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Exploration of alternative ADAPT model formulations for the assessment of Atlantic Cod in Divs. 3NO

by

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Abstract

The stock of Atlantic Cod on the southern Grand Bank (Divs. 3NO) collapsed during the early 1990s and has shown no sustained recovery since that time, despite estimates of fishing mortality being low. The assessment for this stock has long been based on a sequential population analysis using the ADAPT framework and the model formulation has not changed in over two decades. In the most recent assessment of this stock (2018), recommendations were made to explore various details of the data and the impact of various modifications to the assessment. The analyses herein explore these recommendations. An examination of fishing mortality at age suggested that selectivity during the moratorium period (1994-present) was dome-shaped. In terms of data inputs, an identical model formulation to the current assessment model but that also includes data from the EU-Spain RV survey as an additional tuning index was explored. The inclusion of this survey resulted in poorer model fit, with a higher mean square error and an increase in the relative error for estimates of catchability. A model run that excluded the first five years of the Canadian autumn survey series also failed to improve the resulting model fit / residual patterns. Unfortunately, the final recommendation to incorporate a plus-group into the assessment formulation could not be satisfactorily addressed. Numerous attempts to incorporate a plus group within the ADAPT framework-based assessment of this stock all produced unsatisfactory results, either because of failure of models to converge, computational issues, or poor model fits. If the inclusion of a plus-group remains a priority, then consideration should be given to exploring other modelling options beyond ADAPT going forward.

Introduction

The stock of Atlantic Cod on the southern Grand Bank (Divs. 3NO) collapsed during the early 1990s and has shown no sustained recovery since that time, despite estimates of fishing mortality being low. The assessment for this stock has long been based on a sequential population analysis using the ADAPT framework (Gavaris, 1988) and the model formulation has not changed in over two decades. In the most recent assessment of this stock (Rideout et al., 2018), recommendations were made to explore the impact of various modifications to the assessment. The analyses herein explore these recommendations.

Methods

There are three ongoing RV multispecies bottom trawl surveys that cover all or a portion of NAFO Divisions 3NO. These include the Canadian Spring survey, Canadian Autumn survey (Rideout and Ings, 2020) and the EU-Spain survey (González Troncoso et al., 2020). The two Canadian surveys cover the entire stock area down to a depth of 730 m, while the EU-Spain survey covers only the NRA portion of the stock area down to a depth of 1500 m.

The current assessment model used for this stock is a sequential population analysis applying the ADAPT framework (Gavaris, 1988). The model uses both Canadian surveys as well as data from a former Canadian Juvenile survey in order to tune estimates of commercial catch at age. These survey indices are based on a set of index strata <367 m (200 fathoms). The specific inputs are:

- Catch at age: ages 2-12 (1959-2017) (Figs. 1-2)
- Tuning Index 1: Canadian RV Spring (mean number per tow at ages 2-10; 1984-2005, 2007-2017) (Figs. 3-5)
- Tuning Index 2: Canadian RV Fall (mean number per tow at ages 2-10; 1990-2013, 2015-2017) (Figs. 6-8)
- Tuning Index 3: Canadian Juvenile Survey (mean number per tow at ages 2-10; 1989-1994)

To date, the inclusion of the EU-Spain survey has not been accepted as a tuning index for this assessment. Since this survey only covers a small portion of the stock area there is the potential for survey trends to be confounded by the movement of fish in and out of the survey area. The last time that the potential inclusion of the EU-Spain survey was officially explored, Morgan (2006) concluded that its inclusion as a tuning index resulted in a model fit that was worse than when that index was excluded.

Other details of the currently accepted VPA setup include:

- Assume no error in the catch numbers at age.
- No plus group in the catch-at-age
- M assumed to be 0.2 for all ages and years
- For the period prior to the moratorium (1959-1993), F on the oldest age (12) is set equal to the average F for ages 6-9
- For the moratorium period (1994-2017), there are many zeros in the catch at age at older ages. Instead of setting an F constraint on the oldest age, the numbers at age 12 are estimated.
- The numbers at age for ages 3-12 are estimated for the current year
- All indices are assumed to have equal weighting

In response to the use of this model formulation in the last assessment (2018), STACFIS made a number of recommendations to consider for the next assessment, including:

1. STACFIS recommends continuing to monitor the consistency in trends between the Canadian and EU-Spain surveys.
2. STACFIS recommends investigating the removal of the pre-1995 Canadian autumn assessment points for an improvement in model fit / residual pattern.
3. *Priority* - STACFIS recommends investigating the potential use of a plus group in the assessment of Divs. 3NO cod.
4. *Priority* - STACFIS recommends examining the selectivity pattern (i.e. flat-topped vs. dome-shaped)

A number of exploratory ADAPT runs are performed here to assess various aspects of the STACFIS recommendations. At the time that these analyses were performed, catch-at-age estimates for 2018-2020 were not yet available so these analyses are based on data up to and including 2017 (i.e. the same data used in the most recent assessment for this stock – Rideout et al. (2018)).

Results

Recommendation: STACFIS recommends continuing to monitor the consistency in trends between the Canadian and EU-Spain surveys.

Model fits were compared with (Table 1, Fig. 14) and without (Table 2, Fig. 15) the inclusion of the EU-Spain survey as a tuning index. Here we refer to the model formulation used in previous assessments as the "Baseline". In the model formulation, referred to here simply as "Spain", a fourth survey tuning index was included, specifically:

- Tuning Index 4: EU-Spain 3NO RV Survey (Figs. 9-11) (Mean number per tow at ages 2-10: 1997-2017)

All other aspects of the model formulation remained the same as the 'Baserun'.

The mean square error was larger for the run including the Spain run (0.713) compared to the run including only the Canadian spring, autumn and juvenile indices (0.611). There was also an increase in the relative error for estimates of catchability when the indices from the survey from EU-Spain were included. The conclusion that the inclusion of the EU-Spain survey results in a model fit that is worse than when the index is excluded is the same as previous reports (Morgan, 2006).

Recommendation: STACFIS recommends investigating the removal of the pre-1995 Canadian autumn assessment points for an improvement in model fit / residual pattern.

The 'Baseline' run was compared to a run where the first 5 years of the Canadian autumn survey time series were excluded from the analysis (Table 3, Fig. 16). This was referred to as the 'Modified Fall' run. Specifically,

- Tuning Index 2: Canadian RV Fall (mean number per tow at ages 2-10; 1995-2013, 2015-2017)

All other aspects of the model formulation remained the same as the 'Baserun'

The mean square error was marginally lower for the 'Modified Fall' run (0.602) than the 'Baserun' (0.611), but the exclusion of the early autumn data did not visibly improve the existing patterns in the residuals (Fig. 16).

Recommendation: STACFIS recommends investigating the potential use of a plus group in the assessment of Divs. 3NO cod.

Detailed data for catch at age for individual ages older than 12 were not available for most years in the time series. However, many previous assessment documents contained estimates of catch numbers for a 13+ group. Reviewing the history of assessment documents, coupled with available electronic data for this stock allowed us to compile estimates of 13+ for all years in the catch time series.

The ADAPT framework allows plus groups to be incorporated into the VPA in two ways. These are referred to as the "first" and "Fratio" methods and are explained in Gavaris (1988) as:

For the FIRST method, all cohorts must be specified. In addition, the population abundance of the plus group in the first time of the VPA must be specified. Therefore we have $N_{A,1}$ and $N_{A',1}$. We can compute

$$N_{A',2} = N_{A,1}e^{-(F_{A,1}+M_{A,1})\Delta t_1} + N_{A',1}e^{-(F_{A',1}+M_{A',1})\Delta t_1}$$

and

$$N_{A,2} = N_{A-1,1}e^{-(F_{A-1,1}+M_{A-1,1})\Delta t_1}.$$

For the FRATIO method all the cohorts in the terminal time must be specified. In addition, the population abundance for the plus group in the terminal time must be specified. Solve for $F_{(A-1)',T-1}$ using $C_{(A-1)',T-1}$ and $N_{A',T}$ in the catch equation. Then

$$F_{A,T-1} = F_{(A-1)',T-1}\left(C_{A',T-1} + R_{t'} C_{A,T-1}\right) \Big/ R_{t'} C_{(A-1)',T-1}$$

where $R_{t'}$ is an F ratio which may be assigned or estimated. The ratio may be specified for each time period but typically a common ratio is specified for blocks of time periods. Now

$$N_{A,T-1} = C_{A,T-1}\left(F_{A,T-1} + M_{A,T-1}\right) \Big/ F_{A,T-1}\left(1 - e^{-(F_{A,T-1}+M_{A,T-1})\Delta t_j}\right)$$

Also $F_{A',T-1} = R_{t'} F_{A,T-1}$ therefore $N_{A',T-1}$ can be calculated in a similar manner.

Both methods of incorporating a plus group were explored for the 3NO cod ADAPT. The 'first' method allowed the model formulation to be setup identically to the baseline model run (i.e. estimating age 12 during the moratorium period, and calculating F at age 12 for years prior to the moratorium). The difference is that this plus group run requires information on the 13+ group in the first year of the time series (1959). Options for providing this information include assigning a value for N, allowing the model to estimate N, or calculating F based on the F's at age for younger ages. All of these options were investigated thoroughly and either resulted in models that failed to converge, or resulted in extreme values in the F's for the age 13+ group in several years prior to the moratorium (i.e. F=100). It is possible that the F=100 value may represent a code within the ADAPT software to indicate a calculation error but we could not find details of this in the software documentation.

The 'Fratio' method would not converge for an ADAPT formulation that included an age 13+ group because of all the zeroes in the catch-at-age above age 10 since 1994 (i.e. the moratorium period). To work around this issue, the catch numbers at age were summed across ages 10 to 13+ to come up with a 10+ group. The 'Baseline' run was compared to runs that included a 10+ group and two different Fratios. Fratio=0.5 or Fratio=1.0 for the 10+ group. In a model run referred to as "Age10plus Fratio_05" (Table 4, Fig. 17) the Fratio on the plus-group was set at 1 for the directed fishery period (1959-1993) and at 0.5 for the moratorium period (1994-2017). In a second model run, referred to as "Age10plus Fratio_1" the Fratio on the plus-group was set at 1 for the entire time series (Table 5, Fig. 18).

Both of the 10+ group model formulations resulted in a poor fit to the plus-group and a large increase in overall mean square error relative to the "Baseline" run, suggesting that these formulations are not suitable for the assessment of this stock.

Recommendation: STACFIS recommends examining the selectivity pattern (i.e. flat-topped vs. dome-shaped)

An examination of the F estimates at age for the "Baseline" run suggests that selectivity was flat-topped during the directed fishery but was clearly dome-shaped during the moratorium period (Fig. 22).

Discussion

The analyses presented here attempted to address recommendations made by STACFIS with respect to the ADAPT model formulation for the assessment of cod in Divs. 3NO. First, a model run was performed that was identical to the accepted assessment model formulation but also included data from the EU-Spain RV survey of the NAFO Regulatory Area as an additional tuning index. The inclusion of this survey resulted in poorer model fit, with a higher mean square error and an increase in the relative error for estimates of catchability. These results mirror those of Morgan (2006), who previously examined the inclusion of the EU-Spain survey for this stock. The 2006 cohort tracked relatively strong in all three surveys (Canadian Spring, Canadian Autumn, EU-Spain) (Fig. 12, Fig. 13). However, that year class shows up particularly strong in the EU-Spain survey. It is difficult to fully understand to what extent any trends in the EU-Spain survey are related to localized changes in the portion of the population within the NRA or whether trends (all or partially) are related to fish movement in and out of the NRA.

Based on some fit issues related to the first five years of the Autumn survey in the accepted assessment model run, it was suggested to explore removing these five years from the assessment input data. However, removing these first five years of data failed to improve the resulting overall model fit / residual patterns.

After the last assessment of Divs. 3NO cod it was considered a priority to investigate the potential inclusion of a plus group in the catch-at-age. The main reason for this recommendation was the fact that the relatively strong 2006 year class was about to leave the virtual population, which is currently ages 2-12 in the accepted assessment model. Concern over falsely removing this year class from the population was used as justification for not performing stock projections at that time (Rideout et al., 2018). The 2006 year class left the virtual population in 2019, perhaps raising the priority of this research request even higher for the 2021 assessment. Unfortunatley, numerous attempts here to incorporate a plus group within the ADAPT framework-based assessment of this stock all produced unsatisfactory results. Both mechanisms within the ADAPT framework for incorporating plus-groups were explored. Several model formulations with the 'first' method resulted in the failure of models to converge or in thus far irreconcilable computational issues with the model outputs. Model formulations using various F-ratios to incorporate a plus-group resulted in poor model fits to the plus group and large increases in overall mean square error. It is suggested that neither of these plus-group formulations is a suitable replacement to the accepted assessment model. With respect to the 2021 assessment for this stock, a decision will have to be made regarding whether or not to accept the baseline assessment model (which does not include a plus-group) or to reject the assessment model and base the science advice on survey indices. If the inclusion of a plus-group is still considered a priority for the assessment of this stock then consideration should be given to exploring other modelling options beyond ADAPT.

The final recommendation was to examine the selectivity pattern for 3NO cod, something that was not explicitly contained in the last assessment document. An examination of fishing mortality at age from the baseline model runs suggested that selectivity during the moratorium period (1994-present) was dome-shaped.

None of the ADAPT model formulations examined here provided a meaningful improvement over the longstanding model formulation. It could also be noted that none of them suggested meaningful differences in stock trends than those estimated by the baseline model (Figs. 19-21).

References

Gavaris, S. (1988) An adaptive framework for the estimation of population size. CAFSAC Res Doc No. 88/29.

González Troncoso, D., Garrido, I., Gago, A., Román, E., Ramilo, L. (2020) Results for Greenland halibut, American plaice and Atlantic cod of the Spanish survey in NAFO Div. 3NO for the period 1997-2019. NAFO Scientifi Council Report No. 20/008, 44 pp.

Morgan, J. (2006) A comparison of Divisions 3NO Cod ADAPT results using different tuning indices. NAFO SCR Doc. No. 06/36, 12 pp.

Rideout, R.M., Ings, D.W. (2020) Temporal And Spatial Coverage Of Canadian (Newfoundland And Labrador Region) Spring And Autumn Multi-Species RV Bottom Trawl Surveys, With An Emphasis On Surveys Conducted In 2019. NAFO Scientific Council Research Document No. 20/002, 50 pp.

Rideout, R.M., Rogers, B., Ings, D.W. (2018) An Assessment of the Cod Stock in NAFO Divisions 3NO. NAFO Scientific Council Research Document No. 18/028, 52 p.

Figure 1. Catch numbers at age for cod in Divs. 3NO (common scale across all plots). Note that only a portion of the time series is shown. The green area of the plot highlights the range of data used as input for the 3NO cod VPA. The red bars highlight the relatively strong 2006 year class.

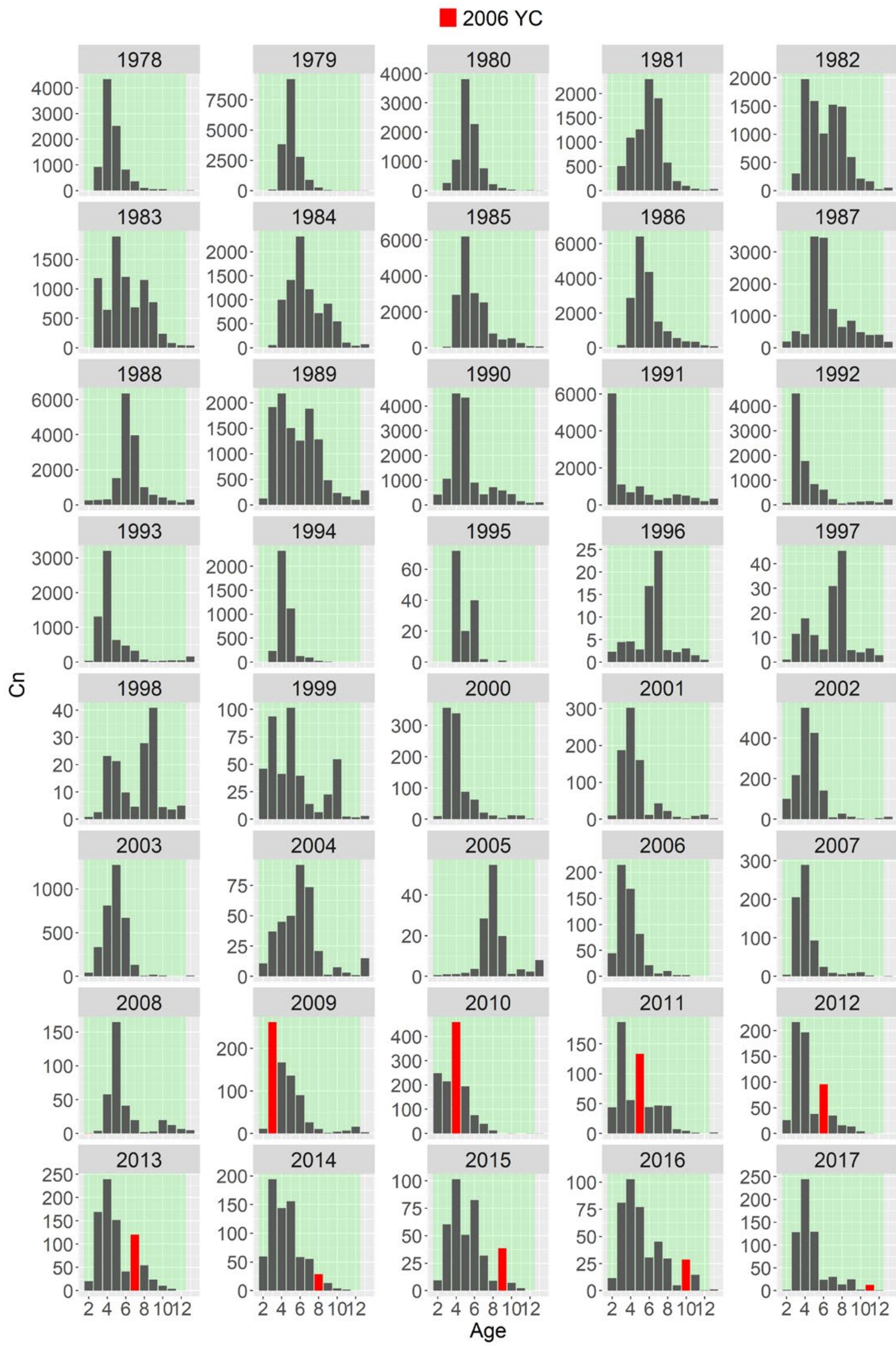


Figure 2. Catch numbers at age for cod in Divs. 3NO (plots scaled independently). Note that only a portion of the time series is shown. The green area of the plot highlights the range of data used as input for the 3NO cod VPA. The red bars highlight the relatively strong 2006 year class.

