Assessment for Eastern Jack Mackerel

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Executive Summary

An assessment modelling framework is developed for eastern jack mackerel to condition the management strategy evaluation that has been developed for this species group. Two modelling approaches are applied: (a) Stochastic Stock Reduction Analysis (SSRA), and (b) a state-space assessment method. The model on which both approaches are based is age-structured and uses pre-specified values for biological parameters (natural mortality, growth, maturity, and stock-recruit steepness). SSRA uses only catches and an estimate of absolute abundance, while the state-space assessment method uses catches (split to gear-type: purse seine and mid-water trawl), an estimate of absolute abundance, and catch age-composition data by gear-type. The selectivity of the gear and the extent of and autocorrelation of variation in recruitment about the stock-recruit relationship (σ_R) are pre-specified for SSRA while these quantities, in addition of the unfished recruitment, annual fishing mortality, and the annual deviations about the stock-recruit relationship, are estimated using the state-space assessment method. The SSRA results in a value for depletion of 0.91 (SD 0.2) for the "best" values for stock-recruit steepness and σ_R (0.75 and 0.6). The best estimate of depletion, is, however, somewhat sensitive to assumptions regarding stock-recruit steepness and σ_R, with a range from 0.53 to 0.94, with lower values of steepness and a greater extent of variation and autocorrelation in recruitment leading to lower values for depletion, and vice versa. A version of the state-space assessment method with dome-shaped selectivity fits the data best, and estimates the stock to be at or above its unfished equilibrium level, with σ_R close to 1, i.e. higher than assumed in recent management strategy evaluation analyses for eastern jack mackerel. The implications of the results for the management strategy evaluation for eastern jack mackerel are highlighted.

1. Introduction

A management strategy evaluation (MSE) should ideally be conditioned to the data for the situation under consideration so that the results pertain to that situation most adequately, although appropriate alternative scenarios also need to be conducted to cover a reasonable range of uncertainties (Punt *et al.*, 2016). Conditioning usually entails fitting the operating model (the model that represents the "reality" for the analyses) to the available data. However, this can be challenging for data-poor situations for which there may be insufficient data to conduct assessments. This is in large part the situation for Australia's Small Pelagic Fishery (SPF). Consequently, past MSE analyses for the SPF (e.g., Smith *et al.*, 2015) have involved setting various parameters based on auxiliary information. These parameters include those such as current depletion, the steepness of the stock-recruit relationship and the extent of variation about the stock-recruit relationship (σ_R), to which the results of projections under various alternative management strategies have been shown to be sensitive (A.D.M. Smith, Pers. Commn).

Eastern jack mackerel (*Trachurus declivis*, *T. murphyi*) could be considered to be "data-moderate" as there is a time-series of catches, an estimate of 2014 spawning stock biomass, and data on the age- and length-composition of the historical catches. Thus, in principle, an assessment could be conducted for eastern jack mackerel. Two approaches to stock assessment are considered here (both of which have been tailored so the results could be used to inform the MSE analyses for eastern jack mackerel)[1]:

- Stochastic Stock Reduction Analyses (SSRA) uses only biological parameters, catches (from a single fleet) and an estimate of spawning stock biomass. The method involves setting the values for most of the population dynamics parameters (growth, maturity, selectivity, stock-recruit steepness, and the extent and autocorrelation of variation in recruitment about the stock-recruit relationship, ρ and σ_R), sampling values for the annual deviations in recruitment about the stock-recruit relationship from a normal distribution and a value for 2014 spawning stock biomass from its (log-normal) sampling distribution and solving for the value of unfished recruitment such that the projected spawning biomass equals the generated value. Repeating this process many (1,000 for the analyses of this report) times leads to a distribution for spawning stock biomass and depletion in each year of the modelled period. This approach is similar to Depletion-Based Stock Reduction Analysis (Dick and MacCall, 2011), except that it is conditioned on an estimate of absolute abundance and is formulated as a state-space rather than a Bayesian model.
- The state-space assessment method takes values for most of the population dynamics parameters (natural mortality, growth, maturity, stock-recruit steepness, and potentially ages-specific selectivity) and fits to data available for eastern jack mackerel. The method allows for multiple fleets (two for the application to eastern jack mackerel) and is coded in Template Model Builder (TMB, Kristensen *et al.*, 2014)[2], which allows analysts who are familiar with R to conduct sensitivity analyses straightforwardly. Unlike most assessments, the assessment involves estimating the extent of variation in recruitment about the stock-recruitment relationship (σ_R) and perhaps also the extent of autocorrelation in recruitment (ρ). The method is similar to the SAM approach to stock assessment (Nielsen and Berg, 2014), which is used fairly extensively in Europe.

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[1] The methods are such that they could be applied fairly easily to other stocks or which data on catches, absolute abundance and (perhaps) catch age-composition are available.

[2] This is the first TMB-based stock assessment in Australia and perhaps the Southern Hemisphere.

2. Methods

2.1 Stochastic Stock Reduction Analysis

The basic population dynamics reflect a single-sex age-structured model, with a plus-group:

$$N_{y,a} = \begin{cases} \dfrac{4hR_0\tilde{S}_y/\tilde{S}_0}{(1-h)+(5h-1)\tilde{S}_y/\tilde{S}_0} e^{\varepsilon_y-\sigma_R^2/2} & \text{if } a=0 \\ N_{y-1,a-1}e^{-Z_{y-1,a-1}} & \text{if } 1 \le a < x \\ N_{y-1,x-1}e^{-Z_{y-1,x-1}} + N_{y-1,x}e^{-Z_{y-1,x}} & \text{if } a = x \end{cases} \tag{1}$$

where $N_{y,a}$ is the number of fish of age *a* at the start of year *y*, $Z_{y,a}$ is the total mortality on animals of age *a* during year *y*:

$$Z_{y,a} = M + S_a F_y \tag{2}$$

M is the instantaneous rate of natural mortality, S_a is the selectivity of the fishery on animals of age *a*, F_y is the fully-selected fishing mortality rate during year *y*, $\tilde{S}_y$ is the spawning stock biomass at the start of the year:

$$\tilde{S}_y = \sum_a w_a f_a N_{y,a} \tag{3}$$

$\tilde{S}_0$ is the average unfished spawning stock biomass, w_a is the weight of an animal of age *a* at the start of the year, f_a is the proportion of animals of age *a* that are mature, *h* is the "steepness" of the stock-recruit relationship, ε_y is the recruitment deviation for year *y*:

$$\varepsilon_y = \rho\varepsilon_{y-1} + \sqrt{1-\rho^2}\eta_y \qquad \eta_y \sim N(0;\sigma_R^2) \tag{4}$$

