Exploration of empirical management procedures based on longline CPUE index and aerial survey index

Hiroyuki Kurota[1], Ko Fujioka[1], Osamu Sakai[1], and Doug S Butterworth[2]
[1]National Research Institute of Far Seas Fisheries, Fisheries Research Agency,
[2]University of Cape Town

We evaluated performance of four Management Procedures (MPs) with empirical algorithms to determine TACs using information from the longline CPUE series and the aerial survey index. This MP exercise shows that TAC levels in the future are quite different depending on six management targets (tuning levels for spawning biomass recovery) that were proposed by the commissioners in April 2010. It also indicates that MPs with larger TAC reduction in the early years, which might not be preferred from a socio-economic viewpoint, enable quicker stock rebuilding and greater TAC increases in later years, even though they achieve the same long-term management target for spawning biomass recovery.

延縄 CPUE と航空機目視調査の指標に基づく経験的な管理方式の開発

黒田 啓行[1] ・ 藤岡 紘[1] ・ 境 磨[1] ・ ダグ バタワース[2]
[1]水産総合研究センター 遠洋水産研究所 ・ [2]ケープタウン大学

延縄 CPUE と航空機目視調査の指標に基づく管理方式を4つ開発し、その性能を評価した。解析の結果から、4 月に本委員会メンバーにより提案された 6 つの管理目標のうち、どの目標を設定するかにより、将来の TAC の量が大きく変わることが明らかになった。また同じ長期的な管理目標を満たす管理方式でも、早期により多くの TAC の削減を行えば、資源再建がより短期で可能であり、その後の TAC もより力強く回復することがわかった。ただし、TAC の早期大幅削減は社会経済な観点からは好まれないかもしれない。

Introduction

In 2000, the CCSBT commissioners decided to start a scientific project to develop a Management Procedure (MP) that specifies how the TAC will be adjusted as new data are collected (CCSBT 2000). Receiving this request from the commissioners, the Scientific Committee (SC) started the development of MP in 2002 (CCBST 2002), and after nearly four years of discussion at several meetings completed a process of selecting a final candidate MP along with a new management target for spawning biomass recovery (CCSBT 2005). Unfortunately, however, following indications of probable substantial historical overcatch,, this MP development process had to return to the starting point.

The first meeting of the CCSBT Strategy and Fisheries Management Working Group (SFMWG) held in 2009 confirmed that MP redevelopment would be finalized in 2010, and it also specified an interim management target (20% of SSB_0) (CCSBT 2009). The second SFMWG meeting held in April 2010 went on to provide guidance on management options to the Extended Scientific Committee (CCSBT 2010) (Table 1). In particular the SFMWG proposed six management targets (tuning options in the context of MP development) in terms of years (two options) and probability (three options) of achieving the target for spawning biomass recovery. The SFMWG also set short-term check points in 12 and 15 years from the start of MP implementation to evaluate the degree of achievement in the shorter term.

In this document, we evaluate the performance of four empirical MPs (these include two variants of the same MP) (HK3_k2, HK3_k4, HK5, HK6), which cover a wide range of MP behaviours (i.e., from risk-prone to risk-averse). These MPs determine TACs based on a longline CPUE index (HK3, HK5) along with an aerial survey index (HK6). Based on the evaluation of these MPs, we discuss general issues to be considered in the further development of MPs.

Projection conditions and specification of MPs

The guidance from the SFMWG to the ESC in April 2010 includes several management options for MP development in addition to the management target (Table 1). Due to time constraints, we have been able to examine MP performance for only a limited set of those options in this exercise (Table 2). This limited set was selected with a view towards understanding the behaviour of all the options as efficiently as possible.

In this exercise, we used the projection program "sbtprojv118.exe" (distributed on 19 May 2010) and conditioning results obtained using a conditioning program "sbtmod22.exe" (distributed on 21 April 2010). Tuning to six management targets was effected by changing a tuning parameter for each MP so as to satisfy a management target within a tolerance of 1% (e.g., 60 ± 1% for a target of 60%). For example, k_2 and l_{min} were selected as the tuning parameters for HK3 and for HK5 and HK6 respectively. The TAC allocations for each fleet were based on nominal allocations except for Japan=3000t in the default (i.e., option 2).

(1) revised HK3

HK3 ("Hiroyuki Kurota ver. 3"; Kurota 2005) is an empirical decision rule that depends on the most recent 10-yr trend of LL1 CPUE index for age 4+. To tune this MP to meet a management target flexibly, different values for a control parameter are used depending on whether the CPUE trend is positive or negative.

$$TAC_{y+1} = TAC_{y+1}^{cpue4+} = \begin{cases} TAC_y \times (1 + k_1\lambda) & \lambda < 0 \\ TAC_y \times (1 + k_2\lambda) & \lambda \geq 0 \end{cases}$$

where λ is the slope of regression of log($CPUE_{age4+}$) against year (from y - yrs_{cpue4+} to y - 2),
k_1, k_2 are parameters to control magnitude of TAC reduction and increase, respectively.

In this exercise, yrs_{cpue4+} was fixed at 11. The control parameters were determined for each tuning criterion as follows.

tuning option	HK3_k2		HK3_k4	
	k_1	k_2	k_1	k_2
1c	2	2.05	4	5.2
2c	2	0.8	4	4.3
3c	NA	NA	4	0.8
4c	2	3.25	4	6.4
5c	2	2.75	4	5.4
6c	2	0.7	4	3.8

HK3_k4 is designed to reduce TACs more quickly and substantially than HK3_k2. This is motivated by a recommendation made during the 2nd SFMWG meeting that: "early TAC changes were preferred over late TAC changes" (CCSBT 2010). Note that we could not find a k_2 value for HK3_k2 for the option 3c (2035-90%), when k_1 was fixed at 2. This indicates that k_1=2 is too small to meet this tuning criterion.

(2)revised HK5

HK5 ("Hiroyuki Kurota ver. 5"; Kurota 2005) is an empirical decision rule that makes use of the LL1 CPUE index of age 4+ and a recruitment index. This MP is a version of HK3 which is extended to incorporate recruitment information. The LL1 CPUE of age 4 in numbers ($CPUE_{age4}$) is used as the recruitment index. It is calculated from the CPUE for age 4+ and the age composition of the LL1 fishery (the ratio of catch comprised of age 4 tuna):

$$CPUE_{age4} = \frac{catch_{age4}}{catch_{age4+}} \times CPUE_{age4+}$$

The main feature of this MP is to choose a minimum TAC from that calculated using the CPUE trend of age 4+ over recent 10 years (TAC^{cpue4+}, which is identical to HK3) and the recruitment CPUE level over the recent three years (TAC^{cpue4}). The TAC is specified as:

$$TAC_{y+1} = \min\left(TAC_{y+1}^{cpue4+},\ TAC_{y+1}^{cpue4}\right)$$

$$TAC_{y+1}^{cpue4+} = \begin{cases} TAC_y \times (1 + k_1\lambda) & \lambda < 0 \\ TAC_y \times (1 + k_2\lambda) & \lambda \geq 0 \end{cases}$$

$$TAC_{y+1}^{cpue4} = TAC_y \times \begin{cases} m_{\max} & if \quad CPUE_{age4,\, y-2} > l_{\max} \\ a \times CPUE_{age4,\, y-2} + b & if \quad l_{\min} \leq CPUE_{age4,\, y-2} \leq l_{\max} \\ m_{\min} & if \quad CPUE_{age4,\, y-2} < l_{\min} \end{cases}$$

where λ is the slope of regression of $ln(CPUE_{age4+})$ against year (from $y - yrs_{cpue4+}$ to $y - 2$),

k_1, k_2 are control parameters,

$CPUE_{age4,y\text{-}2}$ is the mean ln ($CPUE_{age4}$) over years (from $y - yrs_{cpue4}$ to $y - 2$),

$m_{max}, m_{min}, l_{max}, l_{min}$ are control parameters, and

a, b are parameters related to $m_{max}, m_{min}, l_{max}, l_{min}$ to provide a continuous rule.

The parameter values used are k_1 = 2.0, k_2 = 5.0, l_{max} = -1.609438 (= ln0.2), m_{max} = 1.5, m_{min} = 0.5, yrs_{cpue4+} = 11 and yrs_{cpue4} = 4. A tuning parameter l_{min} is set for each tuning option as follows:

tuning option	l_{min}	exp(l_{min})
1c	-3.912023	0.02
2c	-3.688879	0.025
3c	-3.270169	0.038
4c	-4.50986	0.011
5c	-4.135167	0.016
6c	-3.649659	0.026

(4) HK6

A newly developed MP, HK6 ("Hiroyuki Kurota ver. 6") is similar to HK5. The difference is that HK6 uses the aerial survey index to provide the recruitment index instead of the LL1 CPUE index for age 4. The MP then chooses the minimum of the TACs calculated using the CPUE trend for age 4+ over the most recent 10 years (TAC^{cpue4+}, which is identical to HK3) and using the aerial survey index over the most recent three years (TAC^{cpue4}). The TAC is specified as:

$$TAC_{y+1} = \min\left(TAC_{y+1}^{cpue4+},\ TAC_{y+1}^{aerial}\right)$$

$$TAC_{y+1}^{cpue4+} = \begin{cases} TAC_y \times (1 + k_1\lambda) & \lambda < 0 \\ TAC_y \times (1 + k_2\lambda) & \lambda \geq 0 \end{cases}$$

$$TAC_{y+1}^{aerial} = TAC_y \times \begin{cases} m_{\max} & if \quad Aer_{y-1} > l_{\max} \\ a \times Aer_{y-1} + b & if \quad l_{\min} \leq Aer_{y-1} \leq l_{\max} \\ m_{\min} & if \quad Aer_{y-1} < l_{\min} \end{cases}$$

where λ is the slope of the regression of $ln\ (CPUE_{age4+})$ against year (from y - yrs_{cpue4+} to y - 2),
k_1, k_2 are control parameters,
$Aer_{y\text{-}1}$ is the mean aerial survey index (in the natural log space) over years (from $y - yrs_{aerial}$ to $y - 2$),
m_{max}, m_{min}, l_{max}, l_{min} are control parameters, and
a, b are parameters related to m_{max}, m_{min}, l_{max}, l_{min} to provide a continuous rule.

The parameter values used are k_1 = 2.0, k_2 = 5.0, l_{max} = 6.684612 (=ln800), m_{max} = 1.5, m_{min} = 0.5, yrs_{cpue4+} = 11 and yrs_{cpue4} = 3. A tuning parameter l_{min} is set for each tuning option as follows:

tuning option	l_{min}	exp(l_{min})
1c	4.94876	141
2c	5.164786	175
3c	5.598422	270
4c	4.418841	83
5c	4.736198	114
6c	5.225747	186

Results

Implications of constant catch projections

The current catch level (9449t) met the management target for 2035 and 2040 with probabilities of 50% and 68% respectively (Table 3). Short-term check points set for 2022 and 2025 were achieved with probabilities of about 25% and 50%. Results of constant catch projections for several catch levels showed that catch levels needed to be about 4000-9000t and about 6000-11000t to cover a range of tuning criteria (60-90%) for 2035 and 2040 respectively (also see Fig. 1). This implies that TAC levels in the future would be quite different depending on the management target to be finally selected.

