Age structured production model (ASPM) for U.S. South Atlantic Red Snapper (*Lutjanus campechanus*)

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Introduction

The SEDAR 41 data workshop developed time series data for U.S. South Atlantic Red Snapper landings, discards, and abundance. These data were fit with an age structured production model (ASPM) to provide insights into the relationship between removals and population abundance changes. The model code is programmed in AD Model Builder (ADMB), which uses a gradient optimizer for fitting model parameters. Details of the ASPM implementation are listed below and a technical description is included in Appendix 1.

Model Description

Age structured production models have existed since the advent of catch-at-age models in the mid-1980s (Fournier and Archibald 1982, Hilborn 1990, Kimura and Tagart 1982, Ludwig and Walters 1985, Megrey 1989). ASPMs have been used extensively for highly migratory pelagic species, where age collection can be difficult, and other stock assessment analyses as well (Cubillos et al. 2002, Geromont and Butterworth 1999, Nishida et al. 2001, Nishida and Rademeyer 2011, Porch 2003, Restrepo 1997, Restrepo and Legault 1998, Ricard and Basson 2002). ASPMs can be viewed as either a simplified version of statistical catch-at-age models or an extension of basic biomass production models (e.g. ASPIC). The primary advantage of ASPM over basic biomass production models is the incorporation of age structured dynamics into the population model (Butterworth and Rademeyer 2008, Punt et al. 2010, Radomski et al. 2005). The simplification from more advanced statistical catch-at-age models is due to the absence of any age or length composition data. Because no age or length data are used in an ASPM, then year class strength is expected to follow a simple two or three parameter production function (i.e. a stock-recruit function; Butterworth and Rademeyer 2008, Field et al. 2008). With this simplification, ASPMs have a greatly reduced number of parameters compared to a full statistical catch-at-age model. Of course with reduced parameters comes simplifying assumptions (e.g. fixed fleet selectivities).

A parameter analogy can be drawn from ASPM and biomass production models (e.g. ASPIC). In both models fishing mortality (*F*) values are determined for each year for each fleet. Also, catchability (*q*) parameters are estimated for each abundance index. For ASPIC models the production function is determined by logistic growth, defined by the *K* (carrying capacity) and *r* (intrinsic population growth rate) parameters. In ASPM, using a Beverton-Holt stock recruit function, the corresponding parameters are R_0 (virgin recruitment) and steepness (*h* - rate of recruitment increase), respectively. Both models have a parameter for estimating the starting condition of the population. In ASPIC this is the B_1/K parameter, while in this ASPM configuration it is modeled with an initial *F* value parameter (F_{init}).

The advantage of the ASPM over ASPIC is the treatment of the population as age structured. This is considered more realistic and allows for important age specific processes to be incorporated into the population model. Some of the more important age-specific processes include size/weight, maturity, selectivity, and natural mortality.

Data Description

The data inputs used for the ASPM follow the structure outlined in the data workshop report. Specifically, landings and discards were broken into three fleets, commercial handline (cH), headboat (HB), and general recreational (GR) (see details below). The ASPM used four abundance indices developed during the data workshop. These include a commercial handline CPUE index (1992-2009), headboat CPUE index (1976-2009), headboat discard CPUE index (2005-2014), and fishery-independent trap/video index (2010-2014). No age or length data were used in the ASPM. Life history information is fixed to values recommended by the data workshop.

<u>Landings Data</u>

Landings and discard information were input into the ASPM following the structure outlined in the data workshop report (Table 1). Units of the landings and discards match the units in which the data were collected from harvesters (see Table 1 heading).

Abundance Indices

The set of fishery dependent and independent abundance indices from the data workshop report were input into the ASPM. The error values (CVs) were also used in the ASPM (Table 2).

Selectivity

The selectivity configuration was an important part of an ASPM configuration. In this case we used the functions and values obtained from the base Beaufort Assessment Model (BAM) run. This consisted of 3 time blocks (1950-1991, 1992- 2009, and 2010-2014) for each of the separate landings fleets, discard fleets, and CVID index (Tables 3-5). A mixture of logistic (flat-topped) and double logistic (dome-shaped) functions were used to model selectivity for the various landings and discard fleets and CVID index (Tables 3-5).

Life History

Important life history data used in an ASPM includes age-specific quantities for weight, maturity, proportion female, fecundity, and natural mortality. Weight-at-age data is specific to the time block (during 20 inch minimum size limit or not) and fleet (discards or landings). The values used for Red Snapper are from either the data workshop report or the BAM base run. Those values are shown in Table 6.

Results

The ASPM was fit over a range of initial conditions by fixing the F_{init} parameter to values ranging from 0.001 up to 0.6. All model fits converged properly and no parameter estimates were on bounds. For simplicity, all indices were treated with a likelihood weight of 1 (i.e. no iterative re-weighting was done). When freely estimated, the F_{init} parameter was equal to 0.51. This value is quite high and does not result in reasonable estimates for the population, as shown in the results below.

The results indicated a switching behavior was occurring with the model estimates when F_{init} is set to values above 0.15. In the low F_{init} state the model results indicated a wide range of starting biomass levels that converge to nearly identical results after 1985, while the model runs with high F_{init} suggested a population that has been depleted for the entire time series, with variable terminal year results (Fig. 1). The low F_{init} model runs estimated a high steepness parameter and relatively lower R_0 parameter, while the high F_{init} model runs resulted in a range of steepness estimates and variable R_0 parameter estimates (Fig. 1).

The primary data being fit in ASPM were the index time series. The fits to these data are shown in Figures 2-5. The range of values used for the F_{init} parameter resulted in some changes to the fits to the commercial handline and headboat indices, but not much difference in the fits for the headboat discard and trap/video indices (Fig. 2-5).

As mentioned above, when F_{init} was freely estimated, the result was a value of 0.51. A total likelihood profile across values of F_{init} reveals that the higher values of F_{init} are favored by the model fits to the data (Fig. 6). However, the population estimates from those high F_{init} runs were not reasonable (see below). Examination of the negative log-likelihood values (re-scaled) indicated that different values of F_{init} were favored by different indices (Fig. 7). Close examination of this figure also suggests that there is a trade-off between the commercial handline and headboat index with respect to likelihood fits (Fig. 7).

Time series of biomass (B), spawning biomass (SSB), and fishing mortality (*F*) ratios are shown in Figures 8-10. The biomass time series clearly show the influence of F_{init} parameter values on the early years estimates and the switching behavior of results discussed above can be seen as well (Fig. 8-9). The *F* time series estimates also indicate two sets of solutions based on F_{init}, but also show remarkable consistency in all the post 1980 estimates (Fig. 10).

Discussion

As pointed out earlier, ASPMs depend on landings and index data. In most fisheries, as is the case for Red Snapper, landings information is usually known fairly well. This leaves the quality of the indices as the most important data input for an ASPM. Important properties of the indices include; (1) correlation or agreement among the indices for overlapping years, (2) overall length of the time series, and (3) amount of observation and process error in the indices. The ASPM, like all fisheries models, expects a relationship between landings and indices (i.e. fishing mortality is a driving influence on population fluctuations). If this is not the case, either in actuality or if masked by noisy data, then ASPM will provide poor estimates.

For this application of ASPM, the Red Snapper data raised a couple of concerns, including; (1) index time series that are relatively short and do not overlap with decades of removals by the fishery, including the time period of largest landings and (2) (slightly) uncorrelated and somewhat noisy indices. Some apparently noisy indices may actually be the results of large changes in year class strength. An ASPM will struggle to fit these types of indices because year class changes are forced to follow a stock-recruit curve (production function) without any deviation.

Despite the concerns mentioned above, the Red Snapper ASPM results were quite consistent in the terminal year estimates of stock status and other population measures.

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Table 1. Observed time series of landings (L) and discards (D) for commercial lines (cH), headboat (HB), and general recreational (GR) fleets. Commercial values are in units of 1000 lb whole weight. Recreational and discard values are in units of 1000 fish.

