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

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Based on recommendations made during the third Operating Model and Management Procedure Technical Meeting (June 2010, Seattle), we have revised and evaluated "HK" Management Procedures (MPs) using empirical algorithms to determine TACs using information from the longline CPUE series and the aerial survey (AS) index. The exploration of HK variants showed that this MP can behave in a variety of ways as its control parameters and sub-algorithms are changed. As evident also from previous trials, 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, while still achieving the same long-term management target for spawning biomass recovery (though this comparison is complicated by transient effects).

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さらなる評価

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2010 年 6 月にシアトルで開催された管理方式作業部会でのアドバイスに基づき、延縄 CPUE と航空機目視調査の指標に基づく管理方式（HK）の改良を行った。開発作業より、HK 方式はそのコントロールパラメータやアルゴリズムを変化させることにより、多様な振る舞いを示すことが明らかになった。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

The first meeting of the CCSBT Strategy and Fisheries Management Working Group (SFMWG) held in 2009 confirmed that development of a Management Procedure (MP) would be finalized in 2010, and 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 2010a) (**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 a target for spawning biomass recovery. The SFMWG also set short-term check points at 12 and 15 years after the start of MP implementation.

The third Operating Model and Management Procedure Technical Meeting (OMMPTM) held in June 2010 in Seattle selected two candidate MPs (BREM_1 and HK6) to be developed further and to be evaluated under a revised OM at the ESC in September 2010 (CCSBT 2010b). The meeting also discussed possible modifications to these MPs and made some suggestions to the MP developers.

In this document, we evaluate the performance of HK MPs, particularly for HK7, which is a version of HK6 which has been modified to incorporate those suggestions. HK7 determines TACs based on the trend of a longline CPUE index along with the current ratio of the aerial survey index to a target. Based on the evaluation of these MPs, we discuss general issues to be considered in the final selection of an MP.

Projection conditions and robustness trials

For this exercise, we have used the projection program "sbtprojv118.exe" (distributed on 13 August 2010), which corrected an error which was setting the variability of the aerial survey index too high, and conditioning results obtained using a conditioning program "sbtmod22.exe". The new reference set (base5hsqrt.grid; *c1s1l1*) was distributed on 30 June 2010. Default options for testing MPs that were determined in the OMMPTM were used: tuning option 5 (70% chance that the biomass will be above $0.2B_0$ in 2040), a maximum TAC change of 3000t, and an implementation time lag of 1 year (option d). For several MPs with different behaviors, tuning option 2 (70% in 2035) was considered (**Table 2**); in addition. MPs were tuned to within ±1% of the tuning level (i.e., 70 ± 1% for a target of 70%). A TAC change is allowed every three years. The quota allocations for each fleet were based on nominal allocations except for Japan=3000t (i.e., option 2). In addition, sensitivities regarding these options (maximum TAC change, implementation time lag, quota allocation, TAC change frequency) were examined for a reference MP (***HK7_21***).

24 robustness trials were established by the OMMPTM. Due to time constraints, however, we selected the following 8 robustness trials along with the reference set based on our previous results and experience about which trials had greater impacts on results, and examined MP performance under those: *troll*, *Laslett*, *omega75*, *highCPUECV*, *highAerialCV*, *upq*, *lowR*, *updownq*. As pointed out in the OMMPTM, *troll* and *Laslett* are more optimistic scenarios than the reference set, while *omega75* and *lowR* are less productive scenarios. In particular, *omega75* is a very pessimistic robustness trial, which requires substantial TAC reduction. The other four robustness trials are related to reliability of the observed index of longline CPUE and AS index. For the several selected MPs, all robustness trials were computed for the tuning options 2 and 5.

Specification of MPs

In this document, evaluation of performance of the following three MPs (HK6, HK7, HK8) is reported. In particular for HK7, the procedure's behavior and sensitivity to alternative choices for control parameter values was examined in detail (**Table 2**).

HK7

HK7 ("Hiroyuki Kurota ver. 7") determines a TAC from the two candidate TACs: one calculated using the CPUE trend (slope) for age 4+ over the most recent years (δTAC^{cpue}), and the other using the AS (aerial survey) index over the most recent years (δTAC^{aerial}). Essentially, HK6 (see **Appendix 1** for specifications; Kurota et al. 2010) and HK7 are based on the same concept, but HK7 is generalized to incorporate several suggestions made at the OMMPTM (CCSBT 2010) as follows:

1. In calculating a recruitment term, HK7 evaluates the aerial survey (AS) index relative to the historical average value. In addition, in computing TACs, HK7 explicitly defines a target value for the AS index and responds to the extent of the deviation from that target.
2. MPs that are less reactive to a CPUE trend that is estimated over a shorter time period are explored to achieve intermediate performance and responsiveness.
3. A power function (with power > 1) is used both for the CPUE and the AS index to reduce TACs to a greater extent, when the stock status is poor.
4. When the two candidate TAC values (δTAC^{cpue} and δTAC^{aerial}) are "combined", three different ways (which include the original "minimum" method) are applied.

