Benchmarks and Estimated Status from a 1-fleet VPA projection for Red snapper (*Lutjanus campechanus*)

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Methods

A 1-fleet, tuned VPA was implemented in the following manner: total catch at age (CAA) was comprised of directed catch (Handline, Longline, and Recreational), discards, and shrimp bycatch. Modeled ages were 0-15+ or 1-15+. Natural mortality at age was: "low M case" [M_0=1.0, M_1=0.6, M_{2-15+}=0.1] or "high M case" [M_0=0.5, M_1=0.3, M_{2-15+}=0.1]. A moderate penalty was imposed to link selectivities ($s_{a,y}$) in the final 3 years. The estimate of annual fishing on the oldest age group ($F_{15+,y}$) was constrained to be equal to the estimate of $F_{14,y}$ for all years. Five regional indices (units) were used for tuning, where the region was Gulfwide, Eastern Gulf, or Western Gulf: MRFSS (numbers), Video (numbers), Larval (reproductive biomass—used as index of SSB), Fall Trawl Survey (numbers), Summer Trawl Survey (numbers). For cases where the modeled age of recruitment was 1, the Fall Trawl Survey was not used as it indexes age 0 fish. All indices were given equal weighting. This VPA configuration was bootstrapped 200 times, where index-specific residuals were drawn at random, with replacement, and added to the fitted values (i.e., the non-parametric bootstrap option). A variety of projection scenarios were explored, but the basic projection set up was consistent with respect to the following:

The VPA estimates of fishing mortality at age and year, and estimated abundance at age and year, were used in a set of factorial projections for the years 2004-2032. The following specifications were common to all projections:

- a geometric mean of selectivity in the last 3 years (2001-2003) was specified
- the last 3 years of recruitments (2001-2003) were replaced with values predicted from the fitted Beverton-Holt
- F in 2004 was set to the estimate for 2003

The factors considered in the projection were:

1. region (Gulfwide, Eastern Gulf, Western Gulf)
2. age of recruitment (age 0 or age 1)
3. natural mortality ("low M" or "high M" to match the VPA set-up)
4. level of R0, virgin recruitment (either R0 was estimated by fitting a Beverton-Holt function from 1984-2000 VPA estimates of SSB and recruitment, or R0 was fixed at 8.5 times the average of the three lowest VPA estimates of recruitment)

For each model, six projections were performed:

1. TAC of 9.12 million pounds (mp) for the Gulf-wide models, or TAC of 4.56 mp for East and West models
2. TAC of 9.12 mp (or 4.56 mp) and/or fish at geometric mean of 2001-2003 estimated F for 2005-2007, then for years 2008-2032 reduce F by 40%
3. Fish at FMSY for years 2005-2032
4. Fish at F20SPR for years 2005-2032
5. Fish at F30SPR for years 2005-2032
6. Fish at F40SPR for years 2005-2032

For Eastern and Western Gulf models, landed catch for the last 5 years of data (1999-2003) shows roughly a 50-50 split, so the Gulfwide TAC of 9.12 was divided evenly for the projections (i.e., 4.56 mp).

Results

Acceptable fits to the tuning indices were obtained for the Gulf and West VPAs, although the index of spawning stock biomass ("Larval-B") generally showed a poorer fit. Fits for the East VPAs were somewhat poorer than in the Gulf-wide and West VPAs (Figs 1a,b,c). Fits were very similar regardless of assumed natural mortality level or recruitment age.

Benchmark estimates for the Gulfwide projections are given in Table 1. Assuming age 0 recruitment, Fmsy estimates range from 0.27-0.30, MSY estimates range from 21.9-137 mp, and SPRmsy ranges from 0.28-0.31. Assuming age 1 recruitment, Fmsy estimates range from 0.36-0.40, MSY estimates range from 12.8-92.5 mp, and SPRmsy ranges from 0.25-0.30. The higher MSY estimates correspond to the cases where R0 was fixed to 8.5 X the 3 year average low ("high R0" case).

Benchmark estimates for the Eastern Gulf projections are given in Table 2. Assuming age 0 recruitment, Fmsy estimates range from 0.19-0.25, MSY estimates range from 4.62-18.3 mp, and SPRmsy ranges from 0.29-0.33. Assuming age 1 recruitment, Fmsy estimates range from 0.28-0.30, MSY estimates range from 3.42-16.8 mp, and SPRmsy ranges from 0.24-0.28. The higher MSY estimates correspond to the "high R0" cases.

Benchmark estimates for the Western Gulf projections are given in Table 3. Assuming age 0 recruitment, Fmsy estimates range from 0.21-0.39, MSY estimates range from 14.4-64.8 mp, and SPRmsy ranges from 0.28-0.34. Assuming age 1 recruitment, Fmsy estimates range from 0.29-0.48, MSY estimates range from 10.3-74.8 mp, and SPRmsy ranges from 0.28-0.32. The higher MSY estimates correspond to the "high R0" cases.

Across all model treatments, given the stock recruitment relationships, SPRmsy ranged from about 0.24-0.34. Therefore, projections at F40% SPR all suggest recovery of the stock by 2032, while F20% SPR projections do not suggest recovery by 2032 (Table 5). Projections at F30% SPR generally suggest recovery by 2032 for cases where R0 was fixed to 8.5 X the 3 year average low (where most SPRmsy were < 0.3) or near recovery for cases where R0 was estimated (where SPRmsy was just slightly larger than 0.3). Projections for scenario 1, where only a TAC was applied, suggest a strong recovery (in some cases, as early as 2010), except in the Eastern Gulf model runs, where only the "high R0" cases show recovery. Projections at Fmsy predict values of SSB/SSBmsy that are 0.95 or higher, but only in one case is that value greater than 1. Scenarios where a TAC was applied in years 2005-2007 and then F was reduced by 40% all show recovery, or very nearly so, by 2032. Some demonstrative plots are shown in Figures 1-6.

Conclusions

Model runs suggest that Eastern Gulf estimates of SSBmsy are 10-16% of the Gulfwide SSBmsy, and Eastern MSY is 15-20% of Gulfwide MSY. These results follow from the fact that estimated steepness is 1 for all model scenarios, and the estimated R0 values in the Eastern Gulf are 10-20% those of Gulfwide estimates (Table 4).