Year	cH.L	HB.L	GR.L	cH.D	HB.D	GR.D
1950	368.657	-	-	-	-	-
1951	499.765	-	-	-	-	-
1952	385.93	-	-	-	-	-
1953	398.279	-	-	-	-	-
1954	593.207	-	-	-	-	-
1955	493.315	12.501	24.035	-	-	-
1956	483.907	13.652	26.248	-	-	-
1957	867.291	14.803	28.46	-	-	-
1958	612.508	15.953	30.673	-	-	-
1959	657.736	17.104	32.885	-	-	-
1960	671.075	18.255	35.098	-	-	-
1961	796.374	19.908	38.276	-	-	-
1962	645.983	21.561	41.454	-	-	-
1963	488.789	23.214	44.633	-	-	-
1964	537.589	24.867	47.811	-	-	-
1965	558.108	26.52	50.989	-	-	-
1966	554.506	26.676	51.288	-	-	-
1967	725.503	26.831	51.587	-	-	-
1968	865.52	26.986	51.885	-	-	-
1969	538.19	27.142	52.184	-	-	-
1970	513.023	27.297	52.483	-	-	-
1971	457.393	29.995	57.67	-	-	-
1972	406.641	32.693	62.857	-	-	-
1973	296.56	35.391	68.044	-	-	-
1974	478.352	38.088	73.231	-	-	-
1975	600.79	40.786	78.418	-	-	-
1976	571.504	41.246	79.303	-	-	-
1977	596.339	41.707	80.187	-	-	-
1978	594.356	42.167	81.072	-	-	-
1979	420.936	42.627	81.957	-	-	-
1980	385.485	43.087	82.842	-	-	-
1981	378.759	36.031	93.458	-	-	1.641
1982	308.445	19.553	36.294	-	-	1.641
1983	316.818	30.698	68.469	-	-	1.641
1984	253.431	31.146	212.547	-	0.026	22.875
1985	250.824	50.336	288.971	-	0.041	23.713
1986	219.44	16.625	100.736	-	0.014	23.713
1987	191.701	24.996	47.373	-	0.02	23.713
1988	173.689	36.527	80.821	-	0.03	18.601
1989	266.942	23.453	97.147	-	0.019	7.172
1990	226.542	20.919	12.092	-	0.017	7.172
1991	143.546	13.857	34.717	-	0.011	7.172
1992	104.374	5.301	51.908	9.409	0.929	10.358
1993	220.153	7.347	11.326	8.028	1.287	25.215
1994	195.319	8.225	18.313	10.144	1.441	24.62
1995	177.312	8.826	13.482	10.113	1.546	18.829
1996	138.671	5.543	9.342	9.949	0.971	7.565
1997	110.595	5.77	34.238	10.748	1.011	6.132
1998	89.602	4.741	13.015	7.762	0.83	9.912
1999	93.595	6.836	39.579	6.548	1.197	60.203
2000	104.165	8.437	45.347	6.985	1.478	91.981
2001	196.697	12.028	31.587	7.268	2.107	74.986
2002	187.967	12.931	35.062	14.327	2.265	45.644
2003	138.342	5.706	25.977	4.019	0.999	58.952
2004	172.083	10.842	28.914	1.164	6.952	73.866
2005	129.7	8.907	29.443	4.885	3.654	26.956
2006	86.382	5.945	26.769	2.312	6.376	44.302
2007	114.973	6.889	17.646	6.613	26.598	106.662
2008	252.146	18.943	81.638	6.025	27.235	189.434
2009	362.386	21.507	54.666	6.944	21.211	88.991
2010	6.448	0.477	0.062	8.37	14.224	51.237
2011	*confidential*	*confidential*	0.062	15.241	11.796	9.543
2012	8.142	2.127	15.628	7.301	13.333	40.744
2013	31.6	1.52	7.588	7.335	13.321	23.938
2014	65.443	5.904	28.186	10.263	13.284	81.499

Table 2. Observed indices of abundance and CVs from commercial line (cH), headboat (HB), combined chevron trap and video (CVID), and headboat discard (HB.D).

Year	cH	cH CV	HB	HB CV	CVID	CVID CV	HB.D	HB.D CV
1976	-	-	2.37	0.2	-	-	-	-
1977	-	-	2.16	0.2	-	-	-	-
1978	-	-	2.13	0.2	-	-	-	-
1979	-	-	2.23	0.2	-	-	-	-
1980	-	-	1.45	0.2	-	-	-	-
1981	-	-	2.95	0.2	-	-	-	-
1982	-	-	1.2	0.2	-	-	-	-
1983	-	-	1.64	0.2	-	-	-	-
1984	-	-	1.42	0.2	-	-	-	-
1985	-	-	2.07	0.2	-	-	-	-
1986	-	-	0.48	0.2	-	-	-	-
1987	-	-	0.58	0.2	-	-	-	-
1988	-	-	0.56	0.2	-	-	-	-
1989	-	-	0.9	0.2	-	-	-	-
1990	-	-	0.87	0.2	-	-	-	-
1991	-	-	0.69	0.2	-	-	-	-
1992	-	-	0.08	0.2	-	-	-	-
1993	1.09	0.2	0.16	0.2	-	-	-	-
1994	0.89	0.2	0.26	0.2	-	-	-	-
1995	0.89	0.2	0.28	0.2	-	-	-	-
1996	0.61	0.2	0.25	0.2	-	-	-	-
1997	0.59	0.2	0.27	0.2	-	-	-	-
1998	0.66	0.2	0.24	0.2	-	-	-	-
1999	0.8	0.2	0.29	0.2	-	-	-	-
2000	0.74	0.2	0.41	0.2	-	-	-	-
2001	1.27	0.2	0.76	0.2	-	-	-	-
2002	1.38	0.2	0.88	0.2	-	-	-	-
2003	1.04	0.2	0.52	0.2	-	-	-	-
2004	1.42	0.2	0.76	0.2	-	-	-	-
2005	1.19	0.2	0.76	0.2	-	-	0.56	0.3
2006	0.6	0.2	0.43	0.2	-	-	0.41	0.37
2007	0.67	0.2	0.44	0.2	-	-	2.02	0.17
2008	1.22	0.2	1.71	0.2	-	-	1.39	0.21
2009	1.94	0.2	1.81	0.2	-	-	0.63	0.27
2010	-	-	-	-	0.9	0.26	0.56	0.3
2011	-	-	-	-	0.66	0.23	0.41	0.37
2012	-	-	-	-	1.1	0.18	2.02	0.17
2013	-	-	-	-	0.87	0.2	1.39	0.21
2014	-	-	-	-	1.47	0.17	0.63	0.27

Table 3. Selectivity at age for MARMAP chevron traps (CVT), commercial handlines (cH), headboat (HB), and general recreational (GR) landings (L) and discards (D). For time-varying selectivities, values shown are from selectivity block 1 (1950-1991).

Age	CVT	cH.L	HB.L	GR.L	cH.D	HB.D	GR.D
1	0.044	0.014	0.049	0.049	0.987	1	1
2	0.585	0.479	0.66	0.66	1	0.765	0.765
3	0.977	0.984	1	1	0.77	0.333	0.333
4	0.999	1	0.899	0.899	0.436	0.098	0.098
5	1	1	0.75	0.75	0.196	0.025	0.025
6	1	1	0.586	0.586	0.078	0.006	0.006
7	1	1	0.428	0.428	0.029	0.001	0.001
8	1	1	0.295	0.295	0.011	0	0
9	1	1	0.194	0.194	0.004	0	0
10	1	1	0.123	0.123	0.001	0	0
11	1	1	0.123	0.123	0	0	0
12	1	1	0.123	0.123	0	0	0
13	1	1	0.123	0.123	0	0	0
14	1	1	0.123	0.123	0	0	0
15	1	1	0.123	0.123	0	0	0
16	1	1	0.123	0.123	0	0	0
17	1	1	0.123	0.123	0	0	0
18	1	1	0.123	0.123	0	0	0
19	1	1	0.123	0.123	0	0	0
20	1	1	0.123	0.123	0	0	0

Table 4. Selectivity at age for MARMAP chevron traps (CVT), commercial handlines (cH), headboat (HB), and general recreational (GR) landings (L) and discards (D). For time-varying selectivities, values shown are from selectivity block 2 (1992-2009).

Age	CVT	cH.L	HB.L	GR.L	cH.D	HB.D	GR.D
1	0.044	0.001	0.001	0.004	0.987	1	1
2	0.585	0.026	0.031	0.062	1	0.765	0.765
3	0.977	0.426	0.67	0.525	0.77	0.333	0.333
4	0.999	0.954	1	1	0.436	0.098	0.098
5	1	0.998	0.77	0.904	0.196	0.025	0.025
6	1	1	0.526	0.7	0.078	0.006	0.006
7	1	1	0.327	0.494	0.029	0.001	0.001
8	1	1	0.19	0.322	0.011	0	0
9	1	1	0.105	0.197	0.004	0	0
10	1	1	0.057	0.115	0.001	0	0
11	1	1	0.057	0.066	0	0	0
12	1	1	0.057	0.037	0	0	0
13	1	1	0.057	0.02	0	0	0
14	1	1	0.057	0.02	0	0	0
15	1	1	0.057	0.02	0	0	0
16	1	1	0.057	0.02	0	0	0
17	1	1	0.057	0.02	0	0	0
18	1	1	0.057	0.02	0	0	0
19	1	1	0.057	0.02	0	0	0
20	1	1	0.057	0.02	0	0	0

Table 5. Selectivity at age for MARMAP chevron traps (CVT), commercial handlines (cH), headboat (HB), and general recreational (GR) landings (L) and discards (D). For time-varying selectivities, values shown are from selectivity block 3 (2010-2014).