σ_R is the standard deviation of the recruitment deviations in log-space, ρ is extent of autocorrelation in the deviations about the stock-recruit relationship, and *x* is the maximum age-class (assumed to be a plus-group).

The catches by age and year, $C_{y,a}$, are given by the Baranov equation:

$$C_{y,a} = \frac{S_a F_y}{Z_{y,a}} N_{y,a}(1-e^{-Z_{y,a}}) \tag{5}$$

and the catches in weight by:

$$\tilde{C}_y = \sum_a w_{a+1/2} C_{y,a} \tag{6}$$

The initial conditions correspond to a population at unfished equilibrium. There is a *x*-year burn-in with no catches but with recruitment variation so that the initial age-structure could differ from that in the unfished situation.

Most of the parameters of the model (e.g., weight-at-age, maturity-at-age, natural mortality, selectivity-at-age, steepness, ρ, σ_R) are set based on the values used for the MSE (Table 1). The values for *x* and *M* are set to 12 and 0.26yr^{-1} respectively following Smith *et al*. (2015). Thus, the free parameters of the model are unfished recruitment, R_0 (or equivalently $\tilde{S}_0$), the annual fully-selected fishing mortalities, and the annual deviations about the stock-recruitment relationship. The analysis estimates a distribution for R_0 and hence B_0 and the time-series for spawning stock biomass by generating a value for the 2014 spawning stock biomass from its log-normal sampling distribution and values for the recruitment deviations for all years using Equation 4, and then solves for the value for R_0 and hence $\tilde{S}_0$ such that the model-predicted spawning biomass in 2014 equals the generated value. The values for fishing mortality by year are selected so that the model-predicted time-series of catches matches the observed time-series of catches exactly. The ratio of 2015 biomass to pre-fishery equilibrium biomass is then summarized to form a distribution for 2015 depletion.

The base values for stock-recruit steepness in Smith *et al.* (2015) was 0.75 for jack mackerel, with sensitivity examined to values of 0.6 and 0.9. The base value of σ_R was set to 0.6 in Smith *et al.* (2015). Given uncertainty regarding these two key parameters, results from the SSRA are presented for all combinations of steepness = 0.6, 0.75, and 0.9 and σ_R = 0.4, 0.6, 0.8, 1.0, and 1.2[3] with the (0.75, 0.6) combination taken to be the base combination[4]. Smith *et al.* (2015) assumed that ρ was zero. This assessment examines sensitivity to values for ρ of 0, 0.7 and 0.9. Table 2 lists the annual catches. These catches were taken using a variety of gear types (primarily purse seine and midwater trawl), but this is ignored for the purposes of the SSRA. The estimate 2014 spawning stock biomass is 157,805t (Ward *et al.*, 2016), with an assumed CV of 0.5.

2.2 State-space assessment model

2.2.1 Assessment framework

The basic population dynamics are governed by Equation 1, except that the calculation of total mortality accounts for multiple fleets:

$$Z_{y,a} = M + \sum_f S_a^f F_y^f \tag{7}$$

where S_a^f is the selectivity of fishery *f* on animals of age *a*, and F_y^f is the fully-selected fishing mortality rate by fleet *f* during year *y*. The catches by fleet, age and year, $C_{y,a}^f$, are given by the Baranov equation:

$$C_{y,a}^f = \frac{S_a^f F_y^f}{Z_{y,a}} N_{y,a} (1 - e^{-Z_{y,a}}) \tag{8}$$

and the catches by fleet in weight by:

$$\tilde{C}_y^f = \sum_a w_{a+1/2} C_{y,a}^f \tag{9}$$

The initial conditions correspond to a population at unfished equilibrium. There is an *x*-year burn-in with no catches, but with recruitment variation so that initial age-structure could differ from that at unfished equilibrium.

The estimable parameters of that state-space assessment method are R_0, the annual deviations about the stock-recruitment relationship, the annual fishing mortality rates, the

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[3] Smith *et al.* (2015) did not examine values for σ_R as high as 1, but the results of the state-space assessment method suggest these to be plausible.

[4] Because this was the base-case for the analyses conducted by Smith *et al.* (2015)

parameters defining selectivity-at-age, and the extent of variation about the stock-recruitment relationship. The state-space method can also estimate selectivity as a function of age and the extent of autocorrelation in the deviations in recruitment. The likelihood includes components for the catch-in-mass data, the 2014 estimate of spawning stock biomass, and the catch age-composition data. The catch data are assumed to be log-normally distributed, the Daily Egg Production Method estimate of spawning stock biomass is assumed to log-normally distributed with an assumed CV, and the age-composition data are assumed to be multinomially distributed. The choice of effective sample sizes is evaluated by computing annual "inferred" effective sample sizes using the method of McAllister and Ianelli (1997) and taking the harmonic mean of the ratio of the "inferred" to the actual sample sizes as a way to assess whether check the age data are "right weighted" (Punt, in press).

The values for the biological parameters are given in Table 1. The steepness of the stock-recruit relationship is assumed to be 0.75, following Smith *et al*. (2015). Table 2 lists the annual catches (in total and by fleet) and the Table 3 summarizes the age-composition data. The estimate of 2014 spawning stock biomass is 157,805t, with an assumed CV of 0.5. The CV for the catch data is set to 0.05, while the effective sample sizes for the age data are calculated by scaling the observed numbers of aged animals so that the average effective sample size by fleet is 100.