Table 1. Gulfwide benchmark estimates. Models are defined by the assumed age of recruitment (age 0 or 1), level of assumed natural mortality, and whether R0 was estimated or fixed in the stock recruitment relationship applied.

	age 0 low M	age 0 low M	age 0 high M	age 0 high M	age 1 low M	age 1 low M	age 1 high M	age 1 high M
MEASURE	**R0 est**	**high R0**	**R0 est**	**high R1**	**R0 est**	**high R0**	**R0 est**	**high R1**
F at MSY	0.296	0.274	0.301	0.282	0.398	0.362	0.374	0.361
MSY	3.09E+07	1.37E+08	2.19E+07	1.08E+08	1.38E+07	9.25E+07	1.28E+07	8.20E+07
Y/R at MSY	0.513	0.726	0.240	0.341	0.855	1.518	0.660	1.131
S/R at MSY	0.775	0.703	0.348	0.312	1.238	1.030	0.909	0.761
SPR AT MSY	0.313	0.284	0.313	0.281	0.304	0.252	0.301	0.252
SSB AT MSY	4.67E+07	1.33E+08	3.17E+07	9.87E+07	2.00E+07	6.28E+07	1.76E+07	5.52E+07
F at max. Y/R	0.301	0.280	0.305	0.287	0.398	0.362	0.374	0.361
Y/R maximum	0.513	0.727	0.240	0.341	0.855	1.518	0.660	1.131
S/R at Fmax	0.762	0.686	0.343	0.306	1.238	1.030	0.909	0.761
SPR at Fmax	0.308	0.277	0.308	0.275	0.304	0.252	0.301	0.252
SSB at Fmax	4.58E+07	1.29E+08	3.13E+07	9.67E+07	2.00E+07	6.27E+07	1.76E+07	5.51E+07
F 0.1	0.229	0.209	0.232	0.213	0.304	0.264	0.285	0.263
Y/R at F0.1	0.497	0.702	0.233	0.329	0.828	1.462	0.639	1.089
S/R at F0.1	1.006	0.942	0.452	0.423	1.635	1.475	1.205	1.091
SPR at F0.1	0.407	0.381	0.407	0.380	0.401	0.362	0.399	0.361
SSB at F0.1	6.08E+07	1.78E+08	4.14E+07	1.34E+08	2.64E+07	8.99E+07	2.34E+07	7.91E+07
F 20% SPR	0.412	0.353	0.418	0.359	0.538	0.425	0.502	0.423
Y/R at F20	0.488	0.709	0.228	0.333	0.816	1.502	0.632	1.119
S/R at F20	0.498	0.497	0.224	0.224	0.821	0.821	0.608	0.609
SSB at F20	2.98E+07	9.33E+07	2.03E+07	7.06E+07	1.33E+07	5.00E+07	1.18E+07	4.41E+07
F 30% SPR	0.306	0.261	0.311	0.266	0.400	0.313	0.373	0.312
Y/R at F30	0.513	0.725	0.240	0.340	0.855	1.505	0.660	1.122
S/R at F30	0.747	0.746	0.335	0.335	1.231	1.231	0.912	0.910
SSB at F30	4.50E+07	1.41E+08	3.06E+07	1.06E+08	1.99E+07	7.50E+07	1.77E+07	6.59E+07
F 40% SPR	0.232	0.197	0.235	0.200	0.303	0.236	0.283	0.234
Y/R at F40	0.498	0.692	0.233	0.324	0.828	1.418	0.638	1.055
S/R at F40	0.995	0.995	0.447	0.448	1.640	1.637	1.213	1.216
SSB at F40	6.00E+07	1.88E+08	4.09E+07	1.42E+08	2.65E+07	9.97E+07	2.35E+07	8.81E+07

Table 2. Eastern Gulf benchmark estimates. Models are defined by the assumed age of recruitment (age 0 or 1), level of assumed natural mortality, and whether R0 was estimated or fixed in the stock recruitment relationship applied.

	age 0 low M	age 0 low M	age 0 high M	age 0 high M	age 1 low M	age 1 low M	age 1 high M	age 1 high M
MEASURE	**R0 est**	**high R0**	**R0 est**	**high R1**	**R0 est**	**high R0**	**R0 est**	**high R1**
F at MSY	0.192	0.247	0.196	0.233	0.285	0.277	0.295	0.279
MSY	4.63E+06	1.83E+07	4.62E+06	1.53E+07	3.47E+06	1.68E+07	3.42E+06	1.62E+07
Y/R at MSY	0.753	0.947	0.361	0.422	1.230	1.786	0.935	1.331
S/R at MSY	0.780	0.727	0.366	0.351	1.130	0.993	0.827	0.732
SPR AT MSY	0.315	0.294	0.329	0.316	0.277	0.244	0.274	0.242
SSB AT MSY	4.80E+06	1.41E+07	4.69E+06	1.27E+07	3.19E+06	9.37E+06	3.03E+06	8.89E+06
F at max. Y/R	0.209	0.274	0.228	0.276	0.285	0.277	0.295	0.279
Y/R maximum	0.755	0.951	0.364	0.427	1.230	1.786	0.935	1.331
S/R at Fmax	0.706	0.641	0.308	0.287	1.130	0.993	0.827	0.732
SPR at Fmax	0.285	0.259	0.277	0.258	0.277	0.243	0.274	0.242
SSB at Fmax	4.32E+06	1.23E+07	3.86E+06	1.01E+07	3.19E+06	9.37E+06	3.03E+06	8.88E+06
F 0.1	0.157	0.200	0.170	0.202	0.213	0.199	0.220	0.200
Y/R at F0.1	0.730	0.915	0.352	0.411	1.188	1.717	0.904	1.278
S/R at F0.1	0.958	0.911	0.423	0.407	1.553	1.452	1.141	1.074
SPR at F0.1	0.387	0.368	0.381	0.367	0.381	0.356	0.378	0.355
SSB at F0.1	5.97E+06	1.79E+07	5.50E+06	1.50E+07	4.38E+06	1.37E+07	4.17E+06	1.30E+07
F 20% SPR	0.269	0.328	0.287	0.329	0.358	0.317	0.368	0.318
Y/R at F20	0.732	0.938	0.355	0.421	1.201	1.774	0.915	1.322
S/R at F20	0.499	0.498	0.224	0.224	0.822	0.821	0.607	0.608
SSB at F20	2.96E+06	9.34E+06	2.66E+06	7.55E+06	2.32E+06	7.74E+06	2.22E+06	7.38E+06
F 30% SPR	0.199	0.242	0.212	0.243	0.266	0.233	0.272	0.233
Y/R at F30	0.754	0.945	0.363	0.424	1.227	1.766	0.933	1.315
S/R at F30	0.749	0.745	0.336	0.335	1.228	1.228	0.912	0.914
SSB at F30	4.60E+06	1.45E+07	4.26E+06	1.20E+07	3.47E+06	1.16E+07	3.34E+06	1.11E+07
F 40% SPR	0.151	0.182	0.160	0.183	0.201	0.174	0.206	0.175
Y/R at F40	0.723	0.893	0.346	0.401	1.171	1.655	0.889	1.232
S/R at F40	0.993	0.994	0.447	0.446	1.638	1.644	1.212	1.216
SSB at F40	6.20E+06	1.96E+07	5.85E+06	1.66E+07	4.62E+06	1.55E+07	4.43E+06	1.48E+07

Table 3. Western Gulf benchmark estimates. Models are defined by the assumed age of recruitment (age 0 or 1), level of assumed natural mortality, and whether R0 was estimated or fixed in the stock recruitment relationship applied.