Age	CVT	cH.L	HB.L	GR.L	cH.D	HB.D	GR.D
1	0.044	0.007	0.019	0.004	0.036	0.695	0.695
2	0.585	0.066	0.356	0.028	0.202	0.866	0.866
3	0.977	0.405	1	0.183	0.631	0.979	0.979
4	0.999	0.867	0.909	0.635	0.92	1	1
5	1	0.984	0.73	0.931	0.987	0.924	0.924
6	1	0.998	0.557	0.991	0.998	0.775	0.775
7	1	1	0.408	0.999	1	0.596	0.596
8	1	1	0.288	1	1	0.426	0.426
9	1	1	0.198	1	1	0.288	0.288
10	1	1	0.133	1	1	0.186	0.186
11	1	1	0.133	1	1	0.117	0.117
12	1	1	0.133	1	1	0.073	0.073
13	1	1	0.133	1	1	0.044	0.044
14	1	1	0.133	1	1	0.027	0.027
15	1	1	0.133	1	1	0.016	0.016
16	1	1	0.133	1	1	0.01	0.01
17	1	1	0.133	1	1	0.006	0.006
18	1	1	0.133	1	1	0.004	0.004
19	1	1	0.133	1	1	0.002	0.002
20	1	1	0.133	1	1	0.001	0.001

Table 6. Life-history characteristics at age, including natural mortality, weight (discards, landings, and landings under 20 inch min size limit), proportion females mature, proportion female, fecundity/batch, and batch/yr at age.

Age	Nat. mortality	Wgt Discards (lb)	Wgt Landings (lb)	Wgt Land 20 Limit (lb)	Fem. Maturity	Proportion Female	Fecundity/Batch (millions)	Batches/Year
1	0.595	1.2	1.5	3.2	0.43	0.5	3e-04	22
2	0.364	3.1	3.4	5.1	0.73	0.5	0.0014	45
3	0.271	5.6	5.9	7.2	0.91	0.5	0.0036	63
4	0.222	8.3	8.5	9.3	0.97	0.5	0.0068	77
5	0.193	11	11.1	11.4	0.99	0.5	0.0106	88
6	0.174	13.5	13.5	13.3	1	0.5	0.0146	97
7	0.162	15.7	15.7	15.2	1	0.5	0.0185	104
8	0.153	17.5	17.6	16.9	1	0.5	0.0222	109
9	0.146	19.1	19.3	18.4	1	0.5	0.0254	114
10	0.142	20.4	20.7	19.7	1	0.5	0.0283	117
11	0.138	21.5	21.9	20.9	1	0.5	0.0306	120
12	0.135	22.3	22.8	21.9	1	0.5	0.0326	122
13	0.133	23	23.6	22.8	1	0.5	0.0343	123
14	0.132	23.6	24.3	23.6	1	0.5	0.0356	125
15	0.13	24	24.8	24.2	1	0.5	0.0367	126
16	0.129	24.4	25.2	24.8	1	0.5	0.0375	126
17	0.129	24.7	25.6	25.3	1	0.5	0.0382	127
18	0.128	24.9	25.9	25.7	1	0.5	0.0388	128
19	0.128	25.1	26.1	26.1	1	0.5	0.0392	128
20	0.127	25.2	26.3	26.4	1	0.5	0.0396	128

Figure 1. ASPM estimates and parameter values for a range of F_{init} values ranging from 0.001 to 0.6.

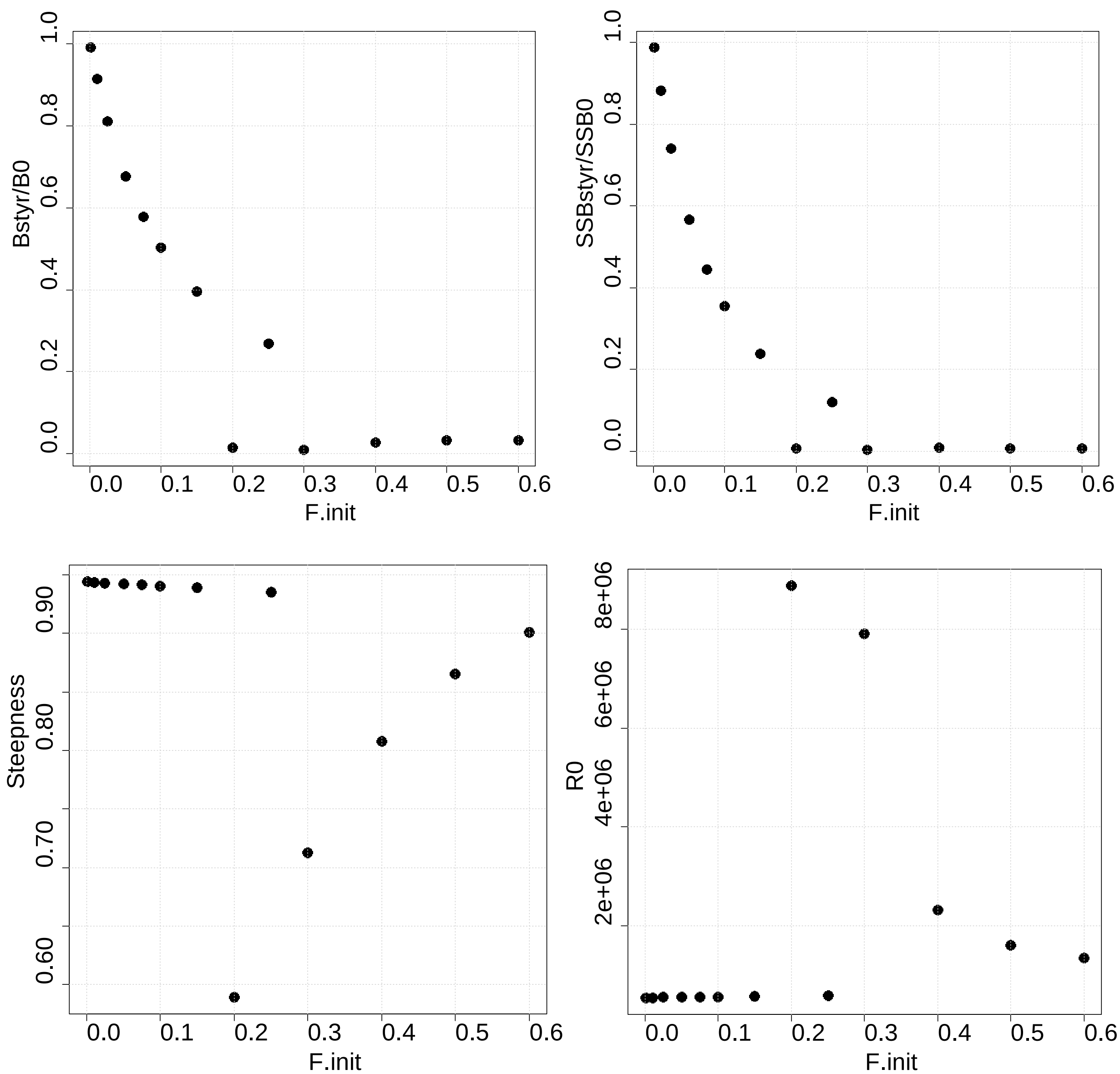


Figure 2. ASPM estimate (colored lines) fits to commercial handline CPUE index of abundance (open circles) for a range of F_{init} values ranging from 0.001 to 0.6.