Figure 3. MNPT for cod from the Canadian Spring RV survey (common scale across all plots). The green portion of the plot highlights the range of data used as input for the 3NO cod VPA. The red bars highlight the relatively strong 2006 year class.

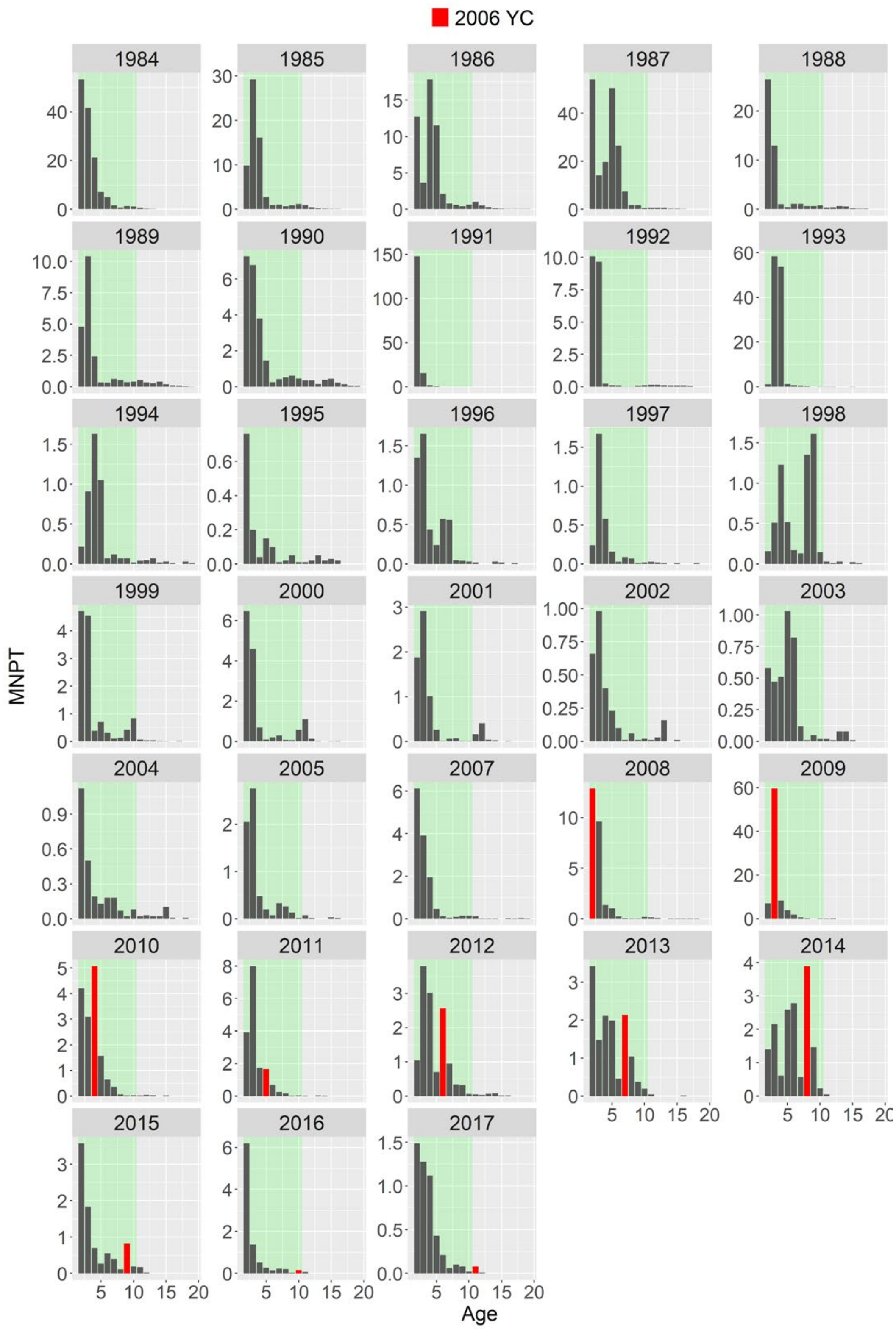


Figure 4. MNPT for cod from the Canadian Spring RV survey (plots scaled independently). The green portion of the plot highlights the range of data used as input for the 3NO cod VPA. The red bars highlight the relatively strong 2006 year class.

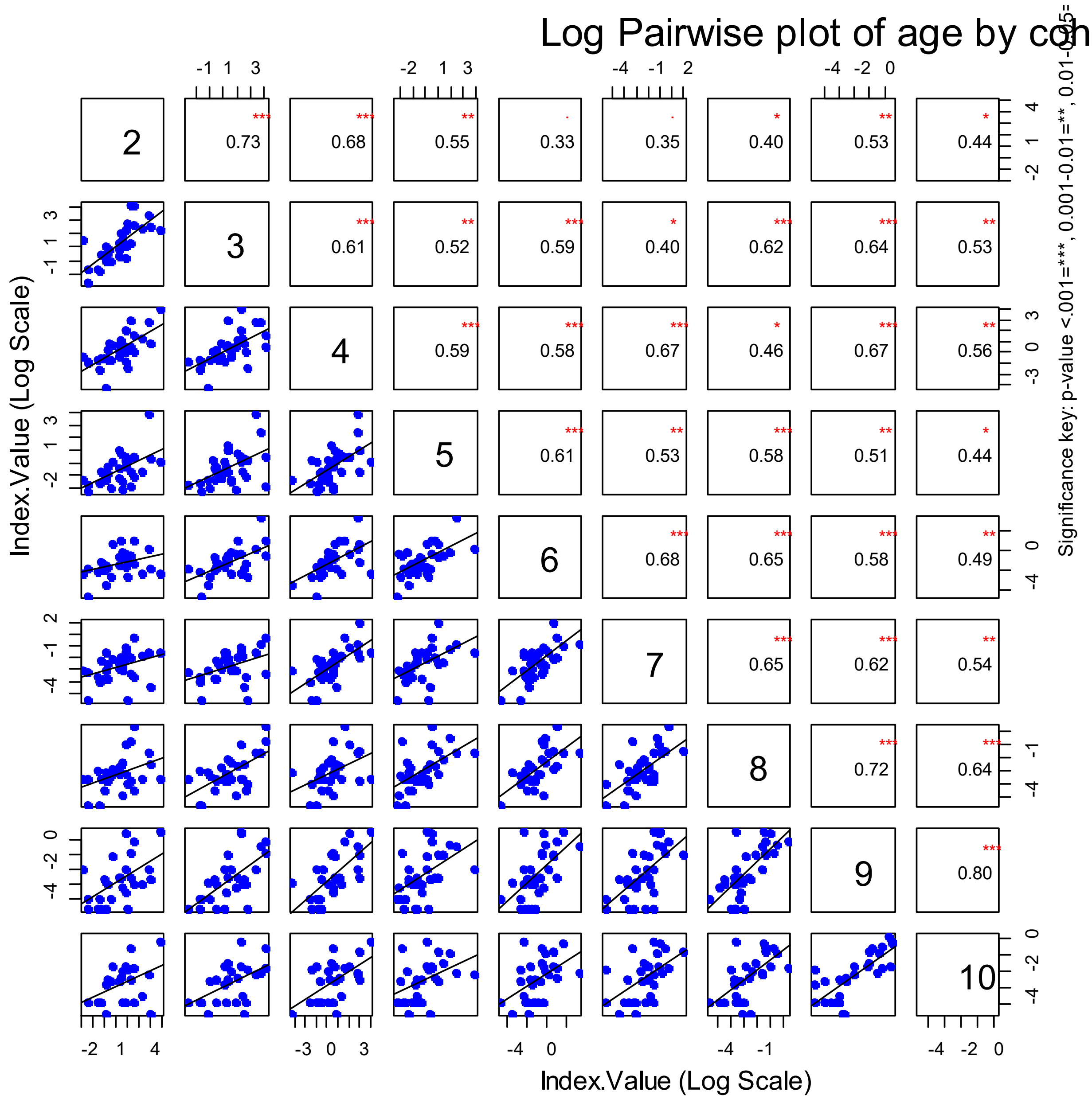


Figure 5. Internal consistency plot for Divs. 3NO cod in the Canadian Spring survey.

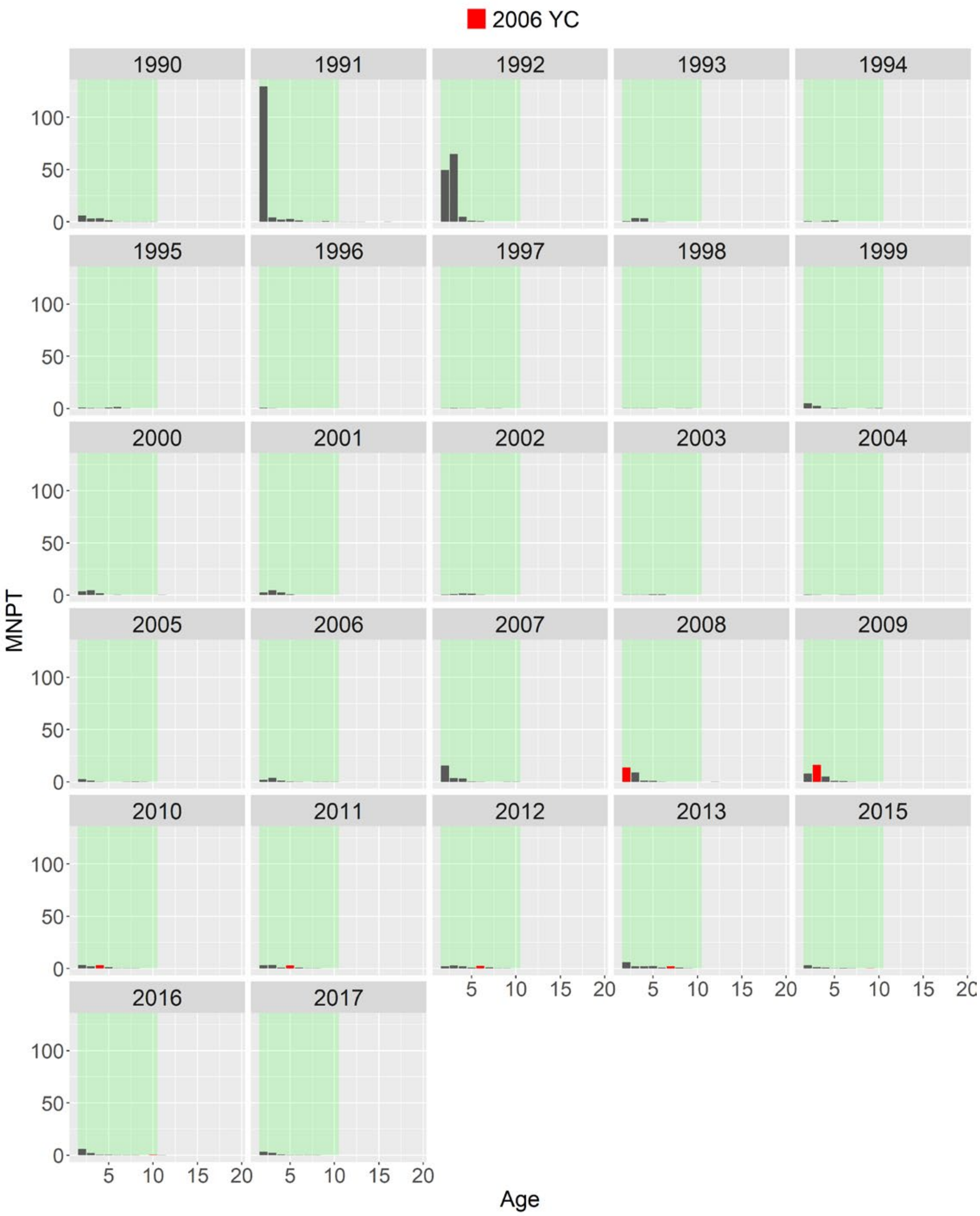


Figure 6. MNPT for cod from the Canadian Autumn RV survey (common scale across all plots). The green portion of the plot highlights the range of data used as input for the 3NO cod VPA. The red bars highlight the relatively strong 2006 year class.

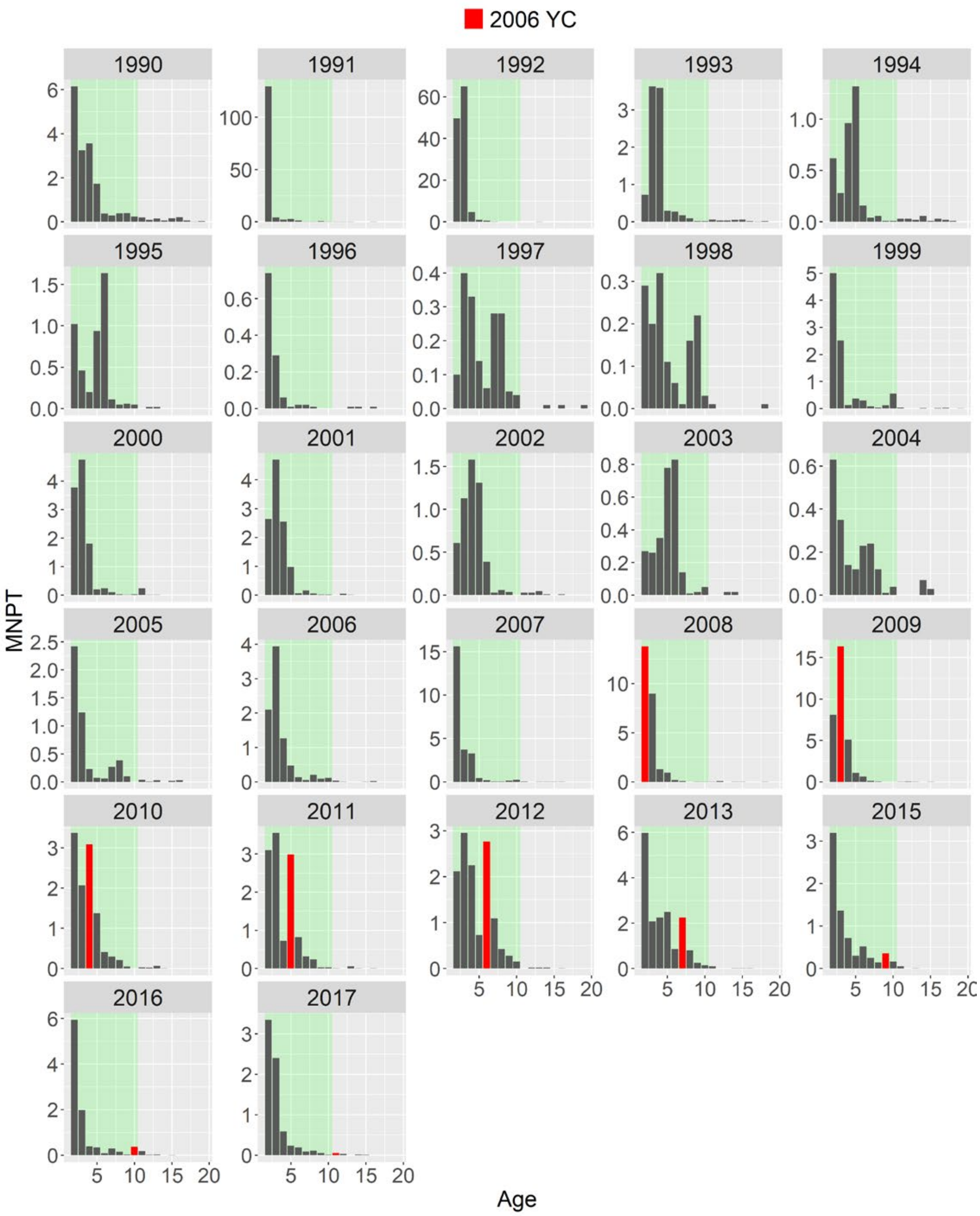


Figure 7. MNPT for cod from the Canadian Autumn RV survey (plots scaled independently). The green portion of the plot highlights the range of data used as input for the 3NO cod VPA. The red bars highlight the relatively strong 2006 year class.