The change of TAC is specified as:

$$\delta TAC_{y+1}^{cpue} = \begin{cases} 1 - k_1 |\lambda|^{\gamma_{cpue}} & \lambda < 0 \\ 1 + k_2 \lambda & \lambda \geq 0 \end{cases}$$

$$\delta TAC_{y+1}^{aerial} = \begin{cases} 1 + \beta_{as} \left(\dfrac{AS_{cur}}{AS_{tar}} - 1 \right) & AS_{cur} \geq AS_{tar} \\ 1 + \beta_{as} \left(\left(\dfrac{AS_{cur}}{AS_{tar}} \right)^{\gamma_{as}} - 1 \right) & AS_{cur} < AS_{tar} \end{cases}$$

where

$$AS_{cur} = \exp\left(\frac{1}{\tau_{as}} \sum_{i=y-\tau_{as}}^{y-1} \ln\left(I_i^{AS}\right)\right)$$

$$AS_{tar} = \alpha_{as} \exp\left(\frac{1}{14}\left(\sum_{i=1993}^{2000} \ln\left(I_i^{AS}\right) + \sum_{i=2005}^{2010} \ln\left(I_i^{AS}\right)\right)\right)$$

$$m_{\min} \le \delta TAC_{y+1}^{aerial} \le m_{\max}$$

where

λ is the slope of the regression of ln (I_i^{CPUE}) against year (from y - τ_{cpue} - 1 to y - 2),

k_1, k_2, and γ_{cpue} are control parameters governing the TAC derived from the CPUE trend,

I_i^{AS} is the aerial survey index in year y,

τ_{as} is the time-period over which the mean of the AS index is calculated,
m_{max}, m_{min} are the upper and lower limit for δTAC^{aerial} and
α_{as}, β_{as}, γ_{as} are control parameters governing the TAC derived from the AS index.

These candidates for the TAC change for each year are combined in one of the following ways:

$$TAC_{y+1} = TAC_y \times \min\left(\delta TAC_{y+1}^{cpue},\ \ \delta TAC_{y+1}^{aerial}\right) \qquad \text{for HK7a (minimum)}$$

$$TAC_{y+1} = TAC_y \times \delta TAC_{y+1}^{cpue} \times \delta TAC_{y+1}^{aerial} \qquad \text{for HK7b (product)}$$

$$TAC_{y+1} = TAC_y \times \left(w \delta TAC_{y+1}^{cpue} + \left(1-w\right) \delta TAC_{y+1}^{aerial}\right) \qquad \text{for HK7c (weighted mean)}$$

When the TAC change computed from the above equation ($|TAC_{y+1}$-$TAC_y|$) is less than 100t and TAC_y is more than 1000t, it is assumed that the TAC does not change to prevent minute TAC changes (i.e., TAC_{y+1} = TAC_y). α_{as} is the main tuning parameter, while k_1 and k_2 are also used as tuning parameters for some trials. Default parameter values used for the reference MP (***HK7_21***) are τ_{cpue} = 7, k_1 = 1.5, k_2 = 2.0, γ_{cpue} = 1.0, τ_{as} = 3, β_{as} = 1.0, γ_{as} = 1.0, m_{max} = 1.5, and m_{min} = 0.5 (**Table 2**).

HK8

HK8 ("Hiroyuki Kurota ver. 8") determines a TAC from two candidate TACs: one calculated using the CPUE trend and target for age 4+ over the most recent years (δTAC^{cpue} and $\delta TAC^{cpue.\mathrm{tar}}$), and the other using the AS (aerial survey) index over the most recent years (δTAC^{aerial}). HK8 is a version of HK7 which is extended to incorporate the concept of a CPUE target. When these three candidate TACs (δTAC^{cpue}, $\delta TAC^{cpue.\mathrm{tar}}$ and δTAC^{aerial}) are combined, three different approaches are applied as for HK7. δTAC^{cpue} and δTAC^{aerial} are computed using the same methods as specified above for HK7.

$\delta TAC^{cpue.\mathrm{tar}}$ is specified as:

$$\delta TAC_{y+1}^{cpue.tar} = \begin{cases} 1+\beta_{cpue.tar}\left(\dfrac{CPUE_{cur}}{CPUE_{tar}}-1\right) & CPUE_{cur} \ge CPUE_{tar} \\ 1+\beta_{cpue.tar}\left(\left(\dfrac{CPUE_{cur}}{CPUE_{tar}}\right)^{\gamma_{cpue.tar}}-1\right) & CPUE_{cur} < CPUE_{tar} \end{cases}$$

where

$$CPUE_{cur} = \exp\left(\frac{1}{\tau_{cpue.tar}}\sum_{i=y-\tau_{cpue.tar}-1}^{y-2}\ln\left(I_i^{CPUE}\right)\right)$$

$$CPUE_{tar} = \alpha_{cpue.tar}\exp\left(\frac{1}{10}\sum_{i=2000}^{2009}\ln\left(I_i^{CPUE}\right)\right)$$

$$m_{\mathrm{min'}} \le \delta TAC_{y+1}^{cpue.tar} \le m_{\mathrm{max'}}$$

where

$\tau_{cpue.tar}$ is the time-period over which the mean of the CPUE index is calculated,
$m_{max'}$, $m_{min'}$ are the upper and lower limits for $\delta TAC^{cpue.tar}$ and
$\alpha_{cpue.tar}$, $\beta_{cpue.tar}$, $\gamma_{cpue.tar}$ are control parameters governing $\delta TAC^{cpue.tar}$.

