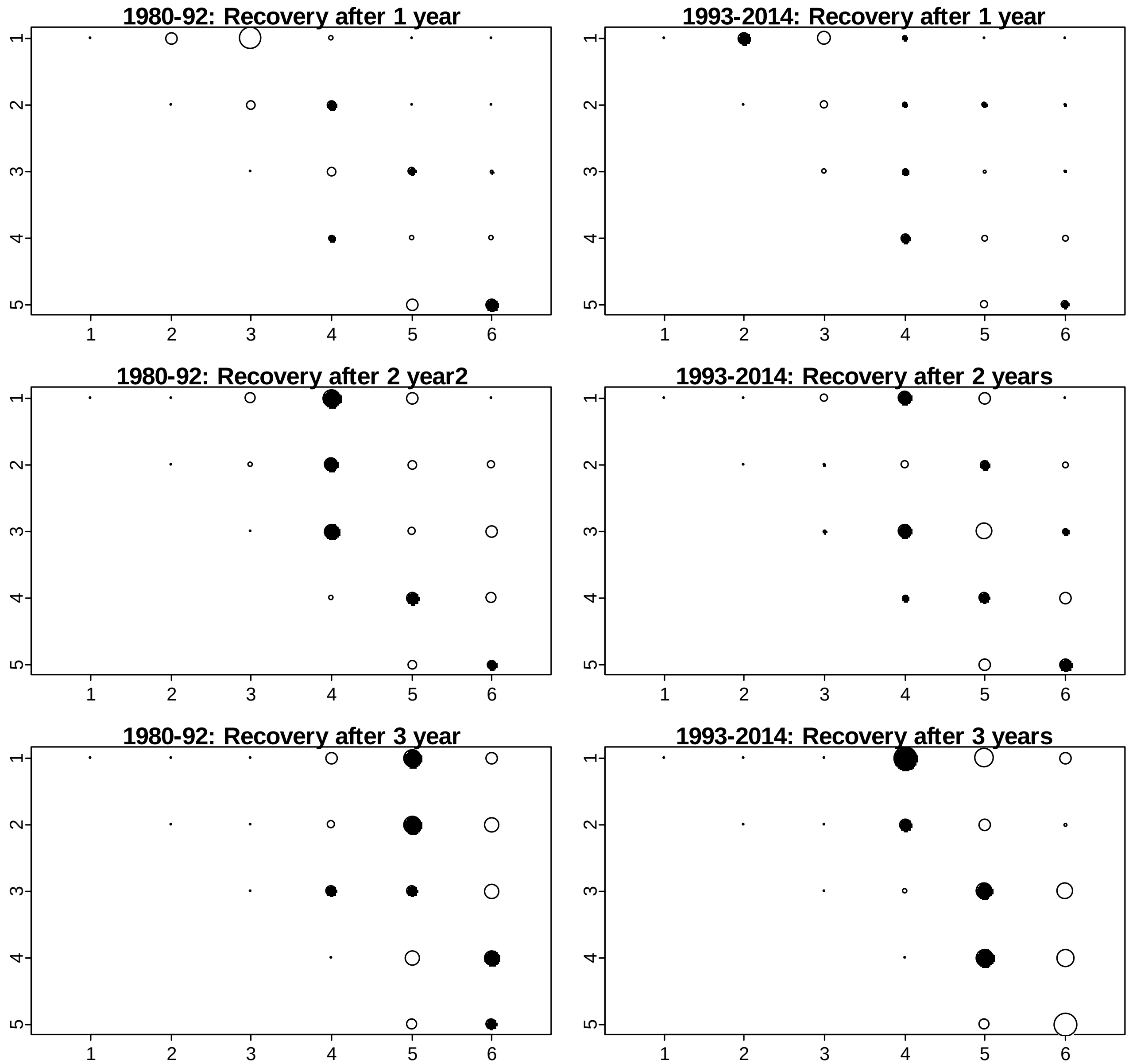


Figure C6-13: Predicted vs. observed length class proportion for tag recovery data 1980-1992, and 1993-2014:



1: 74-83, 2: 84-93, 3: 94-103, 4: 104-113, 5: 114-123, 6: >124

Figure C6-14: Bubble plot of predicted vs. observed length class proportion for tag recovery data 1980-1992, and 1993-2014:

Table C6-1 . 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	-7.1695	0.17949
log_q_2	-7.0052	0.094063
log_N_{76}	9.0903	0.15807
R_0	6.5111	0.069899
$log\_\sigma_R^2$	0.34419	0.4539
log_R_{77}	-0.29935	0.38957
log_R_{78}	-0.74307	0.35276
log_R_{79}	-0.28749	0.37892
log_R_{80}	0.54114	0.27099
log_R_{81}	0.25666	0.28849
log_R_{82}	0.27011	0.32664
log_R_{83}	0.70377	0.26988
log_R_{84}	0.24143	0.30666
log_R_{85}	0.27018	0.30999
log_R_{86}	0.32682	0.268
log_R_{87}	-0.05633	0.2766
log_R_{88}	0.085734	0.26629
log_R_{89}	-0.07167	0.26779
log_R_{90}	-0.55485	0.29819
log_R_{91}	-0.3935	0.27767
log_R_{92}	-0.84682	0.31789
log_R_{93}	-0.61655	0.28252
log_R_{94}	-0.50293	0.27478
log_R_{95}	-0.23298	0.23981
log_R_{96}	0.037987	0.27396
log_R_{97}	0.39147	0.2191
log_R_{98}	-0.67324	0.32479
log_R_{99}	-0.3067	0.30868
log_R_{00}	-0.05292	0.28968
log_R_{01}	0.19657	0.22958
log_R_{02}	0.36501	0.27604
log_R_{03}	-0.2863	0.3422
log_R_{04}	-0.05434	0.29041
log_R_{05}	0.49922	0.20397
log_R_{06}	-0.00669	0.30448
log_R_{07}	0.59322	0.2078
log_R_{08}	0.36102	0.26451
log_R_{09}	-0.00544	0.27545
log_R_{10}	-0.11936	0.2651
log_R_{11}	-0.11415	0.29373
log_R_{12}	0.49332	0.30772
log_R_{13}	0.24683	0.35443
a_1	0.41021	1.8878
a_2	1.873	1.3696
a_3	2.1804	1.3285
a_4	2.4697	1.3048
a_5	1.6508	1.3586
r1	0.62056	0.054306
log_α	-1.7941	0.019085
log_ϕ_{st1}	-14.556	1485
log_ϕ_{st2}		

log_ϕ_w	-1.8158	0.045533
Sw_1	0.42902	0.1003
log_ϕ_1	-1.8039	0.059877
log_ϕ_2		
w^2_t	0.051598	0.017595
q	0.71459	0.1267
σ	4.5222	0.28733
β_1	9.3851	0.79453
β_2	7.8668	0.25217