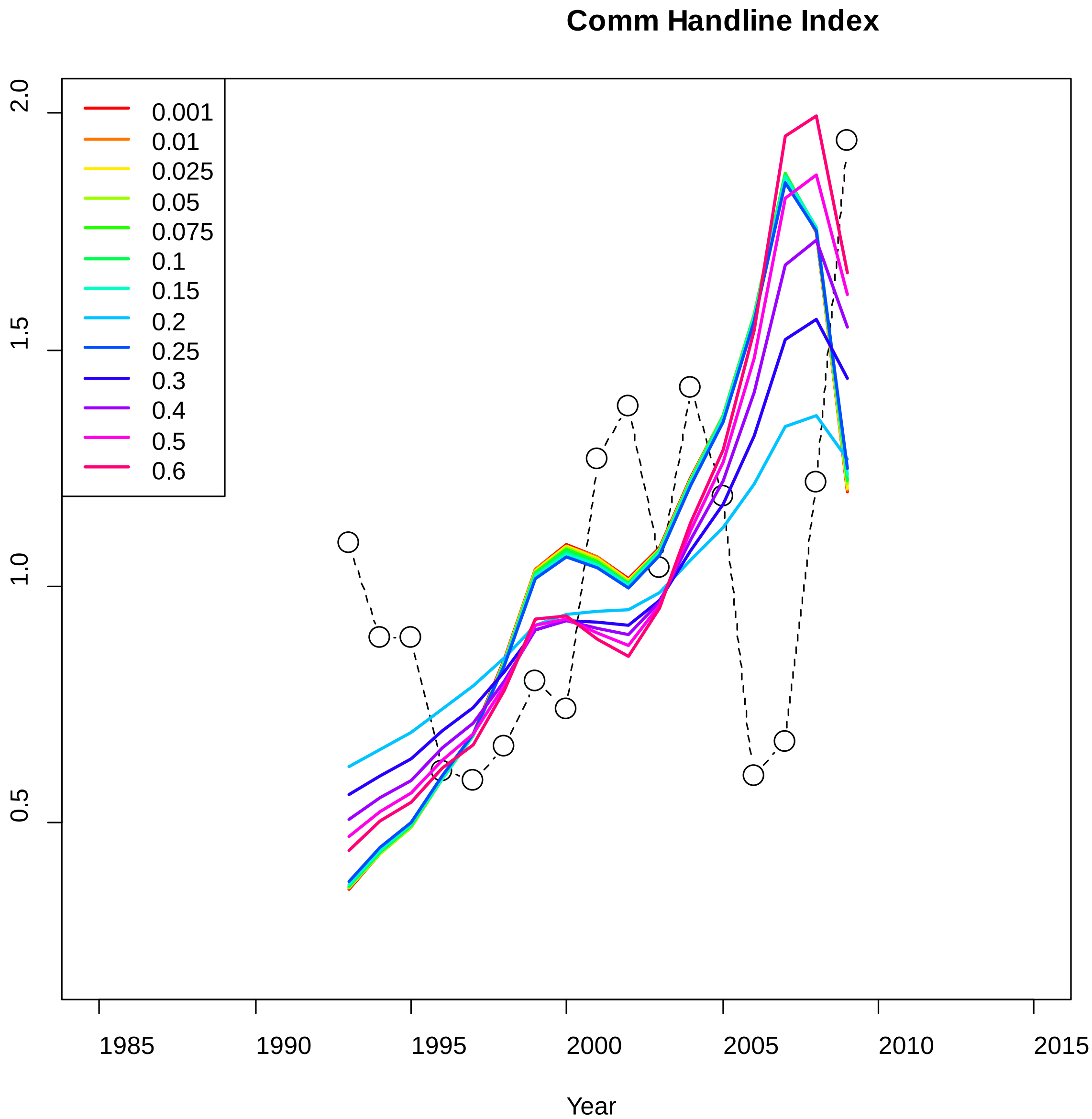


Figure 3. ASPM estimate (colored lines) fits to headboat CPUE index of abundance (open circles) for a range of F_{init} values ranging from 0.001 to 0.6.

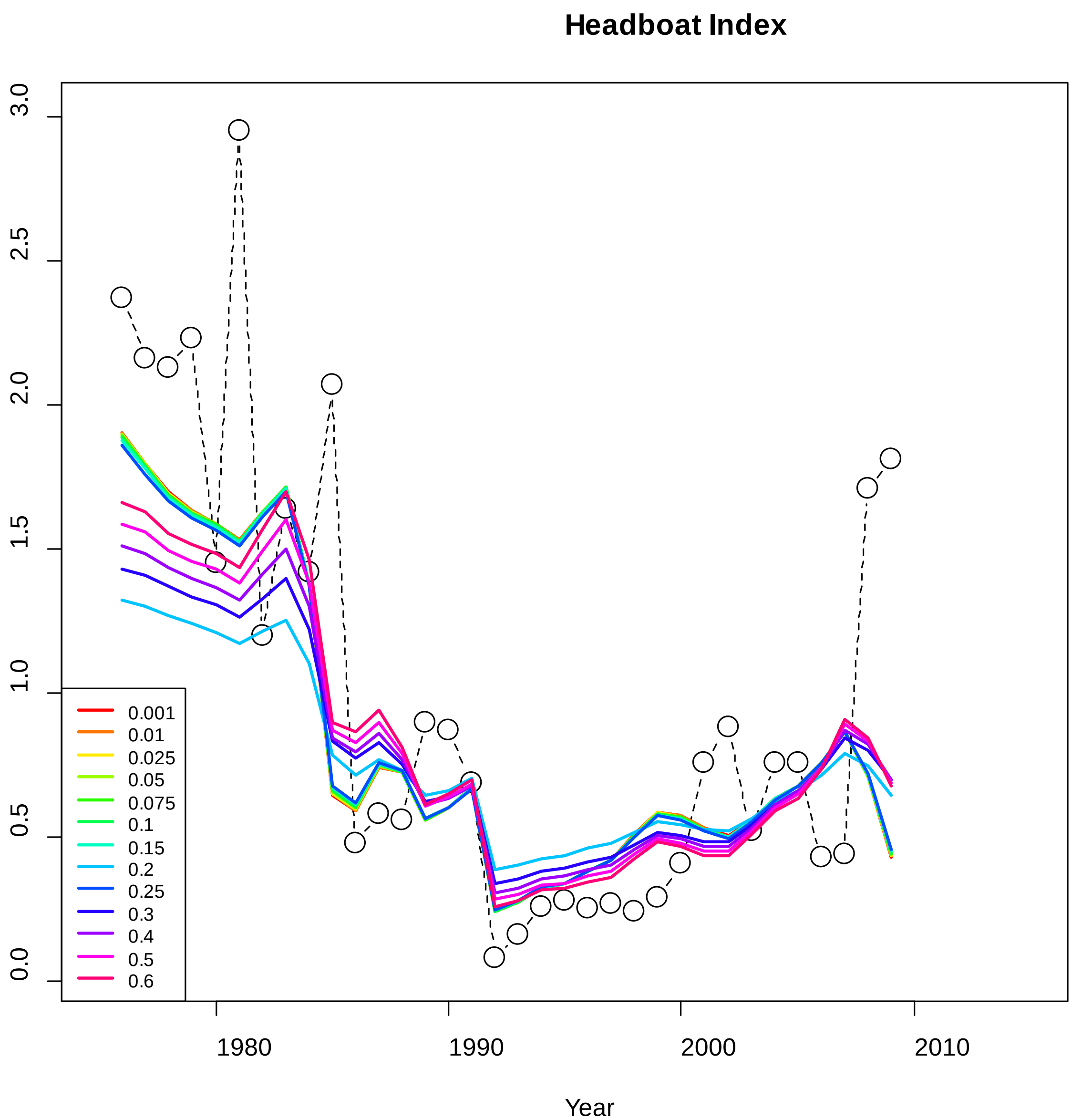


Figure 4. ASPM estimate (colored lines) fits to headboat discard CPUE index of abundance (open circles) for a range of F_{init} values ranging from 0.001 to 0.6.