	age 0 low M	age 0 low M	age 0 high M	age 0 high M	age 1 low M	age 1 low M	age 1 high M	age 1 high M
MEASURE	**R0 est**	**high R0**	**R0 est**	**high R1**	**R0 est**	**high R0**	**R0 est**	**high R1**
F at MSY	0.376	0.207	0.385	0.293	0.476	0.292	0.453	0.293
MSY	1.88E+07	1.28E+08	1.44E+07	6.48E+07	1.12E+07	7.48E+07	1.03E+07	6.46E+07
Y/R at MSY	0.447	0.785	0.213	1.164	0.845	1.564	0.655	1.162
S/R at MSY	0.840	0.757	0.375	0.838	1.315	1.135	0.965	0.843
SPR AT MSY	0.339	0.306	0.338	0.277	0.322	0.278	0.319	0.279
SSB AT MSY	3.54E+07	1.23E+08	2.53E+07	4.66E+07	1.75E+07	5.43E+07	1.52E+07	4.69E+07
F at max. Y/R	0.376	0.207	0.385	0.293	0.476	0.292	0.453	0.293
Y/R maximum	0.447	0.785	0.213	1.164	0.845	1.564	0.655	1.162
S/R at Fmax	0.840	0.757	0.375	0.838	1.315	1.135	0.965	0.843
SPR at Fmax	0.339	0.306	0.338	0.277	0.322	0.278	0.319	0.279
SSB at Fmax	3.54E+07	1.23E+08	2.53E+07	4.66E+07	1.75E+07	5.43E+07	1.52E+07	4.69E+07
F 0.1	0.289	0.154	0.295	0.213	0.363	0.213	0.345	0.214
Y/R at F0.1	0.434	0.758	0.207	1.121	0.819	1.506	0.635	1.119
S/R at F0.1	1.074	1.013	0.482	1.169	1.713	1.578	1.261	1.170
SPR at F0.1	0.434	0.410	0.433	0.387	0.420	0.387	0.417	0.387
SSB at F0.1	4.52E+07	1.65E+08	3.25E+07	6.50E+07	2.28E+07	7.55E+07	1.98E+07	6.51E+07
F 20% SPR	0.563	0.285	0.574	0.372	0.675	0.372	0.642	0.374
Y/R at F20	0.410	0.748	0.196	1.137	0.794	1.525	0.616	1.133
S/R at F20	0.497	0.498	0.224	0.609	0.830	0.822	0.608	0.608
SSB at F20	2.09E+07	8.11E+07	1.51E+07	3.39E+07	1.10E+07	3.93E+07	9.56E+06	3.38E+07
F 30% SPR	0.418	0.209	0.426	0.273	0.505	0.272	0.477	0.274
Y/R at F30	0.445	0.785	0.212	1.162	0.844	1.561	0.654	1.160
S/R at F30	0.746	0.748	0.335	0.910	1.229	1.233	0.910	0.911
SSB at F30	3.14E+07	1.22E+08	2.26E+07	5.06E+07	1.63E+07	5.90E+07	1.43E+07	5.07E+07
F 40% SPR	0.317	0.157	0.322	0.204	0.382	0.204	0.361	0.205
Y/R at F40	0.442	0.761	0.210	1.109	0.827	1.490	0.641	1.107
S/R at F40	0.992	0.997	0.447	1.215	1.638	1.639	1.212	1.215
SSB at F40	4.18E+07	1.62E+08	3.01E+07	6.76E+07	2.18E+07	7.84E+07	1.90E+07	6.76E+07

Table 4. Parameter values of the Beverton-Holt stock-recruitment function used in the projections. R0 is virgin recruitment and h is steepness. (Note: a steepness of 1.0 implies constant recruitment).

Region	Age	M	estimated h	estimated R0 (millions of fish)	8.5 X R0 (3 year average low)
Gulf	0	low M	~ 1.0	61.0	191.3
Gulf	0	high M	~ 1.0	92.3	320.2
Gulf	1	low M	~ 1.0	16.1	60.9
Gulf	1	high M	~ 1.0	19.4	72.4
East	0	low M	~ 1.0	6.6	20.7
East	0	high M	~ 1.0	14.3	40.5
East	1	low M	~ 1.0	2.8	9.4
East	1	high M	~ 1.0	3.7	12.1
West	0	low M	~ 1.0	42.1	162.8
West	0	high M	~ 1.0	67.4	263.3
West	1	low M	~ 1.0	13.3	47.9
West	1	high M	~ 1.0	15.7	55.6

Table 5. Year of recovery for all models and all 6 projection scenarios. F and B columns for each projection scenario are the year that F/Fmsy ≤1 or B/Bmsy ≥1. Models are defined by the assumed age of recruitment (age 0 or 1), level of assumed natural mortality (low or high), and whether R0 was estimated or fixed in the stock recruitment relationship applied.

Projection																	
				TAC		red F 40%		Fmsy		F20% SPR		F30% SPR		F40% SPR	
	Model			F	B	F	B	F	B	F	B	F	B	F	B
Gulf	age 0	low M	R0 est	2005	2016	2005	x	2005	x	x	x	x	x	2005	2022
Gulf	age 0	low M	high R0	2005	2013	2005	2017	2005	x	x	x	2005	2032	2005	2020
Gulf	age 0	high M	R0 est	2006	2017	2006	x	2005	x	x	x	x	x	2005	2021
Gulf	age 0	highM	high R0	2005	1013	2005	2016	2005	x	x	x	2005	2030	2005	2019
Gulf	age 1	low M	R0 est	2009	2021	2008	x	2005	x	x	x	x	x	2005	2018
Gulf	age 1	low M	high R0	2002	2010	2002	2011	2005	x	x	x	2002	2019	2002	2014
Gulf	age 1	high M	R0 est	2010	2022	2008	2030	2005	x	x	x	2005	x	2005	2017
Gulf	age 1	highM	high R0	2002	2010	2002	2011	2002	x	x	x	2002	2019	2002	2014
East	age 0	low M	R0 est	x	x	x	x	2005	x	x	x	x	x	2005	2017
East	age 0	low M	high R0	2005	2015	2005	2021	2005	x	x	x	2005	x	2005	2020
East	age 0	high M	R0 est	x	x	2008	x	2005	x	x	x	x	x	2005	2017
East	age 0	highM	high R0	2005	2016	2005	2024	2005	x	x	x	x	x	2005	2023
East	age 1	low M	R0 est	2005	2016	2005	2024	2005	x	x	x	x	x	2005	2023
East	age 1	low M	high R0	2003	2010	2003	2011	2003	x	x	x	2003	2016	2003	2012
East	age 1	high M	R0 est	x	x	2008	2013	2005	2001	x	2001	2005	2001	2005	2001
East	age 1	highM	high R0	2003	2010	2003	2010	2003	x	x	x	2003	2016	2003	2012
West	age 0	low M	R0 est	2005	2017	x	x	2005	x	x	x	x	x	3005	2024
West	age 0	low M	high R0	2003	2012	2003	2014	2003	x	x	x	x	x	2003	2019
West	age 0	high M	R0 est	2005	2015	2005	2020	2005	x	x	x	x	x	2005	2019
West	age 0	highM	high R0	2003	2012	2003	2014	2003	x	x	x	x	x	2003	2019
West	age 1	low M	R0 est	2005	2015	2005	2022	2005	x	x	x	x	x	2005	2019
West	age 1	low M	high R0	2002	2011	2002	2011	2002	x	x	x	2002	2023	2002	2015
West	age 1	high M	R0 est	2002	2011	2002	2011	2002	x	x	x	2002	2023	2002	2015
West	age 1	highM	high R0	2002	2011	2002	2011	2002	x	x	x	2002	2023	2002	2015