These candidates of the TAC change for each year are combined in one of the following ways:

$$TAC_{y+1} = TAC_y \times \min\left(\delta TAC_{y+1}^{cpue}, \delta TAC_{y+1}^{cpue.tar}, \delta TAC_{y+1}^{aerial}\right) \qquad \text{for HK8a}$$

$$TAC_{y+1} = TAC_y \times \delta TAC_{y+1}^{cpue} \times \delta TAC_{y+1}^{cpue.tar} \times \delta TAC_{y+1}^{aerial} \qquad \text{for HK8b}$$

$$TAC_{y+1} = TAC_y \times \left(w_1\delta TAC_{y+1}^{cpue} + w_2\delta TAC_{y+1}^{cpue.tar} + \left(1-w_1-w_2\right)\delta TAC_{y+1}^{aerial}\right)$$

for HK8c

$\alpha_{cpue.tar}$ is the main tuning parameter. The default values are $\tau_{cpue.tar} = 3$, $\beta_{cpue.tar} = 1.0$, $\gamma_{cpue.tar} = 1.0$, $m_{max'} = 1.5$, and $m_{min'} = 0.5$.

Results

Result for a reference MP (HK7_21)

The terminology "reference" here is not intended to mean that this is the best or most preferable MP, but rather that is a convenient basis to examine sensitivity of MP results to different choices for values of their control parameters and to compare performances amongst these variants. Default parameter values and options used for the reference MP (***HK7_21***) were set so that ***HK7_21*** can reduce TACs smoothly while exhibiting moderate responsiveness to the stock status change (**Fig. 1a**). This feature is evident from lower AAV (average annual variation) and maximum TAC decrease statistics (**Fig. 1b**). This MP also allows the initial TAC in 2013 to increase under tuning option 5 if the stock status is very good. However, the moderate responsiveness leads to slightly higher risk of lower biomass, as indicated by the 10 percentile for stock biomass.

Results of the robustness trials show that this MP is moderately robust to a variety of uncertainties (**Fig. 1b**). Indeed the median of stock biomass increases by 2025 in all the trials. However, the risk of stock depletion is somewhat higher for less productive trials such as *omega75* (assuming a non-linear relationship between CPUE and stock biomass) and *lowR* (assuming low recruitment for four years from 2009). It is also noteworthy that ***HK7_21*** shows almost identical behavior to ***HK6_1*** (**Figs. A7-a, b** in **Appendix 2**).

Periods to compute CPUE slope (τ_{cpue})

When a shorter period (5 years) is used to estimate the CPUE slope (***HK7_22***; the default is 7 years), the TAC for 2013 is highly likely to increase due to the upward trend shown by recent CPUEs (**Figs A1**). This behavior does not lead to a much higher risk of lower biomass for the reference set, but it shows poor performance for one robustness trial, *lowR* (e.g., B_{min}/B_{2009} in **Fig. A1-b**). In contrast, when a longer period (10 years) is used (***HK7_23***), there is a very high probability that the TAC in 2013 is reduced, but in general the responsiveness to a change in stock status is lower, as indicated by a low "maximum TAC decrease". This feature results in higher risk of stock depletion for the *omega75* trial. Based on these results, the reference case specification (7 years) for the period to estimate the CPUE slope is considered to be a well-balanced selection.

Responsiveness to CPUE slope (k_1, k_2)

When the sensitivity to the CPUE slope is higher (e.g., ***HK7_24***), the initial TAC reduction is larger, following which the stock recovery is quicker (**Figs A2**). Due to this feature, the risk of stock depletion is lower for the reference set and less productive trials such as *omega75* and *lowR*. If this high catch variability is acceptable, this MP might be placed amongst final candidates because of its lower risk of stock depletion.

Control parameters for the AS index (τ_{as}, β_{as})

Even when the period to calculate mean AS index is changed (the default is 3 years), MP behavior is not very different for the reference set (**Figs A3**). ***HK7_26*** (2 years) shows slightly worse performance in less productive robustness trials such as *omega75*. On the other hand, the performance of ***HK7_27*** (4 years) is similar to that of the reference MP for robustness trials, even for *highAerialCV* and *lowR*. This is one of the reasons why we selected 3 years as the default.

Responsiveness to the AS index target (***HK7_28***, ***29***) also has little impact on MP behavior for the reference set (**Figs A3**). However, the lower responsiveness of ***HK7_28*** leads to higher risk of stock depletion for less productive robustness trials, particularly for *omega75*. On the other hand, a more sensitive MP, ***HK7_29,*** shows slightly better performance under such robustness trials, though the catch variability statistics are a little higher.

Acceleration of TAC reduction for poor stock status (γ_{cpue}, γ_{as})

When the TAC is reduced further when stock status is very poor (e.g., ***HK7_39***), the 10 percentile of the TAC in the near future (as indicated by *Mean catch 2009-2018* in **Fig. A4-b**) is lower than that for the reference MP, but interestingly the median TAC is higher. Indeed the depletion risk for the reference set (OM) is almost the same as for the reference MP. This result therefore indicates that this power function option enables the mean TAC to increase without increasing the risk. In addition, this option contributes to lower depletion risk for less productive robustness trials such as *omega75*. This option would be useful for steadier stock rebuilding.