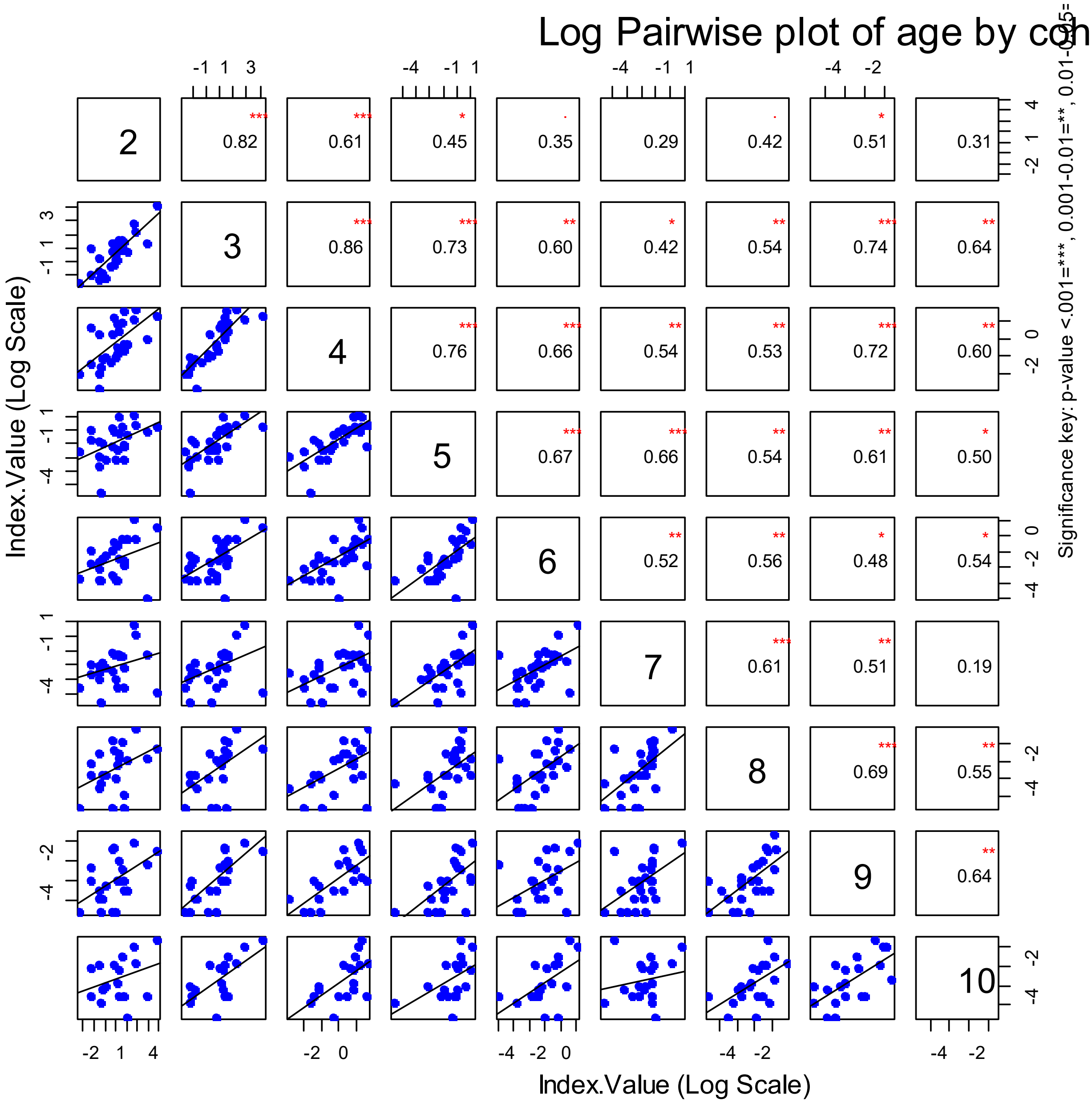


Figure 8. Internal consistency plot for Divs. 3NO cod in the Canadian Autumn survey.

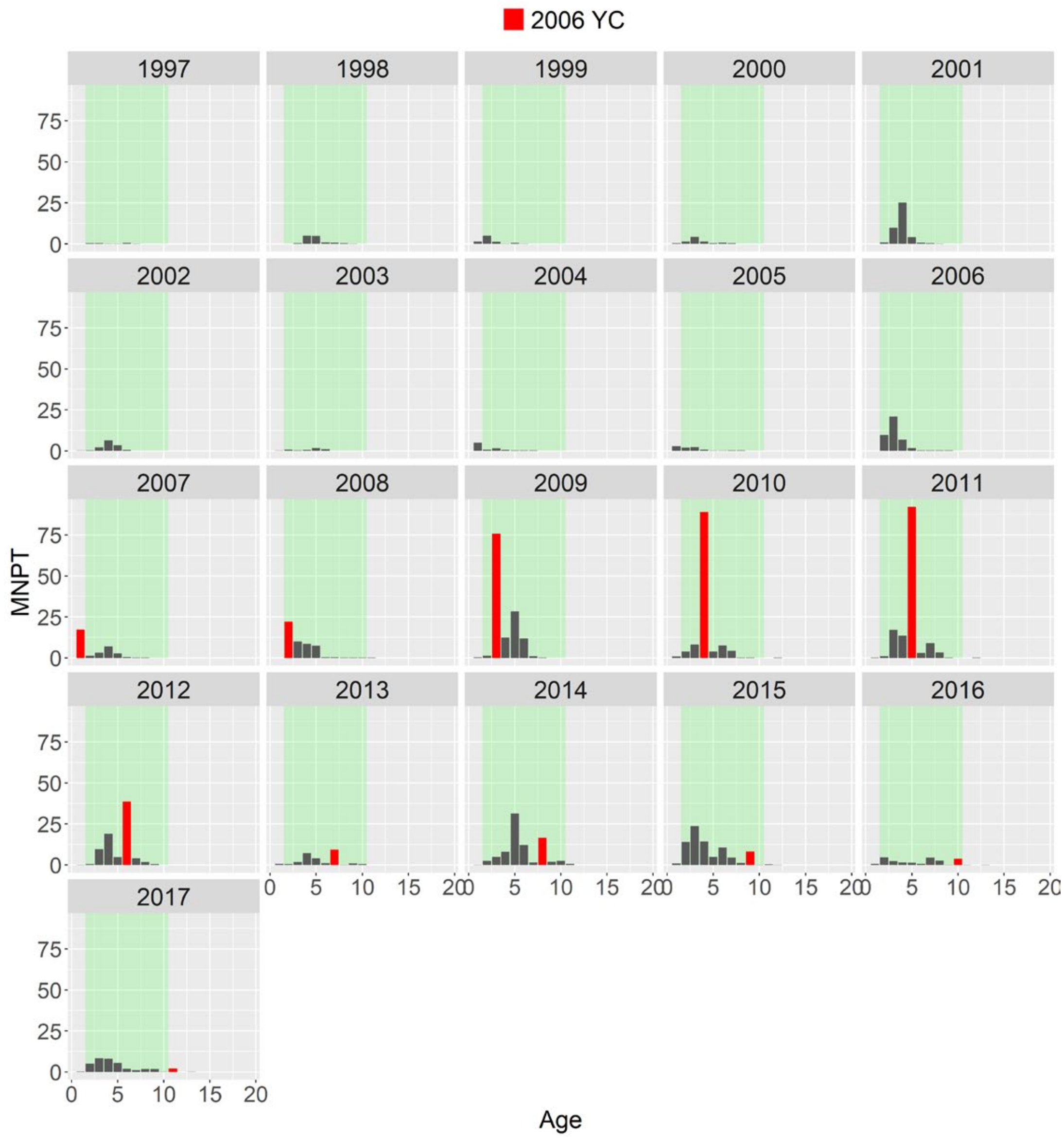


Figure 9. MNPT for cod from the EU-Spain RV survey (common scale across all plots). This survey is not currently included as a tuning index in the VPA. The green portion of the plot highlights the age range of data used from the Canadian RV surveys as input for the 3NO cod VPA. The red bars highlight the relatively strong 2006 year class.

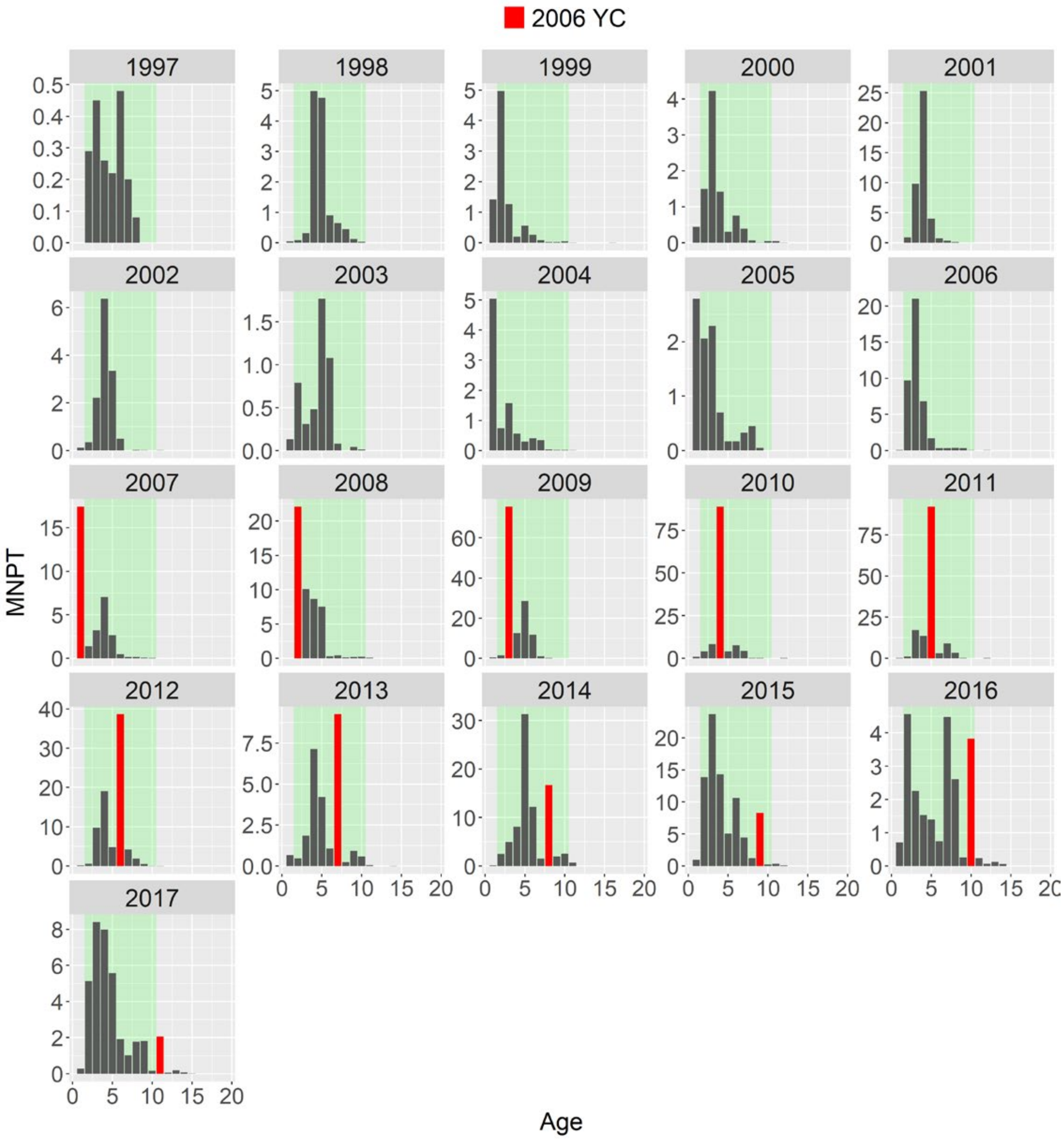


Figure 10. MNPT for cod from the EU-Spain RV survey (plots scaled independently). This survey is not currently included as a tuning index in the VPA. The green portion of the plot highlights the age range of data used from the Canadian RV surveys as input for the 3NO cod VPA. The red bars highlight the relatively strong 2006 year class.

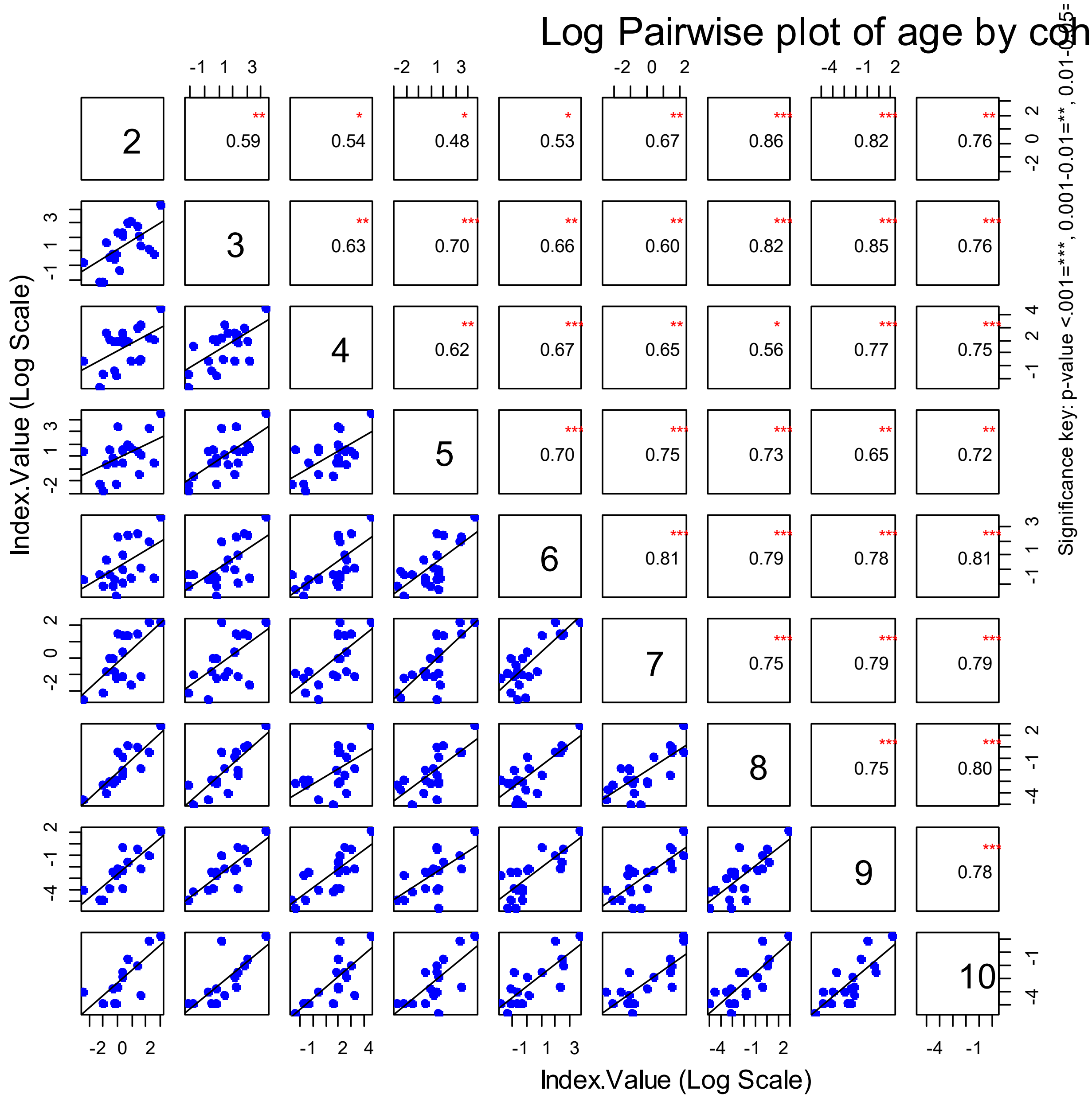


Figure 11. Internal consistency plot for Divs. 3NO cod in the EU-Spain survey.