Performance of each MP

(1) HK3_k2

HK3_k2 is designed to reduce TACs more smoothly and less severely than HK3_k4. This feature is evident from higher "minimum catch" over the projection period and lower AAV (average annual variation) (Table 4, Fig. 2a). However, this MP shows lower "maximum catch" and higher risk of lower biomass, as indicated by the 10 percentile for spawning stock biomass. In addition, there is a lower probability that a short-term check point is satisfied in 2022 or 2025.

Results of the robustness trials show that this simple MP is moderately robust for a variety of uncertainties, because it can achieve the management target for most of the trials (Table 5a, Fig. 4a). Indeed the stock biomass increased in all the trials. Due to lesser sensitivity to CPUE changes, however, this MP could not increase TACs greatly for higher productivity trials such as "troll" (incorporating the troll survey index) and "Laslett" (using an optimistic CPUE series). Moreover, it could not reduce TACs sufficiently for a less productive trial such as "omega75" (assuming a non-linear relationship between CPUE and stock biomass).

(2) HK3_k4

HK3_k4 shows a substantial TAC reduction to about 4000t (less than half of the current TAC) in the early years (Table 4, Fig. 2b). However, TACs increase more quickly and substantially along with the stock biomass in later years. The TAC increases to more than 25000t by the end of the projection period for some of the tuning options (e.g., option 4).

This MP was also shows very robust performance for the robustness trials. Generally it is able to modify TACs in the appropriate manner in relation to the stock biomass and/or productivity (Table 5b, Fig. 4b). However, it does not respond appropriately to the "upq" trial (assuming a longline catchability increase in 2006/7). This could be because it depends on a 10-yr trend in longline CPUEs.

(3) HK5

The general behavior of HK5 is intermediate between HK3_k2 and HK3_k4 for the reference set (Table 4, Fig. 2c) and the robustness trials (Table 5c, Fig. 4c). This indicates a well-balanced MP that achieves both TAC stability and steady stock rebuilding to a reasonable extent.

(4) HK6

HK6 shows almost the same performance as HK5 for the reference set (Table 4, Fig. 2d). This indicates that recruitment information provided by the aerial survey index is similar to that from the longline CPUE for age 4. Indeed, these two indices are moderately correlated with a time lag of one year.

However, results for the robustness trials are a little different from those of HK5. HK6 shows somewhat better performance for the "upq" and "omega75" robustness trials than HK3 and HK5 (Table 5d, Fig. 4d). It is also robust to greater observation errors for the aerial survey index ("highaerialCV"). Nevertheless, HK6 does not work well for the trial "highCPUECV" which assumes high CPUE variability and showed a lower probability of the stock rebuilding, though the reason for this is not clear.

Discussion

Tuning options

This MP exercise shows that TAC levels in the future are quite different depending on the six management targets (two target years and three target probabilities) that were proposed by the commissioners in April 2010. For example, the most challenging "option 3" (2035-90%) requires setting much lower TACs than at the moment for a long time, while the most gentle "option 4"

(2040-60%) would allow a substantial increase in the TACs in later years.

In addition, the tuning of a MP is critical for determining its behavior and performance, sometimes rather more so than the algorithm (TAC decision rule) itself. Note that HK3_k2 and HK3_k4, which are variants of the same MP, show quite different results in terms of performance measures. Therefore, these results suggest that the relative performances among different MPs are likely to depend on the method used for tuning as well as the tuning levels themselves.

The current MP exercise also indicates that MPs designed for to meet tuning option 2 (70%-2035) often meet the option 6 (90%-2040) at the same time. Therefore, some of the tuning options, which are set for the two time periods ending at 2035 and 2040, might be exchangeable so that only a more limited set of the tuning options might be needed for comparing MP performance.

Early pain becomes late gain

Performance comparison between HK3_k2 and HK3_k4 shows that earlier and larger TAC reduction leads to quicker stock rebuilding with less risk of stock depletion, which then incidentally allows a larger TAC increase in the later years. This critical trade-off, “early pain, late gain”, was also seen in the previous MP development process in 2001-2005, and actually influenced the selection of a final candidate MP at that time. From the socio-economic viewpoint, lower TAC variability such as initial lower TAC reduction might be preferred, but this leads to lower probability of stock rebuilding in the early period as indicated by performance measures at the short-term checkpoints in 12 and 15 years’ time. Advice from or decision by the commissioners will be necessary to reconcile this trade-off in the final MP selection.

Implementation time lag

In general, some time lag in MP implementation might be expected to lead to a deterioration in MP performance, because MPs are then compelled to determine TACs based on dated information. As far as examined in this exercise, however, having a one year lag did not make MP performance much worse (Table 4, Fig. 3a). This might be related to the fact that SBT have a long lifespan and hence have relatively stable dynamics compared to those of short-lived fish. Under the current relatively low TAC, emergencies which requires urgent and substantial changes in management measures are unlikely to arise.

The maximum allowed TAC change: 3000t vs 5000t

Constraints on the maximum of TAC change did not impact on MP performance in most cases for this MP evaluation exercise. However, an initial large TAC reduction of more than 3000t was often required to meet the more challenging management targets such as the option 3 “2035-90%”. In such cases, the stricter constraint on TAC change (3000t) required TACs to be kept at low levels for longer periods instead of a more gradual TAC reduction in the early years (Table 4, Fig. 3b). This tradeoff is again a reflection of the “early pain, late gain” feature.

TAC allocation

As far as the two options for TAC allocation for fishing fleets, where the Japanese allocation is different, are concerned, MP performance and global TACs were hardly affected (Table 4, Fig. 3c). However, allocation for each country would be a politically sensitive issue in an actual MP implementation. The current allocation might be changed in the future, though it is difficult to predict how it will be modified. Therefore, some options regarding the allocation should be investigated even though only as robustness trials.

Robustness trials

Most of the robustness trials that influenced performance of HK MPs were those related to longline CPUE series such as “Laslett”, “STwin”, “omega75” and “highCPUECV”. In addition, longline catchability trials such as “upq” and “downq” showed different future trajectories compared to the reference set results. The “troll” scenarios led to a rapid increase of stock biomass together with TAC increase. Taking into account that HK MPs depend heavily on longline CPUEs in determining the TAC, these results were predictable. However, it should be also noted that neither stock collapse nor even further decline of stock biomass occurred in almost all the trials. In this sense, HK MP families are relatively robust to a variety of uncertainties despite the simple structure of their TAC decision rules.

Scenarios regarding historical overcatch did not impact on the performance of HK MPs. Many of the robustness trials such as these could be dropped from the current MP testing. This would lead to saving of time and efforts for calculation.

Use of aerial survey index

For the reference set, HK6 showed almost the same performance as HK5. However, there were some differences in the robustness trials. HK5 did not show good performance for the “upq” trial related to rapid increase of LL1 catchability due to the IQ system introduction. In contrast, HK6 seemed to be able to manage this situation better, though it did not work well for the trial “highCPUECV”. These results indicate that incorporating the aerial survey index might increase the robustness of some MPs to certain scenarios. It is necessary to examine the usefulness of this index further.

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Table 1. Summary table of options for MP development to be examined by the ESC. The options highlighted in bold italics indicate the baseline choices used for the current analysis.

Item	Option 1	Option 2	Option 3	
Year for achievement of the management target	***2035 (25 yrs)***	***2040 (30 yrs)***		
Probability of meeting the management target	***60%***	***70%***	***90%***	Tuning option 1: 2035 - 60% 2: 2035 - 70% 3: 2035 - 90% 4: 2040 - 60% 5: 2040 - 70% 6: 2040 - 90%
Maximum TAC change	3000t	***5000t***		
TAC change frequency	3 years			
Implementation time lag	***0 year***	1 year		c: 3yrs starting 2012 (for lag0) d: 3yrs starting 2013 (for lag1)
Short-term check point: Year	2022 (12 yrs; for tuning year 2035)	2025 (15 yrs; for tuning year 2040)		
Short-term check point: Biomass level	10% of B_0	double B_{2009}		

Table 2. Tuning options examined in this analysis for the reference set and the robustness trials. An option name "number + alphabet" (e.g., 1c) represents the tuning option and the implementation time lag shown in Table 1. The option in parenthesis is applied to a MP (HK6) as a sensitivity test for the time lag, the maximum TAC change, and TAC allocation (option 1: nominal, option 2: nominal except Japan). "-" indicates "not available".

1. Reference set (c1sl13h)

(a) Max change: 5000t, time lag: 0 year
allocation: option 2

		probability		
		60%	70%	90%
year	2035	1c	2c	3c
	2040	4c	5c	6c

(b) Max change: 5000t, time lag: ***1 year***
allocation: option 2

		probability		
		60%	70%	90%
year	2035	-	(2d)	-
	2040	-	-	-

(c) Max change: ***3000t***, time lag: 0 year
allocation: option 2

		probability		
		60%	70%	90%
year	2035	-	(2c)	(3c)
	2040	-	-	-

(d) Max change: 5000t, time lag: 0 year
allocation: ***option 1***

		probability		
		60%	70%	90%
year	2035	-	(2c)	-
	2040	-	-	-

2. Robustness trials – 22 cases

(a) Max change: 5000t, time lag: 0 year
allocation: option 2

		Probability		
		60%	70%	90%
year	2035	1c	2c	3c
	2040	4c	5c	6c

Table 3. Summary results for constant catch projections. The shading represents probabilities to meet the management targets setting for 2035 and 2040 (i.e., from 60% to 90%).

	Management target		**Short-term check point**			
Catch level	Pr[B_{2035}> 0.2*B_0]	Pr[B_{2040}> 0.2*B_0]	Pr[B_{2022}>= 0.1*B_0]	Pr[B_{2022}>= 2*B_{2009}]	Pr[B_{2025}>= 0.1*B_0]	Pr[B_{2025}>= 2*B_{2009}]
0	1.00	1.00	0.89	0.89	0.99	0.99
1000	0.99	1.00	0.84	0.84	0.98	0.98
2000	0.98	1.00	0.77	0.79	0.97	0.96
3000	0.96	1.00	0.71	0.73	0.94	0.93
4000	0.92	0.99	0.65	0.65	0.90	0.90
5000	0.87	0.97	0.58	0.57	0.83	0.83
6000	0.80	0.93	0.51	0.49	0.75	0.77
7000	0.71	0.88	0.44	0.42	0.67	0.69
8000	0.63	0.80	0.36	0.35	0.59	0.61
9000	0.54	0.72	0.31	0.27	0.52	0.52
9449	**0.50**	**0.68**	**0.29**	**0.24**	**0.48**	**0.48**
10000	0.45	0.63	0.26	0.21	0.44	0.43
11000	0.36	0.54	0.22	0.17	0.38	0.35
12000	0.29	0.43	0.19	0.13	0.32	0.28
13000	0.22	0.35	0.14	0.10	0.25	0.21
14000	0.17	0.27	0.11	0.07	0.19	0.15
15000	0.12	0.20	0.08	0.05	0.14	0.11
16000	0.09	0.14	0.06	0.03	0.11	0.08
17000	0.06	0.10	0.05	0.03	0.08	0.06
18000	0.04	0.06	0.04	0.02	0.06	0.04
19000	0.02	0.04	0.03	0.01	0.05	0.03
20000	0.02	0.03	0.02	0.01	0.04	0.02

Table 4. Summary results of future projections under each MP for the reference set. The shading indicates the management target to which the option was tuned.