Combination of multiple candidate TACs

The approach for combining the two candidate TACs from the longline CPUE and the AS index (in the case of HK7; the default is a minimum of the two) has a substantial influence on MP behavior (**Figs A5**). Amongst MPs examined in this exercise, the multiplication approach (combination option b; e.g., ***HK7_30***) shows the highest TAC variability and the lowest risk of stock depletion (as indicated by B_{min}/B_{2009}). However, the 10 percentile of B_{2040} for the reference set is almost the same as for other MPs. This may be because TACs increase too much in later years (i.e., overshoot). It would be better to keep this issue in mind, even though stock biomass would have recovered sufficiently by 2040. It is also noted that ***HK7_130*** shows higher TAC variability than ***HK7_30***, but the depletion risk is not different. The weighted mean approach (combination option c; ***HK7_31-33***) shows intermediate behavior between the reference ***HK7_21*** and ***HK7_30***. The heavier weight on longline CPUE (***HK7_32***) leads to higher TAC in the near future, but also results in a much higher risk of lower biomass for *omega75*.

Addition of CPUE target

A modified MP, ***HK8***, which additionally incorporates a CPUE target term, does not show major improvements compared with the original HK7 MPs as far as examined in this exercise (**Figs A6**). HK7 has already utilized information on the AS index as a target that possibly stabilizes MP behavior sufficiently. Therefore inclusion of a CPUE target as well might not lead to further improvement of MP performance in this case.

Different tuning options

The basic features of the performance of each MP for tuning option 2 (70% in 2035) is generally similar to that for tuning option 5 (70% in 2040) (**Figs 2a, b**). For example, ***HK7_30*** shows higher TAC variability and lower risk of stock depletion for tuning option 2 as well. However, the difference in behavior amongst these MPs seems to be less than for option 5. This might indicate that there is little room for these MPs to achieve the more stringent recovery target.

As for the other management targets, the behavior of HK7 for tuning option 4 (60% in 2040) is relatively similar to that for option 5, and options 1 (60% in 2035) and 6 (90% in 2040) behave similarly to option 2 (**Fig. 3**). To meet the option 3 target (90% in 2035), a large reduction in the TAC is required for a long time.

Implementation conditions for MPs

Using the variants of ***HK7_21***, we examined effect of constraints and implementation conditions used for this MP exercise. Therefore, the following results might be partly a consequence of the relatively mild (less reactive) nature of ***HK7_21***.

When the constraint on the maximum TAC change is relaxed from 3000t to 5000t, the TAC variability is larger as would be expected, and as a result, the depletion risk is lower (**Figs A8**; ***HK7_121*** vs ***HK7_21***). This effect is larger for a more aggressive MP, ***HK7_128*** (vs ***HK7_24***).

As regards the time lag between the TAC decision and implementation, there is not a major difference for the reference set (**Figs A9**), but “no time lag” implementation makes the performance better for robustness trials such as *omega75* (vs ***HK7_127***). Further exploration clarified that this results from a difference in the starting year of the MP implementation (2012 vs 2013) as well as the time-lag itself, because ***HK7_122*** that sets a 2013 TAC in 2012 (not in 2011; i.e., without time-lag) is an intermediate MP between ***HK7_21*** and ***HK7_127***.

Higher frequency of TAC change (biennial change) improves the MP performance (**Figs A10**). In particular, the risk of lower biomass is greatly reduced for *omega75* due to the quicker TAC reduction. Alternative quota allocation, where the Japanese allocation is different, does scarcely affects MP performance (**Figs A11**).

Tuning parameter choice

In this exercise, we generally used the target level of the AS index (α_{as}) as the primary tuning parameter, because this parameter is able to control MP performance and outputs such as TAC levels straightforwardly. As a trial, the alternative parameters (k) were used as tuning parameters (**Figs A12**). This limited example indicates some difference in behavior, particularly for the robustness trials, but the basic features of HK7 performance seem not to change, even if different tuning parameters are used.

Discussion

It is not so straightforward to select a MP based on a single criterion, because different stakeholders are likely to place emphasis on different criteria to evaluate MP performance, and these criteria often involve trade-offs in relationships such as the “early pain, late gain” issue. In addition, this exercise has shown that HK7 has many possible variants developed by changing parameters and options. Nevertheless, we could put forward several MPs from the variants to cover a wide range from less reactive to more reactive (**Figs 1a, b**):

- ***HK7_21*** (moderate TAC reduction with moderate safety against stock depletion)
- ***HK7_29*** (moderate TAC reduction with more robust stock rebuilding)
- ***HK7_39*** (well-balanced between higher average TAC and steady stock rebuilding)
- ***HK7_24*** (very steady stock rebuilding)
- ***HK7_30*** (the most robust and quickest stock rebuilding)

Results for the robustness trials along with the reference set show that more reactive MPs such as ***HK7_30***, which initially reduce TACs more substantially, can generally deal better with poor stock conditions such as *omega75* and reduce short-term risk. From the socio-economic viewpoint, however, lower TAC variability (particularly less initial TAC reduction) might be preferred. Clear advice from or decision by the Commissioners will be necessary to select this trade-off in addition to the management target (tuning option) and implementation conditions.