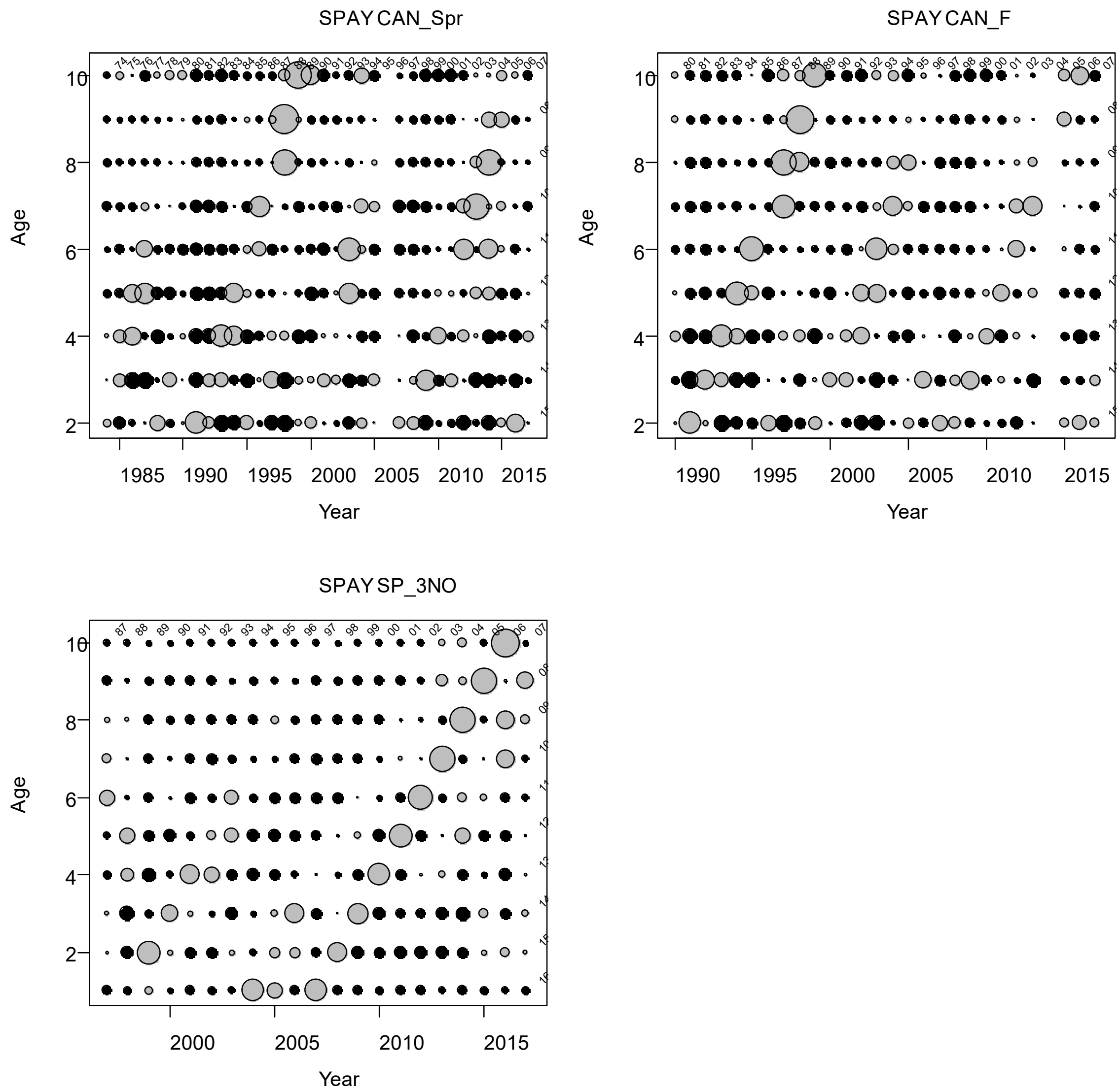


Figure 12. Plots of standardized proportion by age across years (standardized at each age to have a mean of 0 and a variance of 1) for the Canadian Spring (top left), Canadian Autumn (top right), and EU-Spain surveys. A large bubble size implies a large anomaly. Black symbols represent negative anomalies. Grey symbols represent positive anomalies.

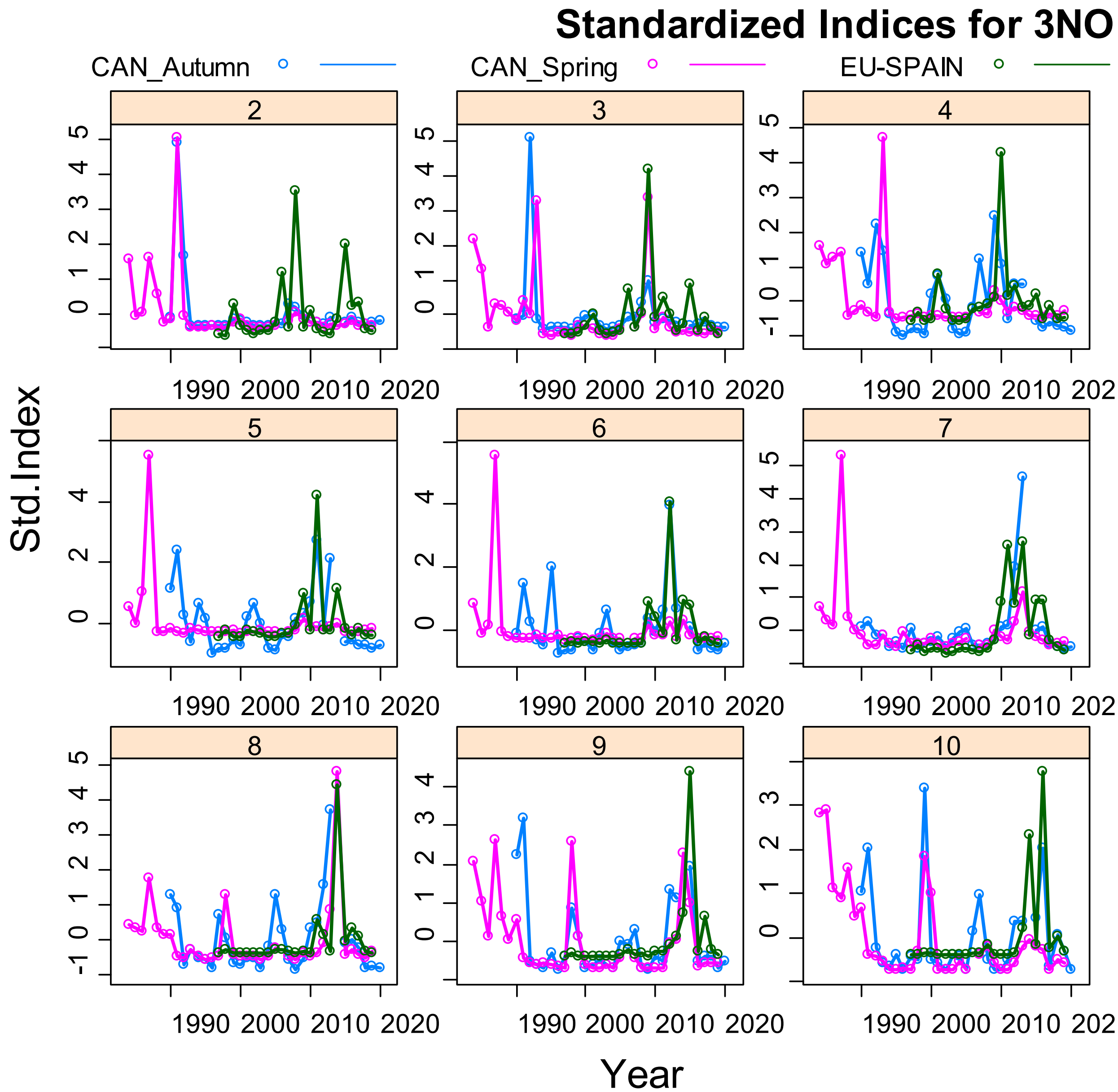


Figure 13. Comparison of standardized indices at age for Divs. 3NO cod from the Canadian Spring, Canadian Autumn, and EU-Spain surveys.

Table 1. Model statistics for the 'Baseline' ADAPT run.

"BASELINE" Run

APPROXIMATE STATISTICS ASSUMING LINEARITY NEAR SOLUTION
ORTHOGONALITY OFFSET......... 0.000155
MEAN SQUARE RESIDUALS 0.610582

Parameter	Est.	Std. Err.	Rel. Err.	Bias	Rel. Bias
N[1994 12]	1.39E2	8.53E1	0.612	1.62E1	0.116
N[1995 12]	7.05E1	3.06E1	0.434	5.35E0	0.076
N[1996 12]	4.03E1	1.36E1	0.337	2.11E0	0.052
N[1997 12]	8.35E1	2.58E1	0.309	3.87E0	0.046
N[1998 12]	1.13E2	3.67E1	0.324	5.73E0	0.051
N[1999 12]	5.69E1	1.92E1	0.337	2.98E0	0.052
N[2000 12]	6.11E1	1.80E1	0.295	2.54E0	0.042
N[2001 12]	5.31E2	1.44E2	0.272	1.90E1	0.036
N[2002 12]	2.50E2	6.71E1	0.268	8.85E0	0.035
N[2003 12]	3.54E1	9.48E0	0.268	1.22E0	0.035
N[2004 12]	4.32E1	1.23E1	0.285	1.59E0	0.037
N[2005 12]	7.58E1	2.20E1	0.290	2.85E0	0.038
N[2006 12]	8.25E1	2.55E1	0.309	3.42E0	0.041
N[2007 12]	2.00E1	6.11E0	0.306	8.79Eý1	0.044
N[2008 12]	1.27E2	4.06E1	0.320	5.87E0	0.046
N[2009 12]	2.76E2	8.54E1	0.309	1.22E1	0.044
N[2010 12]	1.93E2	5.91E1	0.306	8.46E0	0.044
N[2011 12]	5.39E1	1.58E1	0.294	2.30E0	0.043
N[2012 12]	3.51E1	1.10E1	0.313	1.61E0	0.046
N[2013 12]	6.29E1	1.71E1	0.272	2.26E0	0.036
N[2014 12]	1.32E2	3.50E1	0.265	4.57E0	0.035
N[2015 12]	4.17E2	1.03E2	0.247	1.33E1	0.032
N[2016 12]	4.50E2	1.10E2	0.244	1.44E1	0.032
N[2017 12]	9.62E2	2.19E2	0.228	2.81E1	0.029
N[2018 3]	1.88E3	1.07E3	0.569	3.17E2	0.168
N[2018 4]	2.23E3	9.29E2	0.417	2.04E2	0.092
N[2018 5]	1.12E3	4.04E2	0.362	7.60E1	0.068
N[2018 6]	4.89E2	1.73E2	0.353	3.08E1	0.063
N[2018 7]	5.21E2	1.68E2	0.323	2.77E1	0.053
N[2018 8]	2.23E2	7.28E1	0.326	1.15E1	0.052
N[2018 9]	6.05E2	1.71E2	0.282	2.48E1	0.041
N[2018 10]	6.50E2	1.64E2	0.252	2.23E1	0.034
N[2018 11]	2.28E2	5.62E1	0.246	7.28E0	0.032
N[2018 12]	1.54E3	3.52E2	0.229	4.50E1	0.029
q ID#[1]	1.06Eý3	1.55Eý4	0.146	3.59Eý6	0.003
q ID#[2]	1.39Eý3	2.03Eý4	0.146	5.10Eý6	0.004
q ID#[3]	7.19Eý4	1.06Eý4	0.147	3.13Eý6	0.004
q ID#[4]	4.99Eý4	7.52Eý5	0.151	2.66Eý6	0.005
q ID#[5]	3.49Eý4	5.40Eý5	0.155	2.22Eý6	0.006
q ID#[6]	3.37Eý4	5.34Eý5	0.159	2.64Eý6	0.008
q ID#[7]	3.18Eý4	5.17Eý5	0.163	3.06Eý6	0.010
q ID#[8]	3.08Eý4	5.11Eý5	0.166	3.53Eý6	0.011
q ID#[9]	3.77Eý4	6.39Eý5	0.169	5.27Eý6	0.014
q ID#[10]	1.16Eý3	1.90Eý4	0.164	6.15Eý6	0.005
q ID#[11]	1.16Eý3	1.90Eý4	0.164	6.57Eý6	0.006
q ID#[12]	8.06Eý4	1.35Eý4	0.168	5.52Eý6	0.007
q ID#[13]	6.77Eý4	1.17Eý4	0.173	5.59Eý6	0.008
q ID#[14]	5.43Eý4	9.64Eý5	0.178	5.37Eý6	0.010
q ID#[15]	3.79Eý4	6.96Eý5	0.184	4.68Eý6	0.012
q ID#[16]	3.63Eý4	6.92Eý5	0.191	5.34Eý6	0.015
q ID#[17]	2.53Eý4	5.00Eý5	0.198	4.59Eý6	0.018
q ID#[18]	3.23Eý4	6.80Eý5	0.211	7.77Eý6	0.024
q ID#[19]	3.50Eý3	1.13Eý3	0.322	1.63Eý4	0.046
q ID#[20]	1.84Eý3	5.89Eý4	0.321	8.48Eý5	0.046
q ID#[21]	1.32Eý3	4.27Eý4	0.322	6.16Eý5	0.047
q ID#[22]	1.08Eý3	3.48Eý4	0.324	4.93Eý5	0.046
q ID#[23]	7.80Eý4	2.55Eý4	0.327	3.49Eý5	0.045
q ID#[24]	5.63Eý4	1.87Eý4	0.333	2.60Eý5	0.046
q ID#[25]	4.41Eý4	1.49Eý4	0.337	2.18Eý5	0.049
q ID#[26]	2.79Eý4	9.58Eý5	0.343	1.53Eý5	0.055
q ID#[27]	2.44Eý4	8.59Eý5	0.352	1.59Eý5	0.065

"BASELINE" Run

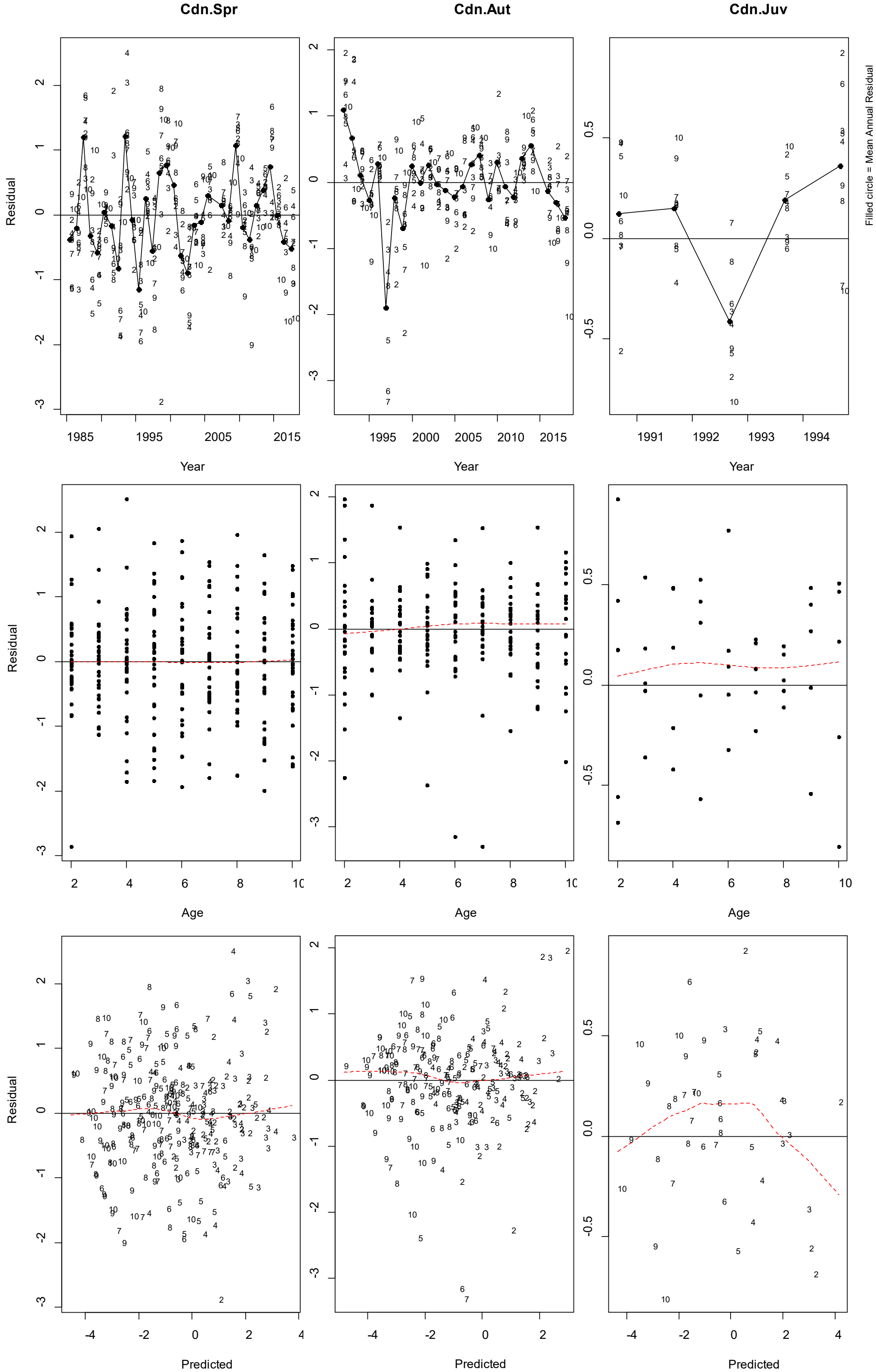


Figure 14. Plots of residuals, model fit, and survey q's for the "Baseline" ADAPT run (continued on next page).