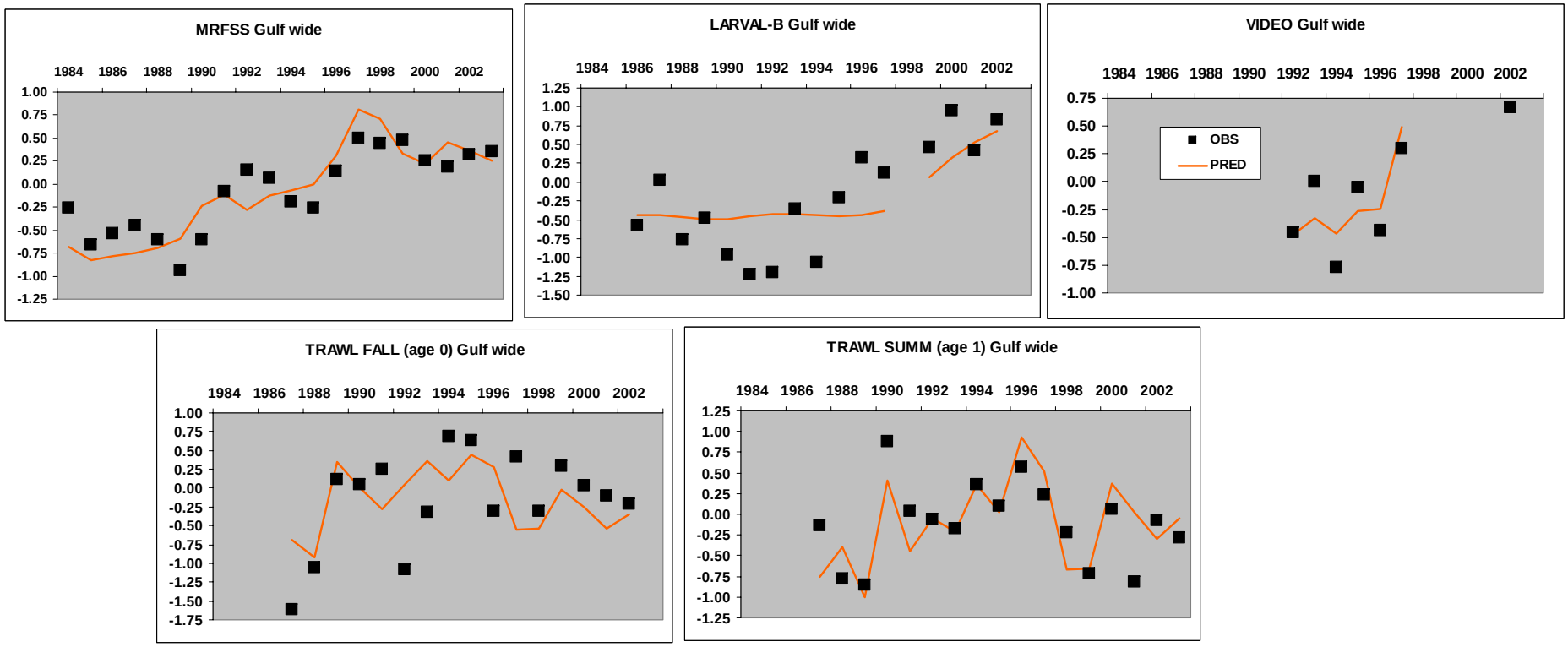

Figure 1a. Fits to tuning indices in a Gulf-wide VPA, low M case, age 0 recruitment assumed (log-scale). All indices are in numbers, except for the "Larval-B" index which is in biomass.

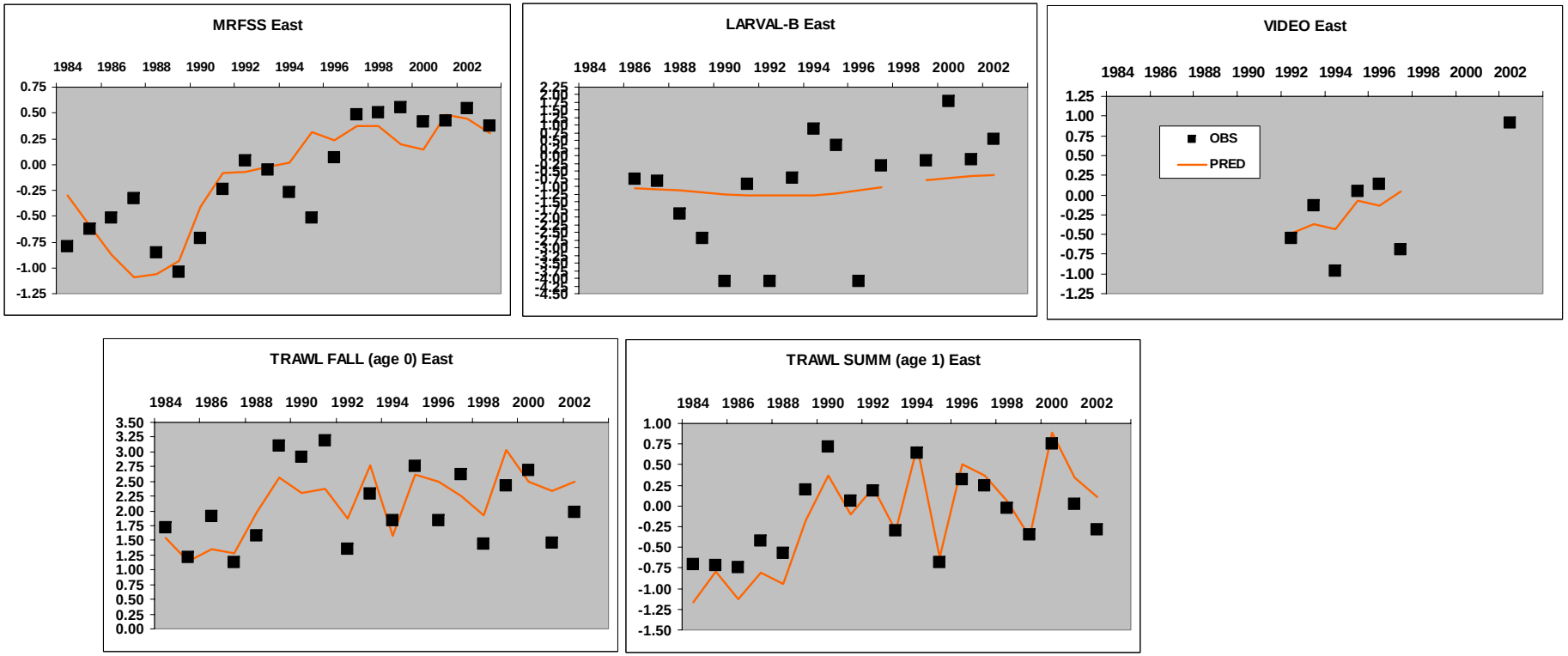

Figure 1b. Fits to tuning indices in an Eastern Gulf VPA, low M case, age 0 recruitment assumed (log-scale). All indices are in numbers, except for the "Larval-B" index which is in biomass.