Five variants of the model are considered:

- selectivity is pre-specified and equals the values used by Smith *et al*. (2015); and $\rho=0$ (denoted "pre-specified");
- selectivity (by fleet) is assumed to be a logistic function of age, with the four parameters defining selectivity-at-age (two for each fleet) estimated and $\rho=0$ (denoted "asymptotic");
- selectivity (by fleet) is assumed to be a double-logistic function of age (Methot and Wetzel, 2013), with the twelve parameters defining selectivity-at-age (six for each fleet) estimated; and $\rho=0$ (denoted "dome-shaped"); and
- selectivity (by fleet) is assumed to be a double-logistic function of age (Methot and Wetzel, 2013), but with the parameters defining the right-hand part of the selectivity pattern and the width of the dome set so that the selectivity pattern is asymptotic – this is equivalent to a three-parameter asymptotic selectivity function; and $\rho= 0$ (denoted "dome-shaped*").
- As for "dome-shaped*", except that ρ is estimated rather than being assumed to be zero (denoted "dome-shaped**").

3. Results

3.1 Stochastic Stock Reduction Analysis

Figure 1 shows the distributions for 2015 depletion, along with the time-series of the distributions for spawning stock biomass and depletion for the base values of stock-recruit steepness and σ_R. The mean of the distribution for 2015 depletion is 0.91, with a standard deviation of 0.2. Table 4 shows the sensitivity of the values for the mean and standard deviation of the distribution for 2015 depletion to the assumed values for stock-recruit steepness, ρ and σ_R. The value for 2015 depletion ranges from 0.53 to 0.94, with lower values of steepness and a greater extent of variation and autocorrelation in recruitment leading to lower values for depletion, and vice versa.

3.2 State-space assessment model

Table 5 compares the negative log-likelihoods for the five model variants, along with the extent to which the input effective sample sizes for the age-composition data would need to be adjusted so that the input and "inferred" effective sample sizes are the same "on average" (the overdispersion factor). The "pre-specified" case is clearly inferior to the other four model variants in terms of negative log-likelihood and the overdispersion factor. The "asymptotic" model variant leads to a poorer fits to the data compared to the "dome-shaped", "dome-shaped*", and "dome-shaped**" models according to AIC. According to AIC, the "dome-shaped" model variant is best. However, this is because it sets selectivity for the plus group for the purse seine fleet as low as possible (Fig. 3) to avoid poor fits to the age-composition data for the plus-group. There is no biological reason why selectivity should drop off very rapidly between ages 11 and 12 for any fleet (Fig 3., top left panel). The selectivity patterns for the "asymptotic", the "dome-shaped", the "dome-shaped*", and the "dome-shaped**" model variants are quite simular for most ages (and markedly different from that for the "pre-specified" model variant) (Fig. 3).

Figures 4 and 5 show the fit of the "dome-shaped*" "dome-shaped**" model variants to the catches, to the estimate of spawning stock biomass for 2014, and to the age-composition data. The models mimic the catches almost exactly (as expected given the CV assumed for the catch data). The "dome-shaped**" mimics the estimate of abundance almost exactly (Fig. 4b). However, the "dome-shaped*" model does not fit the estimate of abundance exactly – the trajectory does, however, go through the lower confidence interval for the estimate of spawning stock biomass (Fig. 4a). The stock is estimated to have declined to low levels between 2000 and 2005. This inference arises because of the narrow range of ages in the catch age-compositions for 2002 to 2009 (Table 3; Fig. 5). Ward *et al.* (2016) note that the causes for the change in age-structure between the 1980s and 1990s are unclear, but may have reflected a population response to fishing pressure, impacts of recruitment variability, and/or changes in food availability driven by the effects of oceanographic processes on primary productivity. This assessment implies that the cause for the change in age-structure is a combination of the first two reasons, given it assumes that availability and selectivity, while different between the two fleet is time-invariant.

The estimate of σ_R from the "dome-shaped*" model is 1.04 (SD 0.114), while the depletion in 2014 is estimated to be 146% (SD 55%). In contrast, the σ_R from the "dome-shaped**" model is 1.44 (SD 0.298), while the depletion in 2014 is estimated to be 821% (SD 456%). The lower centre panels of Fig. 4a,b show the actual versus the "inferred" effective sample sizes based on the McAllister and Ianelli (1997) method. There is a clear linear relationship between the input and inferred sample sizes, which is confirmed by an overdispersion factor of 1/1.067 for the "dome-shaped*" and "dome-shaped**" in Table 5.

T. Ward (pers. commn) notes that the age-composition data for 2014-15 were collected from the factory trawler operating in offshore waters off New South Wales rather than the purse seine or the mid-water trawler off Tasmania. Thus, this most recent age-composition may not be comparable with the earlier data. An analysis that ignored the 2014-15 age-composition data led to qualitatively similar results to those for the "dome-shaped*" model (σ_R=1.11; SD 0.126; depletion = 199% (SD 81%). The lesser precision of the estimate of depletion is unsurprising given there are few data (apart from the estimate of absolute abundance) for recent years.

4. Discussion

The results of this assessment could be used to provide several of the inputs to the management strategy evaluation for eastern jack mackerel. Specifically:

- The SSRA suggests that the stock is likely to be fairly close to the average unfished level (but with uncertainty that depends on stock-recruit steepness, ρ and σ_R). The estimate of 2015 depletion based on the parameter values on which the MSE conducted by Smith *et al.* (2015) was based is 0.91, but given that the results of the state-space assessment method suggest that σ_R is larger than 0.6, it would be prudent to base analyses on an estimate of depletion for σ_R = 1, i.e. the "best estimate" would be 0.86,

- The state-space assessment method also suggests that the stock is likely to be fairly close to the average unfished level. However, it also provides estimates of selectivity by gear-type (the selectivity pattern for mid-water trawl would be best to use as the basis for projections given the recent history of the fishery) as well as σ_R. The results for the model variant in which auto-correlation is estimated suggests very high levels of temporal auto-correlation in recruitment (ρ=0.8990). However, the resulting estimates of σ_R and 2015 depletion are very imprecise (the standard deviations for the "dome-shape**" model variant estimates of σ_R and 2015 depletion are twice (σ_R) and almost ten times (depletion) higher than for the model variant in which ρ=0). The data suggest auto-correlation is significant and the negative log-likelihood is lower when auto-correlation is estimated but the reliability of other parameters may be questionable if ρ is estimated.