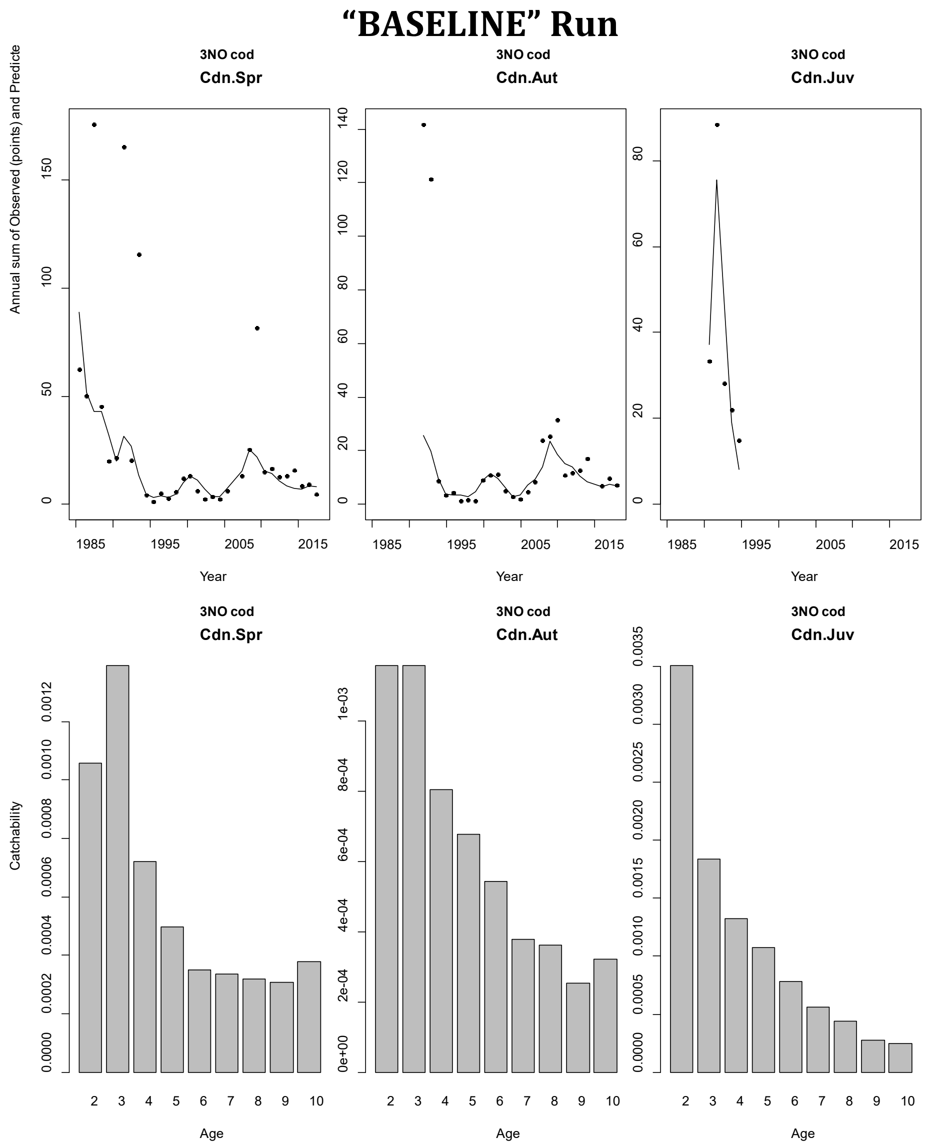


Figure 14. (continued) Plots of residuals, model fit, and survey q's for the "Baseline" ADAPT run.

Table 2. Model statistics for the 'Spain' ADAPT run.

"Spain" Run
APPROXIMATE STATISTICS ASSUMING LINEARITY NEAR SOLUTION
ORTHOGONALITY OFFSET......... 0.000341
MEAN SQUARE RESIDUALS 0.712875

Parameter	Est.	Std. Err.	Rel. Err.	Bias	Rel. Bias
---------	---------	---------	---------	---------	---------
N[1994 12]	1.43E2	9.35E1	0.652	1.93E1	0.135
N[1995 12]	7.21E1	3.35E1	0.465	6.39E0	0.089
N[1996 12]	4.12E1	1.49E1	0.361	2.53E0	0.061
N[1997 12]	8.57E1	2.83E1	0.331	4.66E0	0.054
N[1998 12]	1.17E2	4.06E1	0.346	6.92E0	0.059
N[1999 12]	5.87E1	2.12E1	0.360	3.58E0	0.061
N[2000 12]	6.31E1	1.91E1	0.304	2.87E0	0.045
N[2001 12]	3.62E2	1.05E2	0.289	1.45E1	0.040
N[2002 12]	1.85E2	5.08E1	0.275	6.88E0	0.037
N[2003 12]	3.55E1	9.36E0	0.264	1.24E0	0.035
N[2004 12]	4.17E1	1.20E1	0.287	1.59E0	0.038
N[2005 12]	5.64E1	1.67E1	0.297	2.20E0	0.039
N[2006 12]	6.07E1	1.91E1	0.314	2.61E0	0.043
N[2007 12]	2.14E1	6.40E0	0.299	9.35Eý1	0.044
N[2008 12]	8.01E1	2.58E1	0.322	3.81E0	0.048
N[2009 12]	2.32E2	6.79E1	0.293	9.58E0	0.041
N[2010 12]	1.63E2	4.71E1	0.290	6.62E0	0.041
N[2011 12]	5.44E1	1.44E1	0.265	2.02E0	0.037
N[2012 12]	3.31E1	9.15E0	0.276	1.27E0	0.038
N[2013 12]	7.41E1	1.81E1	0.244	2.33E0	0.031
N[2014 12]	1.38E2	3.35E1	0.243	4.31E0	0.031
N[2015 12]	5.85E2	1.28E2	0.218	1.62E1	0.028
N[2016 12]	7.15E2	1.51E2	0.212	1.93E1	0.027
N[2017 12]	8.16E2	1.72E2	0.211	2.17E1	0.027
N[2018 3]	3.29E3	1.66E3	0.504	4.40E2	0.134
N[2018 4]	3.08E3	1.13E3	0.368	2.26E2	0.074
N[2018 5]	1.68E3	5.28E2	0.315	9.12E1	0.054
N[2018 6]	8.17E2	2.43E2	0.297	3.95E1	0.048
N[2018 7]	6.17E2	1.74E2	0.282	2.67E1	0.043
N[2018 8]	3.12E2	8.67E1	0.278	1.28E1	0.041
N[2018 9]	9.40E2	2.26E2	0.241	3.13E1	0.033
N[2018 10]	1.00E3	2.20E2	0.220	2.89E1	0.029
N[2018 11]	3.21E2	6.97E1	0.217	8.80E0	0.027
N[2018 12]	2.72E3	5.47E2	0.201	6.86E1	0.025
q ID#[1]	9.69Eý4	1.52Eý4	0.157	5.22Eý6	0.005
q ID#[2]	1.29Eý3	2.02Eý4	0.157	7.14Eý6	0.006
q ID#[3]	6.68Eý4	1.06Eý4	0.158	3.95Eý6	0.006
q ID#[4]	4.70Eý4	7.59Eý5	0.161	3.03Eý6	0.006
q ID#[5]	3.33Eý4	5.50Eý5	0.165	2.38Eý6	0.007
q ID#[6]	3.23Eý4	5.48Eý5	0.170	2.69Eý6	0.008
q ID#[7]	3.07Eý4	5.34Eý5	0.174	3.10Eý6	0.010
q ID#[8]	3.02Eý4	5.36Eý5	0.177	3.66Eý6	0.012
q ID#[9]	3.73Eý4	6.75Eý5	0.181	5.56Eý6	0.015
q ID#[10]	1.04Eý3	1.83Eý4	0.176	8.08Eý6	0.008
q ID#[11]	1.05Eý3	1.85Eý4	0.176	8.31Eý6	0.008
q ID#[12]	7.43Eý4	1.33Eý4	0.179	6.33Eý6	0.009
q ID#[13]	6.37Eý4	1.17Eý4	0.184	6.02Eý6	0.009
q ID#[14]	5.21Eý4	9.87Eý5	0.189	5.61Eý6	0.011
q ID#[15]	3.65Eý4	7.14Eý5	0.196	4.75Eý6	0.013
q ID#[16]	3.56Eý4	7.26Eý5	0.204	5.53Eý6	0.016
q ID#[17]	2.47Eý4	5.21Eý5	0.211	4.78Eý6	0.019
q ID#[18]	3.31Eý4	7.47Eý5	0.225	8.72Eý6	0.026
q ID#[19]	3.59Eý3	1.25Eý3	0.347	1.97Eý4	0.055
q ID#[20]	1.89Eý3	6.53Eý4	0.346	1.03Eý4	0.055
q ID#[21]	1.40Eý3	4.86Eý4	0.348	7.58Eý5	0.054
q ID#[22]	1.12Eý3	3.91Eý4	0.349	5.94Eý5	0.053
q ID#[23]	7.71Eý4	2.72Eý4	0.353	4.01Eý5	0.052
q ID#[24]	5.55Eý4	2.00Eý4	0.359	2.97Eý5	0.053
q ID#[25]	4.35Eý4	1.58Eý4	0.364	2.48Eý5	0.057
q ID#[26]	2.76Eý4	1.02Eý4	0.370	1.75Eý5	0.063
q ID#[27]	2.41Eý4	9.15Eý5	0.379	1.80Eý5	0.075

q ID#[28]	5.33Eý4	1.06Eý4	0.199	6.23Eý6	0.012
q ID#[29]	1.78Eý3	3.53Eý4	0.198	2.07Eý5	0.012
q ID#[30]	2.73Eý3	5.46Eý4	0.200	3.32Eý5	0.012
q ID#[31]	2.76Eý3	5.62Eý4	0.204	3.66Eý5	0.013
q ID#[32]	1.96Eý3	4.10Eý4	0.209	2.93Eý5	0.015
q ID#[33]	1.47Eý3	3.21Eý4	0.218	2.62Eý5	0.018
q ID#[34]	6.75Eý4	1.50Eý4	0.222	1.33Eý5	0.020
q ID#[35]	4.68Eý4	1.08Eý4	0.231	1.08Eý5	0.023
q ID#[36]	3.20Eý4	7.80Eý5	0.244	8.79Eý6	0.027

“Spain” Run

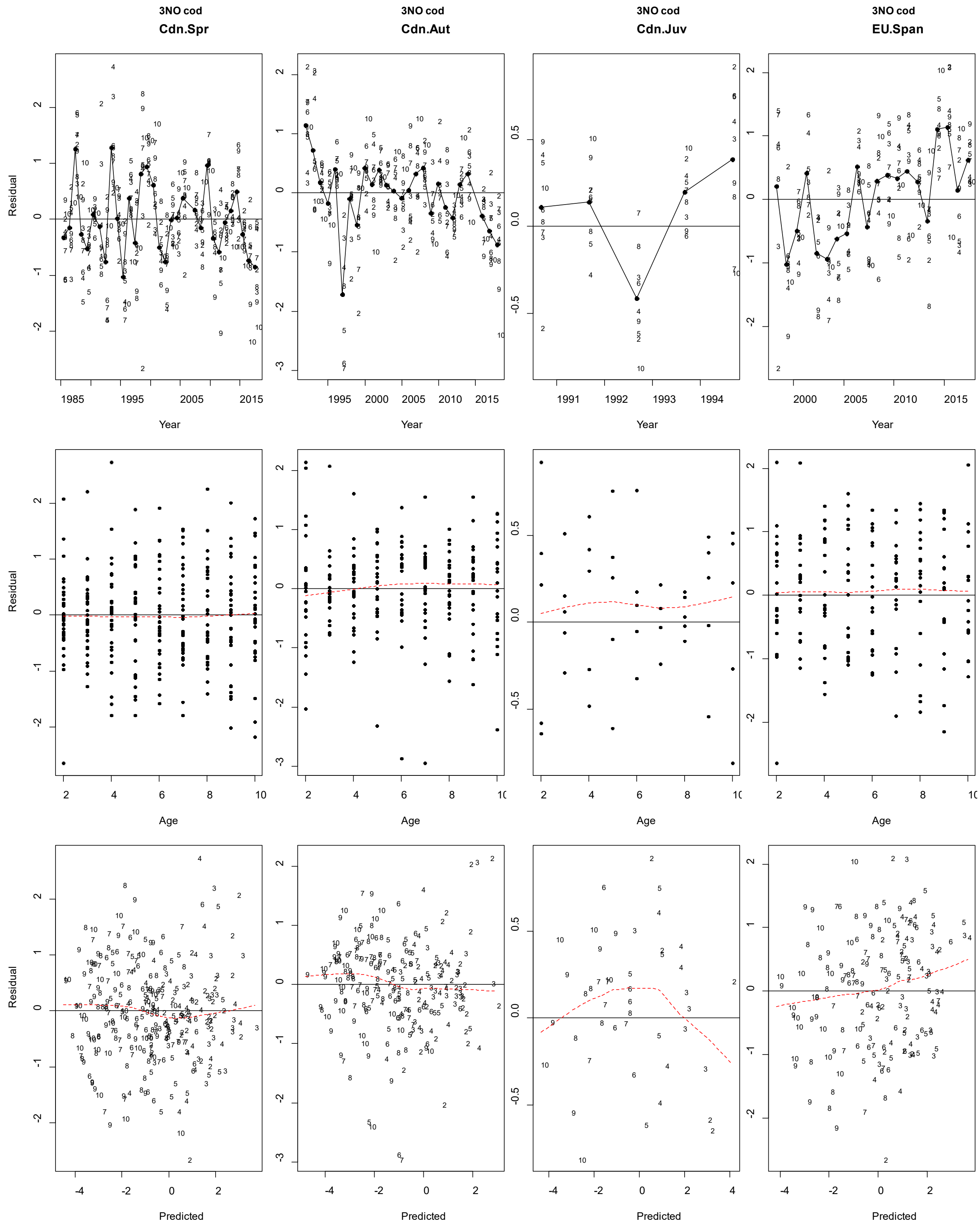


Figure 15. Plots of residuals, model fit, and survey q’s for the “Spain” ADAPT run (continued on next page).

“Spain” Run

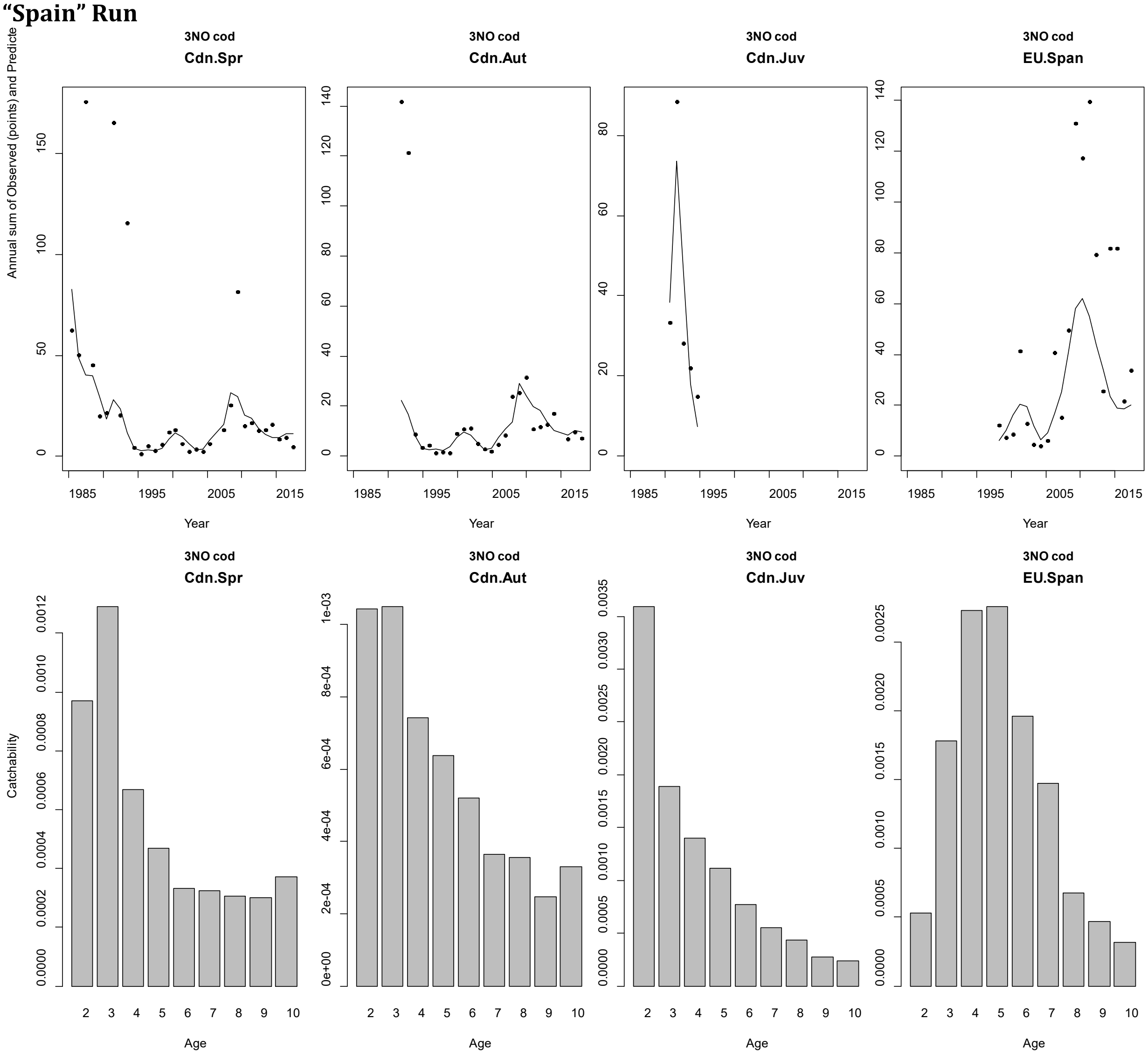


Figure 15. (continued) Plots of residuals, model fit, and survey q’s for the “Spain” ADAPT run.

