SOME INITIAL INVESTIGATIONS OF POSSIBLE MANAGEMENT PROCEDURES FOR SOUTHERN BLUEFIN TUNA BASED UPON AGE-AGGREGATED PRODUCTION MODELS

ミナミマグロの **Management Procedure** としての **Age-aggregated** **(**齢構成をまとめた**)** プロダクションモデルの適用の初歩的な検討

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SUMMARY

This paper reports some initial results for the application of candidate management procedures (MPs) for SBT based upon age-aggregated production models to the trials developed thus far testing such MPs. The specific options tested are based upon models of this type, which incorporate the Schaefer and Fox forms of the surplus production function, as applied in Butterworth and Plagányi (2000) and Butterworth and Johnston (2001) to assess the SBT resource. A particular advantage of these age-aggregated models is their simplicity. The details of these models are set out, together with the associated control rule used to provide a TAC on the basis of the estimates of the parameters of the surplus production function. This rule is a variant of the f_{MSY} strategy which puts emphasis on low interannual TAC variability, and seeks in particular to avoid inappropriate trends in short-term changes to the TAC from its current level. Results are summarized for the various test scenarios coded thus far. Performance for medium to high productivity scenarios seems satisfactory, showing increases in both the TAC and resource abundance. However the TAC is not reduced sufficiently rapidly for the low productivity scenarios to avoid undue resource depletion. A modification to improve performance in such situations, without adversely affecting performance for others, is put forward.

要約

本論文では，ミナミマグロの management procedure として age-aggregated（齢構成をまとめた）プロダクションモデルを適用した初歩的な結果を報告する．検討したプロダクションモデルは，以前ミナミマグロの資源評価を行うために Butterworth and Plagányi (2000)や Butterworth and Johnston (2001)が用いたのと同じ Schaefer 型と Fox 型の余剰生産モデルであ

る．このような齢構成をまとめたプロダクションモデルの最大の利点は，モデルが単純なことにある．モデルの詳細および，モデルから推定されたパラメータに基づく TAC の調整法については本文で詳しく説明する．この TAC 調整法は，f_{MSY} による調整法の変形版であり，TAC の年変動が小さいことに主眼を置いており，その中でも特に，現在からその後数年の TAC における不適切なトレンドを防ぐことに注目している．現段階で与えられている様々な試験シナリオに対して本モデルを適用した結果を紹介する．試験シナリオのうち，資源の生産性が中位～高いと仮定したシナリオについては満足の行く結果が得られ，TAC も資源量も共に上昇した．しかし，資源の生産性が低いと仮定したシナリオについては，不適切な資源の減少を防ぐほど急激には TAC の減少が行われていない．そのような場合において，生産性の中位～高いシナリオのふるまいは変えず，生産性の低いシナリオのふるまいのみを向上させるようなモデルの修正を提唱する．

DATA

The production models applied here require input data in the form of historic (as well as, for future years, simulation generated) values for annual catch (by mass) and CPUE. This is not entirely straightforward in the context of the MP trials developed for SBT, as for some fisheries (LL1, LL3) the historic catch is specified in terms of numbers of fish caught, and the associated estimated mass varies between scenarios because of the effects of different selectivity functions. Clearly a management procedure cannot know with which scenario it is dealing, so that it must be provided with a unique set of annual historic catches by mass for the scenarios to be considered here. The historical catch data used in these evaluations are shown in Table 1. They are the mean catches across eight scenarios (*h3M10*, *h6M10*, *h9M10*, *h6M05*, *h3M15*, *h6M15*, *h9M15*, and *h6M15d1*). The differences in annual catch masses between these scenarios are very slight, so that the somewhat arbitrary nature of this specification is not an issue of consequence in practice.

The CPUE abundance index values used for these evaluations are also shown in Table1, and are the median of the five CPUE series provided (B-ratio proxy, Geostat proxy, Stwindow, Laslett Core Area, Nominal).

METHODS

The assessment component of the management procedures considered here use simple age-aggregated production models to describe the population dynamics of SBT. Annual catch data since the start of the fishery are input and the models are fitted to the observed CPUE trend for the stock. For each projection year, the stock level is reassessed using the production model, now taking account of catch and CPUE information for a further year, and the total allowable catch (TAC) for the following year is set depending on this assessment of the stock. The performance when setting the TAC based on such an assessment method is investigated for two production models (Schaefer and Fox models). Details of these production models and the TAC calculation methods are described below.

SCHAEFER MODEL

The dynamics of the SBT population are assumed to be represented by the discrete logistic equation:

$$B_{y+1} = B_y + rB_y\left(1 - \frac{B_y}{K}\right) - C_y \tag{1}$$

where B_y is the biomass of SBT present at the start of year y,

C_y is the catch by mass (all fisheries combined) for year y,

K is the pre-exploitation biomass, with the associated assumption of a population at pre-exploitation equilibrium when harvests commenced, i.e. $B_{1952} = K$, and

r is the intrinsic growth rate parameter for the population.

For this model $B_{MSY} = K/2$ and $MSY = 1/4\ rK$.

To estimate the parameters r and K, the model is fit to the available index of abundance (CPUE) by assuming:

$$I_y = q\frac{B_y + B_{y+1}}{2}e^{\varepsilon_y} \tag{2}$$

where I_y is the CPUE index for year y,

q is the constant proportionality (the catchability coefficient), and

ε_y from $N\left(0, \sigma^2\right)$.

Catches and CPUE are input for past years as described above, and the operating model generates values for future years for each projection in a trial. (Note that when fitting the model at the end of year y, catch data are available up to that year, but CPUE data to year y-1 only.)

The associated negative log likelihood minimized in the fitting process is:

$$-\ln L = \sum_y \left[\ln\sigma + \frac{\left(\varepsilon_y\right)^2}{2\sigma^2}\right] \tag{3}$$

for which setting partial derivatives to zero ($\frac{\partial\left(-\ln L\right)}{\partial q} = 0$, $\frac{\partial\left(-\ln L\right)}{\partial\sigma} = 0$) yields closed form solutions for best estimates of q and σ :

$$q = \exp\left[\sum_y \left\{\ln I_y - \ln\left(\frac{B_y + B_{y+1}}{2}\right)\right\} / n\right] \tag{4}$$

$$\sigma = \sqrt{\frac{\sum_y (\varepsilon_y)^2}{n}} \tag{5}$$

where n is the number of years for which there are CPUE data.

FOX MODEL

This model is implemented identically to the Schaefer model above, except for the single change of a different functional form for the surplus production function in equation (1), which now becomes:

$$B_{y+1} = B_y + rB_y\left(1 - \frac{\ln(B_y)}{\ln(K)}\right) - C_y \tag{6}$$

For this model $B_{MSY}= Ke^{-1}$ and $MSY=rK/e\ln K$. Note that unlike the Schaefer model for which r is dimensionless, the r in the Fox model has units which depend on the units chosen for catches and hence for biomass and K; the biomass units used for the computations which follow are tons.

TAC SPECIFICATION

The TAC for SBT for each future year is calculated from the following equation:

$$TAC_{y+1} = wTAC_y + (1-w)\cdot M\hat{S}YR_y \cdot \hat{B}_{MSY} \cdot \left(\frac{\hat{B}_y}{\hat{B}_{MSY}}\right)^{\gamma} \tag{7}$$

where $\hat{B}_{MSY}$ is the estimated maximum sustainable yield level (MSYL),

γ is a control parameter,

w is a control parameter (here fixed to be 0.7),

$M\hat{S}YR_y$ is the estimated maximum sustainable yield rate, calculated as $M\hat{S}Y_y / MSYL$.

(here, $\hat{r}_y/2$ for Schaefer model, and $\hat{r}_y / \ln\hat{K}_y$ for Fox model – note that these estimated values change with year y as more data become available), and

$\hat{B}_y$ is the estimated biomass for year y, which (together with $\hat{r}_y$ and $\hat{K}_y$) is re-estimated for each projection year.

For the case w=0, γ=1, equation (7) corresponds to an f_{MSY} policy ($TAC_{y+1} = M\hat{S}YR_y \cdot \hat{B}_y$) which (in terms of the population dynamics model assumed) will see biomass stabilize at *MSYL* in due course. The *w* parameter is introduced to moderate the extent to which the TAC is adjusted from year to year in the interests of industrial stability. The γ parameter's role is to stabilize the TAC trend in the short term: a particular objective in selecting a value for γ is to avoid instances where the TAC outputs show a decrease for the first few years only, followed by a subsequent increase. Setting γ to a value <1 tends to smooth out this undesirable behaviour.

RESULTS

Initially the following seven candidate management procedures (MPs) were tested:

1. Schaefer model, γ =1 ("schae1")
2. Schaefer model, γ =0.8 ("schae08")
3. Schaefer model, γ =0.6 ("schae06")
4. Fox model, γ =1 ("fox1")
5. Fox model, γ =0.8 ("fox08")
6. Fox model, γ =0.6 ("fox06")
7. Fox model, γ =0.4 ("fox04")

Performance statistics for the above seven MPs are compared for each of the eight scenarios (*h3M10*, *h3M15*, etc.) as shown in Figure 1.1 to 1.4 for hierarchy level 3, and in Figure 1.5 for hierarchy level 4 (*hestmcmc*). All these results reflect distributions over 100 stochastic replicates for the scenario in question. Figure 1.1 provides a summary over the eight scenarios using the summary plot developed by CSIRO scientists. In the results shown for individual scenarios, only the cases *h3M10*, *h6M10* and *h9M10* have been shown (Figures 1.2 to 1.4) as the pattern of results for scenarios with the same value of *h* are fairly similar. Median TAC and spawning biomass trajectories are shown in Figures 2.1 and 2.2.