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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			(2 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. Summary table of control parameter values and options used for HK variants examined in this document. The blue-shaded variants as well as the reference ***HK7_21*** are put forward as MPs reflecting qualitatively different performances in this exercise (also see **Figure 1**).

MP	Figure	sensitivity	tuning option	CPUE slope (yrs) τ_{cpue}	response to CPUE slope k_1-k_2	CPUE gamma γ_{cpue}	AS target (yrs) τ_{ac}	AS response β_{as}	AS gamma γ_{as}	AS lower limit m_{min}	AS upper limit m_{max}	CPUE target (yrs) $\tau_{cpue.tar}$	CPUE target response $\beta_{cpue.tar}$	combination	max TAC change	catch opt	time lag (yrs)	TAC allocation	tuning parameter	tuning value (level 5)	tuning value (level 2)	note
HK7_21		reference case	1-6	7	1.5-2.0	1.0	3	1.0	1.0	0.5	1.5			minimum	3000	d	1	2	AS target α_{as}	0.87	1.11	
HK7_22	A1	CPUE slope year	5	5	1.5-2.0	1.0	3	1.0	1.0	0.5	1.5			minimum	3000	d	1	2	AS target α_{as}	0.85		
HK7_23	A1	CPUE slope year	5	10	1.5-2.0	1.0	3	1.0	1.0	0.5	1.5			minimum	3000	d	1	2	AS target α_{as}	0.6		
HK7_24	A2	CPUE slope response	2, 5	7	4.0-6.0	1.0	3	1.0	1.0	0.5	1.5			minimum	3000	d	1	2	AS target α_{as}	0.92	1.125	
HK7_34		CPUE slope response	5	7	6.0-6.6	1.0	3	1.0	1.0	0.5	1.5			minimum	3000	d	1	2	k_2	6.6		
HK7_35		CPUE slope response	5	7	6.0-6.0	1.0	3	1.0	1.0	0.5	1.5			minimum	3000	d	1	2	AS target α_{as}	0.86		
HK7_38	A2	CPUE slope response	5	7	6.0-8.0	1.0	3	1.0	1.0	0.5	1.5			minimum	3000	d	1	2	AS target α_{as}	0.885		
HK7_40	A2	CPUE slope response	5	7	1.5-1.0	1.0	3	1.0	1.0	0.5	1.5			minimum	3000	d	1	2	AS target α_{as}	0.76		
HK7_26	A3	AS year	5	7	1.5-2.0	1.0	2	1.0	1.0	0.5	1.5			minimum	3000	d	1	2	AS target α_{as}	0.8775		
HK7_27	A3	AS year	5	7	1.5-2.0	1.0	4	1.0	1.0	0.5	1.5			minimum	3000	d	1	2	AS target α_{as}	0.899		
HK7_28	A3	AS response	5	7	1.5-2.0	1.0	3	0.5	1.0	0.5	1.5			minimum	3000	d	1	2	AS target α_{as}	0.947		
HK7_29	A3	AS response	2, 5	7	1.5-2.0	1.0	3	1.5	1.0	0.5	1.5			minimum	3000	d	1	2	AS target α_{as}	0.838	1.047	
HK7_25	A4	power function	2, 5	7	1.5-2.0	2.0	3	1.0	1.0	0.5	1.5			minimum	3000	d	1	2	AS target α_{as}	0.92	1.126	
HK7_36	A4	power function	5	7	1.5-2.0	3.0	3	1.0	1.0	0.5	1.5			minimum	3000	d	1	2	AS target α_{as}	0.918		
HK7_37	A4	power function	5	7	1.5-2.0	1.0	3	1.0	2.0	0.5	1.5			minimum	3000	d	1	2	AS target α_{as}	0.817		
HK7_39	A4	power function	2, 5	7	1.5-2.0	2.0	3	1.0	2.0	0.5	1.5			minimum	3000	d	1	2	AS target α_{as}	0.863	1.037	
HK7_30	A5	combination	2, 5	7	1.5-2.0	1.0	3	1.0	1.0	0.5	1.5			multiplication	3000	d	1	2	AS target α_{as}	1.14	1.295	
HK7_131	A5	combination	2, 5	7	1.5-2.0	1.0	3	1.0	1.0	0.5	1.25			multiplication	3000	d	1	2	AS target α_{as}	1.124	1.279	
HK7_130	A5	combination	2, 5	7	4.0-6.0	1.0	3	1.0	1.0	0.5	1.5			multiplication	3000	d	1	2	AS target α_{as}	1.212	1.44	
HK7_129		combination	2, 5	7	4.0-6.0	1.0	3	1.0	1.0	0.5	1.25			multiplication	3000	d	1	2	AS target α_{as}	1.189	1.424	
HK7_31	A5	combination	5	7	1.5-2.0	1.0	3	1.0	1.0	0.5	1.5			weight (0.5-0.5)	3000	d	1	2	AS target α_{as}	1.2		
HK7_32	A5	combination	5	7	1.5-2.0	1.0	3	1.0	1.0	0.5	1.5			weight (0.7-0.3)	3000	d	1	2	AS target α_{as}	1.31		
HK7_33	A5	combination	5	7	1.5-2.0	1.0	3	1.0	1.0	0.5	1.5			weight (0.3-0.7)	3000	d	1	2	AS target α_{as}	1.14		
HK8_11	A6	add CPUE target	5	7	1.5-2.0	1.0	3	1.0	1.0	0.5	1.5	3	1	minimum	3000	d	1	2	LL target $\alpha_{cpue.tar}$	0.52		
HK8_12	A6	add CPUE target	5	7	1.5-2.0	1.0	3	1.0	1.0	0.5	1.5	3	1	multiplication	3000	d	1	2	LL target $\alpha_{cpue.tar}$	1.09		
HK8_13	A6	add CPUE target	5	7	1.5-2.0	1.0	3	1.0	1.0	0.5	1.5	3	1	weight (0.4-0.3-0.3)	3000	d	1	2	LL target $\alpha_{cpue.tar}$	1.3		
HK8_14		add CPUE target	5	7	1.5-2.0	1.0	3	1.0	1.0	0.5	1.5	3	1	multiplication	3000	d	1	2	LL target $\alpha_{cpue.tar}$	0.85		from HK7_30
HK8_15		add CPUE target	5	7	1.5-2.0	1.0	3	1.0	1.0	0.5	1.5	3	1	weight (0.4-0.3-0.3)	3000	d	1	2	LL target $\alpha_{cpue.tar}$	1.16		from HK7_32
HK6_1	A7	original	5	7	1.5-2.0		3			0.5	1.5			minimum	3000	d	1	2	l_{min}	203		l_{max}=800
HK7_121	A8	max TAC change	5	7	1.5-2.0	1.0	3	1.0	1.0	0.5	1.5			minimum	5000	d	1	2	AS target α_{as}	0.874		
HK7_128	A8	max TAC change	5	7	4.0-6.0	1.0	3	1.0	1.0	0.5	1.5			minimum	5000	d	1	2	AS target α_{as}	0.989		
HK7_122	A9	time lag	5	7	1.5-2.0	1.0	3	1.0	1.0	0.5	1.5			minimum	3000	d	0	2	AS target α_{as}	0.857		
HK7_127	A9	time lag	5	7	1.5-2.0	1.0	3	1.0	1.0	0.5	1.5			minimum	3000	c	0	2	AS target α_{as}	0.8805		
HK7_123	A10	TAC change frequency	5	7	1.5-2.0	1.0	3	1.0	1.0	0.5	1.5			minimum	3000	b	1	2	AS target α_{as}	0.8665		
HK7_124	A11	allocation	5	7	1.5-2.0	1.0	3	1.0	1.0	0.5	1.5			minimum	3000	d	1	1	AS target α_{as}	0.895		
HK7_125	A12	tuning parameter	2	7	8.4-1.5	1.0	3	1.0	1.0	0.5	1.5			minimum	3000	d	1	2	k_1, k_2			AS target=0.87