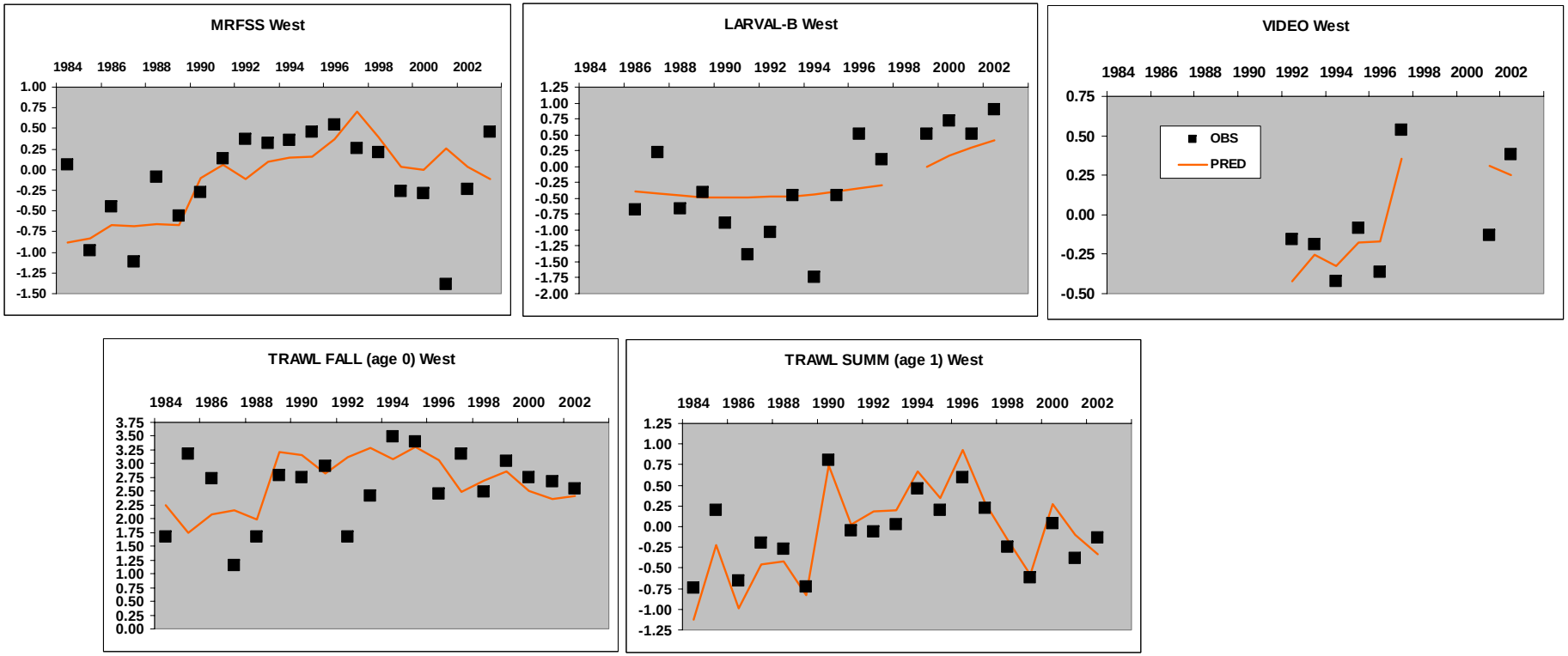

Figure 1c. Fits to tuning indices in an Western Gulf VPA, low M case, age 0 recruitment assumed (log-scale). All indices are in numbers, except for the "Larval-B" index which is in biomass.