Among the seven MP candidates considered, the candidate MPs corresponding to the Schaefer model with γ=0.8 and the Fox model withγ=0.6 behave best for *h*=0.6 scenarios in terms of smoothing the anticipated TAC trajectory in the short term (see Fig. 2.1). Of these two the Fox model option is much the better in terms of lesser interannual catch variability.

Detailed performances (comparison between the eight scenarios) for the Fox model, γ=0.6, MP for hierarchy=3 and hierarchy=4 are shown in Figure 3.1 and 3.2, and the change in spawning biomass compared to B_{MSY} is shown in Fig. 4. These performance statistics are also tabulated in Table2, together with values for B_{2022}/B_{MSY} and C_{2021}/MSY. Individual trajectories for catch and spawning biomass, and median with 90% probability envelopes are shown in Figure 4.1 and Figure 4.2 respectively.

DISCUSSION AND FURTHER DEVELOPMENTS

In most respects the performance of the Fox model, γ=0.6 management procedure candidate appears reasonable for these initial trials. For most scenarios the average interannual TAC variability is less than 3%. TACs do not change greatly for the next five years, but do show increases over the following 15 years for those scenarios that reflect a more productive resource, as well as securing an increase in abundance over this period (often to the 1980 level by 2020). The plots in Figure 3.1 are misleading for scenario *h6M05* for which the combination of no increase in abundance and an increased TAC might seem unsatisfactory; reference to Table 2c shows, however, that for this scenario resource biomass remains above B_{MSY}, so that the MP is not setting inappropriately high TACs.

Figure 4 shows that this Fox, γ=0.6 candidate MP could be criticised for moving spawning biomass in some higher *h* scenarios further above B_{MSY} than might seem desirable, as potential for higher catches is sacrificed. However, what might be seen as the greater problem area are the two scenarios reflecting a low productivity resource with *h*=0.3. Although feedback control is coming into play to arrest spawning biomass decline (see Figures 2.1 and 2.2), the reduction in TAC is not sufficiently rapid to reverse this decline over the 20 year simulation period, or to stop the resource being reduced below its B_{MSY} level (see Table 2).

How can performance be improved for these two scenarios, without at the same time sacrificing on performance for the more productive scenarios? What is needed is to reduce TACs faster than equation (7) achieves once the Fox model's estimation procedure has identified the resource to have relatively poor productivity. Figure 5 shows trajectories of estimates of the *r* parameter of the Fox model for 10 projections for each of the eight scenarios under consideration. This suggests that the poorer productivity cases separate out after about five years, with *r* values that drop below 1.0. To adjust equation (7) to react appropriately in these circumstances by lowering the TAC more quickly, $\hat{r}_y$ (the value of $\hat{r}$ as estimated at the end of year *y*) in that equation was replaced by r^* where:

$$r^* = \begin{cases} \hat{r}_y & \text{for } \hat{r}_y \geq 1.0 \text{ or } \quad y \leq 2007 \\ \hat{r}_y{}^p & \text{for } \hat{r}_y < 1.0 \text{ and } y \geq 2012. \\ \left(\frac{2012-y}{5}\right)\hat{r}_y + \left(\frac{y-2007}{5}\right)\hat{r}_y{}^p & \text{for } \hat{r}_y < 1.0 \text{ and } 2007 < y < 2012 \end{cases} \qquad (8)$$

where p is a control parameter to be chosen >1, to attempt a faster but still smooth TAC reduction in these circumstances.

The results of this modification compared to these of the original Fox model, γ=0.6 MP are shown in Fig. 6 for the choices p=3 and p=4. For p=3 and more so for p=4, TACs are reduced sufficiently rapidly to arrest and reverse the downward trend in (median) spawning biomass.

From this it is evident that a modification of the form of equation (8) can effect better performance for lower productivity scenarios without compromising results for higher productivity scenarios. However the present scenarios for testing do not provide a completely sufficient basis to test this option, which relies on the *h3* vs *h6* and *h9* scenarios being eventually separated by the $\hat{r}$ estimates shown in Figure 5, by about 2007. Further scenarios with h values intermediate between 0.3 and 0.6 would need to be provided in future trials to check that the modification did not cause inappropriate behaviour in those circumstances.

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Table 1. Estimates of total catch (tons) for 1952-2001 and CPUE values for 1969-2000 input to the management procedure.

	Catch	CPUE
1952	89	-
1953	2639	-
1954	3427	-
1955	2171	-
1956	3836	-
1957	23859	-
1958	17743	-
1959	43298	-
1960	72453	-
1961	92408	-
1962	57892	-
1963	58579	-
1964	56401	-
1965	54969	-
1966	46495	-
1967	54473	-
1968	62159	-
1969	54514	2.4883
1970	43778	2.0917
1971	41100	1.8920
1972	47259	1.9679
1973	42614	1.5681
1974	41021	1.7207
1975	30840	1.2603
1976	41709	1.5825
1977	37118	1.4921
1978	35352	1.3433
1979	36811	1.0826
1980	40612	1.1299
1981	40211	1.1385
1982	35759	0.9015
1983	45560	0.9571
1984	35623	0.8455
1985	31101	0.7100
1986	27920	0.4974
1987	23929	0.4720
1988	22352	0.4146
1989	18690	0.4206
1990	14006	0.4200
1991	13704	0.4752
1992	13142	0.5220
1993	15686	0.7138
1994	12233	0.6909
1995	11881	0.7199
1996	14517	0.4729
1997	15710	0.4854
1998	20359	0.5151
1999	20171	0.4730
2000	15817	0.5856
2001	15966	-

Table 2a. Tabulated performance statistics for the Fox model candidate MP with γ =0.6 for Hierarchy=1.

Hierarchy -Scenario	quantile	d[i]	mean(cat [y:y+4])	mean(cat [y:y+19])	propAS	B(2007)/ B(2002)	B(2022)/ B(2002)	B(2020)/ B(1980)	NB(2022) /NB(2002	AAV	B2022/ BMSY	C2021/ MSY
	0.1	−0.039	14385.7	11414.4	0.273	0.855	0.561	0.209	0.635	0.031	0.647	2.380
1_h3M10	median	−0.030	14385.7	11414.4	0.273	0.855	0.561	0.209	0.635	0.031	0.647	2.380
	0.9	−0.024	14385.7	11414.4	0.273	0.855	0.561	0.209	0.635	0.031	0.647	2.380
	0.1	0.004	15005.3	16610.9	0.272	1.108	1.531	0.677	1.439	0.012	1.092	0.884
1_h6M10	median	0.010	15005.3	16610.9	0.272	1.108	1.531	0.677	1.439	0.012	1.092	0.884
	0.9	0.019	15005.3	16610.9	0.272	1.108	1.531	0.677	1.439	0.012	1.092	0.884
	0.1	0.005	15278.6	19417.9	0.273	1.223	1.994	1.019	1.373	0.024	3.651	0.675
1_h9M10	median	0.021	15278.6	19417.9	0.273	1.223	1.994	1.019	1.373	0.024	3.651	0.675
	0.9	0.045	15278.6	19417.9	0.273	1.223	1.994	1.019	1.373	0.024	3.651	0.675
	0.1	0.000	15363	18912.3	0.273	0.963	1.018	0.518	1.216	0.020	1.472	1.358
1_h6M05	median	0.017	15363	18912.3	0.273	0.963	1.018	0.518	1.216	0.020	1.472	1.358
	0.9	0.045	15363	18912.3	0.273	0.963	1.018	0.518	1.216	0.020	1.472	1.358
	0.1	−0.045	14125.3	11515.2	0.274	0.883	0.761	0.325	0.927	0.024	0.460	0.921
1_h3M15	median	−0.016	14125.3	11515.2	0.274	0.883	0.761	0.325	0.927	0.024	0.460	0.921
	0.9	−0.014	14125.3	11515.2	0.274	0.883	0.761	0.325	0.927	0.024	0.460	0.921
	0.1	−0.009	14572.6	15654.4	0.274	1.145	1.855	1.135	1.659	0.012	1.574	0.606
1_h6M15	median	0.013	14572.6	15654.4	0.274	1.145	1.855	1.135	1.659	0.012	1.574	0.606
	0.9	0.017	14572.6	15654.4	0.274	1.145	1.855	1.135	1.659	0.012	1.574	0.606
	0.1	0.003	14754.2	16972.2	0.276	1.303	2.074	1.536	1.354	0.015	4.185	0.493
1_h9M15	median	0.015	14754.2	16972.2	0.276	1.303	2.074	1.536	1.354	0.015	4.185	0.493
	0.9	0.024	14754.2	16972.2	0.276	1.303	2.074	1.536	1.354	0.015	4.185	0.493
	0.1	−0.014	14400.5	15172.4	0.276	1.088	1.866	1.042	1.748	0.013	1.522	0.840
1 h6M15d1	median	0.013	14400.5	15172.4	0.276	1.088	1.866	1.042	1.748	0.013	1.522	0.840
	0.9	0.018	14400.5	15172.4	0.276	1.088	1.866	1.042	1.748	0.013	1.522	0.840

Table 2b. Tabulated performance statistics for the Fox model candidate MP with γ =0.6 for Hierarchy=2.