			Target		Checkpoint				Performance statistics							
MP	tuning option		Pr[B35>0.2*B0]	Pr[B40>0.2*B0]	Pr[B22>=0.1*B0]	Pr[B22>=2*B09]	Pr[B25>=0.1*B0]	Pr[B25>=2*B09]	Mean[C09:C31]	Min[C09(Med):C39(Med)]	Max[C09(Med):C39(Med)]	Med[B32/B09]	10%tile[B32/B09]	AAV	Mean[C09(Med):C39(Med)]	B40(Med)/B09(Med)
HK3_k2	1c		0.60	0.79	0.42	0.40	0.67	0.69	9298	6707	17774	3.69	2.06	0.051	10852	5.75
	2c		0.70	0.89	0.43	0.41	0.69	0.71	7942	6707	11810	4.12	2.25	0.028	8365	6.98
	3c	NA														
	4c		0.45	0.60	0.40	0.39	0.64	0.67	10709	6710	24529	3.29	1.87	0.067	13402	4.42
	5c		0.51	0.70	0.41	0.39	0.65	0.68	10113	6710	22168	3.46	1.96	0.061	12374	4.96
	6c		0.71	0.90	0.43	0.41	0.69	0.71	7839	6707	11810	4.15	2.26	0.026	8182	7.06
HK3_k4	1c		0.60	0.72	0.57	0.57	0.85	0.84	9968	4283	27309	3.89	2.40	0.105	13540	4.95
	2c		0.69	0.85	0.57	0.58	0.86	0.86	9145	4283	25259	4.14	2.57	0.100	12330	5.56
	3c		0.90	0.99	0.60	0.60	0.89	0.88	5671	4283	11810	5.12	3.08	0.040	5851	8.61
	4c		0.51	0.60	0.56	0.55	0.84	0.83	10713	4283	28615	3.65	2.23	0.110	14565	4.41
	5c		0.58	0.70	0.57	0.57	0.85	0.84	10107	4283	27705	3.84	2.38	0.106	13750	4.84
	6c		0.74	0.90	0.58	0.58	0.86	0.86	8598	4283	23339	4.29	2.65	0.095	11438	5.99
HK5	1c		0.59	0.79	0.42	0.41	0.72	0.74	9528	6423	24478	3.73	2.30	0.074	12264	5.23
	2c		0.71	0.89	0.46	0.45	0.77	0.78	8678	5993	22949	4.02	2.50	0.078	11232	5.80
	3c		0.90	0.98	0.57	0.57	0.89	0.88	6402	4165	18035	4.81	3.06	0.095	8258	7.36
	4c		0.45	0.60	0.40	0.39	0.65	0.68	10704	6657	26437	3.33	1.97	0.072	13686	4.36
	5c		0.53	0.70	0.41	0.39	0.68	0.71	10117	6585	25461	3.56	2.15	0.072	12938	4.83
	6c		0.73	0.90	0.47	0.46	0.78	0.79	8506	5869	22641	4.07	2.53	0.079	11013	5.90
Hk6	1c		0.60	0.78	0.43	0.43	0.72	0.73	9466	6347	24030	3.73	2.32	0.076	12176	5.21
	2c		0.70	0.87	0.47	0.46	0.77	0.78	8650	5997	22316	3.99	2.55	0.081	11076	5.83
	3c		0.90	0.98	0.58	0.58	0.88	0.88	6224	4234	16413	4.76	3.08	0.100	7689	7.40
	4c		0.45	0.60	0.40	0.39	0.65	0.68	10536	6635	26130	3.32	2.03	0.072	13609	4.37
	5c		0.52	0.70	0.41	0.40	0.69	0.71	10028	6542	25062	3.51	2.19	0.074	12916	4.81
	6c		0.73	0.90	0.48	0.48	0.79	0.79	8316	5850	21773	4.09	2.61	0.082	10712	6.02
HK6	2d	time lag: 1year	0.70	0.89	0.44	0.43	0.74	0.75	8309	5988	19937	4.01	2.50	0.075	10567	5.96
	2c	Max TAC change: 3000t	0.70	0.90	0.45	0.44	0.75	0.76	8648	6114	19387	4.01	2.50	0.071	10566	6.08
	3c	Max TAC change: 3000t	0.90	0.99	0.52	0.52	0.85	0.85	6139	4361	13684	4.74	3.00	0.094	7280	7.65
	2c	TAC allocation: 1	0.70	0.87	0.47	0.45	0.77	0.77	8437	5903	22184	3.96	2.55	0.082	10882	5.83

Table 5. Summary results of future projections under each MP for the robustness trials.

(a) HK3_k2

	Target		Checkpoint				Performance statistics							
	Pr[B35>0.2*B0]	Pr[B40>0.2*B0]	Pr[B22>=0.1*B0]	Pr[B22>=2*B09]	Pr[B25>=0.1*B0]	Pr[B25>=2*B09]	Mean[C09:C31]	Min[C09(Med):C39(Med)]	Max[C09(Med):C39(Med)]	Med[B32/B09]	10%tile[B32/B09]	AAV	Mean[C09(Med):C39(Med)]	B40(Med)/B09(Med)
c1s1l1	0.70	0.89	0.43	0.41	0.69	0.71	7942	6707	11810	4.12	2.25	0.028	8365	6.98
c1s1l2	0.77	0.93	0.49	0.45	0.77	0.74	8049	6783	11810	4.25	2.32	0.028	8486	7.17
troll	1.00	1.00	1.00	1.00	1.00	1.00	10611	8340	12603	8.05	5.44	0.025	11081	10.01
mixtag	0.70	0.89	0.43	0.44	0.69	0.72	7976	6736	11810	4.24	2.29	0.028	8401	7.27
recuncor	0.74	0.90	0.49	0.49	0.73	0.74	8105	6851	11810	4.32	2.35	0.027	8536	7.19
downwearlysize	0.62	0.84	0.37	0.34	0.63	0.61	7866	6670	11810	3.60	1.99	0.028	8242	6.32
regimeshift	0.79	0.93	0.61	0.42	0.81	0.73	7981	6744	11810	4.03	2.31	0.027	8373	6.54
aerdome	0.71	0.90	0.44	0.43	0.70	0.71	7972	6736	11810	4.15	2.20	0.028	8400	7.00
aerflat	0.70	0.89	0.44	0.41	0.69	0.70	7944	6704	11810	4.09	2.17	0.028	8353	6.93
c0s1l1	0.73	0.90	0.55	0.41	0.76	0.69	7861	6672	11810	3.91	2.14	0.027	8234	6.48
c2s1l1	0.69	0.89	0.40	0.34	0.68	0.65	7984	6717	11810	3.85	2.03	0.028	8390	6.53
c3s1l1	0.69	0.88	0.44	0.27	0.68	0.57	8023	6722	11810	3.42	1.83	0.028	8404	5.49
Laslett	0.92	0.98	0.81	0.47	0.95	0.75	9048	7755	11810	3.99	2.35	0.024	9563	6.08
STwin	0.45	0.73	0.16	0.24	0.38	0.52	6885	5612	11810	3.42	1.75	0.034	7119	6.51
run3	0.85	0.96	0.71	0.49	0.90	0.76	8599	7371	11810	4.22	2.39	0.025	9088	6.65
run6	0.69	0.89	0.42	0.37	0.69	0.66	7947	6687	11810	3.92	2.11	0.028	8322	6.58
omega75	0.23	0.42	0.08	0.17	0.19	0.35	7227	6401	11810	2.54	0.95	0.025	7365	4.60
highCPUECV	0.58	0.81	0.27	0.32	0.52	0.59	7231	6070	11810	3.67	1.96	0.032	7517	6.61
highaerialCV	0.70	0.89	0.43	0.41	0.69	0.71	7942	6707	11810	4.12	2.25	0.028	8365	6.98
upq	0.45	0.68	0.20	0.27	0.40	0.53	8158	7008	11810	3.40	1.62	0.026	8573	6.13
downq	0.86	0.97	0.66	0.52	0.88	0.81	7685	6403	11810	4.54	2.63	0.029	8077	7.36
downupq	0.82	0.95	0.61	0.48	0.84	0.76	8217	6906	11810	4.28	2.42	0.027	8667	6.95
truncCPUE	0.85	0.96	0.61	0.46	0.86	0.76	8117	6847	11810	4.29	2.39	0.028	8535	7.06

(b) HK3_k4

	Target		Checkpoint				Performance statistics							
	Pr[B35>0.2*B0]	Pr[B40>0.2*B0]	Pr[B22>=0.1*B0]	Pr[B22>=2*B09]	Pr[B25>=0.1*B0]	Pr[B25>=2*B09]	Mean[C09:C31]	Min[C09(Med):C39(Med)]	Max[C09(Med):C39(Med)]	Med[B32/B09]	10%tile[B32/B09]	AAV	Mean[C09(Med):C39(Med)]	B40(Med)/B09(Med)
c1s1l1	0.69	0.85	0.57	0.58	0.86	0.86	9145	4283	25259	4.14	2.57	0.100	12330	5.56
c1s1l2	0.76	0.89	0.66	0.62	0.91	0.87	9425	4380	25477	4.25	2.60	0.099	12655	5.67
troll	1.00	1.00	1.00	1.00	1.00	1.00	15994	7146	27336	6.63	4.38	0.084	18489	7.48
mixtag	0.69	0.84	0.58	0.60	0.85	0.87	9229	4334	25506	4.24	2.61	0.099	12441	5.78
recuncor	0.71	0.85	0.64	0.65	0.88	0.87	9532	4515	25656	4.24	2.64	0.098	12762	5.58
downwearlysize	0.61	0.79	0.51	0.48	0.80	0.78	8828	4241	24452	3.73	2.30	0.099	11827	5.23
regimeshift	0.79	0.89	0.74	0.60	0.92	0.86	9196	4351	23622	3.98	2.53	0.098	12130	5.12
aerdome	0.69	0.84	0.59	0.59	0.86	0.85	9251	4323	25306	4.14	2.52	0.099	12422	5.55
aerflat	0.68	0.84	0.59	0.58	0.86	0.84	9121	4286	25027	4.11	2.49	0.100	12288	5.51
c0s1l1	0.76	0.89	0.69	0.55	0.90	0.84	8711	4230	24078	3.97	2.53	0.098	11699	5.37
c2s1l1	0.64	0.80	0.55	0.50	0.84	0.78	9342	4305	24452	3.87	2.18	0.100	12378	5.16
c3s1l1	0.61	0.79	0.57	0.42	0.83	0.69	9455	4318	23745	3.45	1.90	0.101	12297	4.34
Laslett	0.81	0.88	0.89	0.55	0.98	0.81	12110	5977	27210	3.51	2.22	0.086	15451	4.27
STwin	0.50	0.74	0.26	0.42	0.61	0.73	7112	3141	20701	3.87	2.19	0.116	9574	6.01
run3	0.80	0.89	0.82	0.60	0.96	0.86	10781	5352	26828	3.89	2.45	0.090	14143	4.85
run6	0.67	0.84	0.57	0.54	0.84	0.81	9117	4248	24560	3.95	2.33	0.100	12167	5.34
omega75	0.28	0.48	0.13	0.32	0.31	0.61	6766	3880	17145	3.41	1.90	0.090	8531	5.31
highCPUECV	0.61	0.81	0.42	0.50	0.74	0.79	7621	3596	21239	3.98	2.39	0.110	10215	5.92
highaerialCV	0.69	0.85	0.57	0.58	0.86	0.86	9145	4283	25259	4.14	2.57	0.100	12330	5.56
upq	0.33	0.48	0.29	0.41	0.55	0.70	9586	4756	24535	3.38	1.96	0.095	12547	4.51
downq	0.91	0.98	0.79	0.69	0.96	0.92	8576	3889	24467	4.64	2.92	0.104	11679	6.19
downupq	0.79	0.89	0.74	0.63	0.93	0.88	9923	4534	26042	4.12	2.56	0.098	13220	5.34
truncCPUE	0.83	0.92	0.77	0.62	0.95	0.87	9519	4505	24819	4.24	2.53	0.099	12679	5.59