Table 3. Model statistics for the 'Modified Fall' ADAPT run.

"Modified Fall" Run
APPROXIMATE STATISTICS ASSUMING LINEARITY NEAR SOLUTION
ORTHOGONALITY OFFSET......... 0.000177
MEAN SQUARE RESIDUALS 0.601759

Parameter	Est.	Std. Err.	Rel. Err.	Bias	Rel. Bias
N[1994 12]	9.04E1	8.68E1	0.960	2.17E1	0.241
N[1995 12]	8.18E1	4.36E1	0.533	9.15E0	0.112
N[1996 12]	4.15E1	1.73E1	0.417	3.31E0	0.080
N[1997 12]	9.03E1	3.21E1	0.356	5.71E0	0.063
N[1998 12]	1.18E2	4.29E1	0.364	7.70E0	0.065
N[1999 12]	6.58E1	2.33E1	0.354	3.98E0	0.060
N[2000 12]	6.81E1	2.08E1	0.305	3.14E0	0.046
N[2001 12]	5.87E2	1.66E2	0.282	2.32E1	0.039
N[2002 12]	3.01E2	8.16E1	0.271	1.13E1	0.037
N[2003 12]	4.38E1	1.18E1	0.269	1.59E0	0.036
N[2004 12]	5.38E1	1.49E1	0.277	1.99E0	0.037
N[2005 12]	9.72E1	2.70E1	0.278	3.60E0	0.037
N[2006 12]	1.06E2	3.13E1	0.297	4.29E0	0.041
N[2007 12]	2.45E1	7.48E0	0.306	1.09E0	0.044
N[2008 12]	1.59E2	4.94E1	0.311	7.23E0	0.045
N[2009 12]	3.50E2	1.05E2	0.300	1.52E1	0.043
N[2010 12]	2.45E2	7.31E1	0.298	1.07E1	0.043
N[2011 12]	6.74E1	1.96E1	0.290	2.89E0	0.043
N[2012 12]	4.36E1	1.33E1	0.305	1.98E0	0.046
N[2013 12]	7.87E1	2.09E1	0.266	2.84E0	0.036
N[2014 12]	1.65E2	4.30E1	0.260	5.79E0	0.035
N[2015 12]	5.15E2	1.26E2	0.245	1.68E1	0.033
N[2016 12]	5.51E2	1.33E2	0.242	1.81E1	0.033
N[2017 12]	1.17E3	2.66E2	0.228	3.55E1	0.030
N[2018 3]	2.31E3	1.31E3	0.567	3.88E2	0.168
N[2018 4]	2.66E3	1.10E3	0.415	2.44E2	0.092
N[2018 5]	1.35E3	4.83E2	0.357	9.17E1	0.068
N[2018 6]	5.86E2	2.03E2	0.347	3.67E1	0.063
N[2018 7]	6.49E2	2.05E2	0.317	3.41E1	0.053
N[2018 8]	2.83E2	8.95E1	0.317	1.43E1	0.050
N[2018 9]	7.53E2	2.08E2	0.277	3.08E1	0.041
N[2018 10]	7.99E2	2.00E2	0.250	2.79E1	0.035
N[2018 11]	2.85E2	6.94E1	0.244	9.30E0	0.033
N[2018 12]	1.87E3	4.28E2	0.229	5.69E1	0.030
q ID#[1]	9.61Eý4	1.42Eý4	0.148	2.92Eý6	0.003
q ID#[2]	1.27Eý3	1.87Eý4	0.148	4.20Eý6	0.003
q ID#[3]	6.51Eý4	9.72Eý5	0.149	2.62Eý6	0.004
q ID#[4]	4.46Eý4	6.83Eý5	0.153	2.22Eý6	0.005
q ID#[5]	3.10Eý4	4.87Eý5	0.157	1.80Eý6	0.006
q ID#[6]	2.97Eý4	4.79Eý5	0.161	2.08Eý6	0.007
q ID#[7]	2.80Eý4	4.62Eý5	0.165	2.41Eý6	0.009
q ID#[8]	2.72Eý4	4.57Eý5	0.168	2.86Eý6	0.011
q ID#[9]	3.35Eý4	5.76Eý5	0.172	4.64Eý6	0.014
q ID#[10]	8.48Eý4	1.57Eý4	0.185	6.75Eý6	0.008
q ID#[11]	9.59Eý4	1.78Eý4	0.185	8.21Eý6	0.009
q ID#[12]	6.32Eý4	1.20Eý4	0.189	6.37Eý6	0.010
q ID#[13]	5.26Eý4	1.03Eý4	0.195	6.43Eý6	0.012
q ID#[14]	4.01Eý4	8.01Eý5	0.200	5.73Eý6	0.014
q ID#[15]	2.88Eý4	5.86Eý5	0.204	4.73Eý6	0.016
q ID#[16]	2.89Eý4	6.09Eý5	0.211	5.48Eý6	0.019
q ID#[17]	2.01Eý4	4.38Eý5	0.218	4.32Eý6	0.021
q ID#[18]	2.64Eý4	6.17Eý5	0.233	6.89Eý6	0.026
q ID#[19]	3.33Eý3	1.07Eý3	0.321	1.51Eý4	0.045
q ID#[20]	1.77Eý3	5.64Eý4	0.319	7.90Eý5	0.045
q ID#[21]	1.28Eý3	4.10Eý4	0.321	5.72Eý5	0.045
q ID#[22]	1.05Eý3	3.37Eý4	0.322	4.54Eý5	0.043
q ID#[23]	7.53Eý4	2.45Eý4	0.326	3.11Eý5	0.041
q ID#[24]	5.46Eý4	1.82Eý4	0.334	2.31Eý5	0.042
q ID#[25]	4.33Eý4	1.48Eý4	0.341	2.02Eý5	0.047
q ID#[26]	2.76Eý4	9.71Eý5	0.352	1.54Eý5	0.056
q ID#[27]	2.48Eý4	9.14Eý5	0.368	1.86Eý5	0.075

"Modified Fall" Run

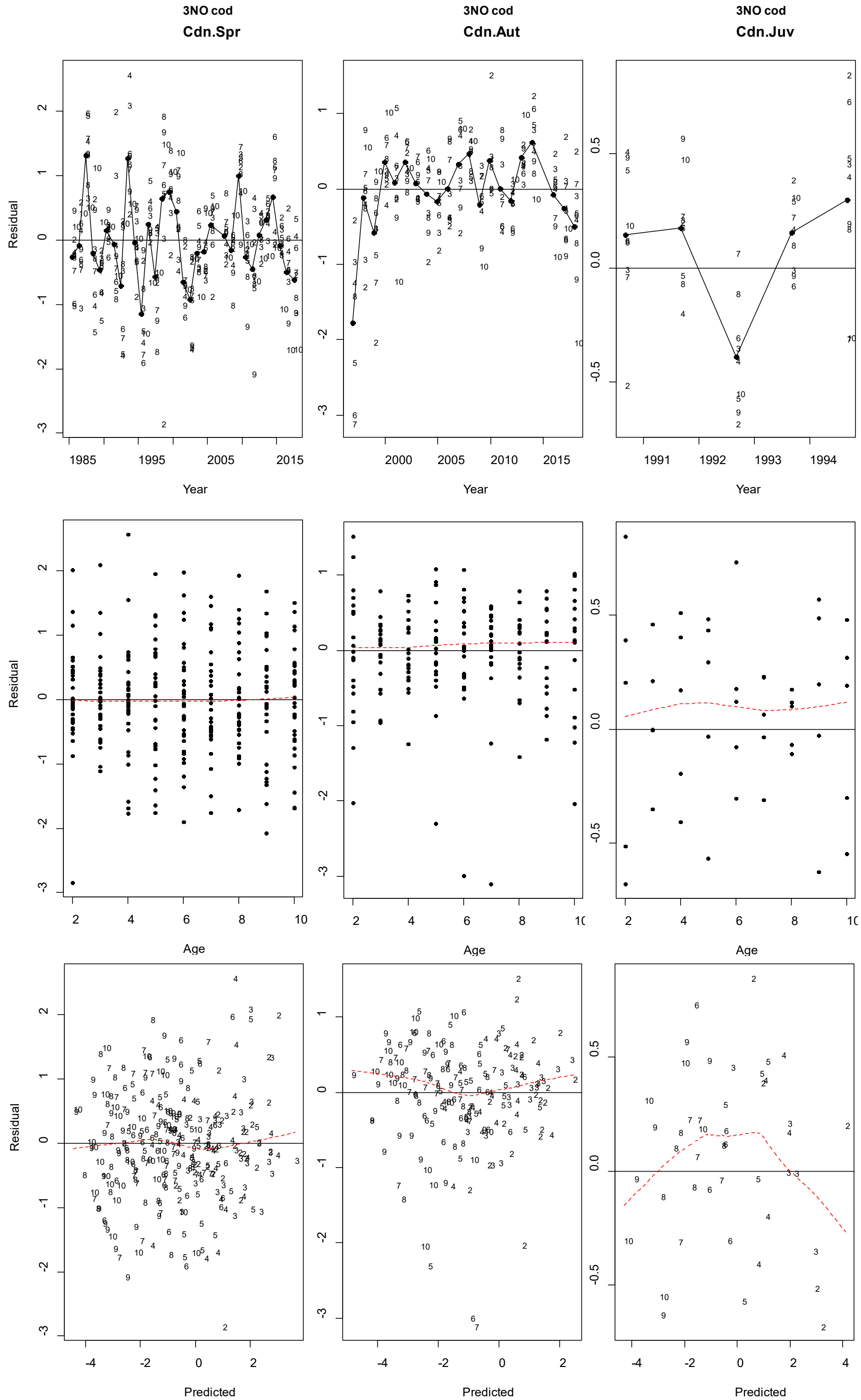


Figure 16. Plots of residuals, model fit, and survey q's for the "Modified Fall" ADAPT run (continued on next page).

"Modified Fall" Run

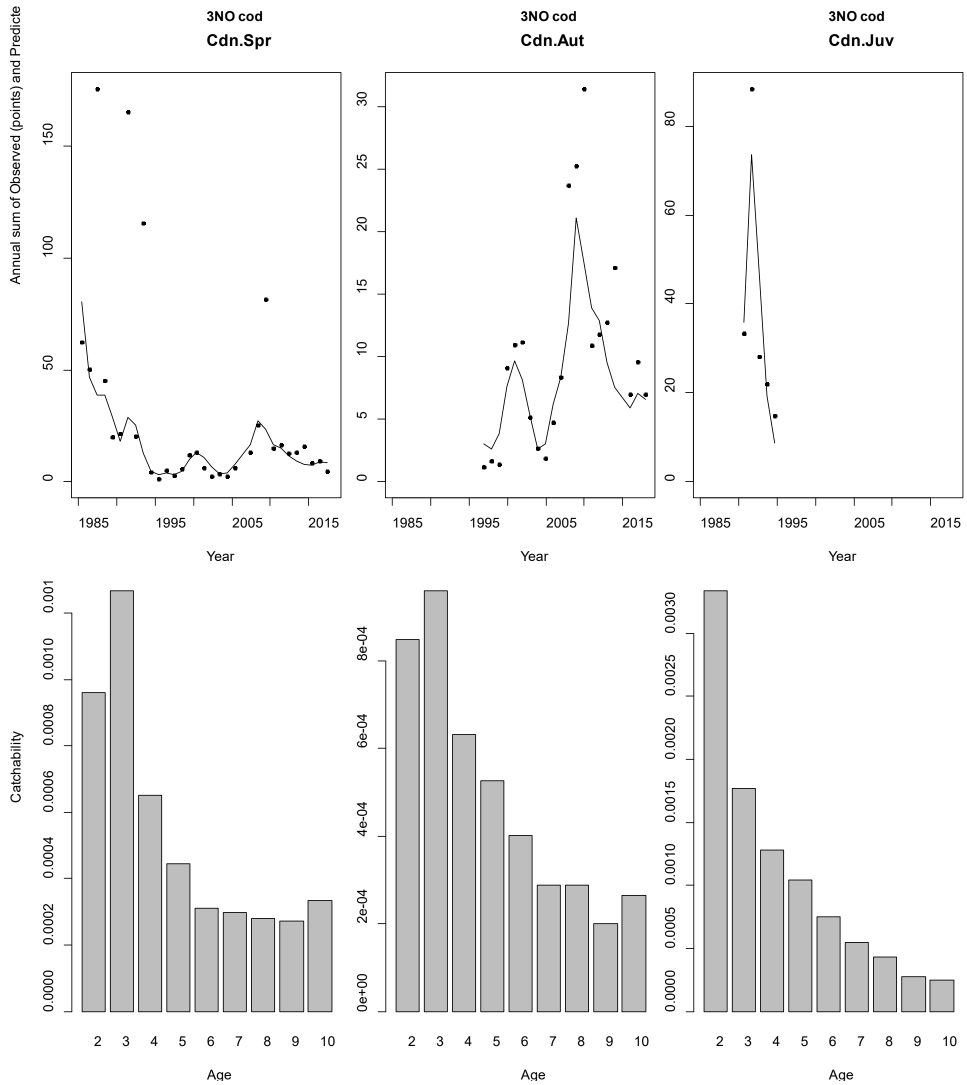


Figure 16. (continued) Plots of residuals, model fit, and survey q's for the "Modified Fall" ADAPT run.

Table 4. Model statistics for the 'Age10plus Fratio_05' ADAPT run.