Hierarchy -Scenario	quantile	d[i]	mean(cat [y:y+4])	mean(cat [y:y+19])	propAS	B(2007)/ B(2002)	B(2022)/ B(2002)	B(2020)/ B(1980)	NB(2022) /NB(2002	AAV	B2022/ BMSY	C2021/ MSY
	0.1	-0.054	13938.6	11036.1	0.273	0.849	0.523	0.196	0.595	0.028	0.604	2.227
2_h3M10	median	-0.031	14382.3	11439.3	0.273	0.855	0.560	0.210	0.633	0.032	0.646	2.366
	0.9	-0.008	14865.6	11809	0.273	0.861	0.594	0.220	0.673	0.036	0.685	2.572
	0.1	-0.009	14545.4	15967	0.272	1.100	1.467	0.648	1.407	0.012	1.047	0.841
2_h6M10	median	0.011	15004.3	16639.3	0.272	1.108	1.531	0.677	1.437	0.015	1.092	0.879
	0.9	0.030	15516.4	17172.2	0.272	1.115	1.591	0.701	1.473	0.019	1.136	0.933
	0.1	-0.002	14809.8	18668.5	0.273	1.217	1.939	0.989	1.360	0.022	3.551	0.646
2_h9M10	median	0.021	15280.9	19438.3	0.273	1.223	1.992	1.019	1.371	0.024	3.648	0.673
	0.9	0.050	15806	20081.7	0.273	1.229	2.049	1.045	1.390	0.028	3.752	0.709
	0.1	-0.008	14893.1	18194	0.273	0.960	0.990	0.504	1.195	0.019	1.432	1.297
2_h6M05	median	0.016	15365.2	18937.1	0.273	0.963	1.018	0.518	1.215	0.022	1.472	1.354
	0.9	0.048	15891.9	19539.2	0.273	0.966	1.044	0.529	1.241	0.026	1.509	1.428
	0.1	-0.052	13688	11109.4	0.274	0.878	0.727	0.311	0.889	0.023	0.440	0.862
2_h3M15	median	-0.024	14118.8	11540.1	0.274	0.883	0.759	0.325	0.925	0.027	0.459	0.913
	0.9	0.001	14595.7	11929.3	0.274	0.889	0.791	0.336	0.963	0.030	0.478	0.992
	0.1	-0.013	14119.5	15032.7	0.274	1.138	1.808	1.103	1.637	0.011	1.534	0.576
2_h6M15	median	0.010	14568.8	15692.3	0.274	1.145	1.853	1.135	1.656	0.015	1.573	0.604
	0.9	0.030	15068.3	16207.6	0.274	1.151	1.902	1.162	1.682	0.022	1.614	0.641
	0.1	-0.006	14296.2	16295.2	0.276	1.296	2.031	1.499	1.343	0.014	4.099	0.471
2_h9M15	median	0.014	14752.7	17003.7	0.276	1.303	2.070	1.534	1.352	0.017	4.178	0.492
	0.9	0.035	15261.8	17586.3	0.276	1.309	2.122	1.568	1.368	0.022	4.282	0.521
	0.1	-0.017	13950.4	14569.4	0.276	1.079	1.808	1.006	1.721	0.011	1.475	0.798
2 h6M15d1	median	0.009	14396.2	15212.3	0.276	1.088	1.864	1.042	1.745	0.016	1.521	0.836
	0.9	0.029	14890.4	15694.3	0.276	1.096	1.924	1.073	1.776	0.023	1.570	0.889

Table 2c. Tabulated performance statistics for the Fox model candidate MP with γ =0.6 for Hierarchy=3 and 4.

Hierarchy -Scenario	quantile	d[i]	mean(cat [y:y+4])	mean(cat [y:y+19])	propAS	B(2007)/ B(2002)	B(2022)/ B(2002)	B(2020)/ B(1980)	NB(2022) /NB(2002	AAV	B2022/ BMSY	C2021/ MSY
	0.1	−0.058	13953.7	10904.4	0.273	0.849	0.504	0.188	0.525	0.023	0.582	2.067
3_h3M10	median	−0.029	14405.1	11484.8	0.273	0.855	0.578	0.218	0.677	0.031	0.667	2.517
	0.9	0.000	14878.8	12294.6	0.273	0.862	0.725	0.259	0.864	0.040	0.836	2.985
	0.1	−0.012	14535.8	15739.6	0.272	1.099	1.311	0.579	1.163	0.011	0.936	0.796
3_h6M10	median	0.012	15025.4	16593.8	0.272	1.107	1.554	0.699	1.492	0.017	1.109	0.897
	0.9	0.033	15517.7	17721	0.272	1.116	2.010	0.855	1.820	0.024	1.435	1.024
	0.1	−0.003	14790	18334.2	0.273	1.217	1.683	0.861	1.077	0.020	3.081	0.610
3_h9M10	median	0.021	15310.4	19304.4	0.273	1.223	1.973	1.020	1.353	0.025	3.612	0.670
	0.9	0.050	15801	20479.3	0.273	1.229	2.442	1.192	1.678	0.031	4.471	0.753
	0.1	−0.009	14872.6	17840.6	0.273	0.960	0.922	0.471	0.959	0.018	1.333	1.213
3_h6M05	median	0.017	15383.2	18787	0.273	0.963	1.019	0.521	1.202	0.023	1.472	1.354
	0.9	0.048	15886.2	19984.6	0.273	0.966	1.174	0.581	1.517	0.029	1.697	1.538
	0.1	−0.055	13701.5	10972.1	0.274	0.877	0.662	0.280	0.752	0.021	0.400	0.796
3_h3M15	median	−0.023	14142	11571.3	0.274	0.883	0.782	0.340	0.989	0.028	0.473	0.967
	0.9	0.011	14612.4	12396.6	0.274	0.889	1.010	0.415	1.264	0.034	0.610	1.125
	0.1	−0.016	14121.9	14845.5	0.274	1.138	1.587	0.964	1.356	0.011	1.346	0.547
3_h6M15	median	0.011	14592.4	15670.2	0.274	1.145	1.893	1.173	1.704	0.017	1.606	0.616
	0.9	0.034	15075.3	16722.9	0.274	1.151	2.383	1.418	2.079	0.025	2.023	0.700
	0.1	−0.009	14289.3	16050.5	0.276	1.296	1.741	1.290	1.085	0.013	3.513	0.445
3_h9M15	median	0.015	14774.1	16916.4	0.276	1.302	2.075	1.547	1.357	0.018	4.187	0.494
	0.9	0.036	15264.4	17888.6	0.276	1.309	2.595	1.842	1.664	0.025	5.237	0.554
	0.1	−0.020	13957	14356.2	0.276	1.079	1.576	0.877	1.432	0.012	1.286	0.752
3 h6M15d1	median	0.010	14420.2	15192.8	0.276	1.088	1.898	1.075	1.813	0.018	1.548	0.856
	0.9	0.035	14899.3	16235.5	0.276	1.096	2.488	1.348	2.181	0.025	2.030	0.978
	0.1	−0.034	14000.4	12655.6	0.270	0.874	0.804	0.289	0.896	0.014	–	–
4 hestmcm	median	0.003	14492.8	15250	0.275	0.964	1.276	0.508	1.389	0.022	–	–
	0.9	0.039	15123.4	18070.5	0.280	1.091	2.002	0.879	2.103	0.033	–	–

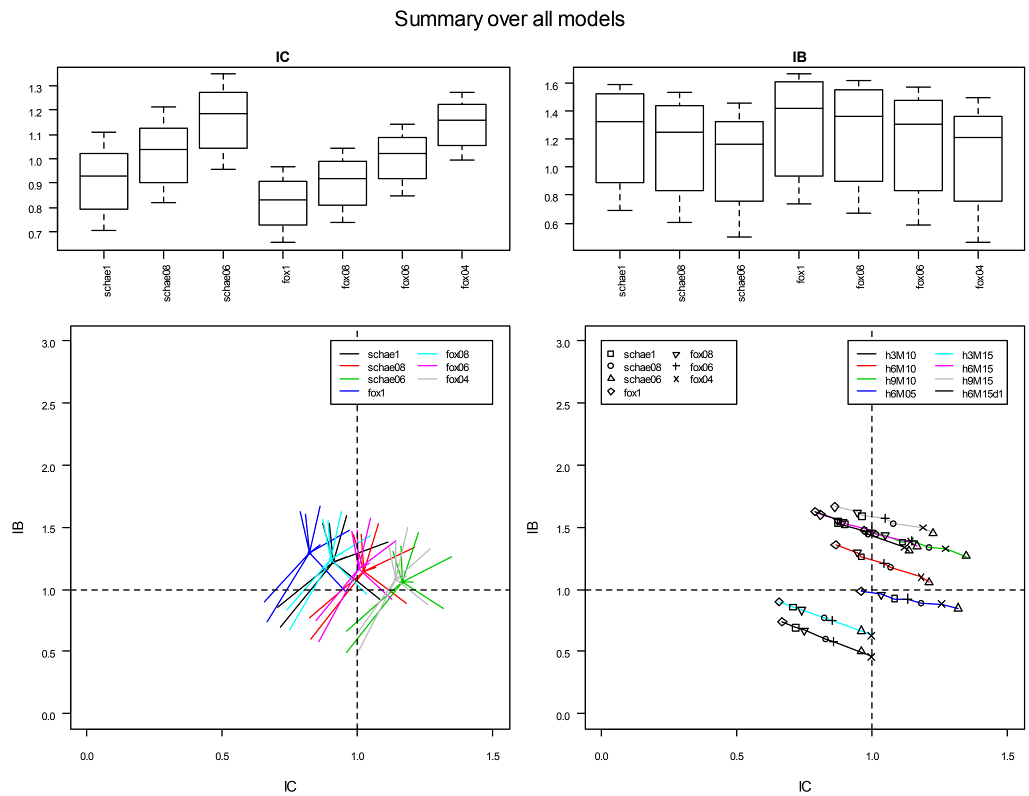

Figure 1.1. Summary performance for the seven initial candidate MPs.