Table 5. (continued)

(c) HK5

	Target		Checkpoint				Performance statistics							
	Pr[B35>0.2*B0]	Pr[B40>0.2*B0]	Pr[B22>=0.1*B0]	Pr[B22>=2*B09]	Pr[B25>=0.1*B0]	Pr[B25>=2*B09]	Mean[C09:C31]	Min[C09(Med):C39(Med)]	Max[C09(Med):C39(Med)]	Med[B32/B09]	10%tile[B32/B09]	AAV	Mean[C09(Med):C39(Med)]	B40(Med)/B09(Med)
c1s1l1	0.71	0.89	0.46	0.45	0.77	0.78	8678	5993	22949	4.02	2.50	0.078	11232	5.80
c1s1l2	0.77	0.91	0.53	0.50	0.85	0.81	9011	6095	23488	4.15	2.53	0.078	11613	5.93
troll	1.00	1.00	1.00	1.00	1.00	1.00	15621	8340	28216	6.84	4.55	0.066	18215	7.68
mixtag	0.71	0.88	0.46	0.48	0.77	0.80	8760	6090	23261	4.14	2.55	0.078	11336	6.06
recuncor	0.70	0.87	0.52	0.51	0.79	0.79	9345	6529	23865	4.07	2.53	0.075	11992	5.71
downwearlysize	0.59	0.82	0.39	0.37	0.71	0.69	8482	6005	22188	3.60	2.23	0.077	10790	5.39
regimeshift	0.80	0.91	0.64	0.46	0.87	0.80	8791	6098	21748	3.87	2.44	0.075	11149	5.43
aerdome	0.69	0.88	0.47	0.45	0.77	0.77	8958	6183	23212	3.99	2.43	0.077	11497	5.74
aerflat	0.69	0.88	0.47	0.45	0.78	0.77	8707	6058	22921	3.98	2.41	0.078	11218	5.75
c0s1l1	0.80	0.94	0.60	0.44	0.86	0.78	8023	5716	21215	3.92	2.57	0.079	10310	5.80
c2s1l1	0.62	0.81	0.42	0.37	0.73	0.69	9229	6260	22721	3.70	2.00	0.077	11640	5.17
c3s1l1	0.55	0.73	0.44	0.30	0.71	0.57	9750	6414	22249	3.16	1.65	0.076	11910	4.26
Laslett	0.81	0.89	0.85	0.47	0.97	0.76	12098	7544	27324	3.42	2.18	0.071	15205	4.28
STwin	0.49	0.77	0.16	0.28	0.43	0.60	6661	4955	16061	3.65	1.99	0.084	7974	6.30
run3	0.82	0.92	0.75	0.52	0.95	0.81	10398	6743	25888	3.86	2.43	0.074	13402	5.05
run6	0.68	0.87	0.46	0.41	0.77	0.73	8635	5988	22247	3.86	2.25	0.077	11031	5.56
omega75	0.27	0.56	0.08	0.20	0.22	0.47	6089	4812	11810	3.27	1.92	0.073	6610	5.78
highCPUECV	0.58	0.84	0.28	0.35	0.59	0.67	7400	5498	18670	3.74	2.26	0.082	9148	5.96
highaerialCV	0.71	0.89	0.46	0.45	0.77	0.78	8678	5993	22949	4.02	2.50	0.078	11232	5.80
upq	0.30	0.50	0.19	0.28	0.41	0.57	9176	6494	22365	3.22	1.82	0.075	11479	4.65
downq	0.94	0.99	0.71	0.59	0.95	0.88	7911	5517	21493	4.59	2.93	0.081	10253	6.59
downupq	0.80	0.92	0.65	0.52	0.91	0.83	9527	6218	24608	4.03	2.53	0.077	12394	5.54
truncCPUE	0.83	0.93	0.66	0.50	0.91	0.81	9229	6213	23138	4.10	2.47	0.077	11883	5.76

(d) HK6

	Target		Checkpoint				Performance statistics							
	Pr[B35>0.2*B0]	Pr[B40>0.2*B0]	Pr[B22>=0.1*B0]	Pr[B22>=2*B09]	Pr[B25>=0.1*B0]	Pr[B25>=2*B09]	Mean[C09:C31]	Min[C09(Med):C39(Med)]	Max[C09(Med):C39(Med)]	Med[B32/B09]	10%tile[B32/B09]	AAV	Mean[C09(Med):C39(Med)]	B40(Med)/B09(Med)
c1s1l1	0.70	0.87	0.47	0.46	0.77	0.78	8650	5997	22316	3.99	2.55	0.081	11076	5.83
c1s1l2	0.77	0.91	0.54	0.50	0.85	0.81	8944	6072	22942	4.13	2.58	0.080	11485	5.96
troll	1.00	1.00	1.00	1.00	1.00	1.00	13958	8336	25188	7.32	4.93	0.065	16223	8.31
mixtag	0.70	0.88	0.47	0.49	0.77	0.80	8690	6013	22678	4.10	2.62	0.080	11225	6.09
recuncor	0.70	0.86	0.53	0.52	0.79	0.80	9169	6337	23207	4.07	2.58	0.078	11713	5.75
downwearlysize	0.60	0.82	0.41	0.37	0.72	0.69	8241	5957	21256	3.60	2.28	0.080	10483	5.49
regimeshift	0.81	0.91	0.65	0.47	0.88	0.80	8789	6104	21286	3.83	2.51	0.078	11108	5.39
aerdome	0.70	0.88	0.48	0.47	0.77	0.78	8628	6115	22065	4.02	2.52	0.080	10992	5.86
aerflat	0.68	0.86	0.47	0.45	0.77	0.76	8727	6081	22439	3.94	2.45	0.079	11167	5.73
c0s1l1	0.75	0.90	0.60	0.44	0.85	0.77	8540	5960	22074	3.76	2.46	0.080	10977	5.51
c2s1l1	0.66	0.84	0.44	0.39	0.75	0.71	8750	6073	21540	3.76	2.21	0.079	10968	5.52
c3s1l1	0.65	0.83	0.46	0.30	0.74	0.60	8847	6116	20721	3.34	1.92	0.079	10853	4.70
Laslett	0.88	0.94	0.86	0.50	0.98	0.80	11046	7261	25183	3.64	2.35	0.073	13913	4.80
STwin	0.46	0.77	0.16	0.27	0.45	0.60	6571	4907	16035	3.63	2.09	0.087	7999	6.23
run3	0.84	0.93	0.77	0.52	0.95	0.82	10131	6709	25104	3.88	2.51	0.076	13039	5.17
run6	0.69	0.86	0.46	0.41	0.77	0.73	8598	6006	21558	3.84	2.34	0.080	10908	5.63
omega75	0.31	0.64	0.09	0.23	0.25	0.53	5496	3969	11810	3.52	2.15	0.084	6026	6.24
highCPUECV	0.35	0.55	0.25	0.30	0.51	0.58	8984	5931	22494	3.16	1.96	0.078	11451	4.62
highaerialCV	0.67	0.84	0.45	0.45	0.76	0.77	8993	6132	23680	3.91	2.51	0.078	11657	5.54
upq	0.46	0.73	0.23	0.33	0.50	0.66	7763	5948	19418	3.65	2.23	0.082	9631	5.80
downq	0.86	0.95	0.69	0.56	0.93	0.85	9039	5882	23915	4.26	2.71	0.081	11821	5.89
downupq	0.80	0.92	0.65	0.52	0.90	0.82	9539	6264	24238	4.00	2.56	0.079	12261	5.57
truncCPUE	0.83	0.92	0.67	0.50	0.91	0.81	9310	6220	23204	4.06	2.51	0.079	11951	5.71

Figure 1. Trajectories of spawning stock biomass under each constant catch level from 0t to 20000t (median, lower 40percentile, lower 30percentile, lower 10percentile).