The analyses are based on several assumptions that should be considered when interpreting the results of this work. In particular, the analyses assumed there were negligible catches prior to 1984/85, that the values assumed for growth and stock-recruit steepness are correct (with the results in Table 4 confirming that estimates of depletion will be sensitive to assumptions about the value of this parameter). The results from the state-space assessment method rely on the assumption that the age-composition data are based on representative samples of the catch. Finally, catches of jack mackerel likely consist of at least two species, but the extent to which this is the case is unknown and cannot be addressed using this (or probably any) modelling framework.

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Table 1. Values for the biological parameters for eastern jack mackerel (source: Smith *et al*., 2015).

Age	**Weight**	**Proportion mature**	**Selectivity**
0	5.3	0	0
1	41.3	0	0
2	107.0	0.04	0.68
3	187.0	0.22	0.86
4	267.9	0.56	1.00
5	341.9	0.80	1.00
6	405.4	0.90	1.00
7	457.9	0.95	1.00
8	500.0	1.00	1.00
9	533.2	1.00	1.00
10	558.9	1.00	1.00
11	578.8	1.00	1.00
12	605.6	1.00	1.00

Table 2. Catches (t) of eastern jack mackerel in total and by gear-type (Source: T. Ward, pers. Commn)

Year	Total	Purse Seine	Midwater
1984/85	4854	4854	0
1985/86	21014	21014	0
1986/87	36804	36804	0
1987/88	33194	33194	0
1988/89	7573	7573	0
1989/90	7115	7115	0
1990/91	15247	15247	0
1991/92	15910	15910	0
1992/93	9045	9045	0
1993/94	7879	7879	0
1994/95	5180	5180	0
1995/96	447	447	0
1996/97	1925	1925	0
1997/98	9910	9910	0
1998/99	4146	4146	0
1999/2000	1785	1785	0
2000/01	381	371	10
2001/02	642	100	542
2002/03	991	157	834
2003/04	3363	98	3265
2004/05	2640	190	2451
1005/06	1059	108	951
2006/07	431	118	312
2007/08	235	28	208
2008/09	634	362	272
2009/10	1508	1320	189
2010/11	160	105	55
2011/12	63	63	0
2012/13	1	1	0
2013/14	2	2	0
2014/15	317	6	311

Table 3. Catch proportions-at-age for eastern jack mackerel. The catches of animals aged 0 and 1 are ignored when fitting the model. (Source: T. Ward, pers. Commn)

Year .	Sample size	Age												
		0	1	2	3	4	5	6	7	8	9	10	11	12+
Mid-water trawl														
2001	31	0.000	0.000	1.225	7.422	20.677	18.070	11.223	12.527	8.933	7.280	2.847	5.762	4.034
2002	687	0.000	0.000	5.953	25.657	36.555	19.421	3.683	1.978	1.189	0.693	0.333	0.315	0.145
2003	4736	0.000	0.000	11.830	31.759	38.925	13.564	1.315	0.629	0.429	0.202	0.142	0.081	0.049
2004	1717	0.000	0.000	7.032	21.331	48.504	20.060	1.495	0.578	0.453	0.160	0.146	0.045	0.021
2009	87	0.000	0.543	48.992	35.840	9.887	2.176	1.503	0.511	0.000	0.000	0.000	0.000	0.000
2014	102	0.000	0.000	1.980	10.891	18.812	15.842	11.881	21.782	9.901	5.941	0.990	0.000	1.980
Purse-seine														
1984	455	0.000	0.000	0.251	4.931	29.526	26.339	11.535	9.942	7.635	4.680	2.787	1.570	0.803
1985	2899	0.000	0.000	0.441	3.200	25.804	33.339	13.768	9.910	6.190	3.564	1.927	1.206	0.651
1986	2245	0.000	0.000	0.035	1.269	16.683	27.398	14.192	12.798	10.411	7.129	4.115	3.540	2.411
1987	1227	0.000	0.000	0.051	1.461	19.657	33.929	16.341	12.131	7.553	4.288	2.402	1.419	0.768
1988	160	0.000	0.000	0.190	2.305	11.296	22.011	16.026	15.849	13.970	8.550	5.667	2.778	1.358
1989	1343	0.000	0.000	0.914	7.213	12.781	17.695	14.113	14.885	13.190	8.564	5.290	3.382	1.972
1990	1271	0.000	0.000	0.630	9.186	32.870	20.507	7.878	8.311	8.442	5.303	3.514	2.044	1.158
1991	1973	0.000	0.000	6.548	21.063	38.218	23.628	4.204	2.239	1.650	0.979	0.636	0.496	0.339
1992	1417	0.000	0.000	6.239	34.546	31.711	14.297	4.915	3.563	2.162	1.249	0.712	0.400	0.207
1993	1592	0.000	0.000	2.881	22.524	46.051	21.086	3.093	1.726	1.185	0.624	0.416	0.255	0.159
1994	2842	0.000	0.000	0.817	13.893	56.361	25.862	1.865	0.487	0.385	0.093	0.151	0.043	0.023
1995	1326	0.000	0.000	0.032	2.165	28.602	35.967	12.490	8.560	5.523	3.065	1.797	1.122	0.676
2009	270	0.000	1.339	46.345	37.537	11.380	3.534	1.312	0.537	0.000	0.000	0.000	0.000	0.000

Table 4. Mean and standard deviation of 2015 depletion (expressed as percentages) for eastern jack mackerel as a function of stock-recruit steepness and, extent of recruitment auto-correlation, and σ_R based on SSRA.