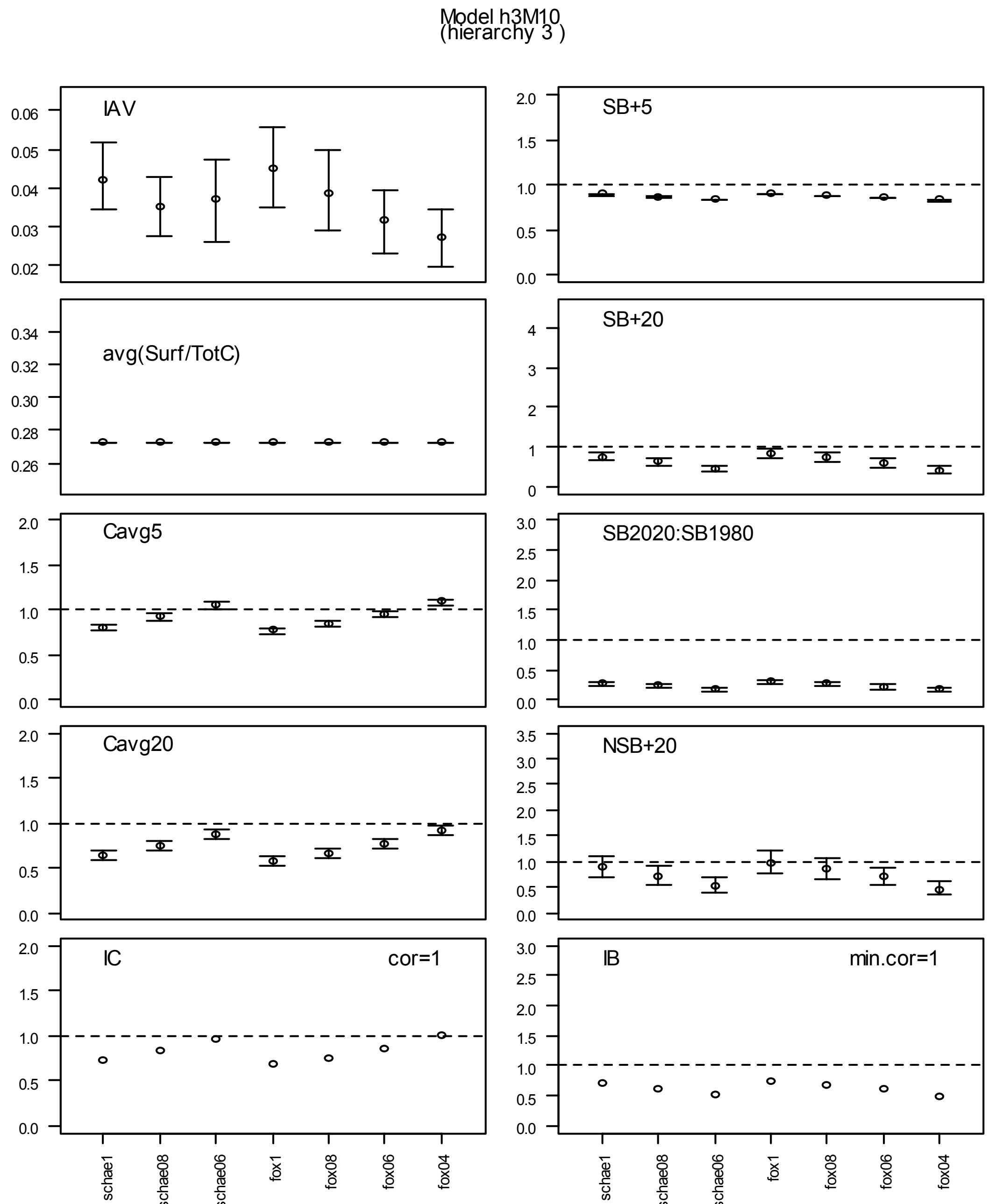

Figure 1.2. Performance statistics for seven candidate MPs for scenario *h3M10*.

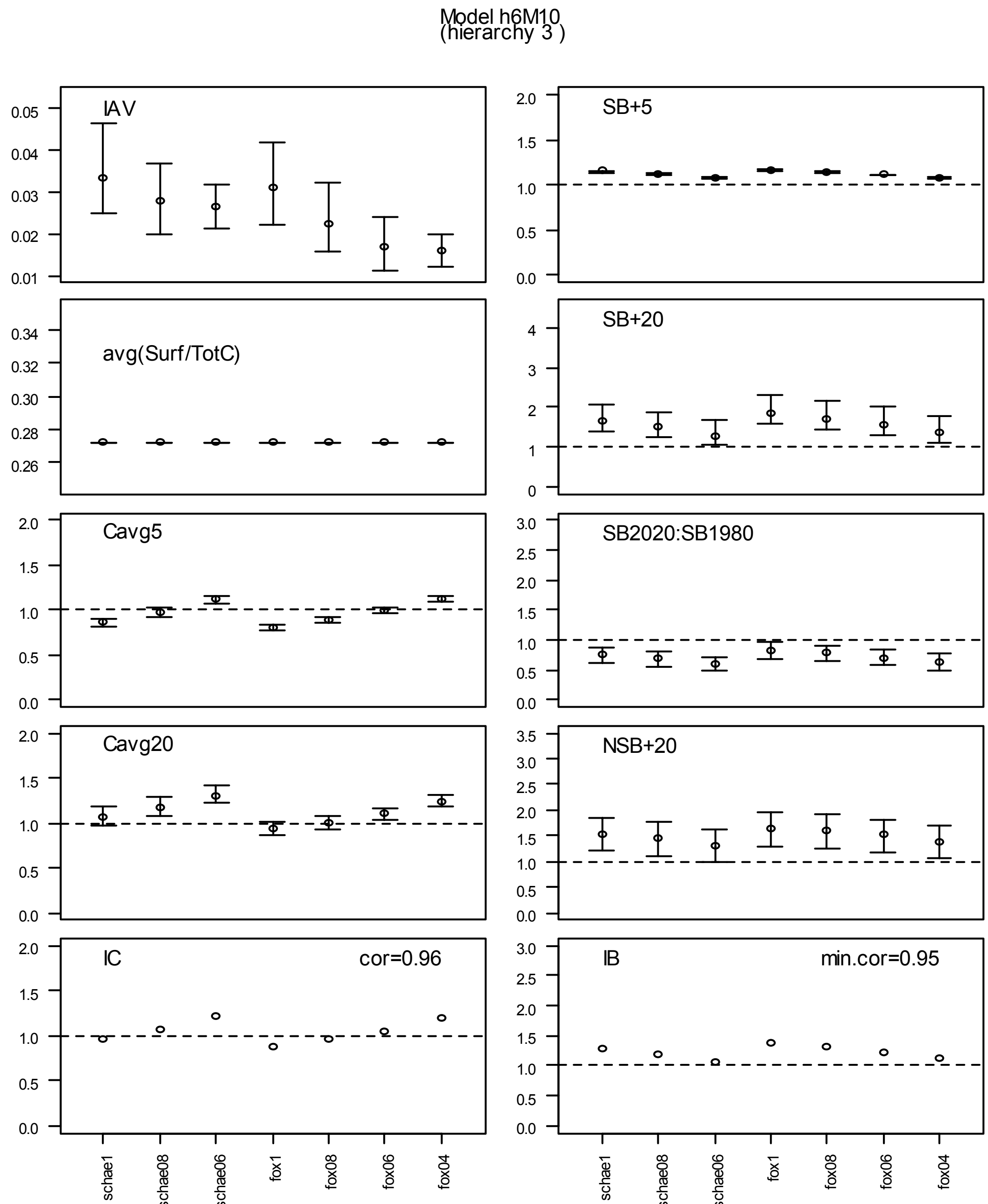

Figure 1.3. Performance statistics for seven candidate MPs for scenario *h6M10*.

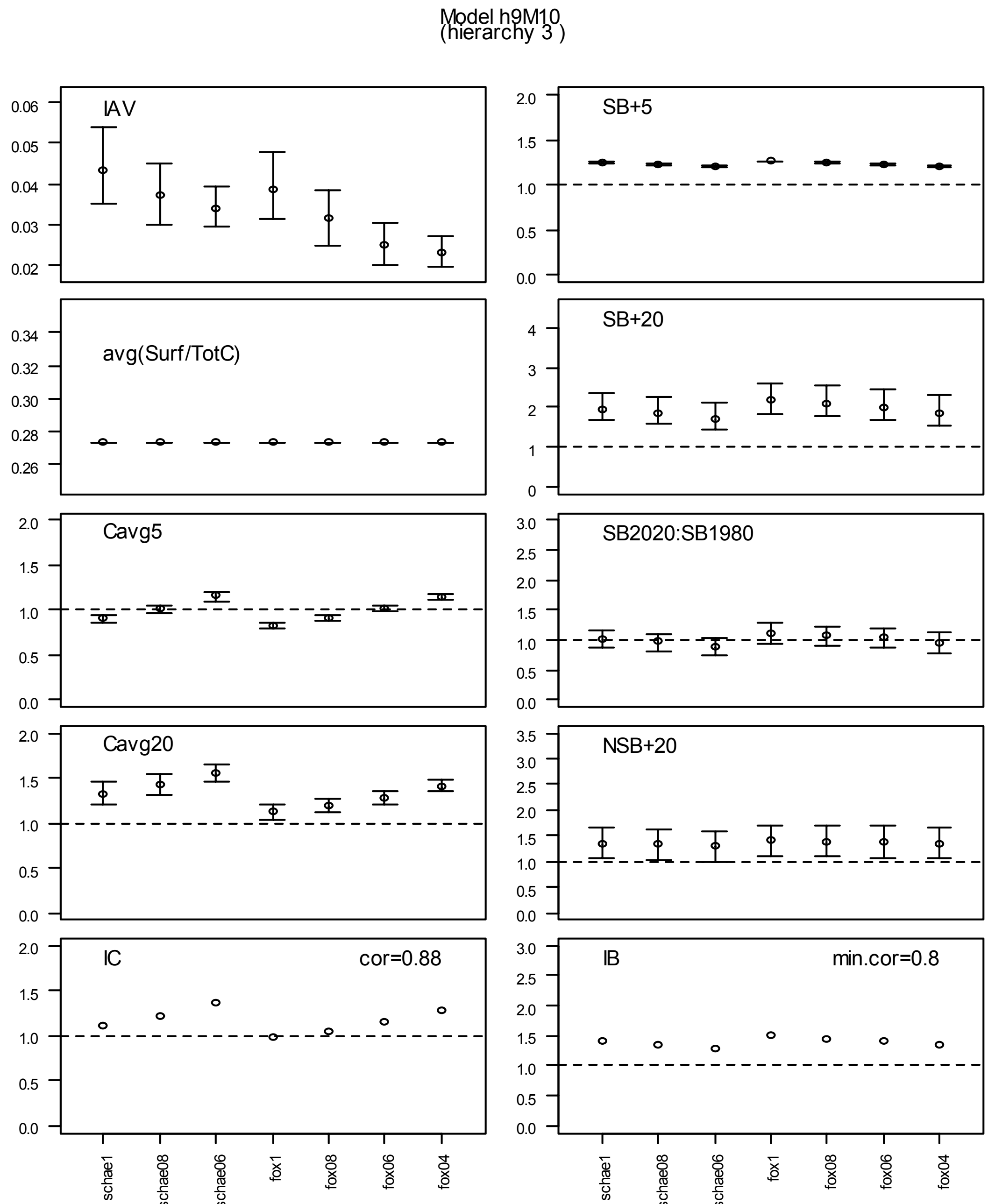

Figure. 1.4. Performance statistics for seven candidate MPs for scenario *h9M10*.