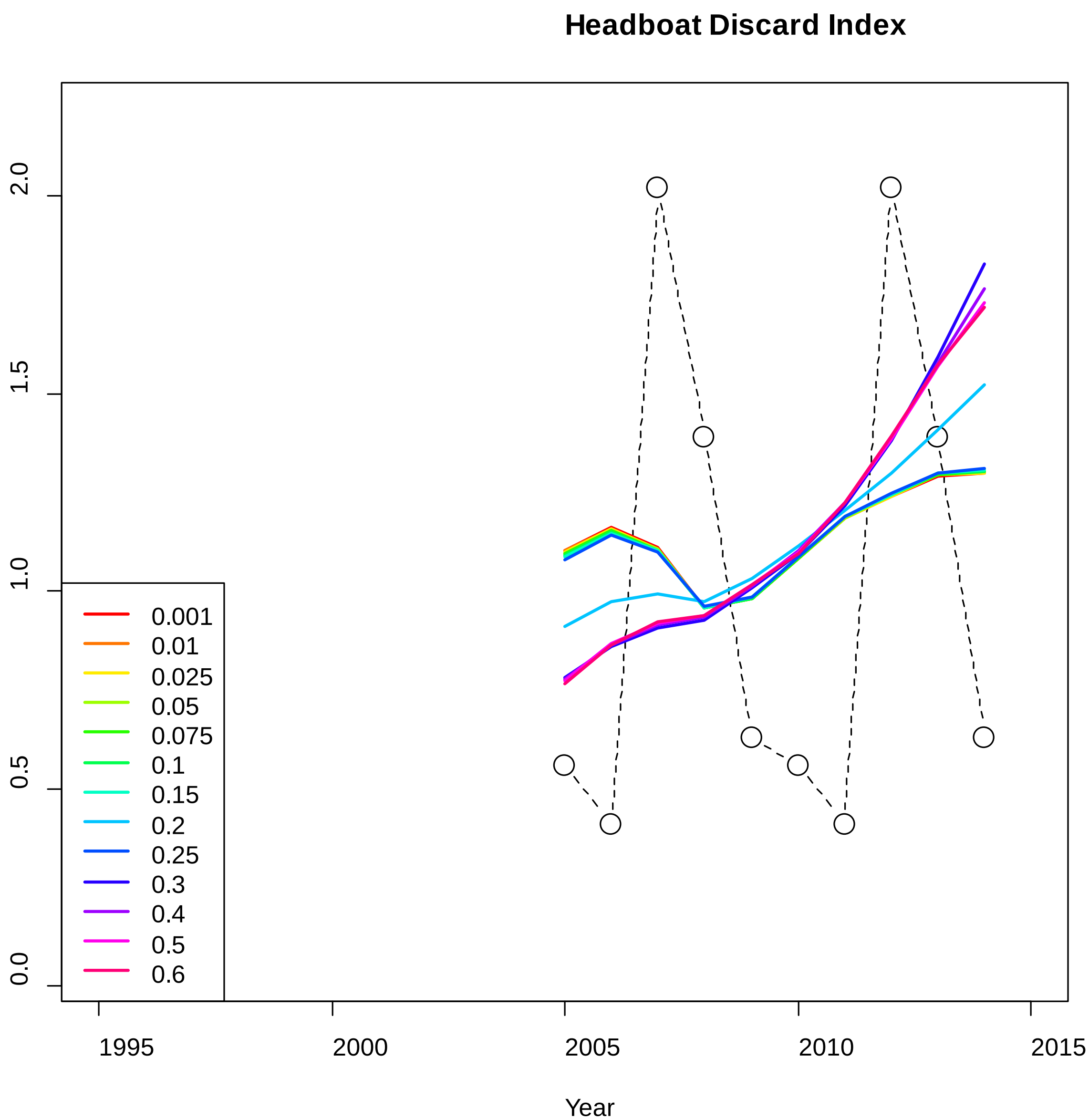


Figure 5. ASPM estimate (colored lines) fits to chevron trap/video CPUE index of abundance (open circles) for a range of F_{init} values ranging from 0.001 to 0.6.

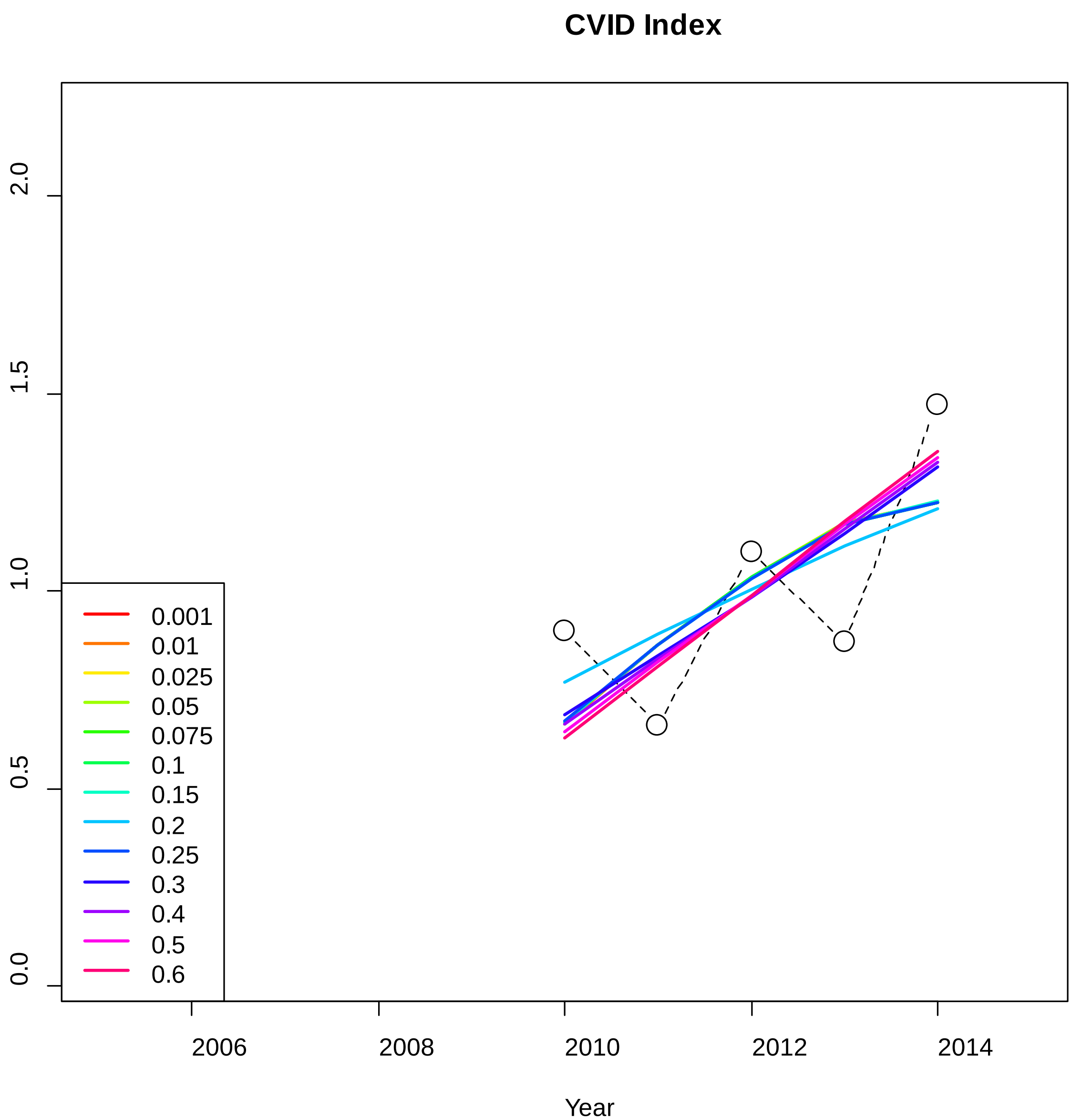


Figure 6. ASPM re-scaled total negative log-likelihood values for a range of F_{init} values ranging from 0.001 to 0.6.

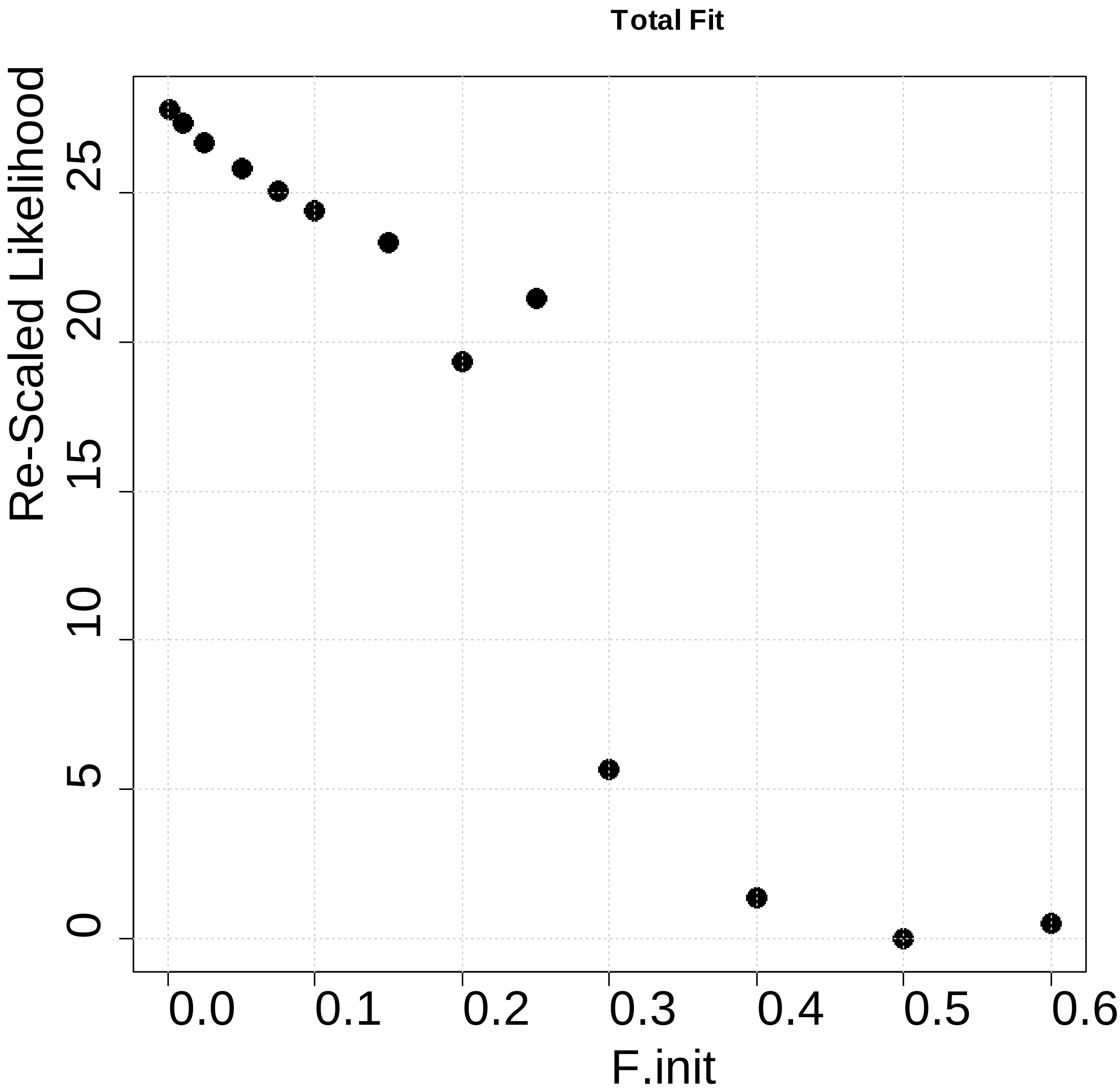


Figure 7. ASPM re-scaled negative log-likelihood values for CPUE abundance index fits for a range of F_{init} values ranging from 0.001 to 0.6.