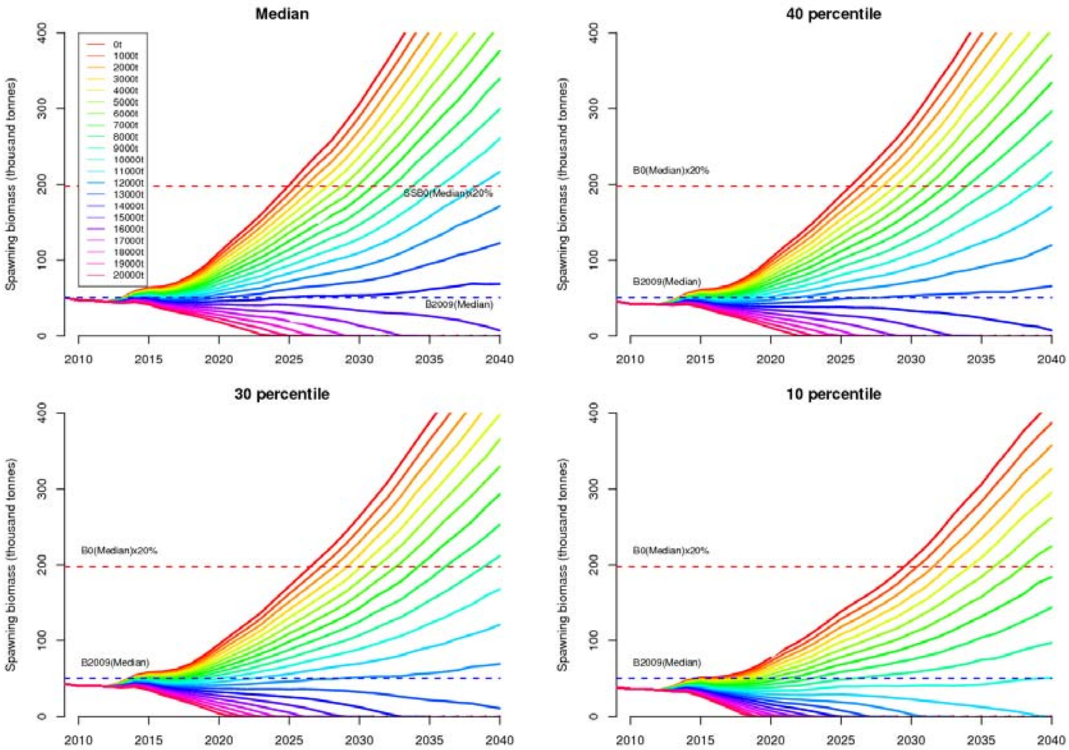
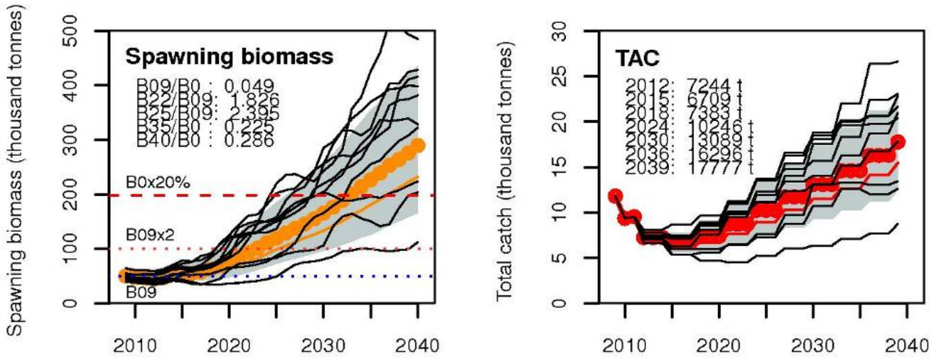
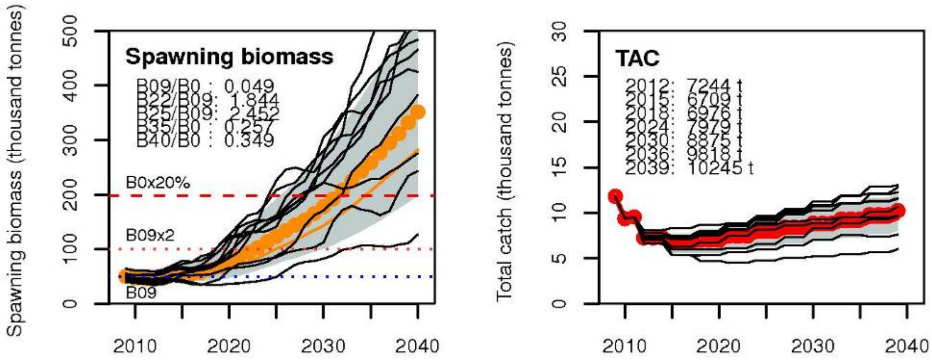


Figure 2a. Future projection results of spawning stock biomass (left panels) and TAC (right panels) under a MP ***HK3_k2*** for the reference set. 2000 trajectories are represented by the 10th and 90th percentiles (shaded area), the median (thick bold line with circles), the 70th percentile (colored thin line) and 10 individual realizations (thin lines).

- Option 1 (2035-60%)



- Option 2 (2035-70%)

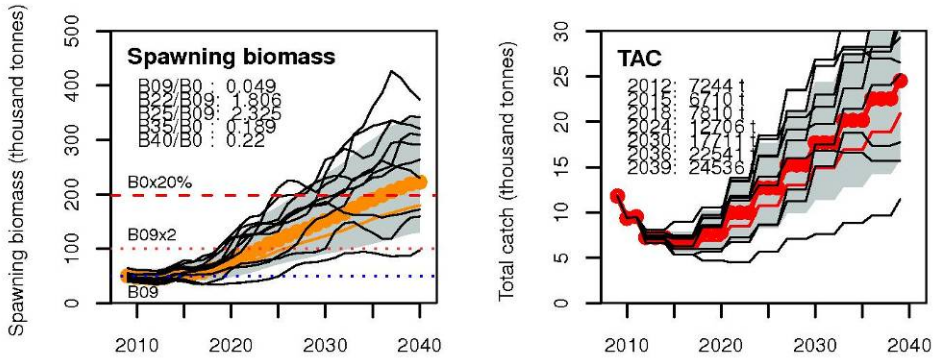


- Option 3 (2035-90%)

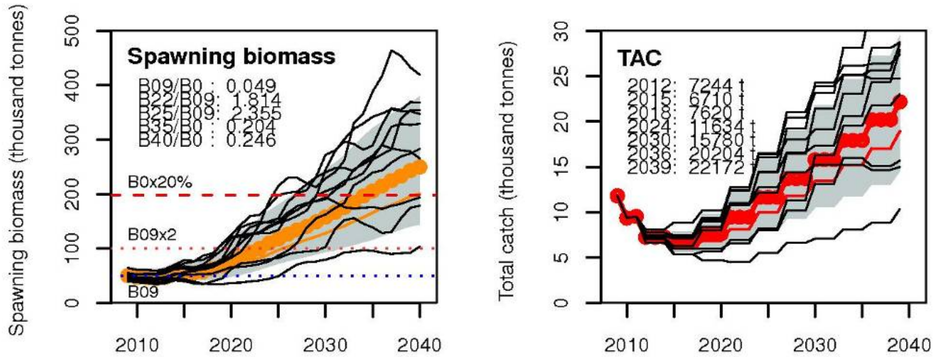
not available

Figure 2a. (continued)

- Option 4 (2040-60%)



- Option 5 (2040-70%)



- Option 6 (2040-90%)

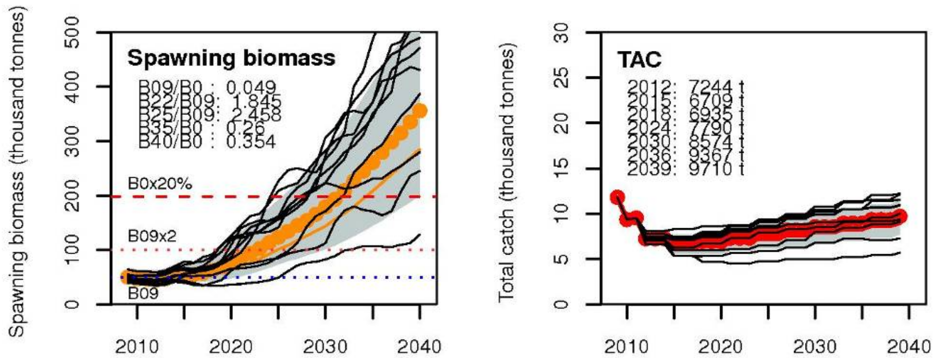
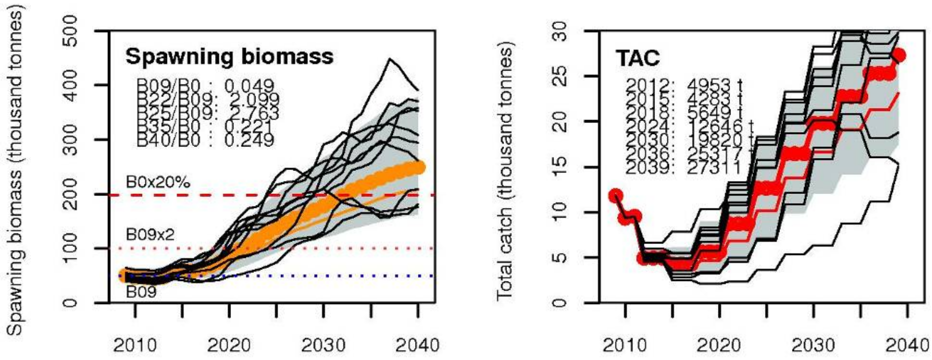
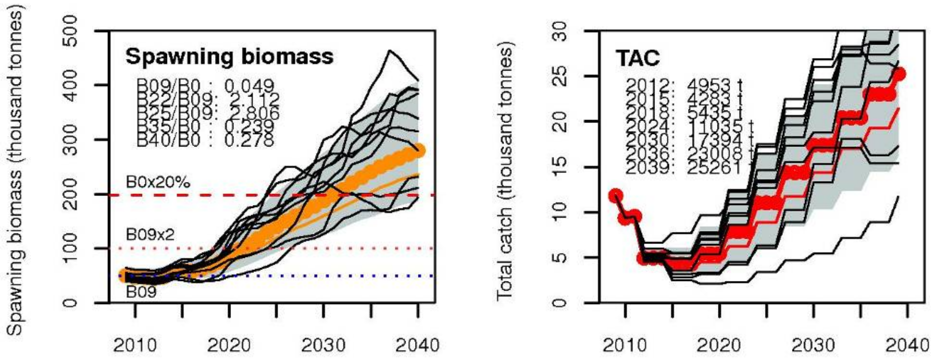


Figure 2b. Future projection results of spawning stock biomass (left panels) and TAC (right panels) under a MP ***HK3_k4*** for the reference set.

- Option 1 (2035-60%)



- Option 2 (2035-70%)



- Option 3 (2035-90%)

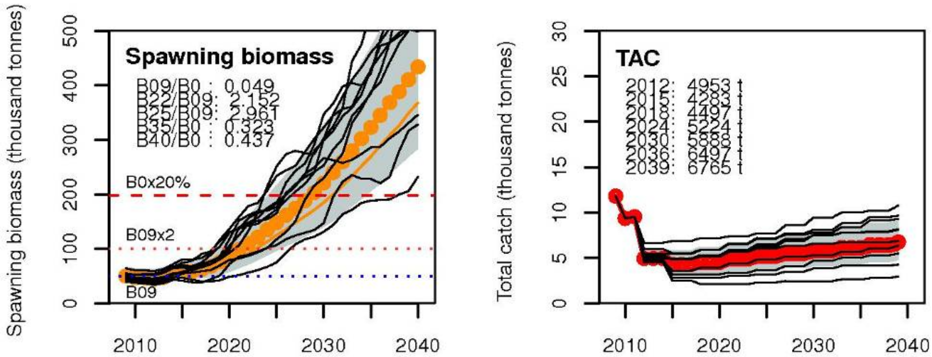
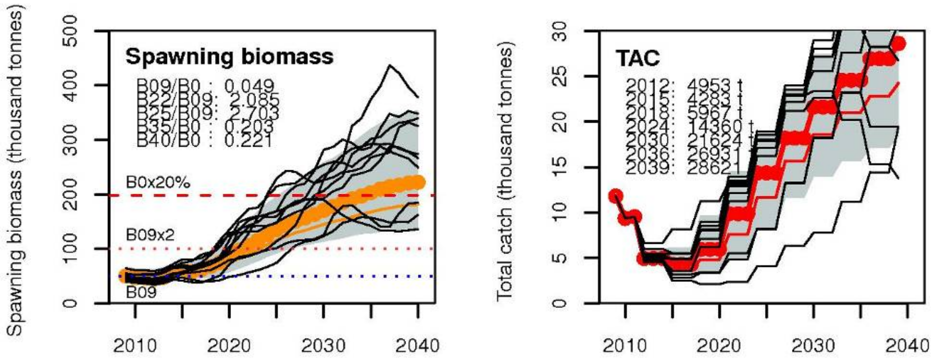
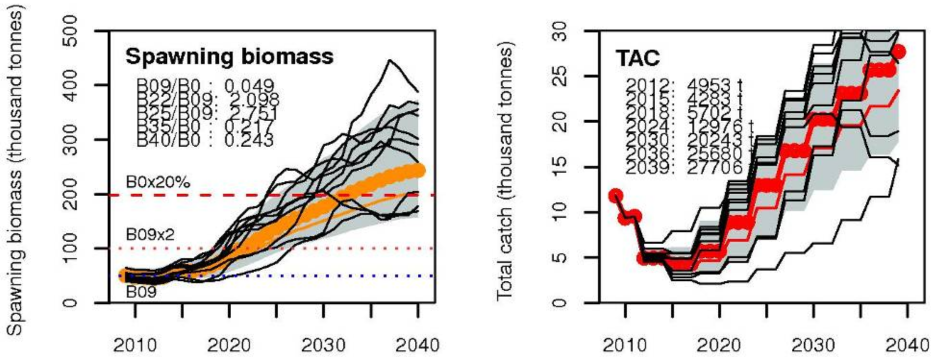