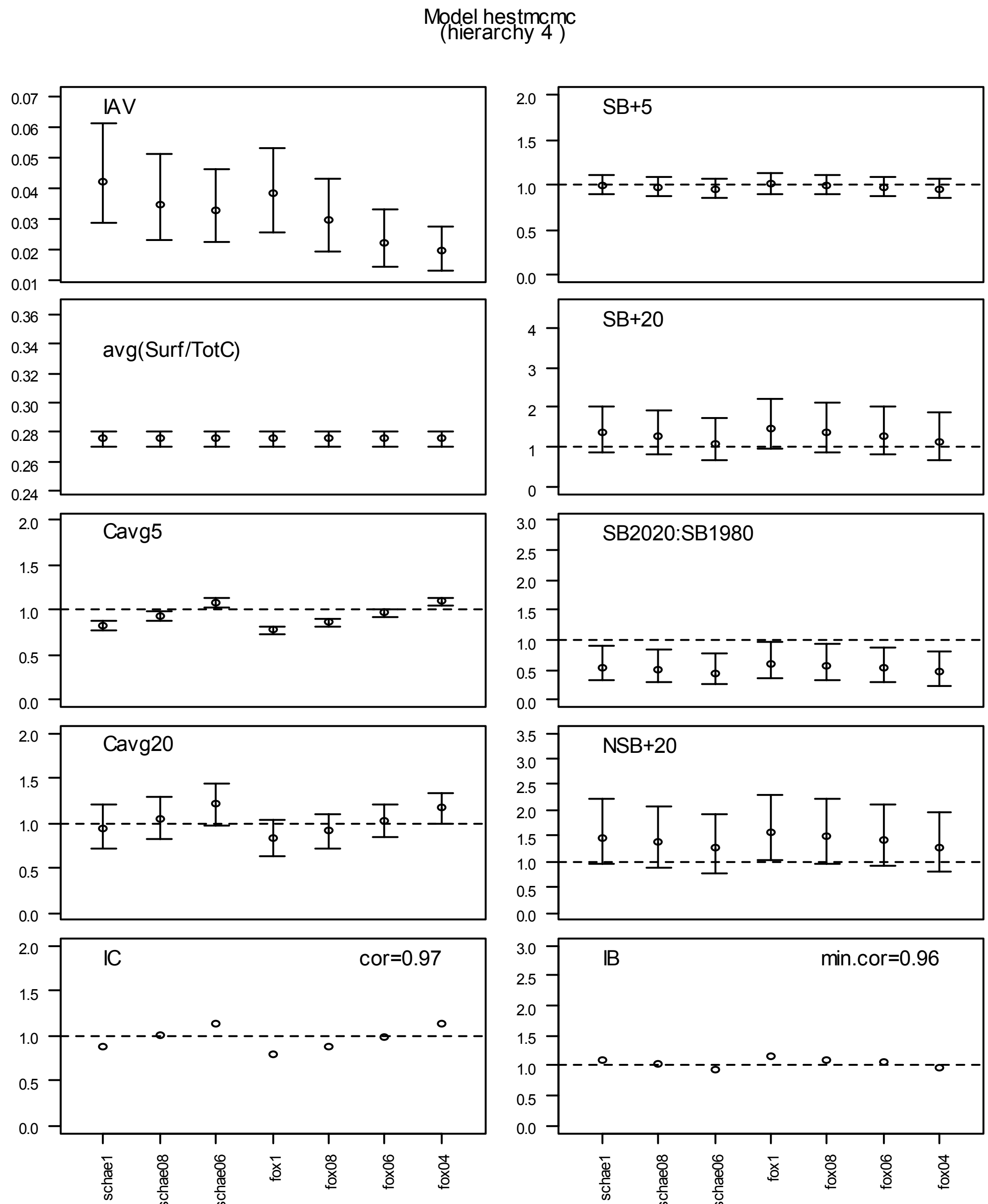

Figure 1.5. Performance statistics for seven candidate MPs for scenario *hestmcmc*.

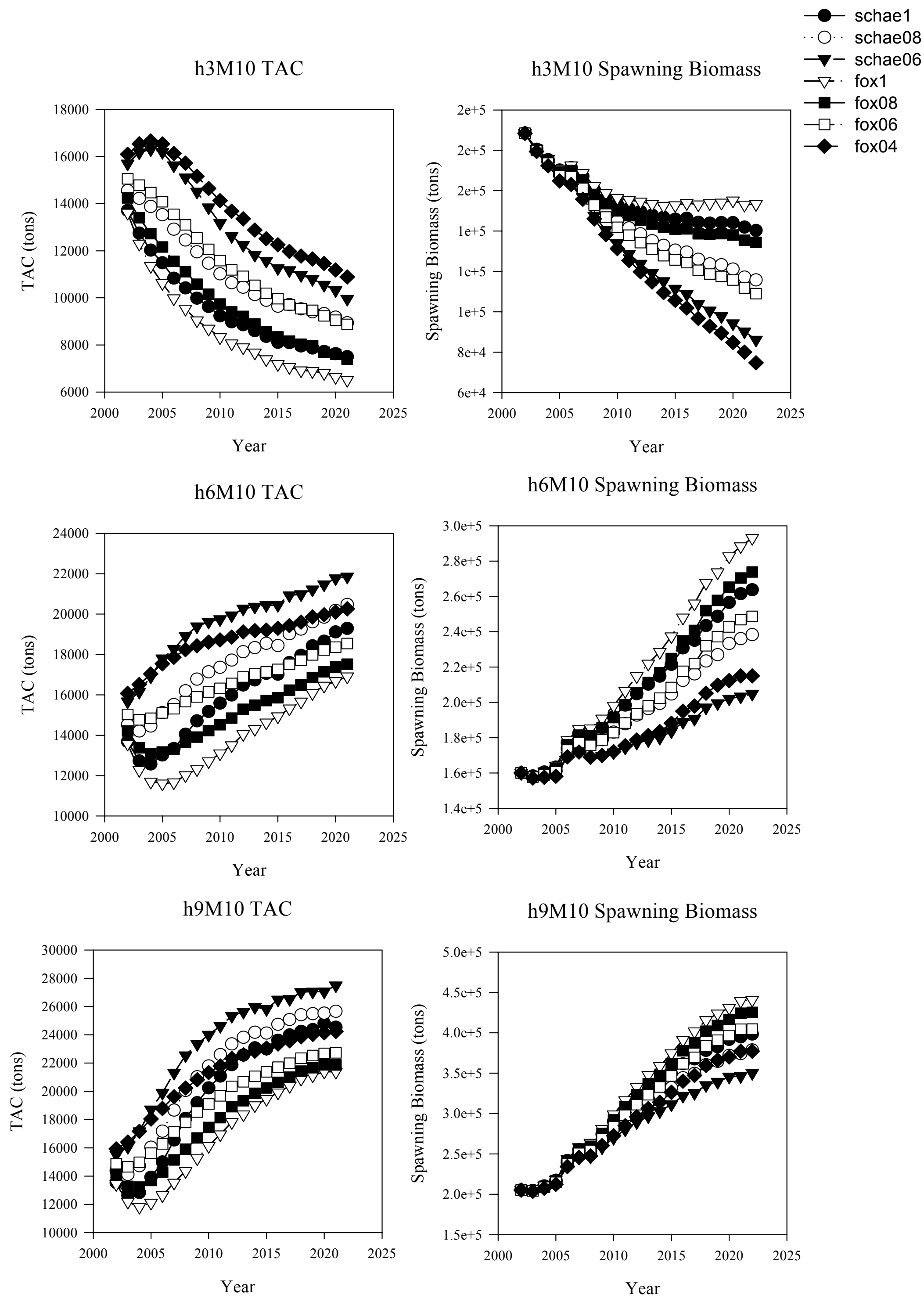

Figure 2.1. Median TAC and spawning biomass trajectories for seven candidate MPs for the *h3M10*, *h6M10* and *h9M10* scenarios.