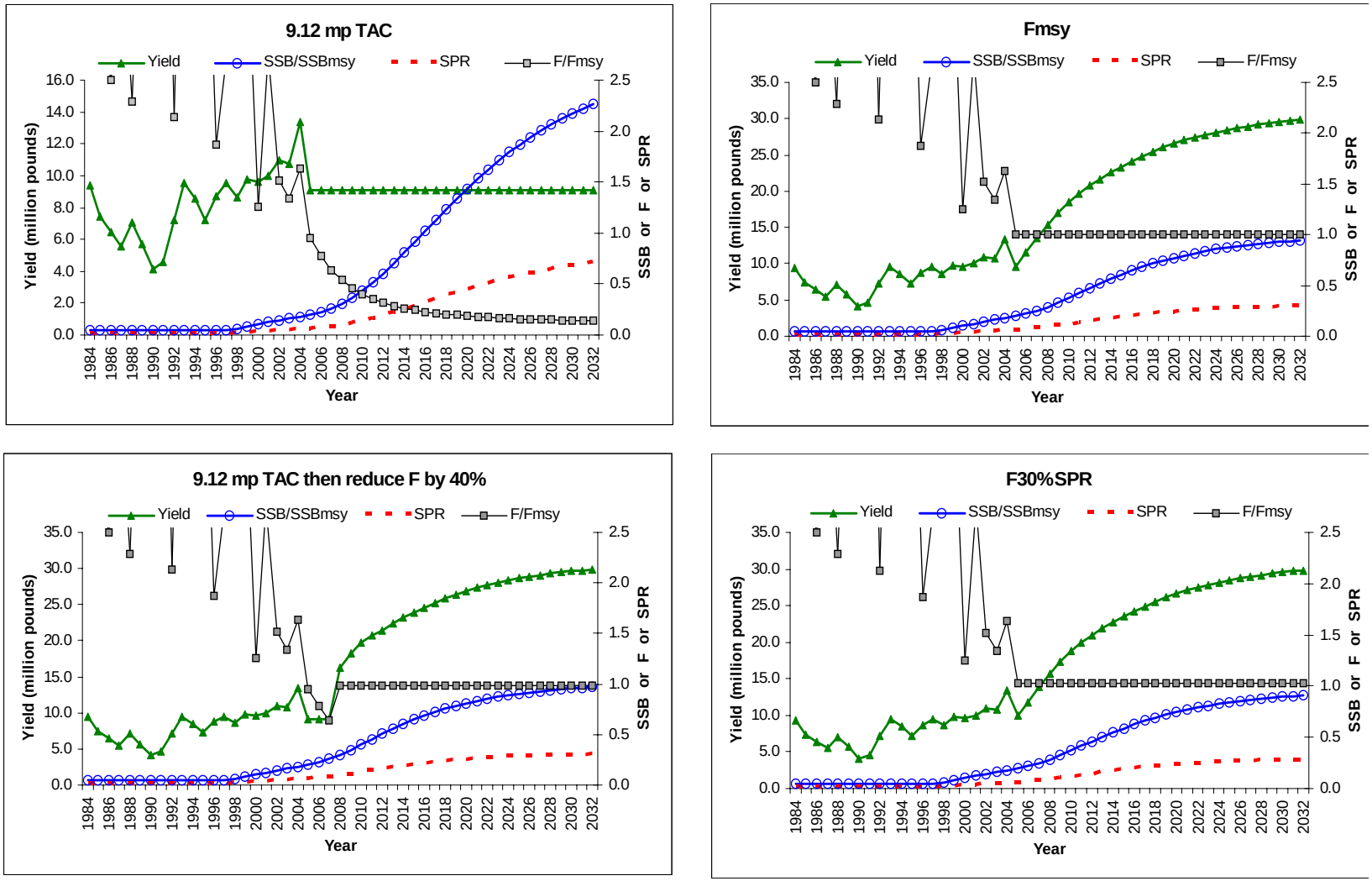

Figure 1. Gulfwide projections, assuming low M, R0 estimated, recruitment age 0.

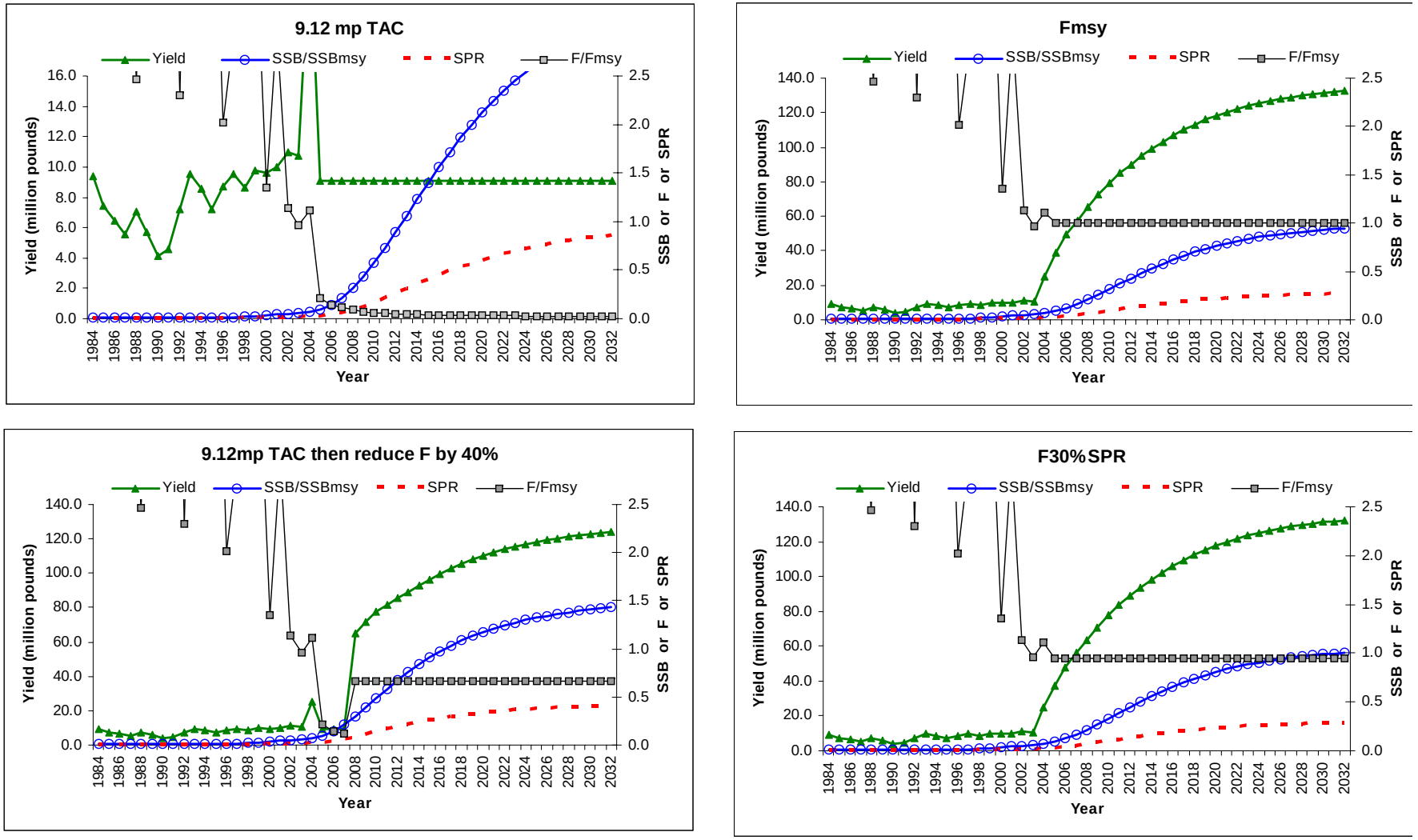

Figure 2. Gulfwide projections, assuming low M, high R0, recruitment age 0.