		ρ=0		**ρ=0.7**		**ρ=0.9**	
Steepness	σ_R	**Mean depletion**	**SD depletion**	**Mean depletion**	**SD depletion**	**Mean depletion**	**SD depletion**
0.6	0.4	88.6	15.7	85.7	25.0	83.7	33.6
0.75	0.4	92.0	15.0	89.7	24.7	87.9	32.5
0.9	0.4	94.3	14.2	92.6	24.4	91.0	32.1
0.6	0.6	87.2	20.7	81.0	33.9	77.5	46.2
0.75	0.6	91.0	20.4	85.9	33.9	82.5	45.2
0.9	0.6	93.6	19.9	89.8	34.2	87.0	45.6
0.6	0.8	84.9	26.6	74.9	41.6	69.9	56.6
0.75	0.8	89.2	26.7	80.7	42.3	75.6	56.3
0.9	0.8	92.3	26.6	85.8	43.2	81.6	58.4
0.6	1.0	81.4	33.5	67.7	47.7	61.5	63.4
0.75	1.0	86.4	34.0	74.4	49.2	68.0	64.6
0.9	1.0	90.1	34.4	80.6	51.4	75.3	70.0
0.6	1.2	76.7	42.3	59.8	52.2	53.1	67.8
0.75	1.2	82.4	43.3	67.1	54.9	59.9	70.9
0.9	1.2	87.0	44.1	74.4	58.4	68.5	80.1

Table 5. Fit statistics and model outputs for the four model runs based on the state-space assessment method for the choices for selectivity. The values in parenthesis are asymptotic standard errors.

Model	**Negative log-likelihood**	**Age-composition adjustment**	σ_R	**ρ**	**2015 depletion (%)**	**SSB (2015) ('000t)**
Pre-specified	286.767	0.1317	1.000 (0.113)	0	104.6 (33.6)	73.5 (24.8)
Asymptotic	-65.718	0.9229	1.049 (0.115)	0	152.2 (57.4)	85.1 (31.8)
Dome-shaped	-79.201	1.0642	1.092 (0.130)	0	103.4 (41.3)	107.8 (41.4)
Dome-shaped*	-69.305	1.0000	1.039 (0.114)	0	146.3 (54.7)	82.5 (30.5)
Dome-shaped**	-72.854	1.0674	1.437 (0.298)	0.902 (0.041)	820.8 (455.6)	185.2 (88.0)

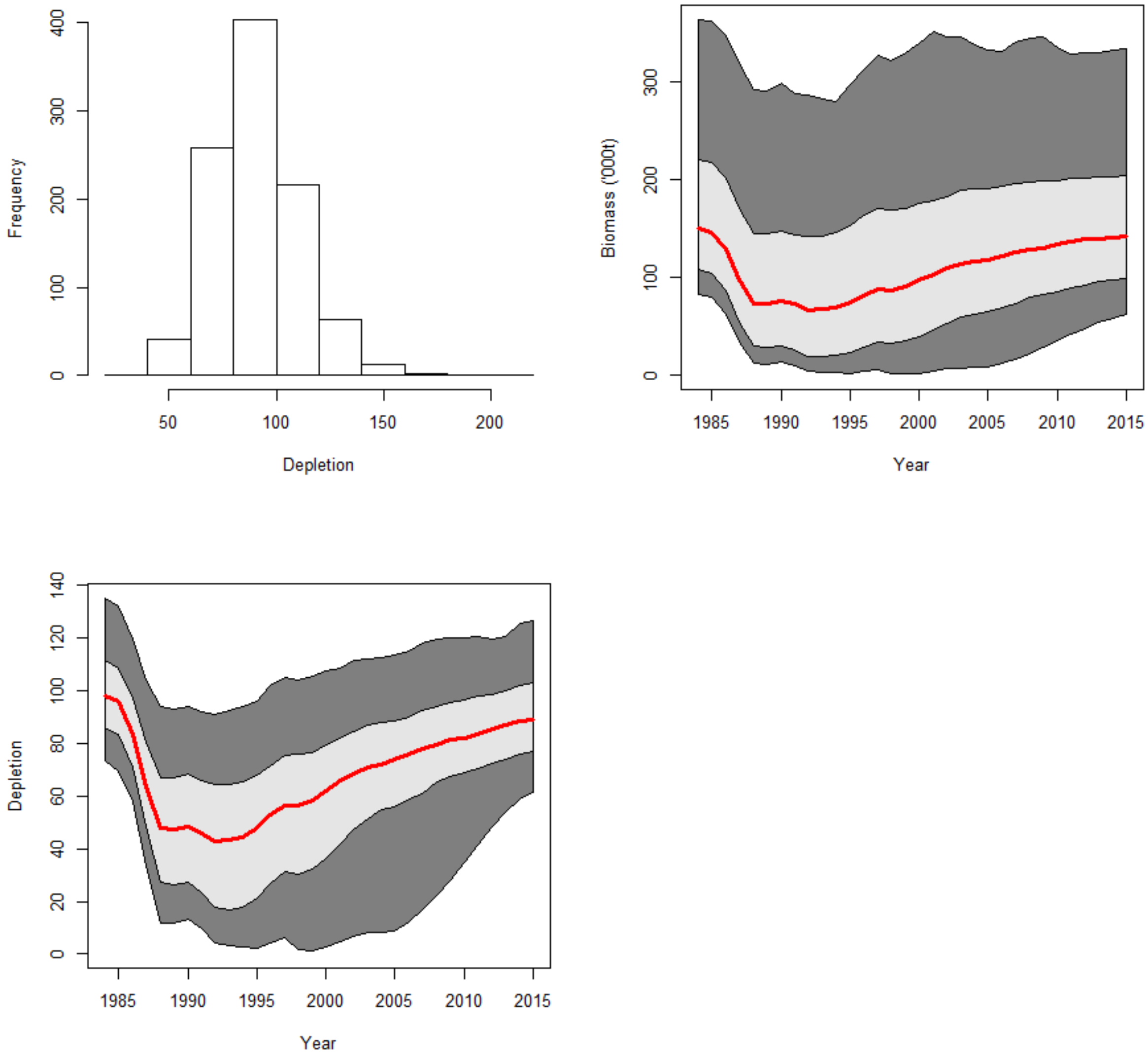


Figure 1. Distribution for 2015 depletion of eastern jack mackerel (expressed as a percentage) and the time-series for spawning stock biomass and depletion when steepness = 0.75, ρ=0, and σ_R = 0.6 based on SSRA.