Figure 2b. (continued)

- Option 4 (2040-60%)



- Option 5 (2040-70%)



- Option 6 (2040-90%)

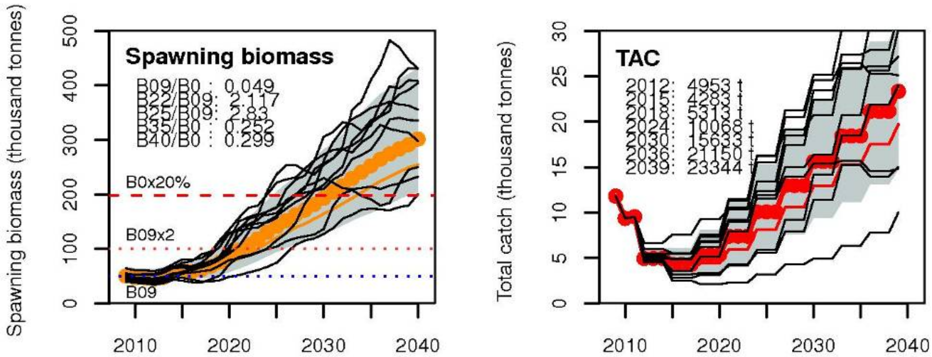
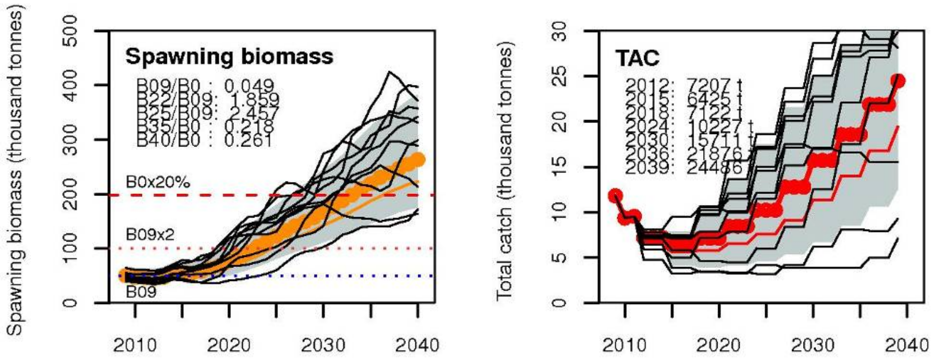
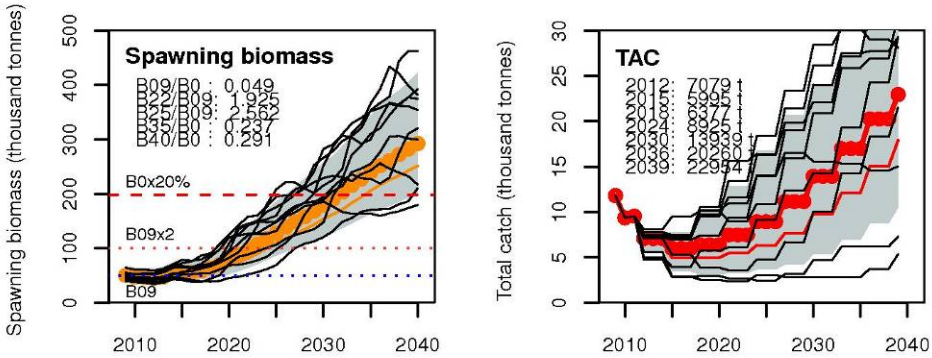


Figure 2c. Future projection results of spawning stock biomass (left panels) and TAC (right panels) under a MP ***HK5*** for the reference set.

- Option 1 (2035-60%)



- Option 2 (2035-70%)



- Option 3 (2035-90%)

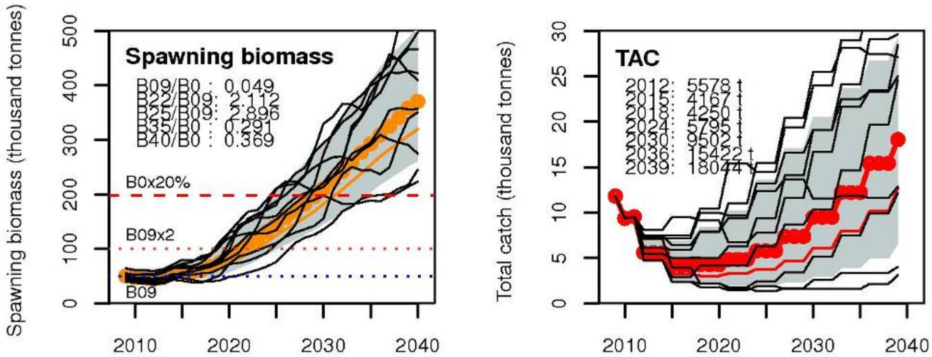
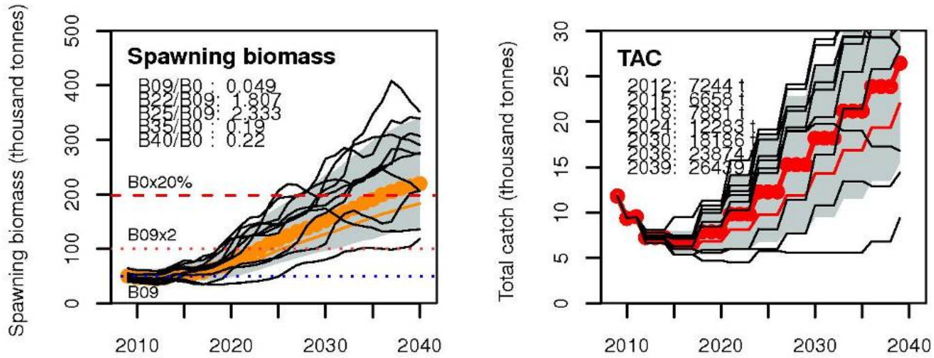
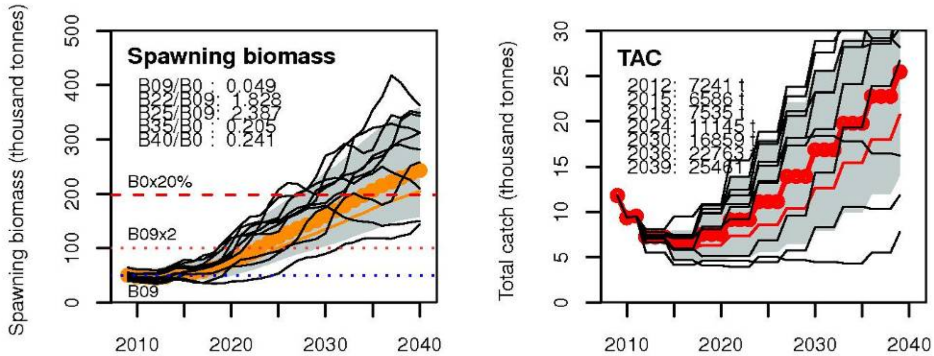


Figure 3c. (continued)

- Option 4 (2040-60%)



- Option 5 (2040-70%)



- Option 6 (2040-90%)

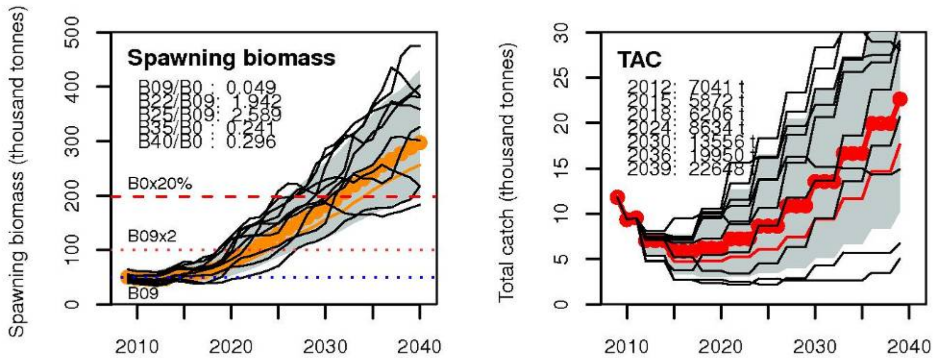
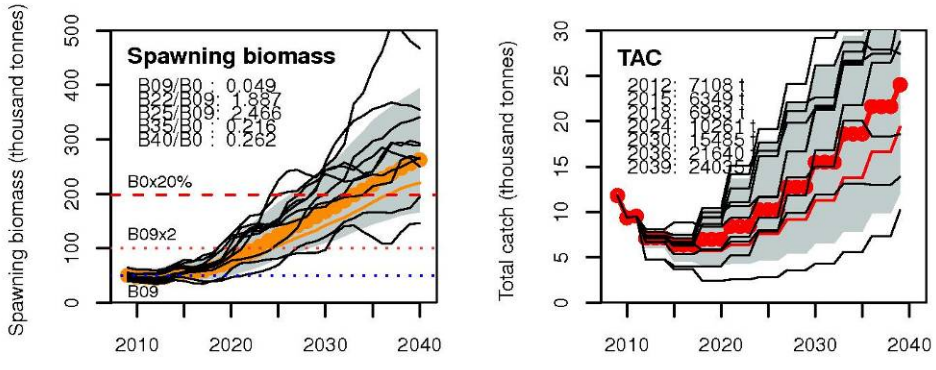
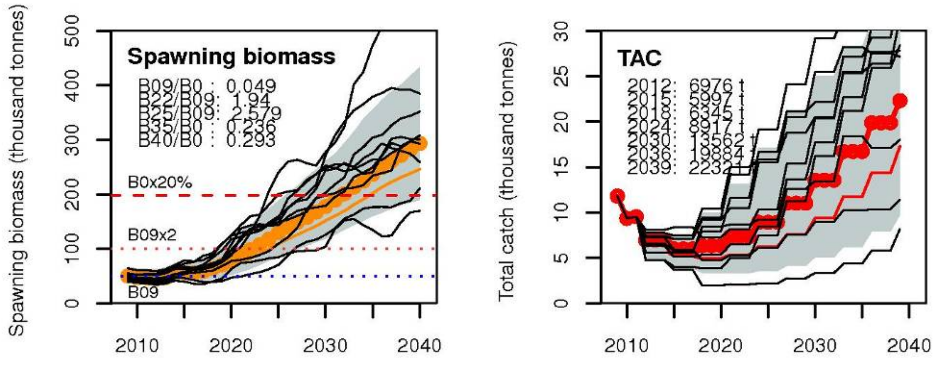


Figure 2d. Future projection results of spawning stock biomass (left panels) and TAC (right panels) under a MP ***HK6*** for the reference set.