"Age10plus Fratio_05" Run

APPROXIMATE STATISTICS ASSUMING LINEARITY NEAR SOLUTION

ORTHOGONALITY OFFSET......... 0.002132
MEAN SQUARE RESIDUALS 1.203797

Parameter	Est.	Std. Err.	Rel. Err.	Bias	Rel. Bias
N[2018 3]	1.45E6	1.16E6	0.798	4.64E5	0.319
N[2018 4]	1.68E6	9.87E5	0.589	2.83E5	0.169
N[2018 5]	7.99E5	4.15E5	0.519	9.86E4	0.123
N[2018 6]	3.23E5	1.67E5	0.516	3.75E4	0.116
N[2018 7]	3.13E5	1.50E5	0.479	3.07E4	0.098
N[2018 8]	1.19E5	6.01E4	0.503	1.21E4	0.102
N[2018 9]	3.19E5	1.35E5	0.424	2.40E4	0.075
N[2018 10]	2.57E6	4.41E5	0.171	3.29E4	0.013
q ID#[1]	1.33Eý3	2.62Eý4	0.197	2.08Eý5	0.016
q ID#[2]	1.77Eý3	3.48Eý4	0.196	2.84Eý5	0.016
q ID#[3]	9.68Eý4	1.90Eý4	0.197	1.64Eý5	0.017
q ID#[4]	7.18Eý4	1.43Eý4	0.199	1.31Eý5	0.018
q ID#[5]	5.36Eý4	1.07Eý4	0.200	1.02Eý5	0.019
q ID#[6]	5.51Eý4	1.11Eý4	0.202	1.09Eý5	0.020
q ID#[7]	5.83Eý4	1.19Eý4	0.204	1.17Eý5	0.020
q ID#[8]	6.81Eý4	1.40Eý4	0.206	1.39Eý5	0.020
q ID#[9]	2.37Eý4	4.88Eý5	0.206	4.83Eý6	0.020
q ID#[10]	1.54Eý3	3.38Eý4	0.220	3.12Eý5	0.020
q ID#[11]	1.59Eý3	3.49Eý4	0.219	3.33Eý5	0.021
q ID#[12]	1.22Eý3	2.68Eý4	0.220	2.75Eý5	0.023
q ID#[13]	1.12Eý3	2.50Eý4	0.223	2.67Eý5	0.024
q ID#[14]	9.90Eý4	2.22Eý4	0.225	2.42Eý5	0.024
q ID#[15]	7.55Eý4	1.72Eý4	0.228	1.93Eý5	0.026
q ID#[16]	8.12Eý4	1.89Eý4	0.233	2.15Eý5	0.026
q ID#[17]	7.77Eý4	1.86Eý4	0.240	2.15Eý5	0.028
q ID#[18]	3.41Eý4	8.55Eý5	0.251	1.04Eý5	0.031
q ID#[19]	4.09Eý3	1.83Eý3	0.448	4.08Eý4	0.100
q ID#[20]	2.10Eý3	9.40Eý4	0.448	2.09Eý4	0.100
q ID#[21]	1.65Eý3	7.38Eý4	0.448	1.64Eý4	0.100
q ID#[22]	1.28Eý3	5.75Eý4	0.448	1.28Eý4	0.100
q ID#[23]	9.48Eý4	4.25Eý4	0.448	9.43Eý5	0.100
q ID#[24]	7.37Eý4	3.31Eý4	0.448	7.35Eý5	0.100
q ID#[25]	7.75Eý4	3.47Eý4	0.448	7.74Eý5	0.100
q ID#[26]	1.69Eý3	7.56Eý4	0.448	1.69Eý4	0.100
q ID#[27]	4.96Eý4	2.22Eý4	0.448	4.96Eý5	0.100

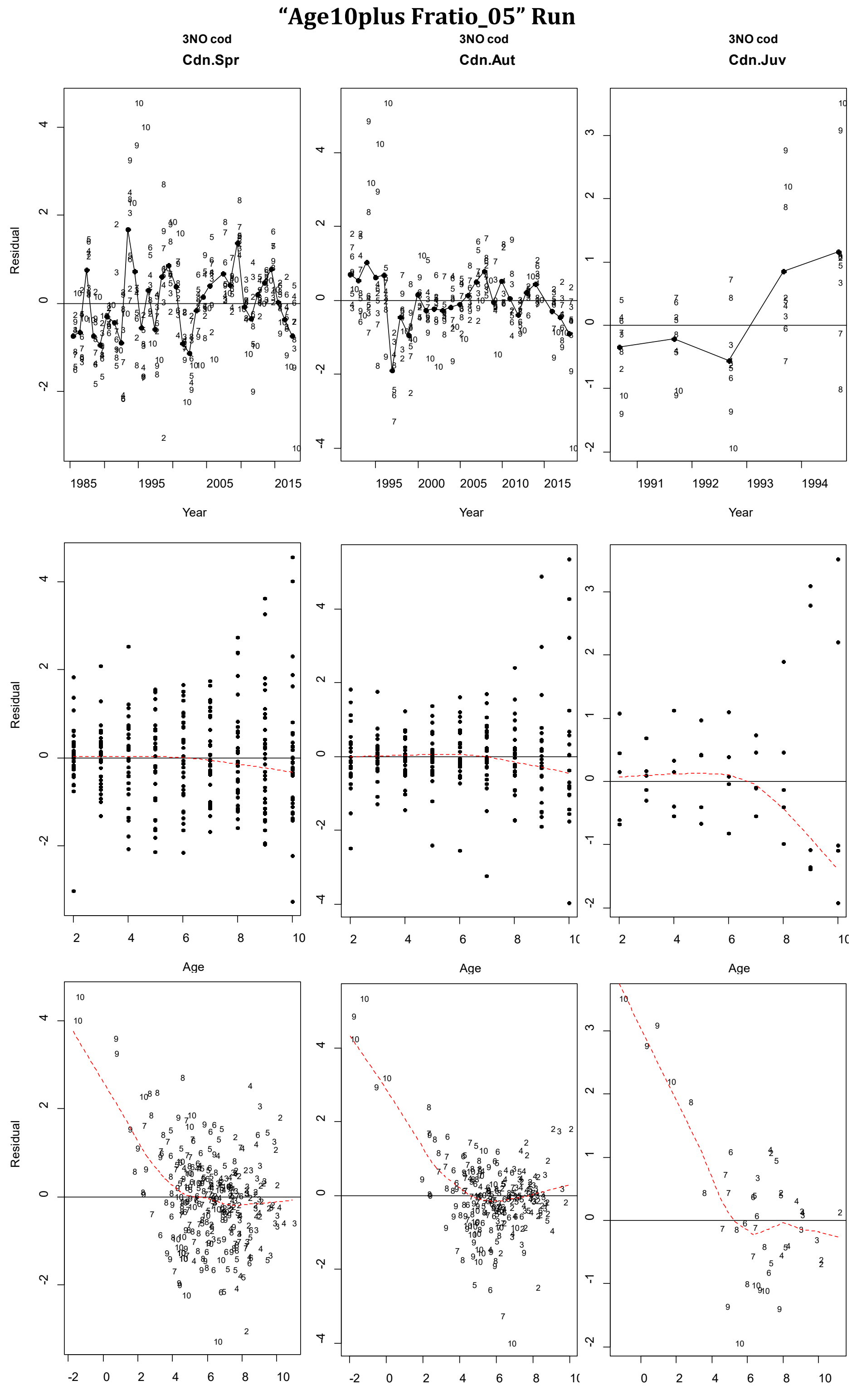


Figure 17. Plots of residuals, model fit, and survey q's for the "Age10plus Fratio_05" ADAPT run (continued on next page).

"Age10plus Fratio_05" Run

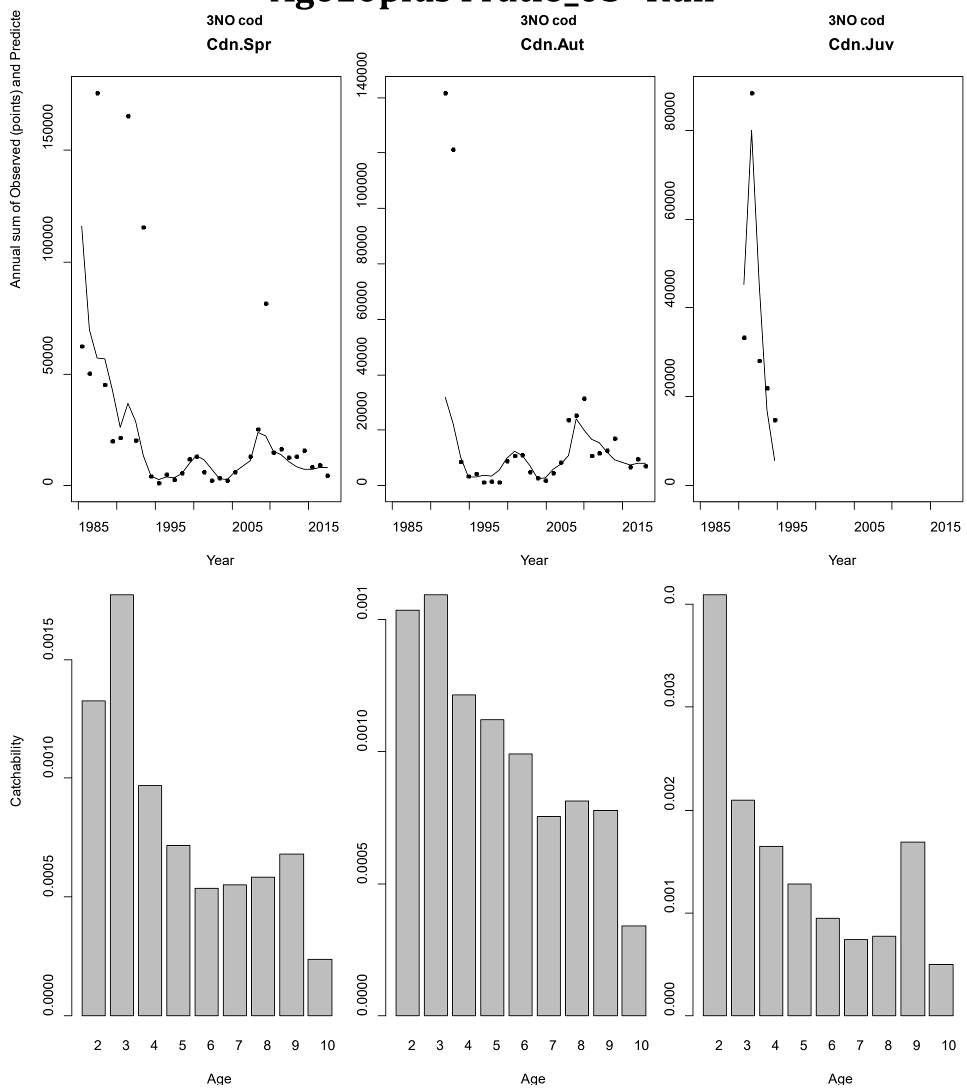


Figure 17. (continued) Plots of residuals, model fit, and survey q's for the "Age10plus Fratio_05" ADAPT run.

Table 5. Model statistics for the 'Age10plus Fratio_1' ADAPT run.

"Age10plus Fratio_1" Run

APPROXIMATE STATISTICS ASSUMING LINEARITY NEAR SOLUTION

ORTHOGONALITY OFFSET......... 0.001742
MEAN SQUARE RESIDUALS 1.492029

Parameter	Est.	Std. Err.	Rel. Err.	Bias	Rel. Bias
---------	---------	---------	---------	---------	---------
N[2018 3]	1.21E6	1.08E6	0.889	4.80E5	0.395
N[2018 4]	1.38E6	9.09E5	0.661	2.89E5	0.210
N[2018 5]	6.30E5	3.73E5	0.593	9.86E4	0.157
N[2018 6]	2.38E5	1.43E5	0.601	3.62E4	0.152
N[2018 7]	2.09E5	1.19E5	0.570	2.77E4	0.133
N[2018 8]	6.85E4	4.32E4	0.630	1.04E4	0.151
N[2018 9]	1.75E5	9.18E4	0.524	1.91E4	0.109
N[2018 10]	1.60E6	3.10E5	0.194	2.54E4	0.016
q ID#[1]	1.55Eý3	3.37Eý4	0.217	2.97Eý5	0.019
q ID#[2]	2.09Eý3	4.50Eý4	0.216	4.07Eý5	0.020
q ID#[3]	1.17Eý3	2.53Eý4	0.216	2.42Eý5	0.021
q ID#[4]	9.31Eý4	2.01Eý4	0.216	2.04Eý5	0.022
q ID#[5]	7.46Eý4	1.61Eý4	0.216	1.70Eý5	0.023
q ID#[6]	8.34Eý4	1.80Eý4	0.216	1.98Eý5	0.024
q ID#[7]	9.64Eý4	2.09Eý4	0.216	2.27Eý5	0.024
q ID#[8]	1.25Eý3	2.70Eý4	0.217	2.88Eý5	0.023
q ID#[9]	7.05Eý4	1.53Eý4	0.217	1.63Eý5	0.023
q ID#[10]	1.88Eý3	4.53Eý4	0.241	4.65Eý5	0.025
q ID#[11]	1.98Eý3	4.74Eý4	0.239	5.03Eý5	0.025
q ID#[12]	1.60Eý3	3.83Eý4	0.239	4.40Eý5	0.027
q ID#[13]	1.60Eý3	3.84Eý4	0.240	4.60Eý5	0.029
q ID#[14]	1.59Eý3	3.80Eý4	0.239	4.59Eý5	0.029
q ID#[15]	1.37Eý3	3.27Eý4	0.240	4.12Eý5	0.030
q ID#[16]	1.61Eý3	3.92Eý4	0.244	4.87Eý5	0.030
q ID#[17]	1.75Eý3	4.37Eý4	0.249	5.37Eý5	0.031
q ID#[18]	1.35Eý3	3.59Eý4	0.266	4.73Eý5	0.035
q ID#[19]	4.56Eý3	2.28Eý3	0.499	5.67Eý4	0.124
q ID#[20]	2.29Eý3	1.14Eý3	0.499	2.84Eý4	0.124
q ID#[21]	1.86Eý3	9.30Eý4	0.499	2.32Eý4	0.124
q ID#[22]	1.56Eý3	7.76Eý4	0.499	1.93Eý4	0.124
q ID#[23]	1.20Eý3	6.00Eý4	0.499	1.50Eý4	0.124
q ID#[24]	1.00Eý3	5.00Eý4	0.499	1.25Eý4	0.124
q ID#[25]	1.00Eý3	5.00Eý4	0.499	1.25Eý4	0.124
q ID#[26]	2.18Eý3	1.09Eý3	0.499	2.71Eý4	0.124
q ID#[27]	7.75Eý4	3.87Eý4	0.499	9.64Eý5	0.124

"Age10plus Fratio_1" Run

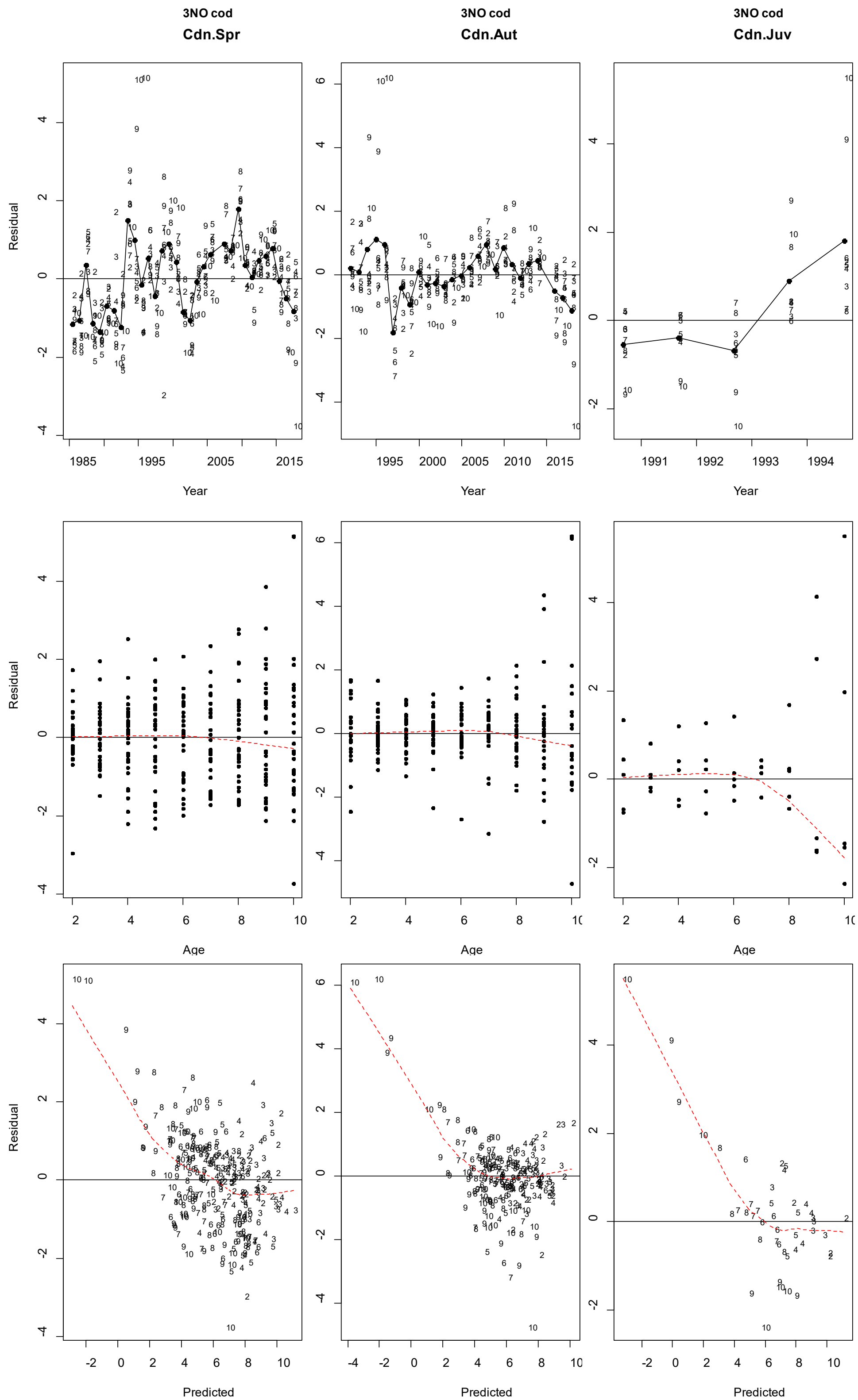


Figure 18. Plots of residuals, model fit, and survey q's for the "Age10plus Fratio_1" ADAPT run (continued on next page).