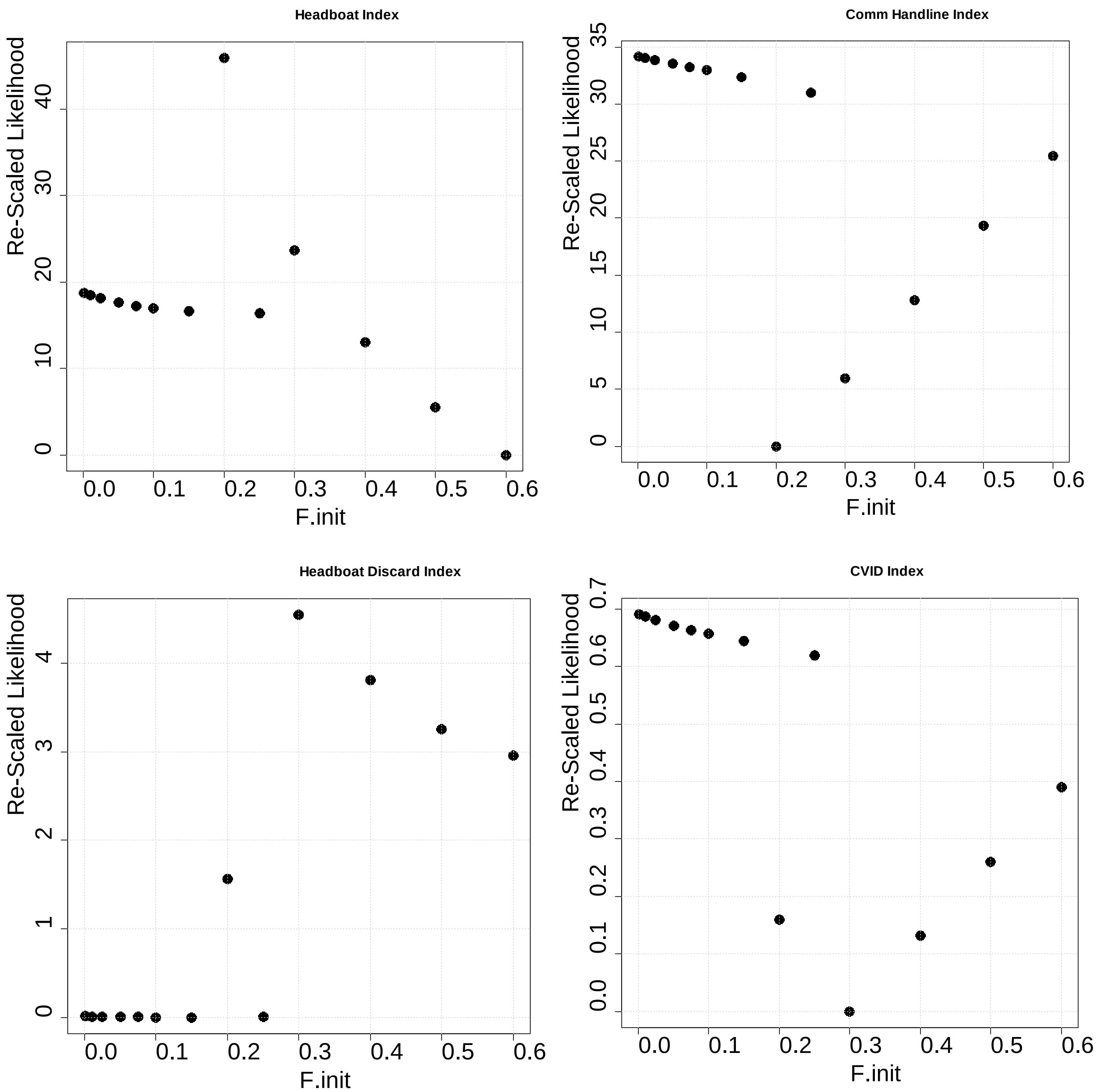


Figure 8. ASPM time series estimates of total biomass (B) relative to virgin biomass (B_0) for a range of F_{init} values ranging from 0.001 to 0.6. Dashed line at 0.4 represents an approximation of B_{MSY} under typical Beverton-Holt dynamics.

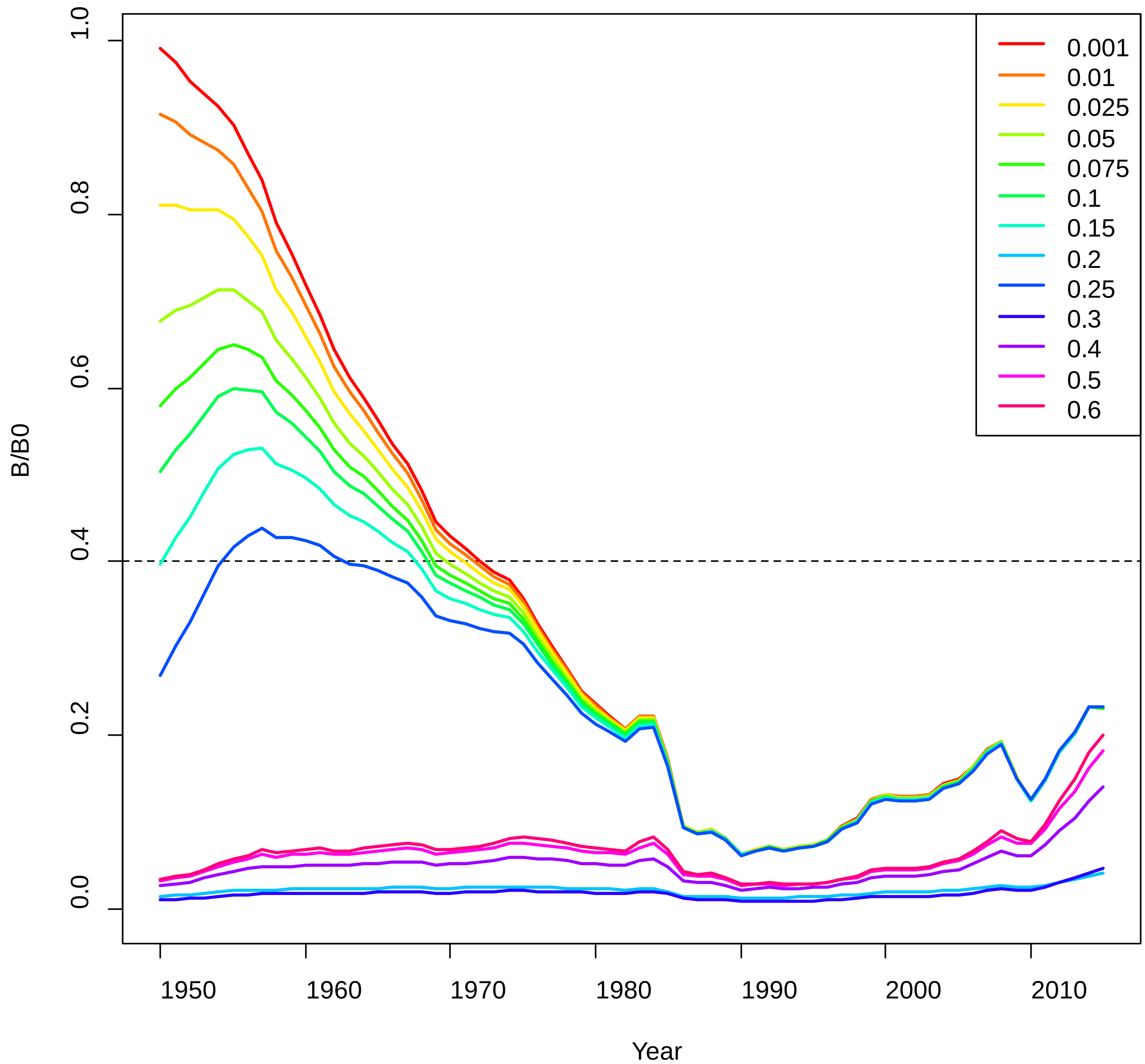


Figure 9. ASPM time series estimates of spawning biomass (SSB) relative to spawning biomass at maximum sustainable yield (SSB_{msy}) for a range of F_{init} values ranging from 0.001 to 0.6.