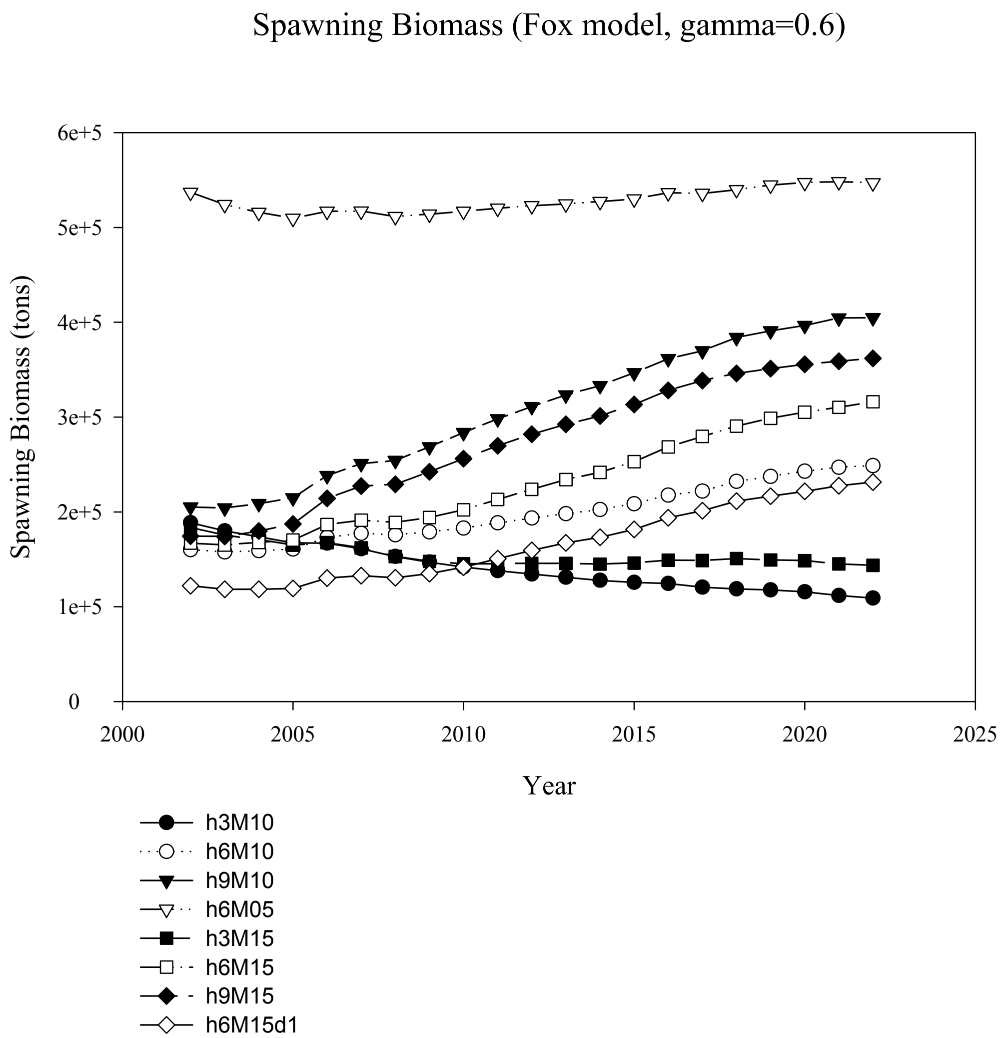

Figure 2.2. Median spawning biomass trajectories for the Fox, γ =0.6 candidate MP for the eight fixed *h* scenarios.

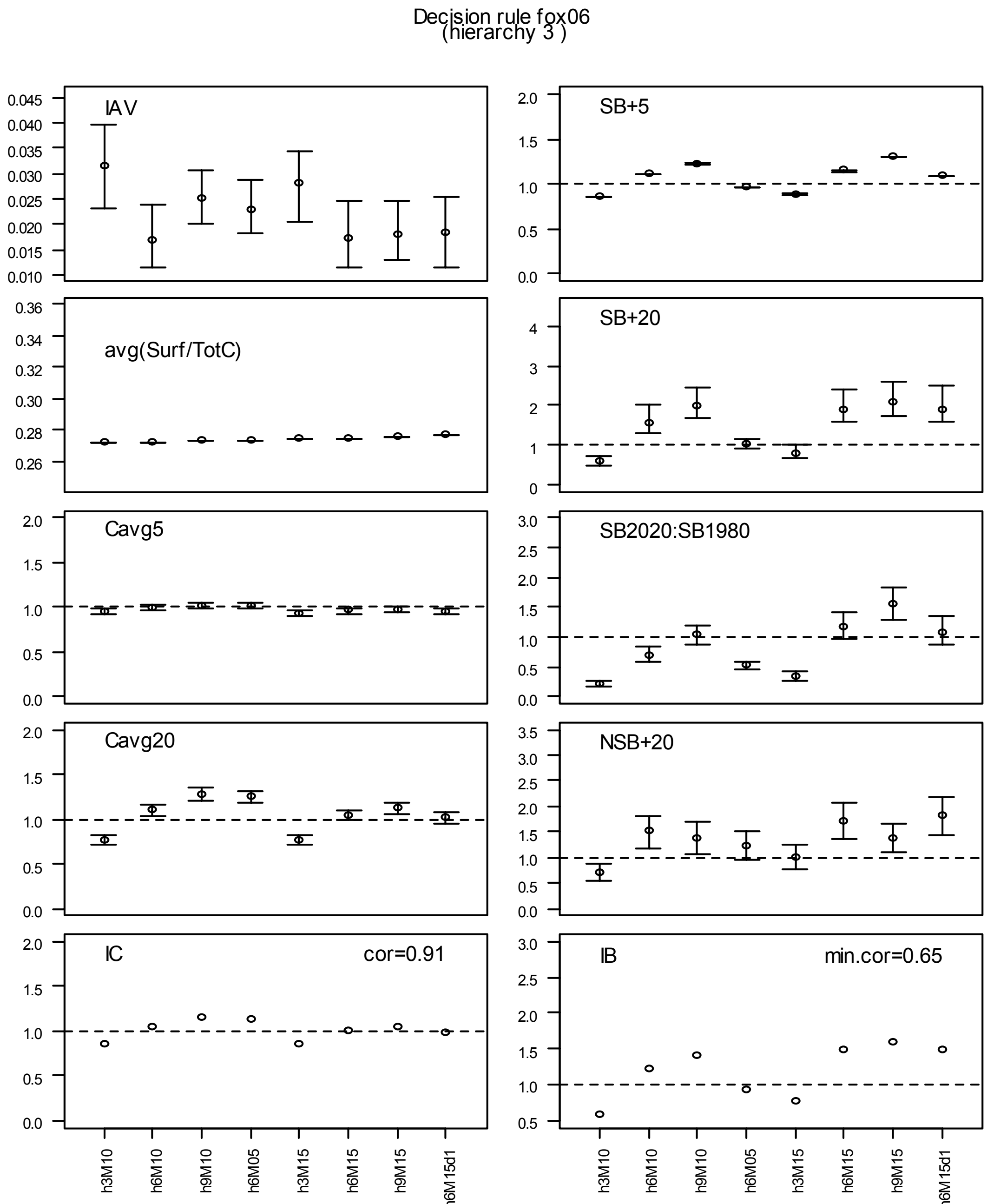

Figure 3.1. Performance statistics for the Fox, γ =0.6 candidate MP for eight fixed *h* scenarios.

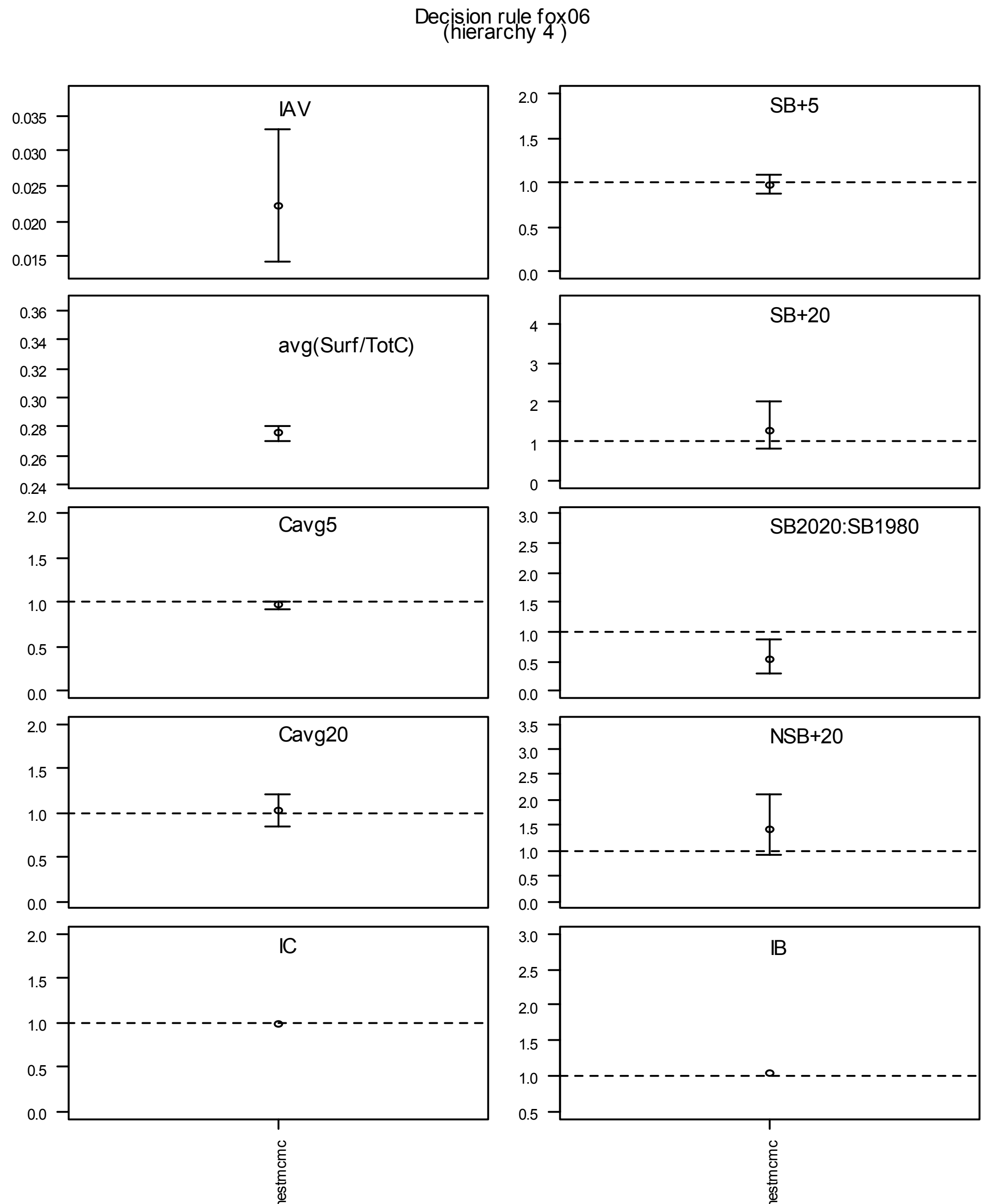

Figure 3.2. Performance statistics for the Fox, γ =0.6 candidate MP for the *hestmcmc* scenario.