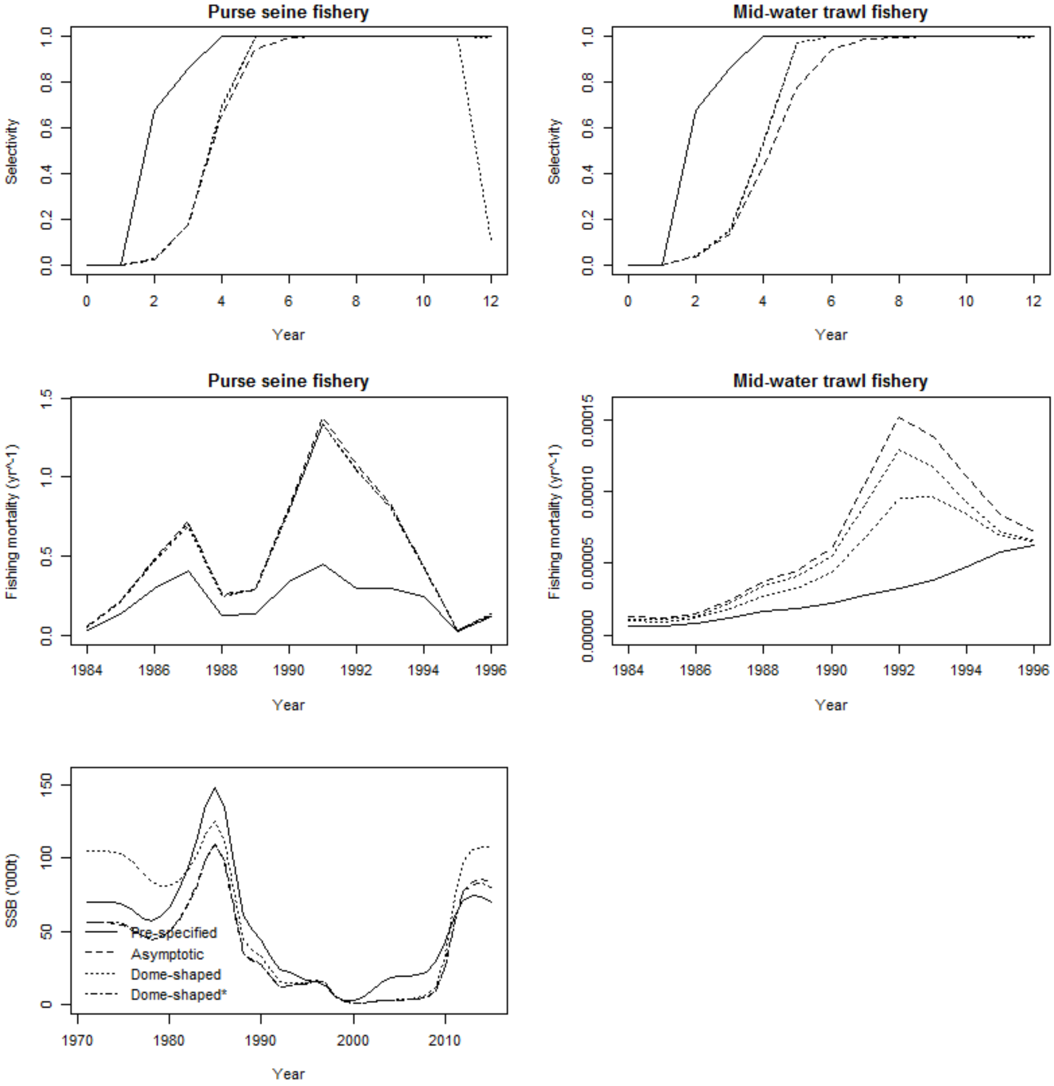
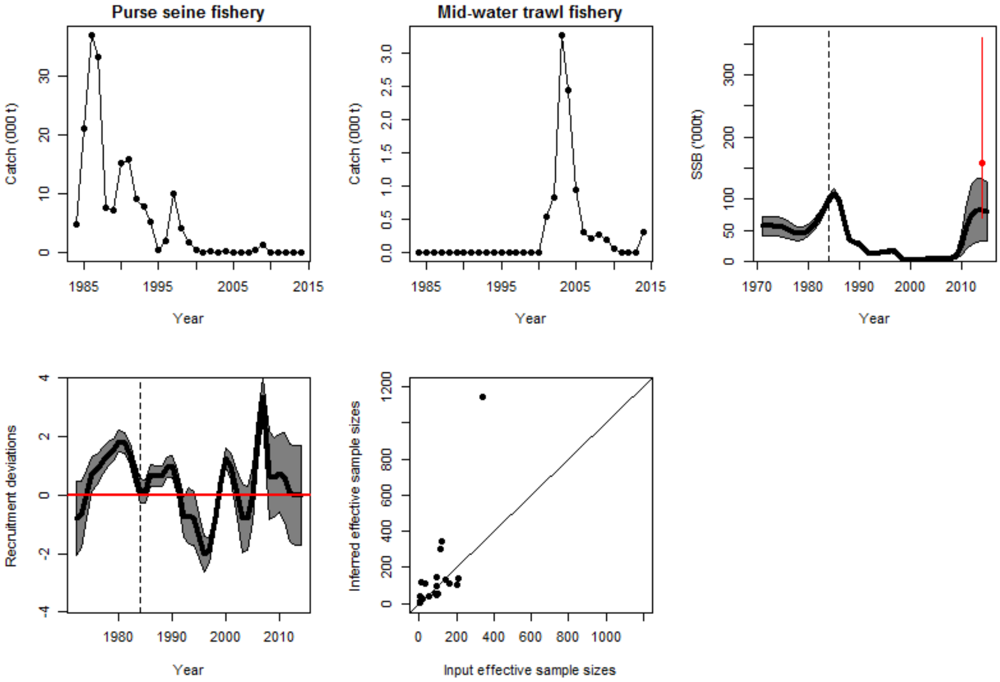