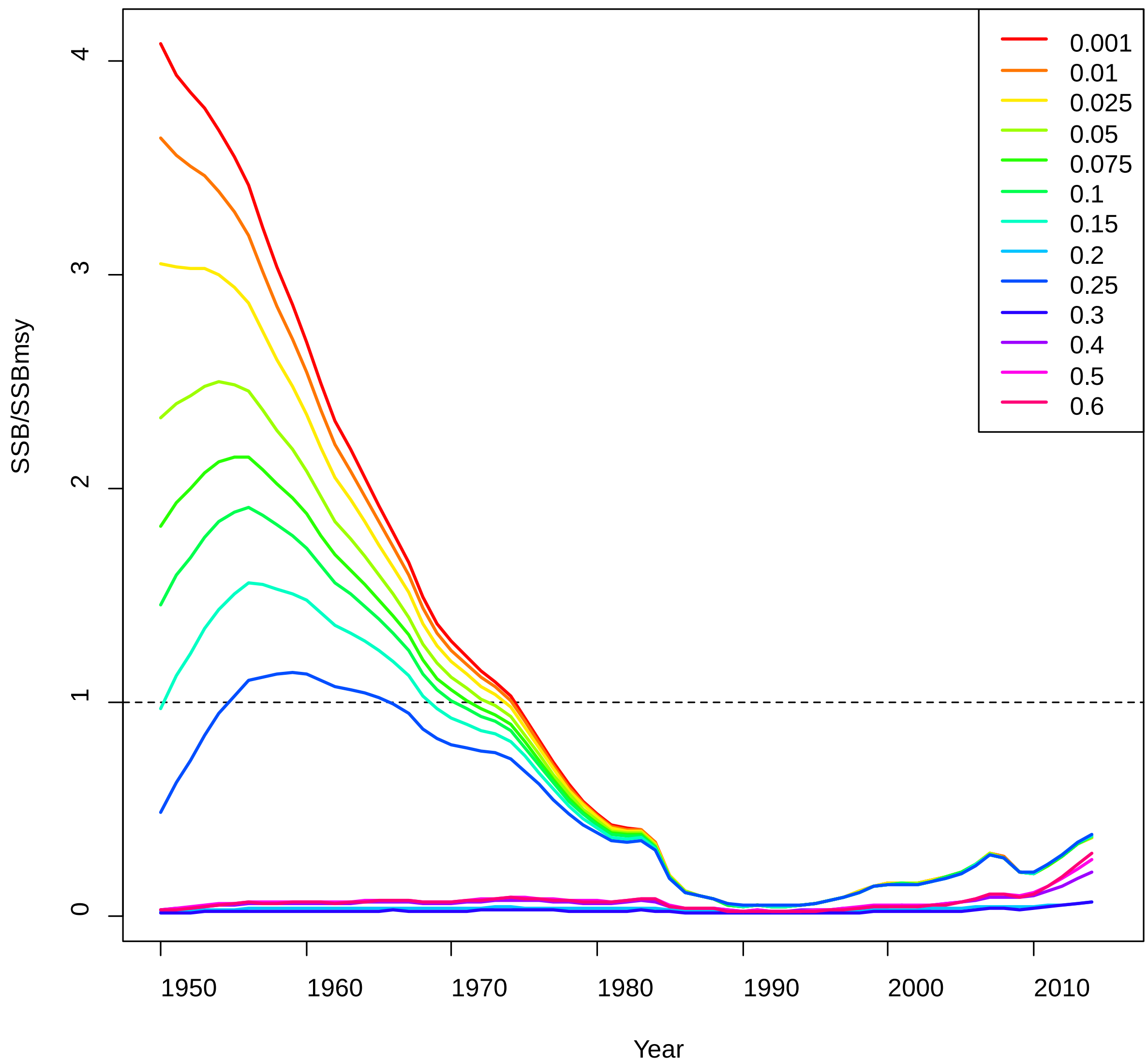
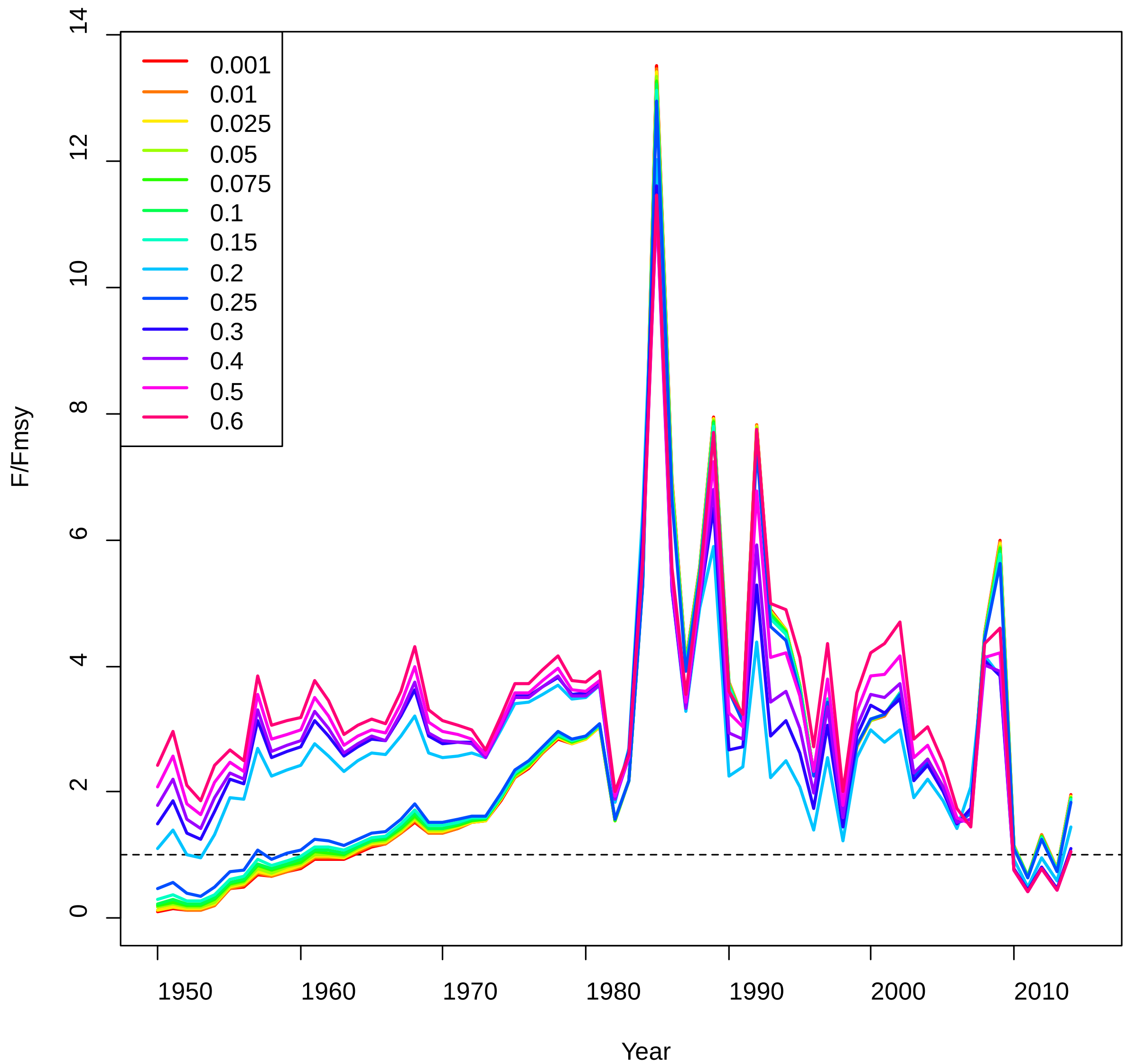


Figure 10. ASPM time series estimates of fishing mortality (*F*) relative to fishing mortality at maximum sustainable yield (F_{msy}) for a range of F_{init} values ranging from 0.001 to 0.6.



Appendix 1. Age structured production model (ASPM) technical documentation.