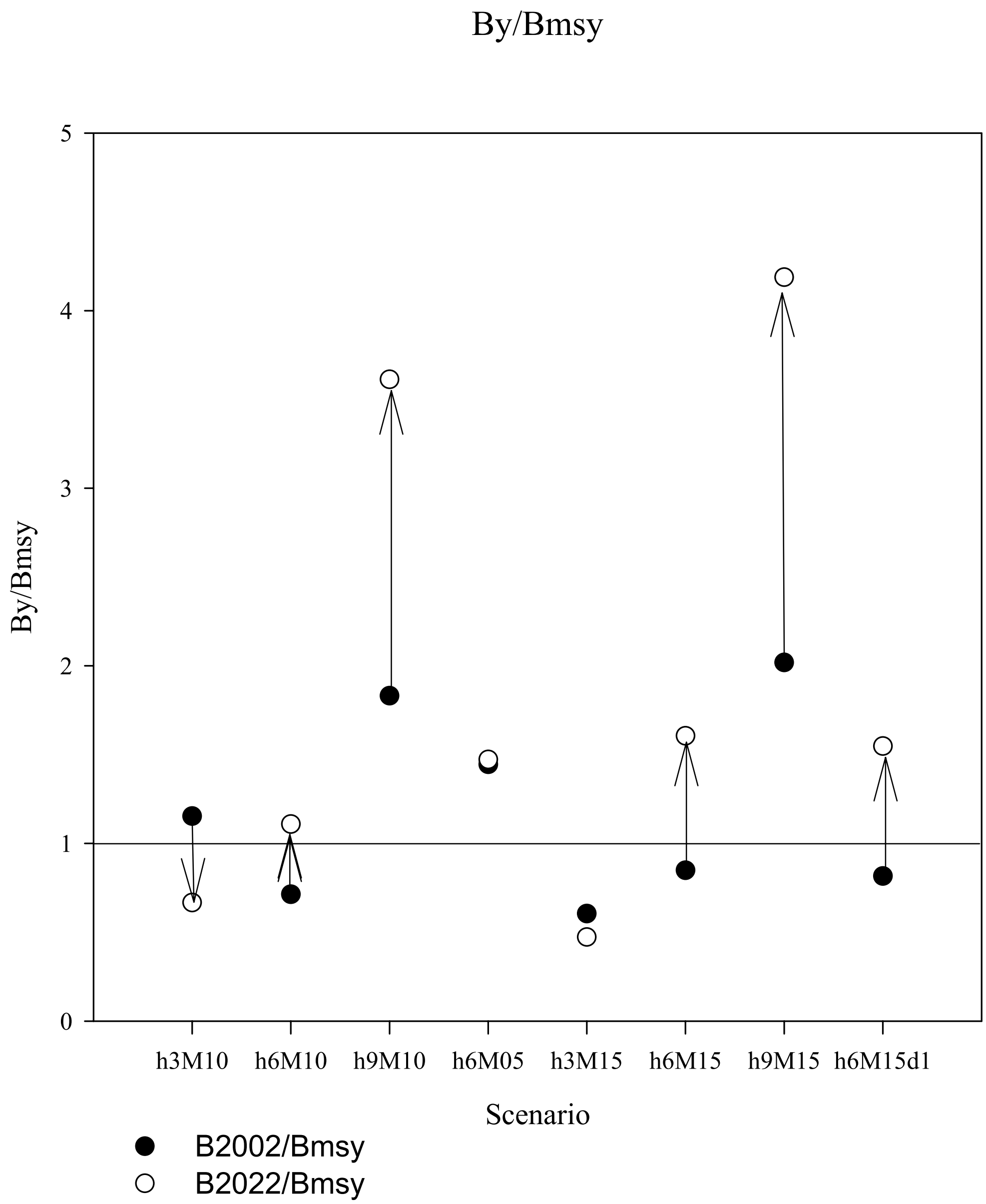

Figure 4. This plot shows how the median spawning biomass changes compared to B_{MSY} over the 20 year projection period considered.

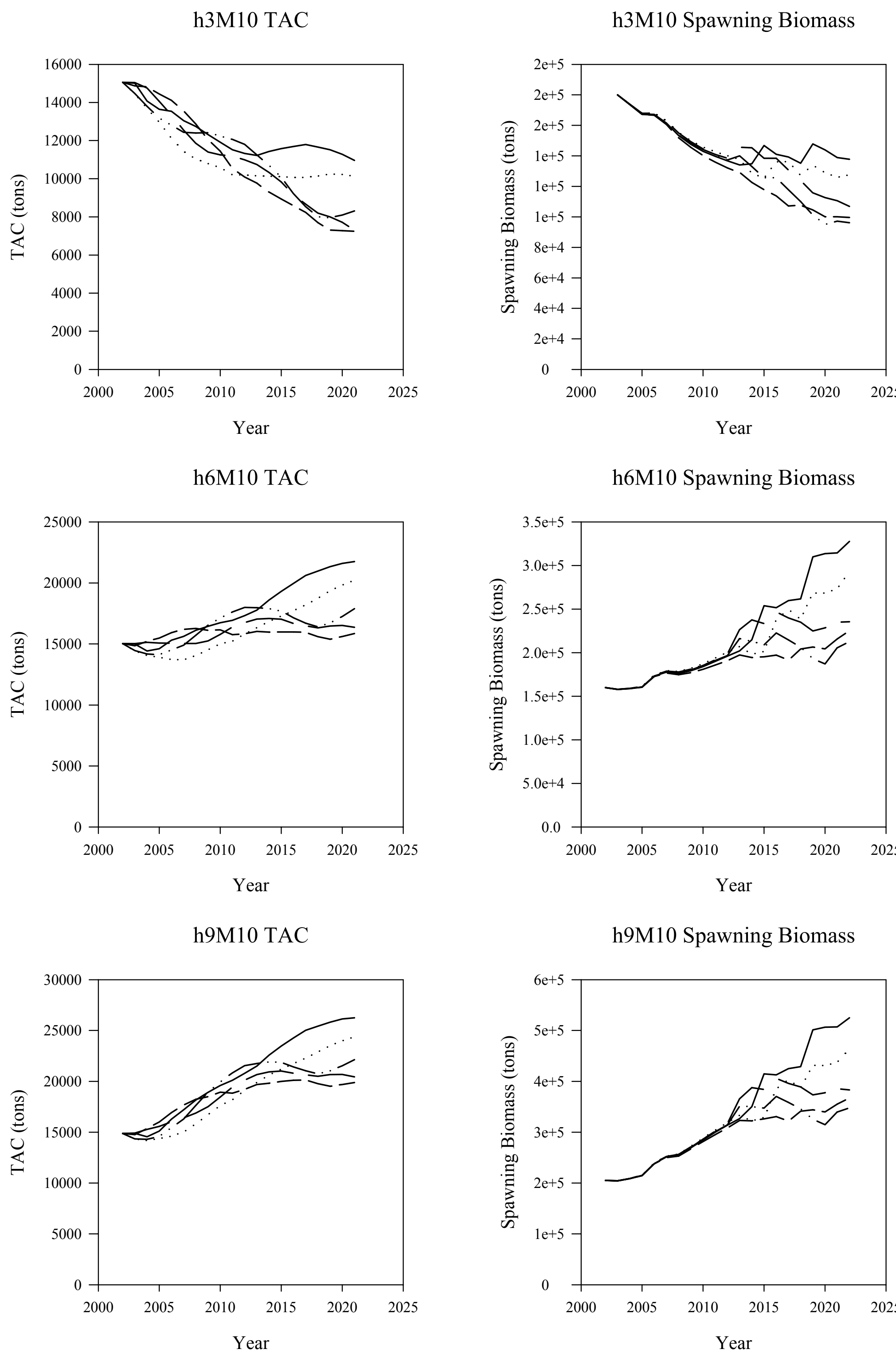

Figure 4.1. 5 trajectories of TAC and spawning biomass for scenarios *h3M10*, *h6M10*, and *h9M10* for simulation hierarchy=3. The MP is fox model, γ =0.6.