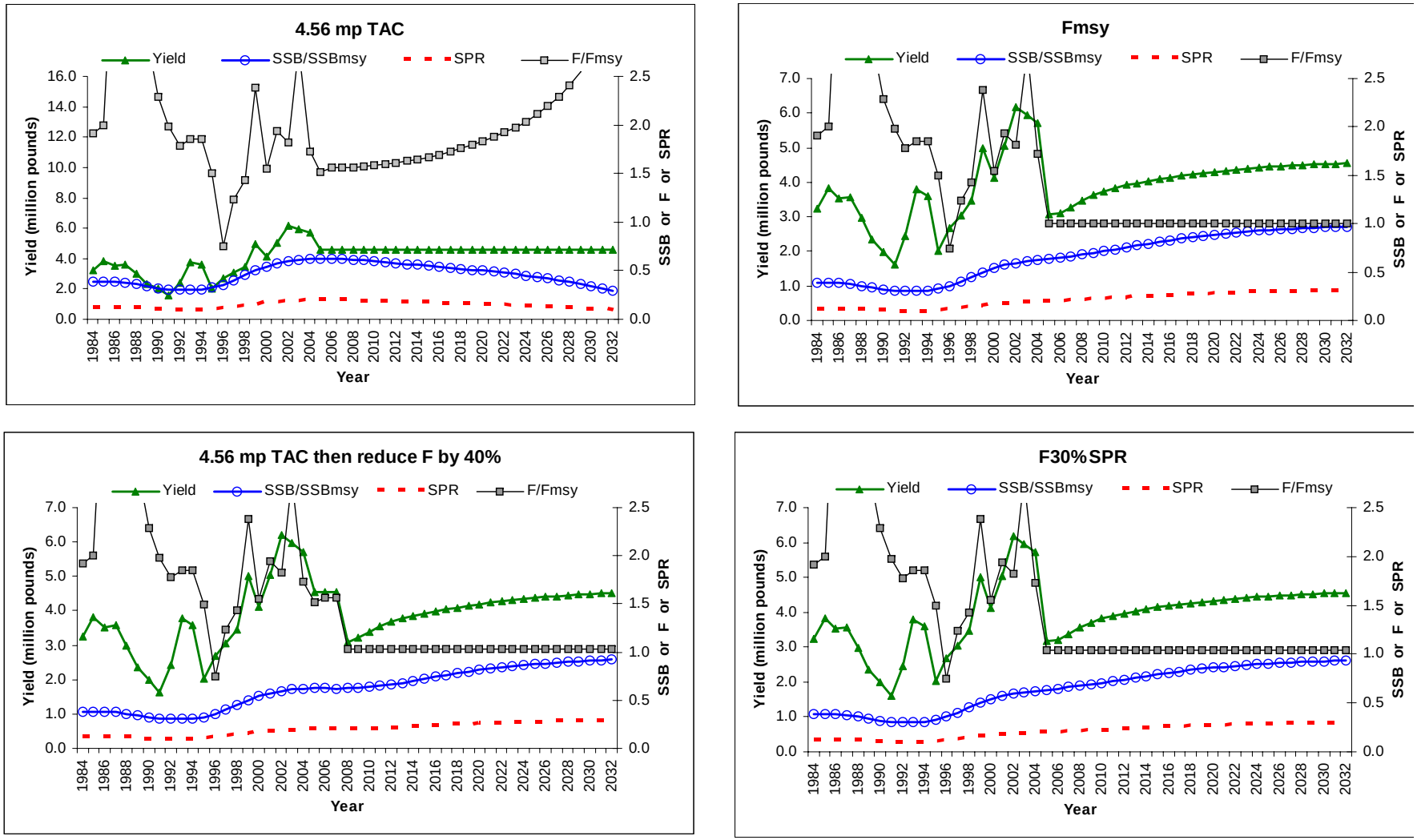

Figure 3. East projections, assuming low M, R0 estimated, recruitment age 0.

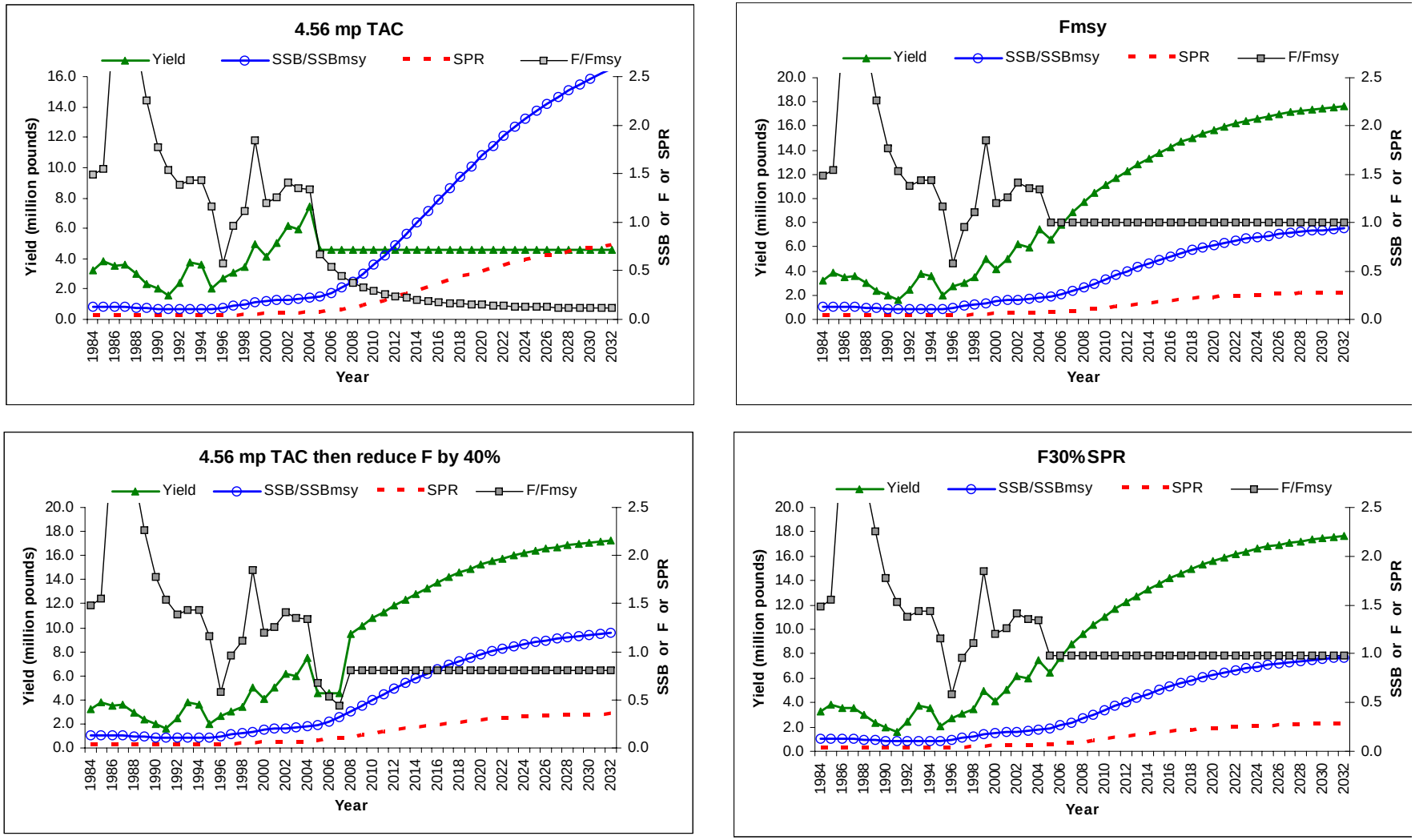

Figure 4. East projections, assuming low M, high R0, recruitment age 0.