- Option 1 (2035-60%)



- Option 2 (2035-70%)



- Option 3 (2035-90%)

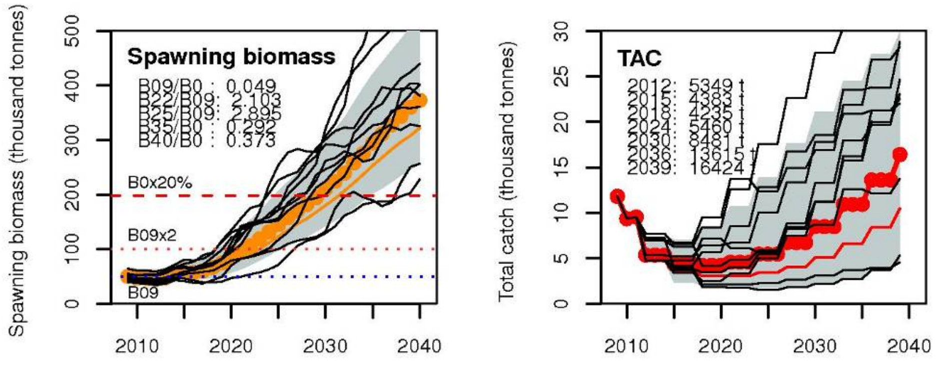
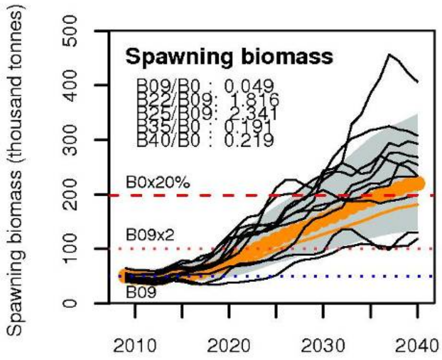
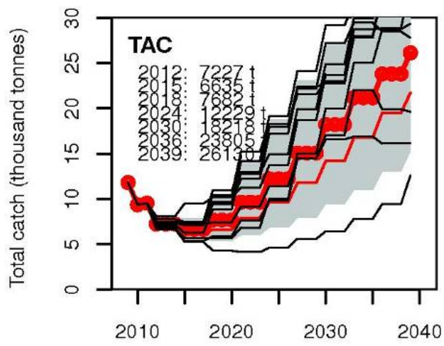


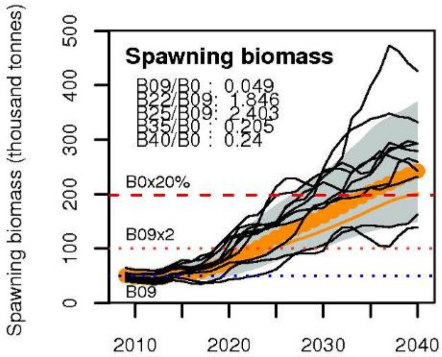
Figure 2d. (continued)

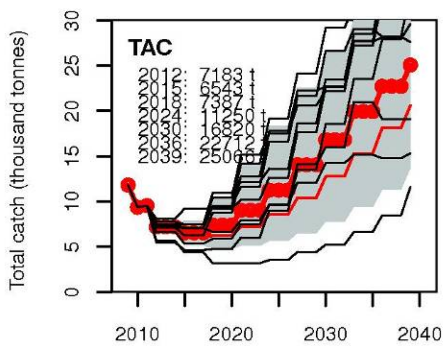
- Option 4 (2040-60%)



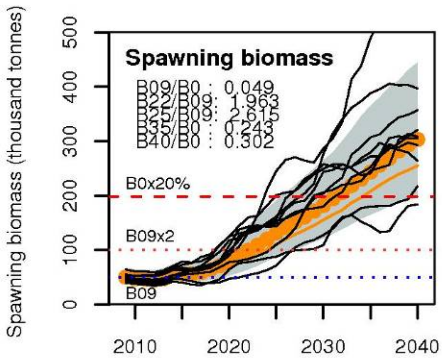


- Option 5 (2040-70%)





- Option 6 (2040-90%)



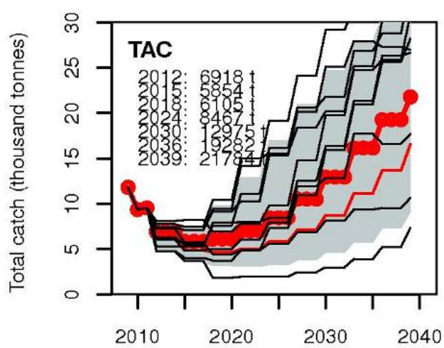
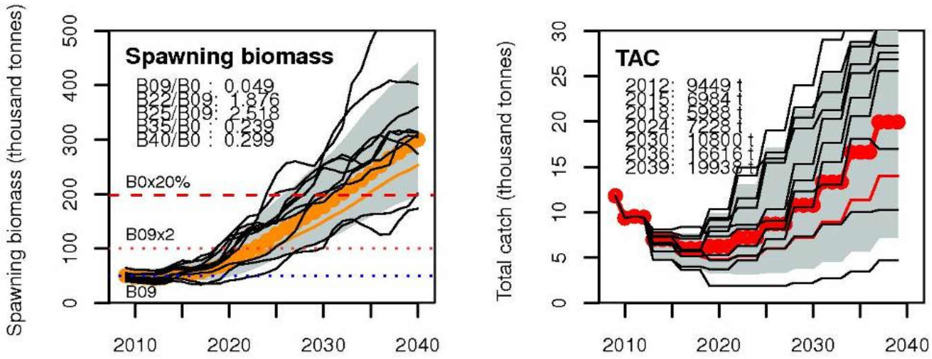


Figure 3. Future projection results of spawning stock biomass (left panels) and TAC (right panels) using a MP HK6 under different projection conditions.

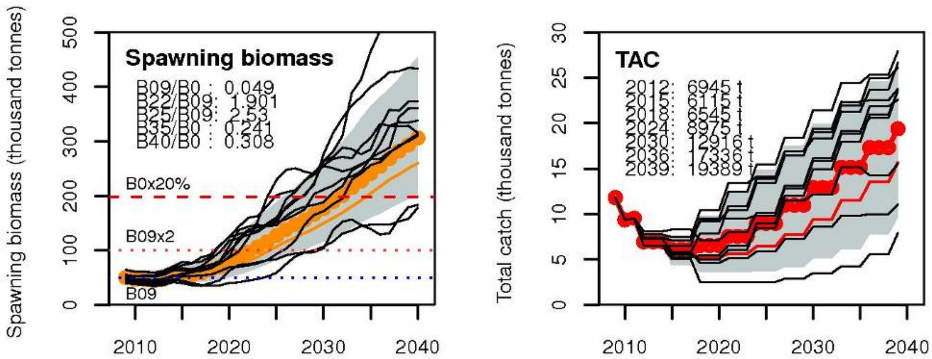
(a) time lag of MP implementation: ***1 year***

- Option 2 (2035-70%)



(b) the maximum of TAC change: ***3000t***

- Option 2 (2035-70%)



- Option 3 (2035-90%)

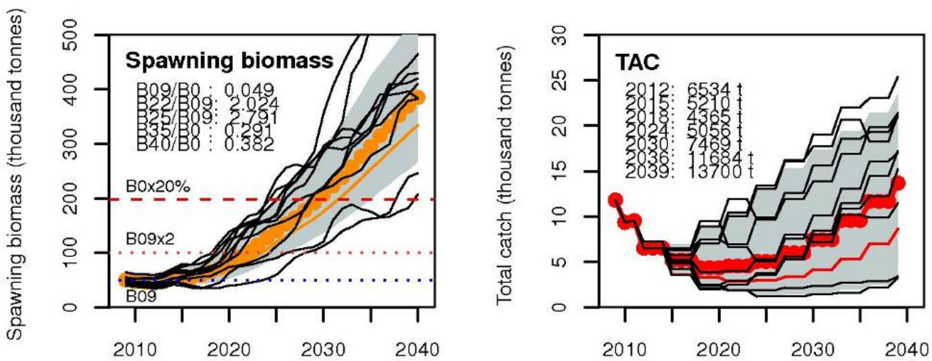


Figure 3. (continued)

(c) TAC allocation: ***option 1***

- Option 2 (2035-70%)

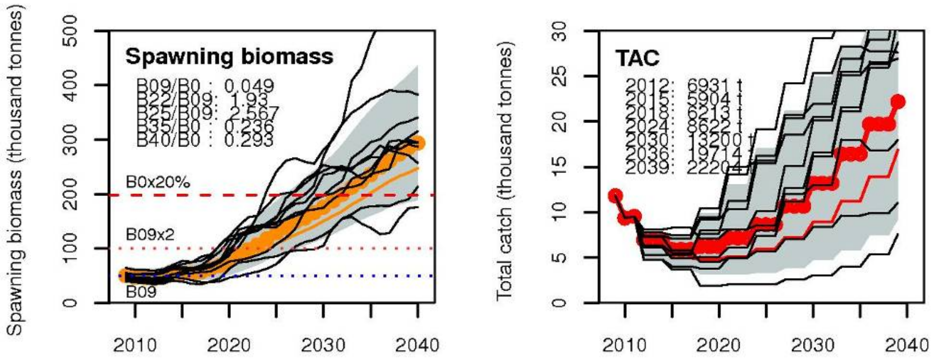


Figure 4a. Future projection results of spawning stock biomass (left panels) and TAC (right panels) under a MP ***HK3_k2*** for the robustness trials with the tuning option 2 (2035-70%).