Fig. 1a. Time trajectory plot for catch and stock biomass for the reference set and the omega75 robustness trial, showing the median (solid), higher 10 percentile (dot) and lower 10 percentile (dash) for selected MPs under ***tuning option 5***.

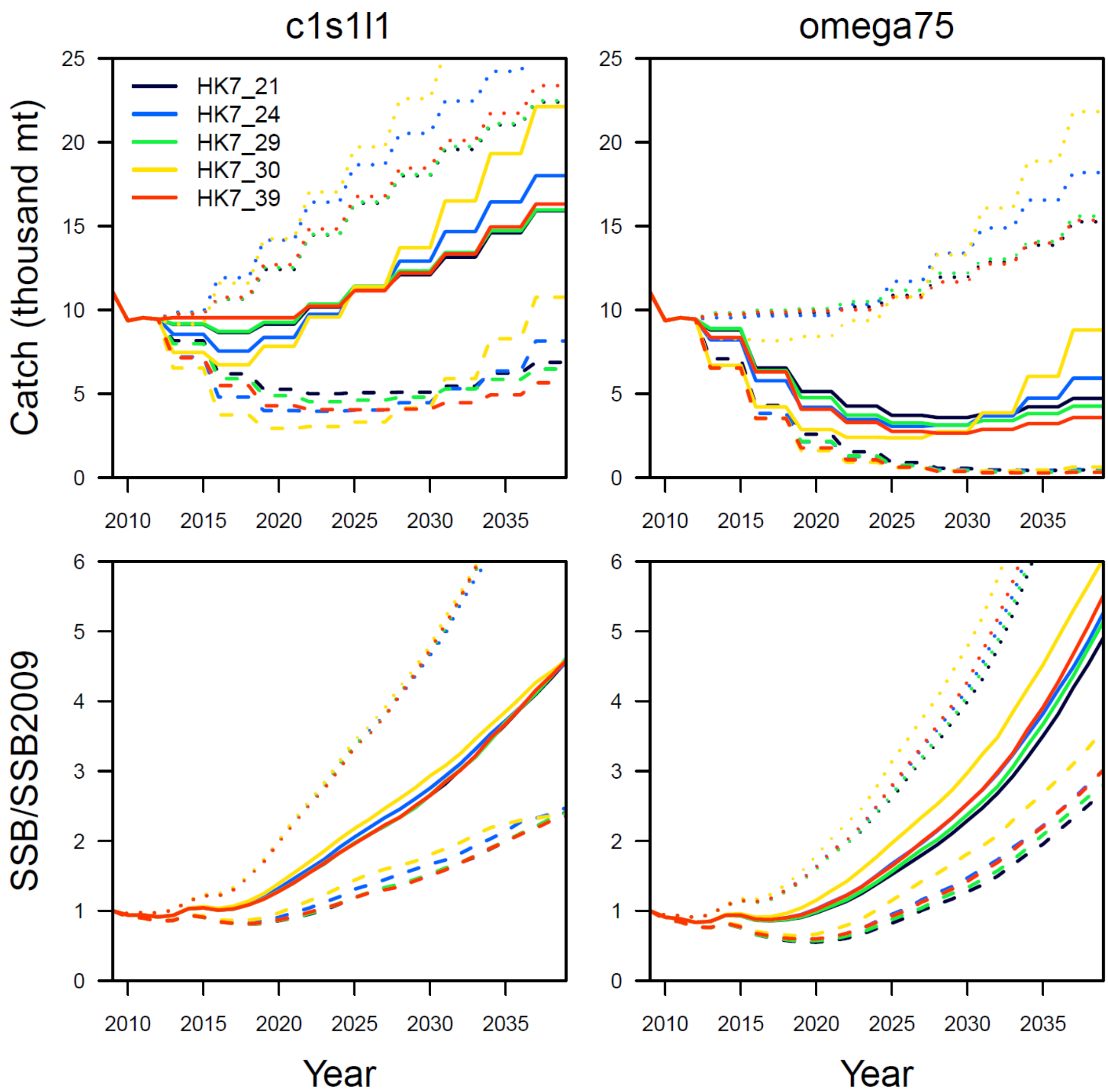


Fig. 1b. Comparison of MP performance for the reference set and the robustness trials, showing the median and 10 percentiles for selected MPs under ***tuning option 5***.