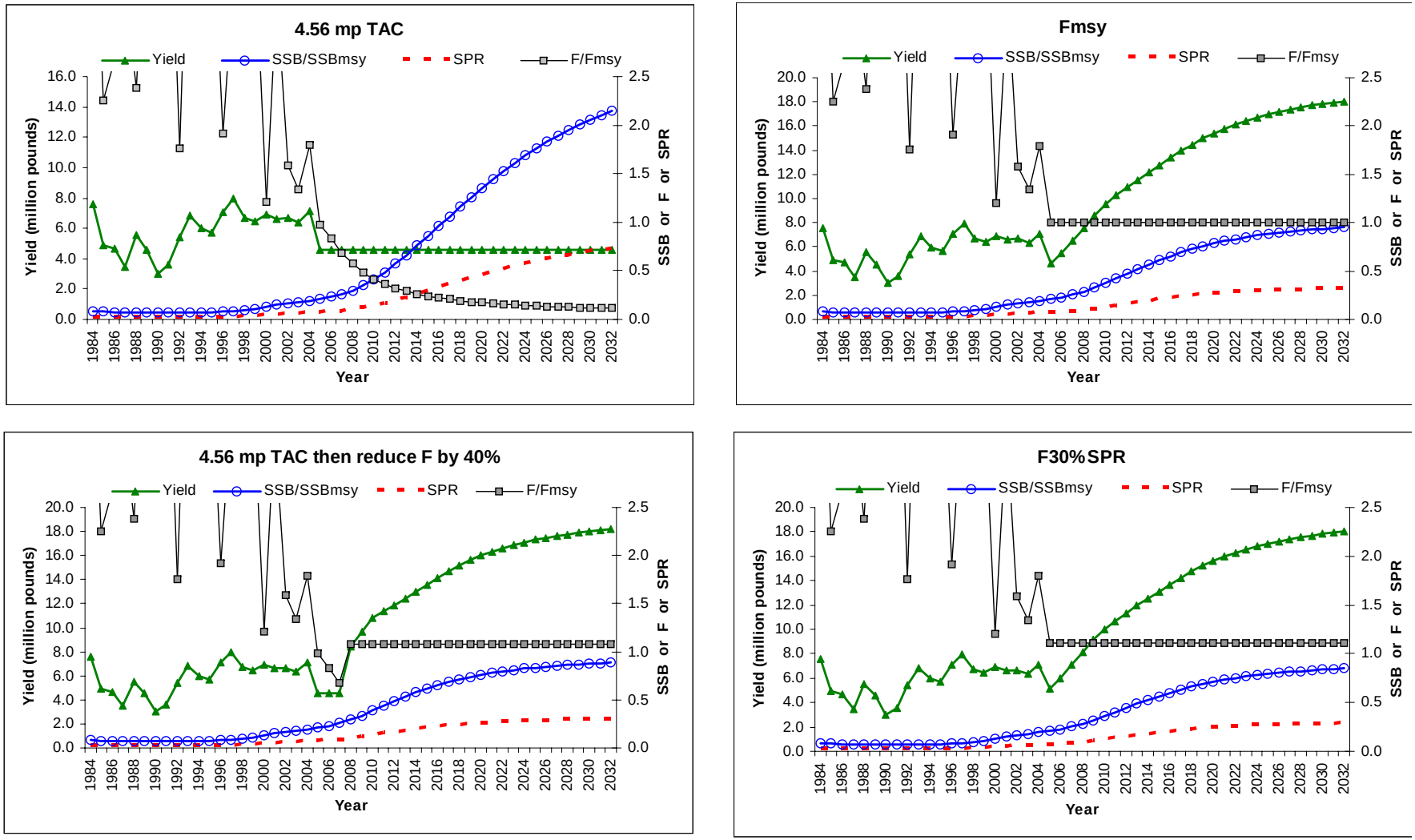

Figure 5. West projections, assuming low M, R0 estimated, recruitment age 0.

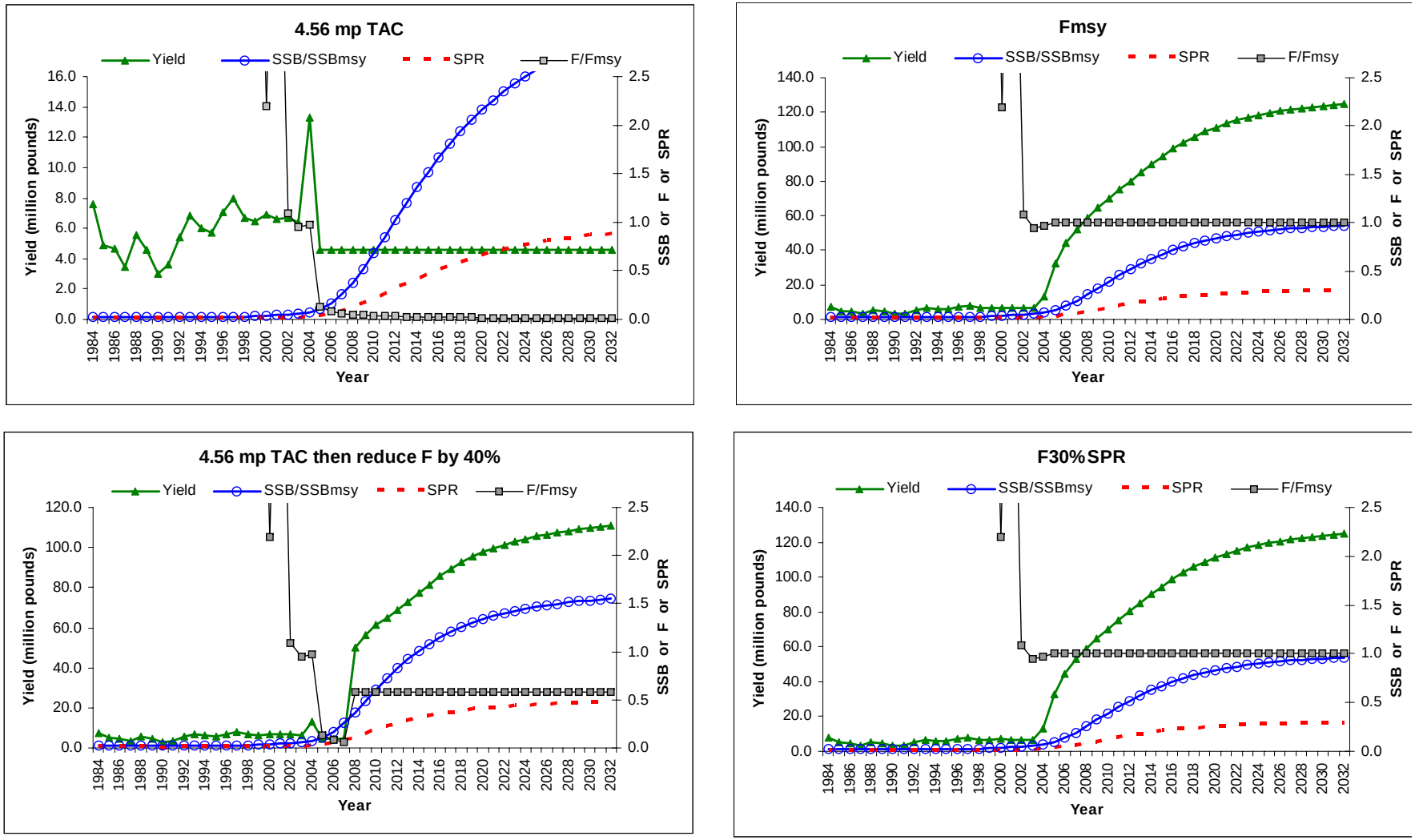

Figure 6. West projections, assuming low M, high R0, recruitment age 0.