Figure 3. Estimates of selectivity-at-age and the time-series of fishing mortality (by fleet) for the four model variants (upper two rows on panels) and the time-series of spawning stock biomass by model variant (lower left panel). The results in this figure are based on the state-space assessment method.

(a) Dome-shaped*



(b) Dome-shaped**

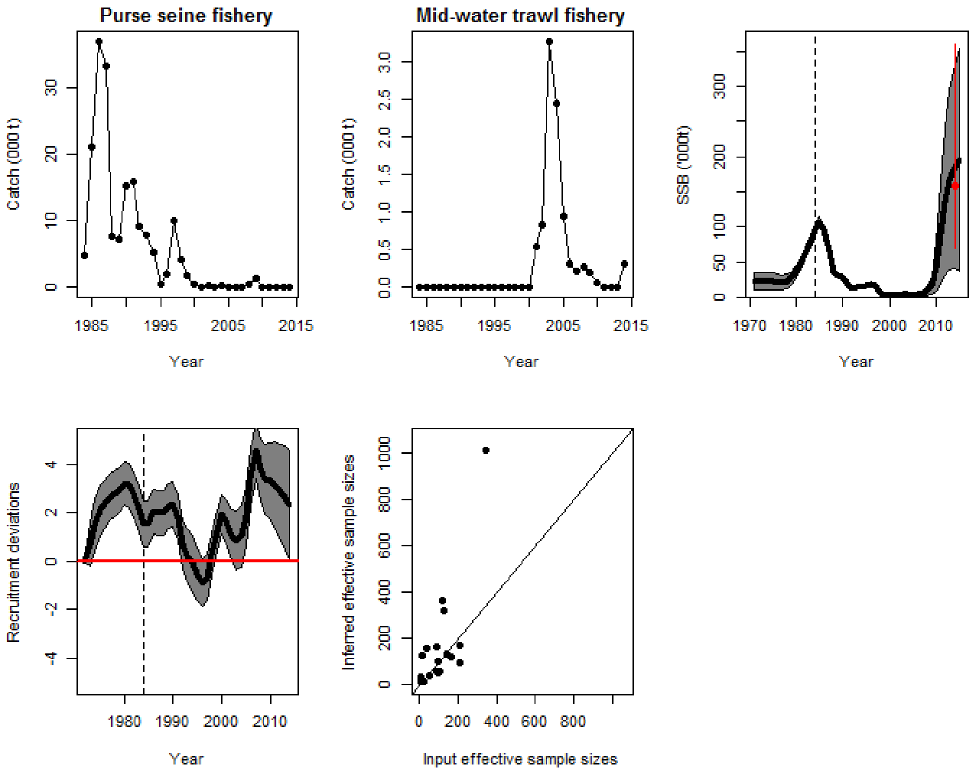


Figure 4. Fits to the catch data and the estimates of spawning stock biomass (data dots; model predictions lines; upper panels), along with the estimated recruitment residuals, and the inferred versus the input effective sample sizes (lower panels). The results in the figure pertain to the "dome-shaped*" and "dome-shaped**" model variants of the state-space assessment method.