Model description

ASPM is fundamentally an age-structured population model with birth and death processes. New biomass is acquired through growth and recruitment, while abundance of existing cohorts experiences exponential decay from fishing and natural mortality. The population is assumed closed to immigration and emigration. The model follows an annual time step for n years, $y_1,\ldots, y_n$, and it includes A age classes 1-A+, where the oldest age class A+ allows for the accumulation of fish (i.e., plus group). The youngest age class (recruits) is typically age-1 fish produced by the previous year's spawners, but it could instead be age-0 fish produced by the current year's spawners (and consequently with A+1 age classes). Subsequent descriptions assume age-1 is the youngest age class.

Initialization

ASPM computes initial abundance at age, i.e., abundance in the first modeled year as an equilibrium age structure based on natural and initial fishing mortality (F_{init}), where F_{init} is estimated, either freely or with a prior or else fixed at user-specified values.

Life History Information

All the life history information is treated as input into the model. This includes weight at age, which may be derived from length at age, natural mortality, which may be treated as constant or age specific, sex ratio at age, and maturity at age, which may also be a function of length. Fecundity at age may also be included and thus, ASPM is flexible in treating the reproductive output measure, often referred to as spawning stock (S).

Recruitment

Expected annual recruitment (R_y) is computed from either the Beverton-Holt or Ricker spawner-recruit model. In ASPM, the Beverton-Holt formulation is,

$$R_{y+1} = \frac{0.8 R_0 h S_y}{0.2 R_0 \varphi_0 (1-h) + S_h (h - 0.2)}$$

where R_0 is virgin recruitment, h is steepness, and φ_0 is the unfished spawners per recruit. The analogous Ricker formulation is,

$$R_{y+1} = \frac{S_y}{\varphi_0} \exp\left(h\left(1 - \frac{S_y}{R_0\varphi_0}\right)\right)$$

Under Beverton-Holt, the expected equilibrium recruitment (R_{eq}) associated with any F is,

$$R_{eq} = \frac{R_0[4h\varphi_F - (1-h)\varphi_0]}{(5h-1)\varphi_F}$$

and under Ricker,

$$R_{eq} = \frac{R_0}{\tau_F}\left(1 + \frac{\log(\tau_F)}{h}\right)$$

where φ_F is spawners per recruit given F, and $\tau_F = \varphi_F/\varphi_0$ is the spawning potential ratio.

In the first year $N_{1,1} = R_{eq}$, based on F_{init}. Computation of R_{eq}, along with the mortality schedule, implies an equilibrium age structure, which would apply to calculations of the initialization (described above) as well as calculations of biological reference points (described below).

Selectivity

In ASPM, selectivity is modeled as a function of age. Selectivity at age ranges on the interval [0,1] and can be modeled for three different types of data: landings, discards, and indices. Because no age or length data is used for ASPM, selectivity has to be fixed. It may be fixed by entering values of selectivity at each age, or through a parametric approach. The parametric approach has the benefit of allowing easy exploration of alternate selectivity assumptions. Parametric functions used in ASPM are similar to those used in other stock assessment models, such as SS (Methot and Wetzel, 2013) or BAM (Williams and Shertzer, 2015).

Fishing

For each fleet being modeled, the ASPM estimates a separate full fishing mortality rate for each year of the time series ($F_{(f,d),y}$), with landings (denoted by subscript f) and discards (denoted by subscript d) treated as distinct fleets.

Age-specific rates are computed as the product of full F and selectivity (s) at age (i.e., $F_{(f,d),a,y} = s_{(f,d),a,y}F_{(f,d),y}$). Then, the across-fleet annual F_y is represented by apical F, computed as the maximum of F at age summed across fleets,

$$F_{a,y} = \sum_{(f,d)} F_{(f,d),a,y}$$

$$F_y = \max(F_{a,y})$$

Landings and Discards

In ASPM, landings (L) and discards (D) are treated as separate fleets (f or d, respectively). The numbers at age for any of these fleets are predicted using the Baranov catch equation,

$$(L_N \text{ or } D_N)_{(f,d),a,y} = \frac{F_{(f,d),a,y}}{Z_{a,y}} N_{a,y}\left[1 - \exp(-Z_{a,y})\right]$$

where $Z_{a,y} = M_a + F_{a,y}$ [summed across (f,d)] is total mortality at age and $N_{a,y}$ is annual abundance at age. Then, landings or discards at age in weight (L_W or D_W) are calculated multiplying (L_N or D_N) by the fleet specific weight at age. Annual totals are then just the sum across all ages (a) in year (y).

Stock Dynamics

Abundance of recruits ($N_{1,y}$) is described above in the section titled Recruitment. Abundance of each subsequent age at the start of each year is computed assuming exponential decay,

$$N_{a+1,y+1} = N_{a,y}\exp(-Z_{a,y}) \quad \forall_a \in (1 \ldots A-1)$$

$$N_{A,y+1} = N_{A-1,y}\exp(-Z_{A-1,y}) + N_{A,y}\exp(-Z_{A,y})$$

In addition, ASPM can compute abundance later in the year,

$$N'_{a,y} = N_{a,y}\exp(-t_{\text{index}}Z_{a,y})$$

for matching observed indices of abundance. In this calculation, t_{index} represents the fraction of the year over which to apply total mortality, most typically t_{index} = 0.5 for calculating mid-year abundance. Similarly, ASPM computes abundance at the time of peak spawning,

$$N''_{a,y} = N_{a,y}\exp(-t_{\text{spawn}}Z_{a,y})$$

to derive spawning stock. Here, t_{spawn} represents the fraction of the year when peak spawning occurs (e.g., $t_{\text{spawn}} = 0.25$ reflects peak spawning at the end of March).

Indices of Abundance

Predicted indices ($U_{u,y}$) for each index (u) are computed from numbers at age, scaled to the relevant portion of the age structure by selectivity (s). A predicted index could additionally be computed in weight, if the observed index is measured in weight.

$$U_{u,y} = \begin{cases} \hat{q}_{u,y} \sum_a s_{u,a} N'_{a,y} & : \text{ if in numbers} \\ \hat{q}_{u,y} \sum_a s_{u,a} w_a N'_{a,y} & : \text{ if in weight} \end{cases}$$

Catchability ($q_{u,y}$) scales indices of abundance to the estimated population at large. For most applications of ASPM, catchability is assumed to be constant across time. Variable catchability could be considered, but the parameters would likely be inestimable, suggesting the better course of action for time varying catchability would be to modify the observed index values to account for the changes in catchability.

Fitting Criteria

Observed landings can be supplied in numbers or in weight for any given fleet. For fitting landings data, ASPM uses the corresponding prediction ($L_{(N \text{ or } W)}$ or $D_{(N \text{ or } W)}$), computed such that units of predictions and observations match. The landings contribution (Λ^L) to the total objective function is

$$\Lambda^L = \sum_f \sum_y \frac{\left[\log\left((L_{f,y} + \epsilon)/(\breve{L}_{f,y} + \epsilon)\right)\right]^2}{2\left(\sigma^L_{f,y}\right)^2}$$

where $\epsilon = 1e^{-5}$ to prevent the optimization procedure from attempting to compute the log of zero (an undefined value), and where $\sigma^L_{f,y}$ are standard deviations in log space. These standard deviations are computed as

$$\sigma^L_{f,y} = \sqrt{\log\left(1 + \left(CV^L_{f,y}/\omega^L_f\right)^2\right)}$$

where $CV_{f,y}^{L}$ are user-supplied coefficients of variation in arithmetic space and ω_f^L are user-supplied weights. Analogous contributions to the total objective function are computed for discards (Λ^D) and indices of abundance (Λ^U).

Biological Reference Points

Biological reference points (benchmarks) are calculated based on maximum sustainable yield (MSY) estimates from the spawner-recruit model. These benchmarks include MSY, fishing mortality rate at MSY (F_{MSY}), dead discards at MSY (D_{MSY}), and spawning stock at MSY (SSB_{MSY}). The point of maximum yield is identified from the spawner-recruit curve and parameters describing growth, natural mortality, maturity, and selectivity. The value of F_{MSY} is the F that maximizes equilibrium landings (i.e., MSY). The values of D_{MSY} and SSB_{MSY} are those that correspond to F_{MSY}.

The MSY-based benchmarks and proxies are conditional on the fixed selectivity functions. For computation of benchmarks, three composite selectivities are computed from the terminal year of the assessment: 1) selectivity associated with landings, 2) selectivity associated with dead discards, and 3) the sum of the previous two, which describes total fishing mortality and has a peak value of one. The composite selectivities are F-weighted average selectivities across fleets, with F from each fleet estimated as the full F averaged over the last X years of the assessment. Typically, $X = 3$ years.

References

Methot, R.D. and C.R. Wetzel. 2013. Stock synthesis: A biological and statistical framework for fish stock assessment and fishery management. Fisheries Research 142:86-99.

Williams, E.H. and K.W. Shertzer. 2015. Technical documentation of the Beaufort Assessment Model (BAM). NOAA Tech. Memo. NMFS-SEFSC-671.