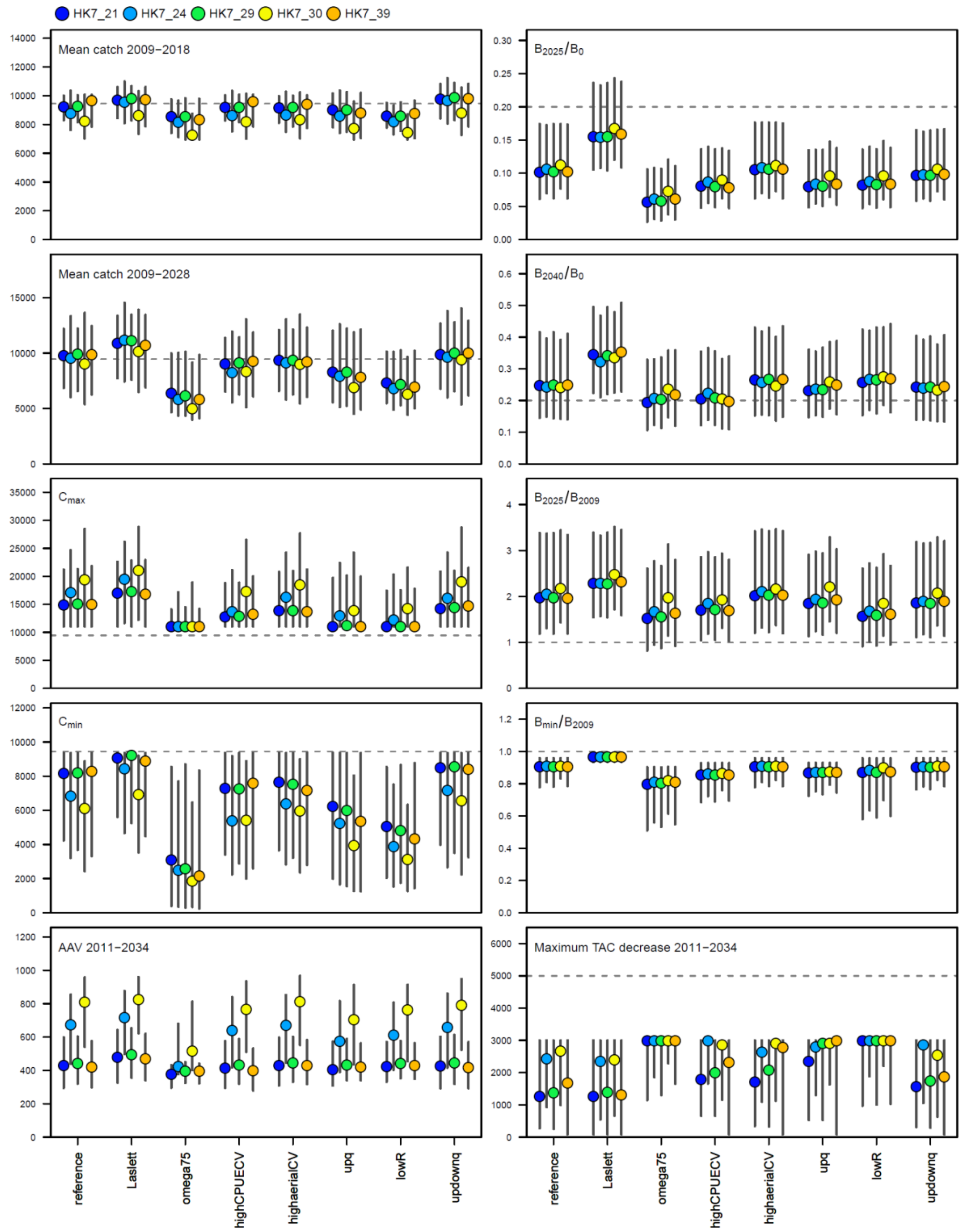


Fig. 2a. Time trajectory plot for catch and stock biomass for the reference set and the omega75 robustness trial, showing the median (solid), higher 10 percentile (dot) and lower 10 percentile (dash) for selected MPs under ***tuning option 2***.