(a) Dome-shaped*

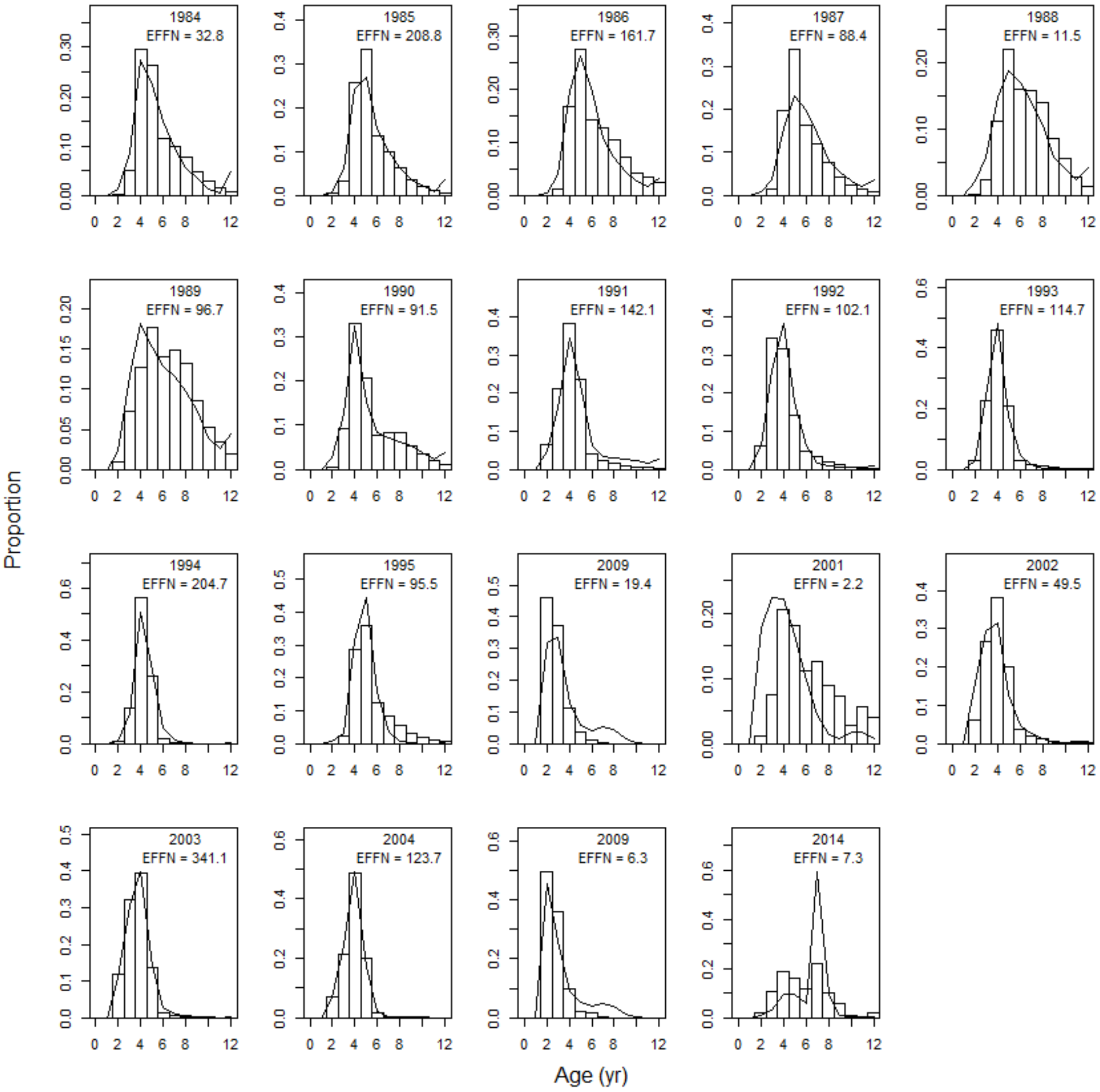
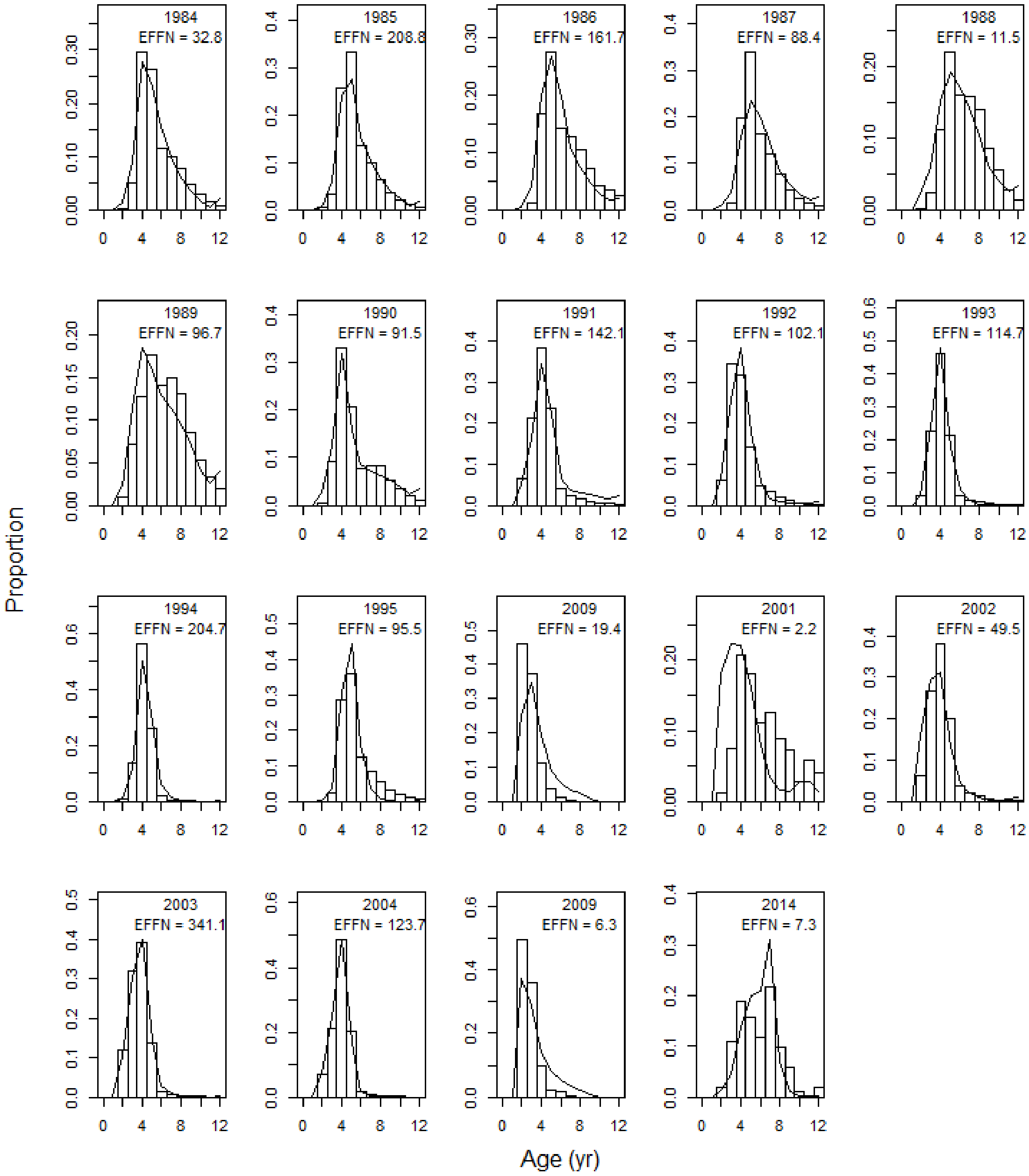


Figure 5. Observed (bars) and model-predicted (lines) catch age-composition data. The results in the figure pertain to the “dome-shaped*” and “dome-shaped**” model variants of the state-space assessment method. There are two panels for 2009 because age-composition data are available for both the mid-water trawl and purse-seine fisheries for those years (Table 3).

(b) Dome-shaped**



(Figure 5 Continued)