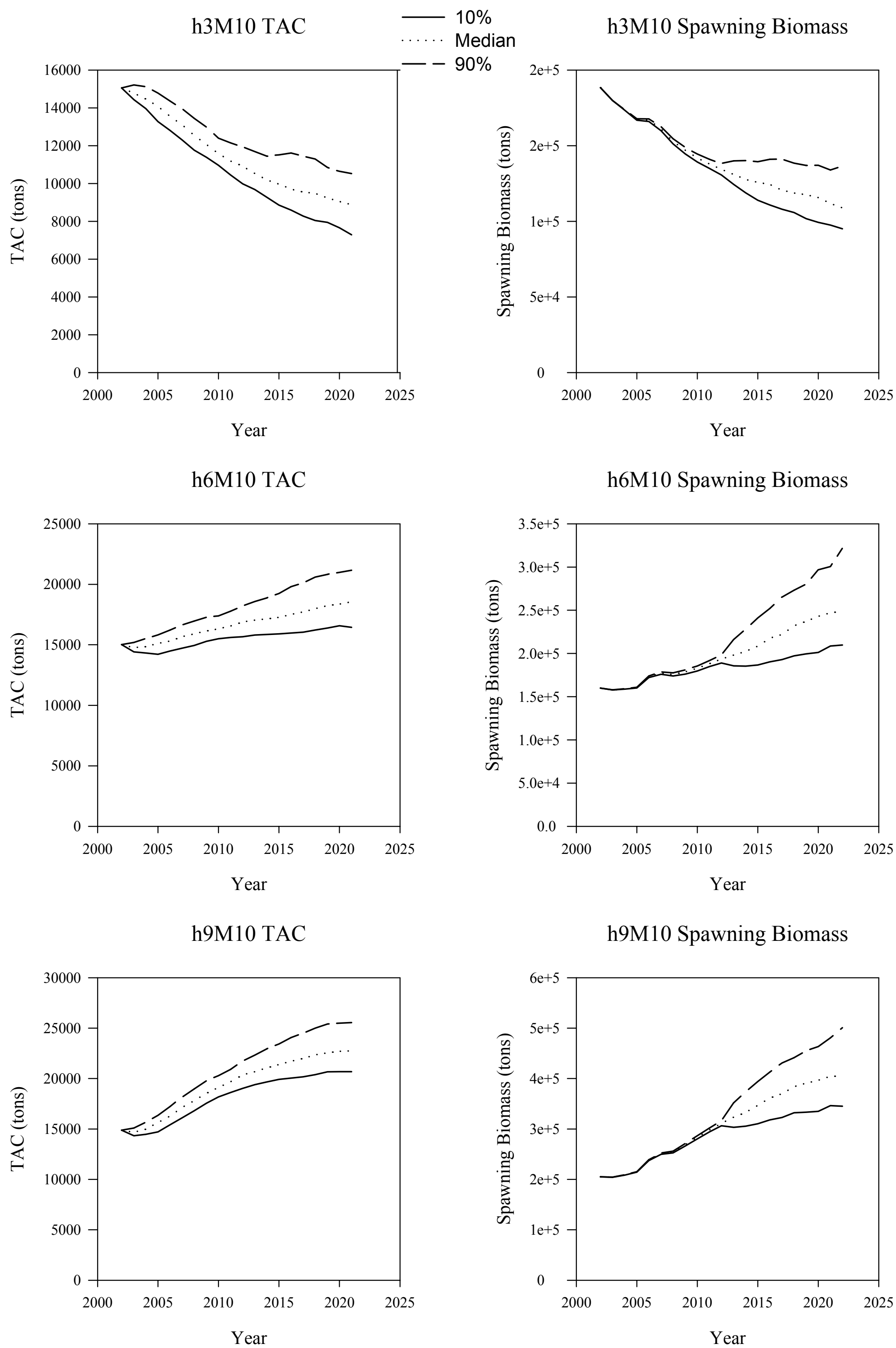

Figure 4.2. Median with 90% probability envelopes of TAC and spawning biomass for scenarios *h3M10*, *h6M10*, and *h9M10* for simulation hierarchy=3. The MP is fox model, γ =0.6.

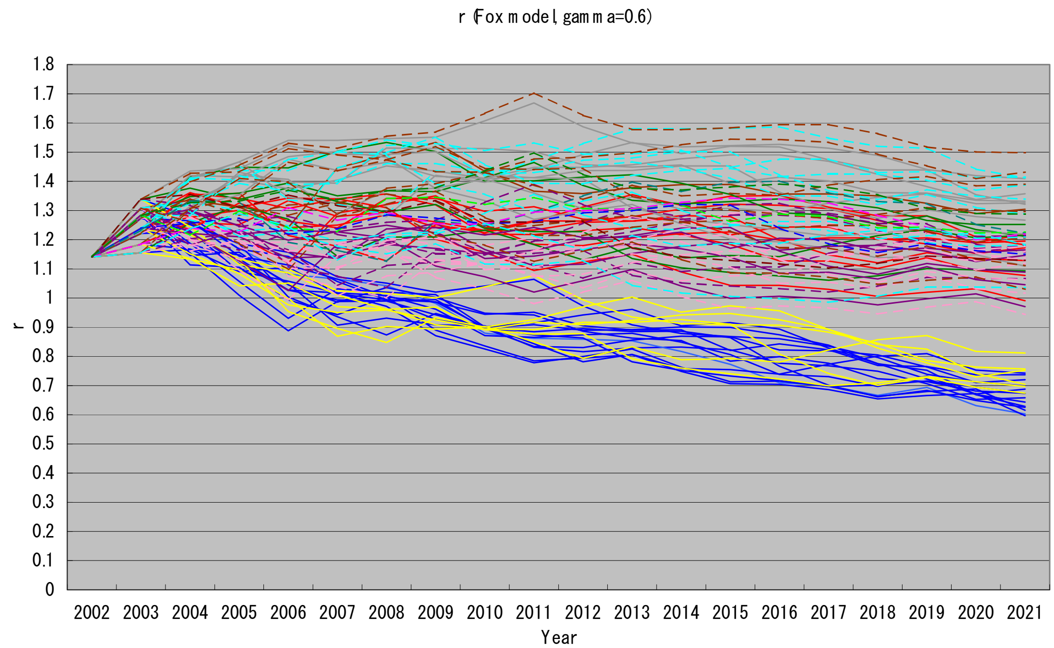

Figure 5. Trajectories of estimates of *r* for 10 replicates of each of the eight fixed *h* scenarios for the Fox, γ=0.6 candidate MP. The lower grouping of trajectories (blue and yellow on electronic versions) correspond to the results for the two scenarios with *h*=0.3, and exclude the other scenarios.

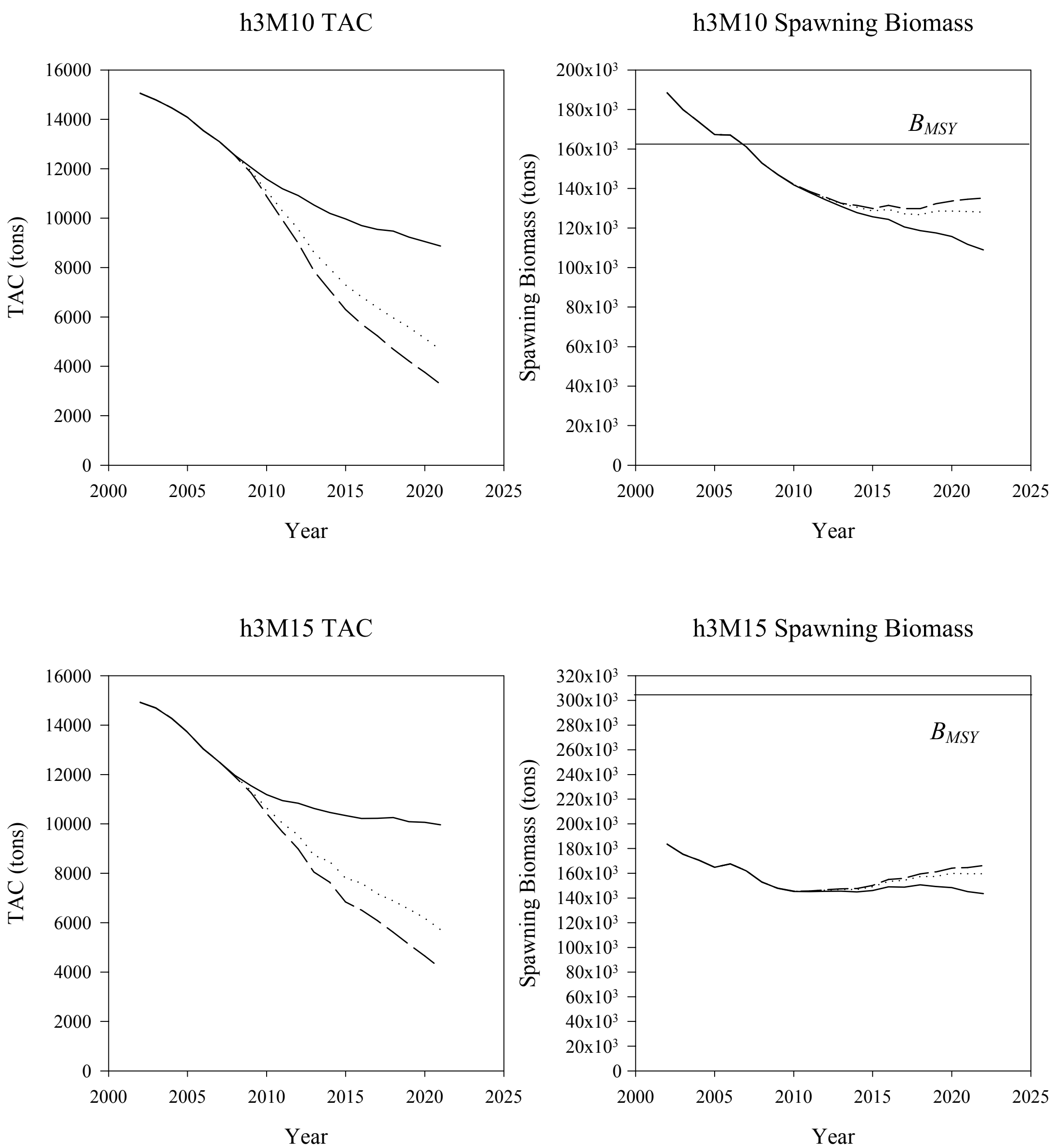

Figure 6. The plots show median values for the TAC and spawning biomass for simulation hierarchy=3. The solid lines are those without adjusting the *r* values, and the other lines are for the *r*-variant case of equation (8); *p*=3 (dotted) and *p*=4 (dashed).