"Age10plus Fratio_1" Run

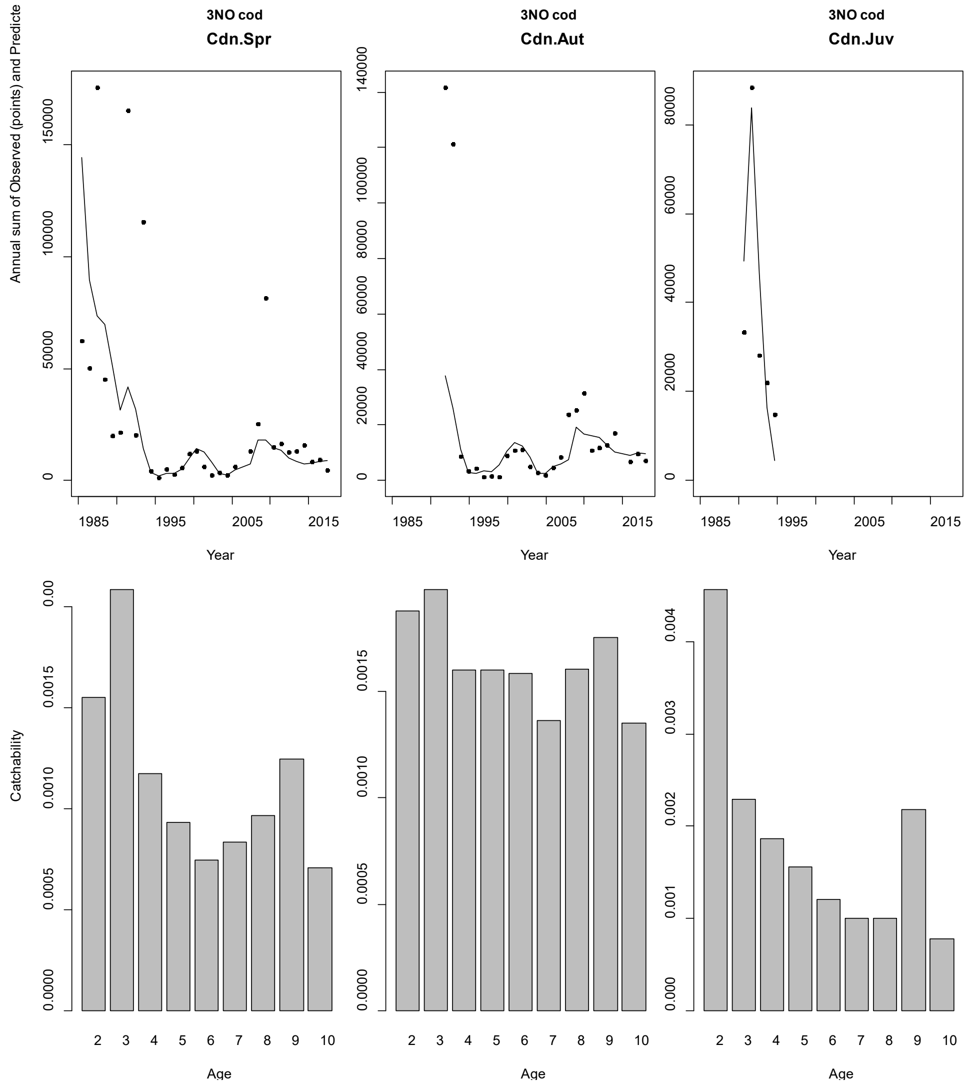
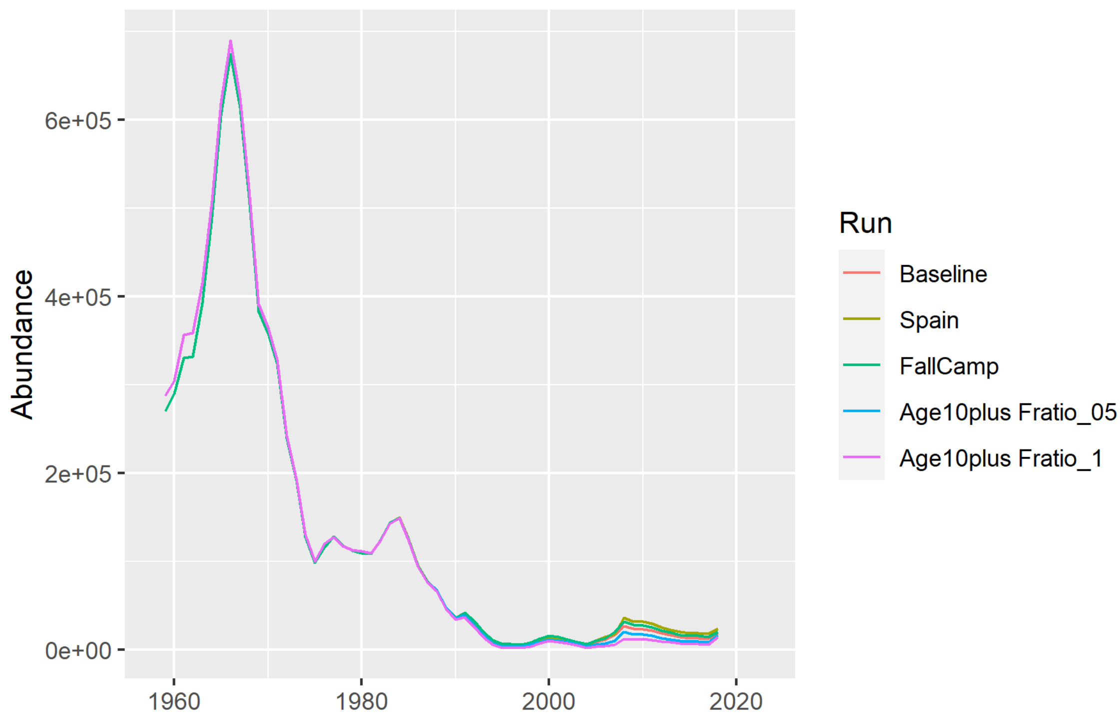


Figure 18. (continued) Plots of residuals, model fit, and survey q's for the "Age10plus Fratio_1" ADAPT run.



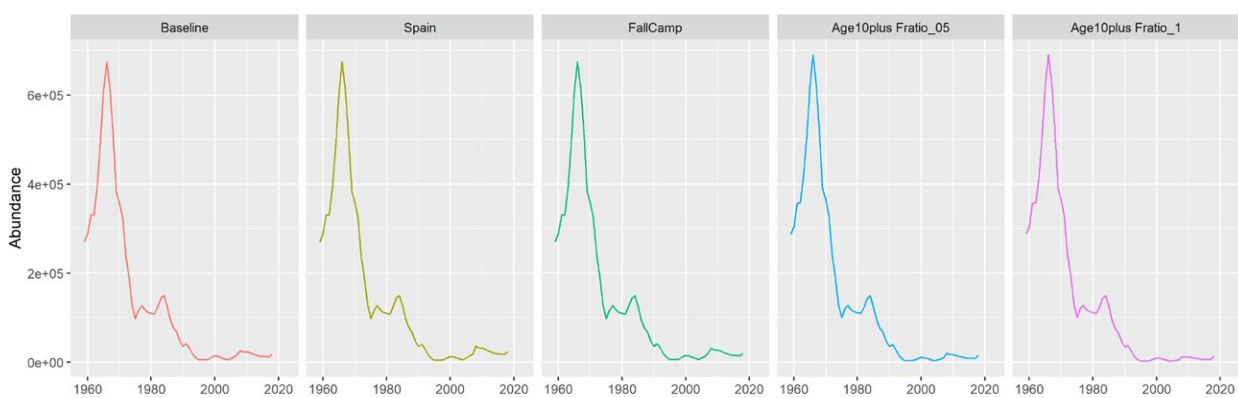


Figure 19. Estimates of abundance from the different model formulations.

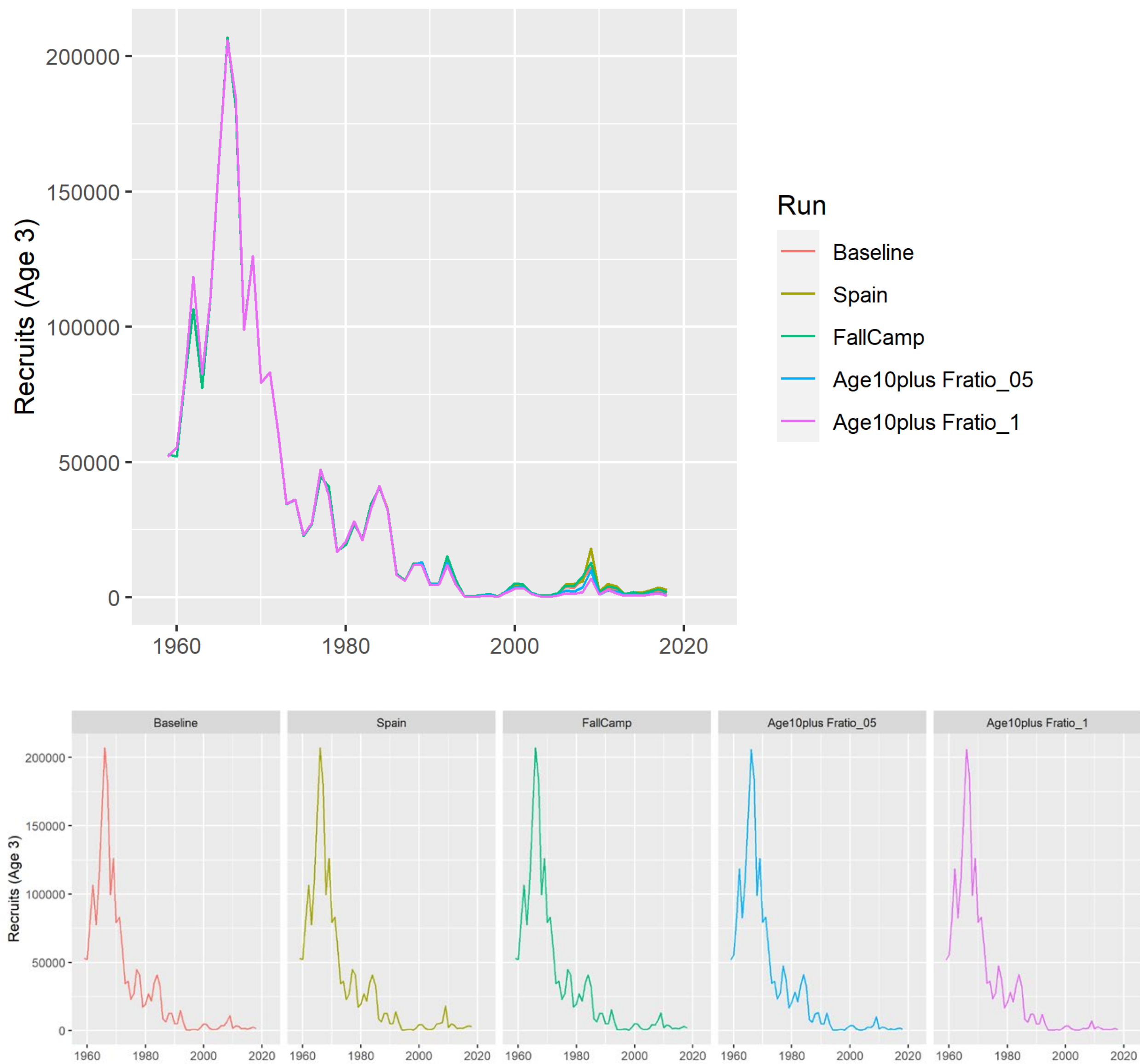


Figure 20. Estimates of recruitment from the different model formulations.

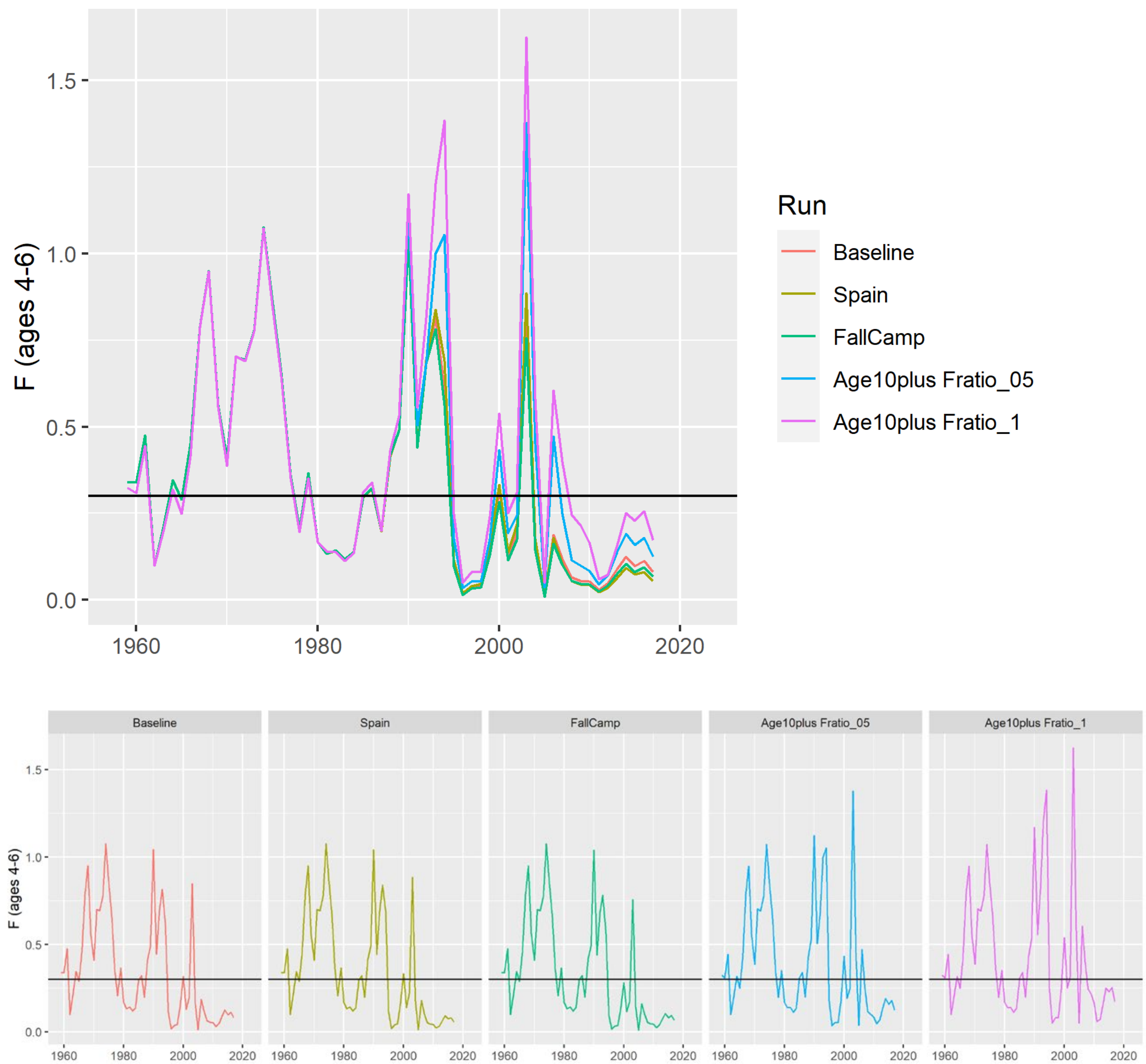


Figure 21. Estimates of average fishing mortality from the different model formulations.

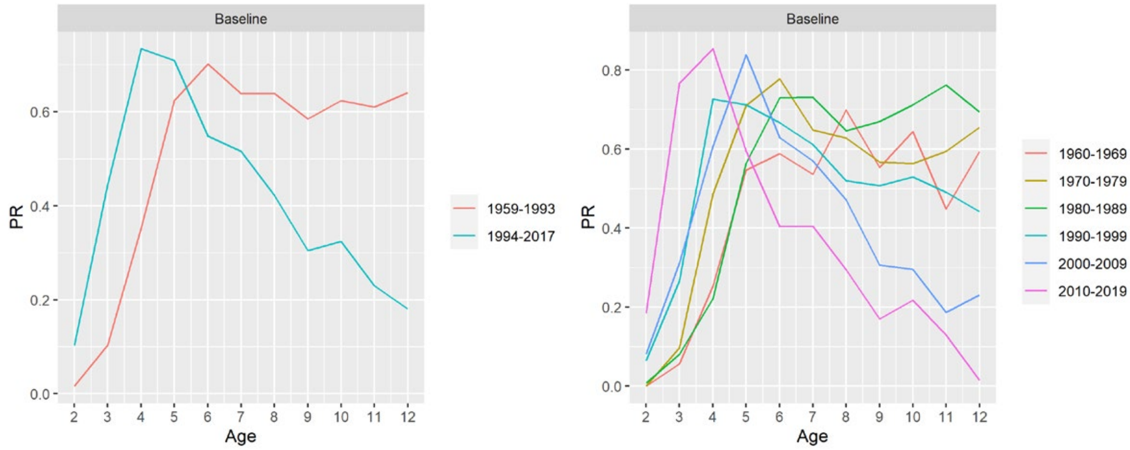


Figure 22. Estimates of selectivity from the baseline model formulation.