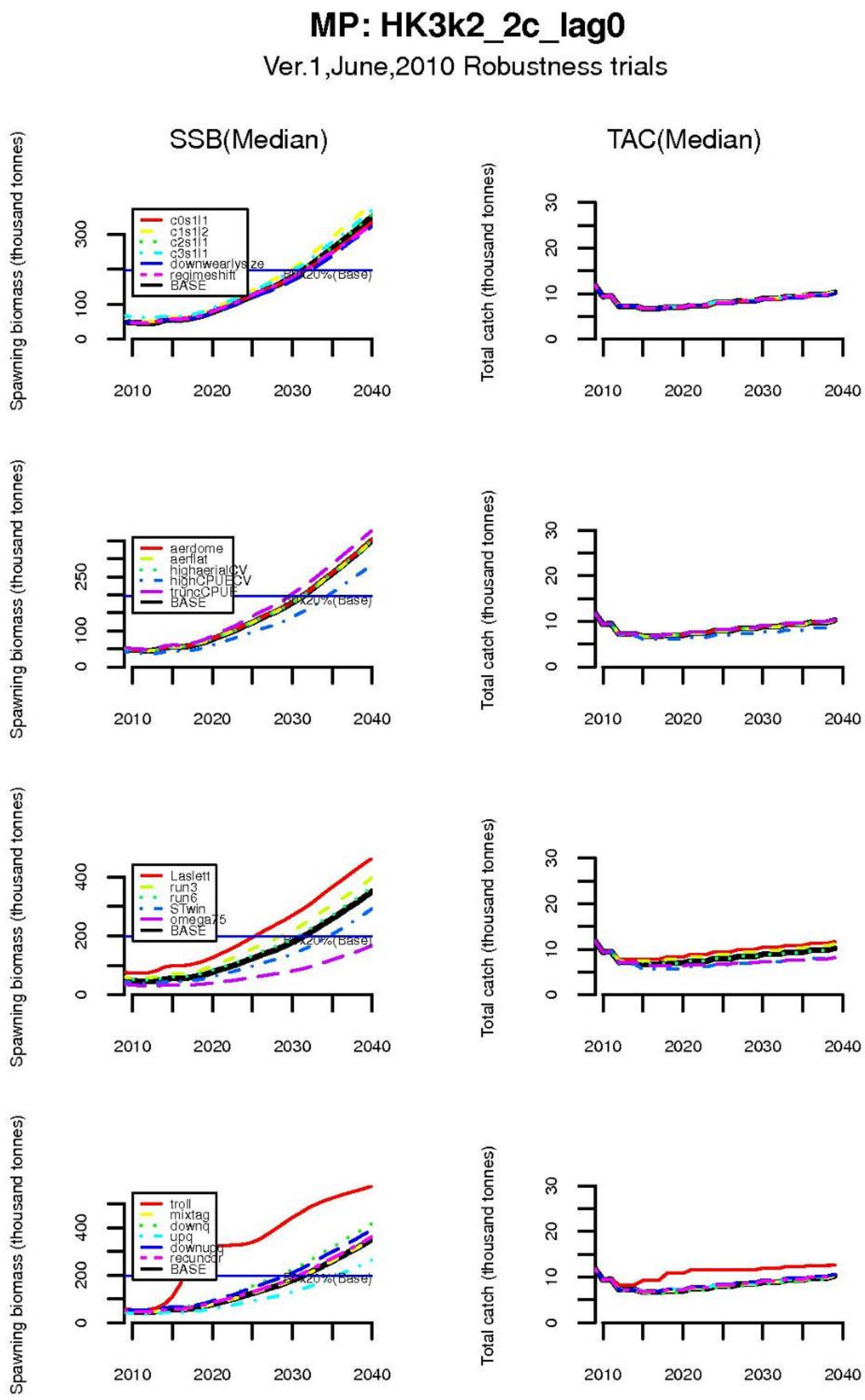


Figure 4b. Future projection results of spawning stock biomass (left panels) and TAC (right panels) under a MP ***HK3_k4*** for the robustness trials with the tuning option 2 (2035-70%).

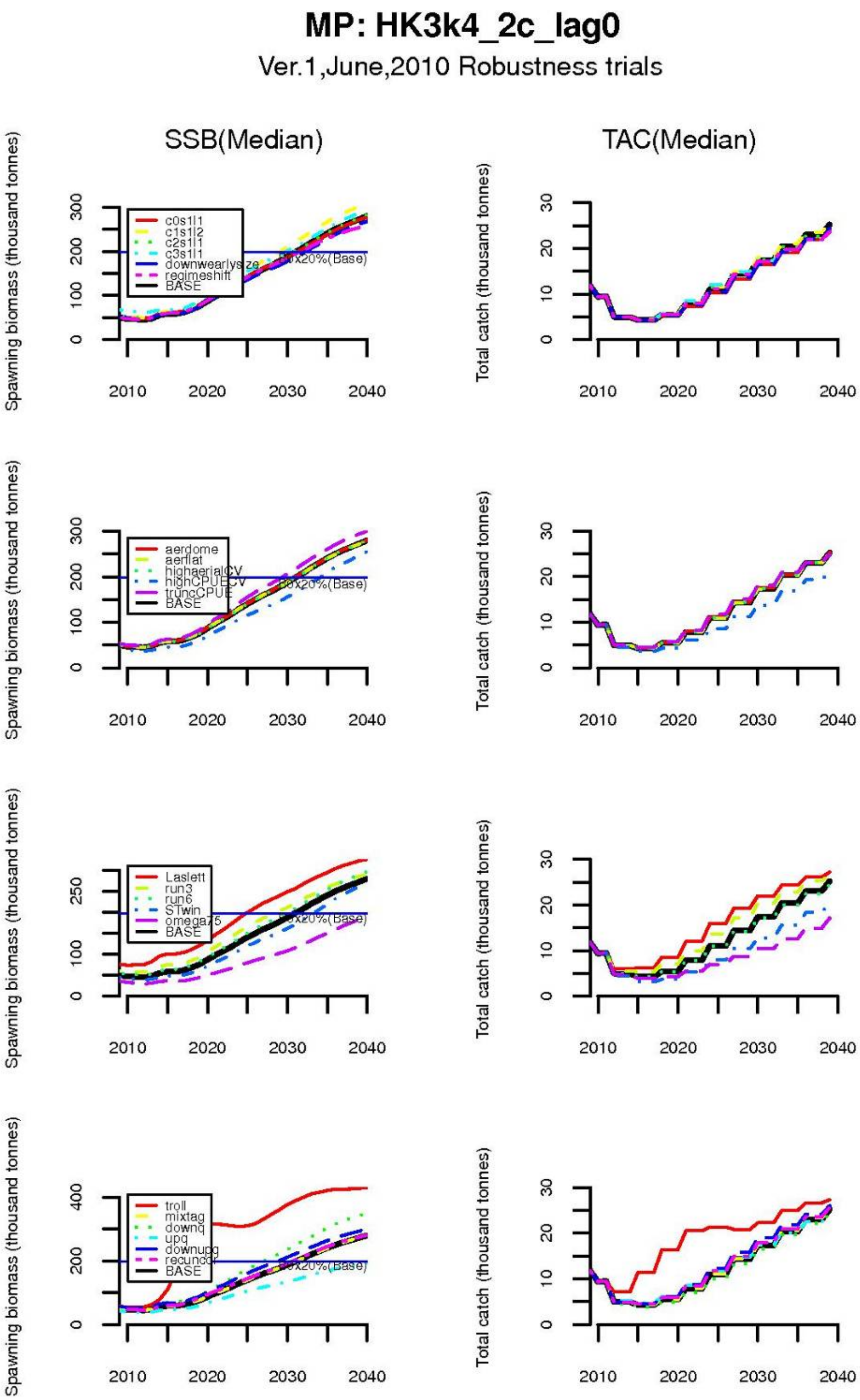


Figure 4c. Future projection results of spawning stock biomass (left panels) and TAC (right panels) under a MP ***HK5*** for the robustness trials with the tuning option 2 (2035-70%).

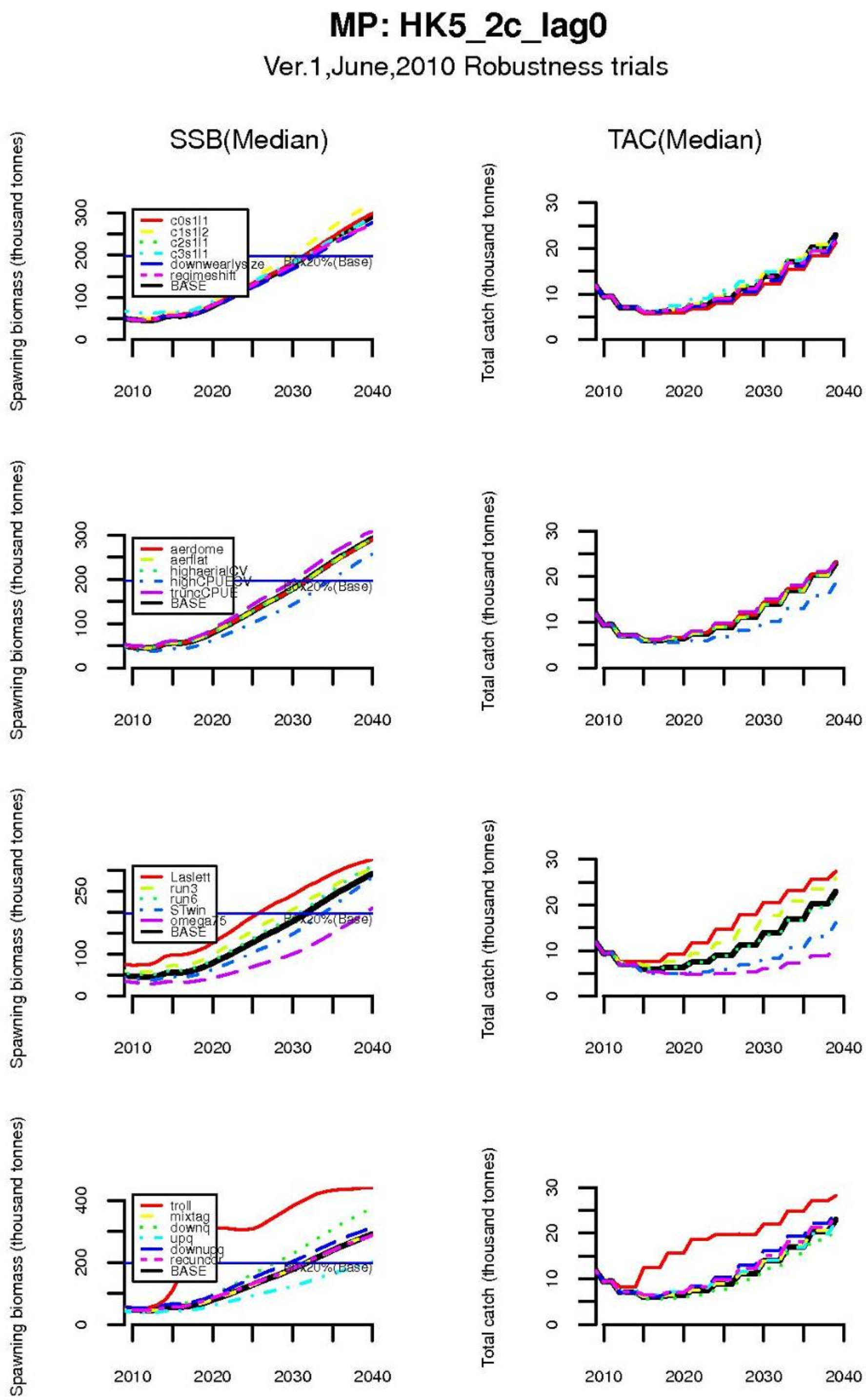


Figure 4d. Future projection results of spawning stock biomass (left panels) and TAC (right panels) under a MP ***HK6*** for the robustness trials with the tuning option 2 (2035-70%).