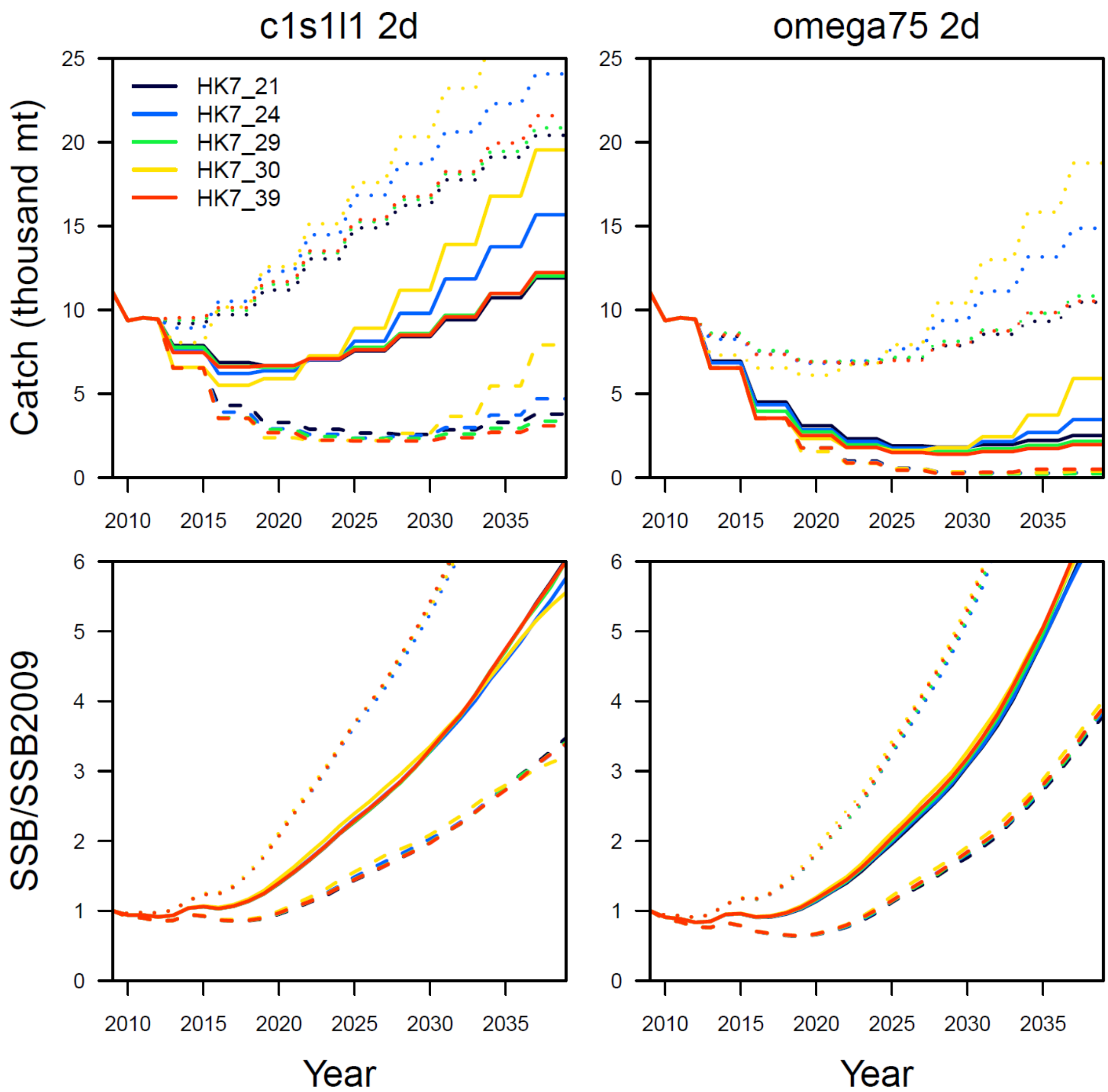


Fig. 2b. Comparison of MP performance for the reference set and the robustness trials, showing the median and 10 percentiles for selected MPs under ***tuning option 2***.

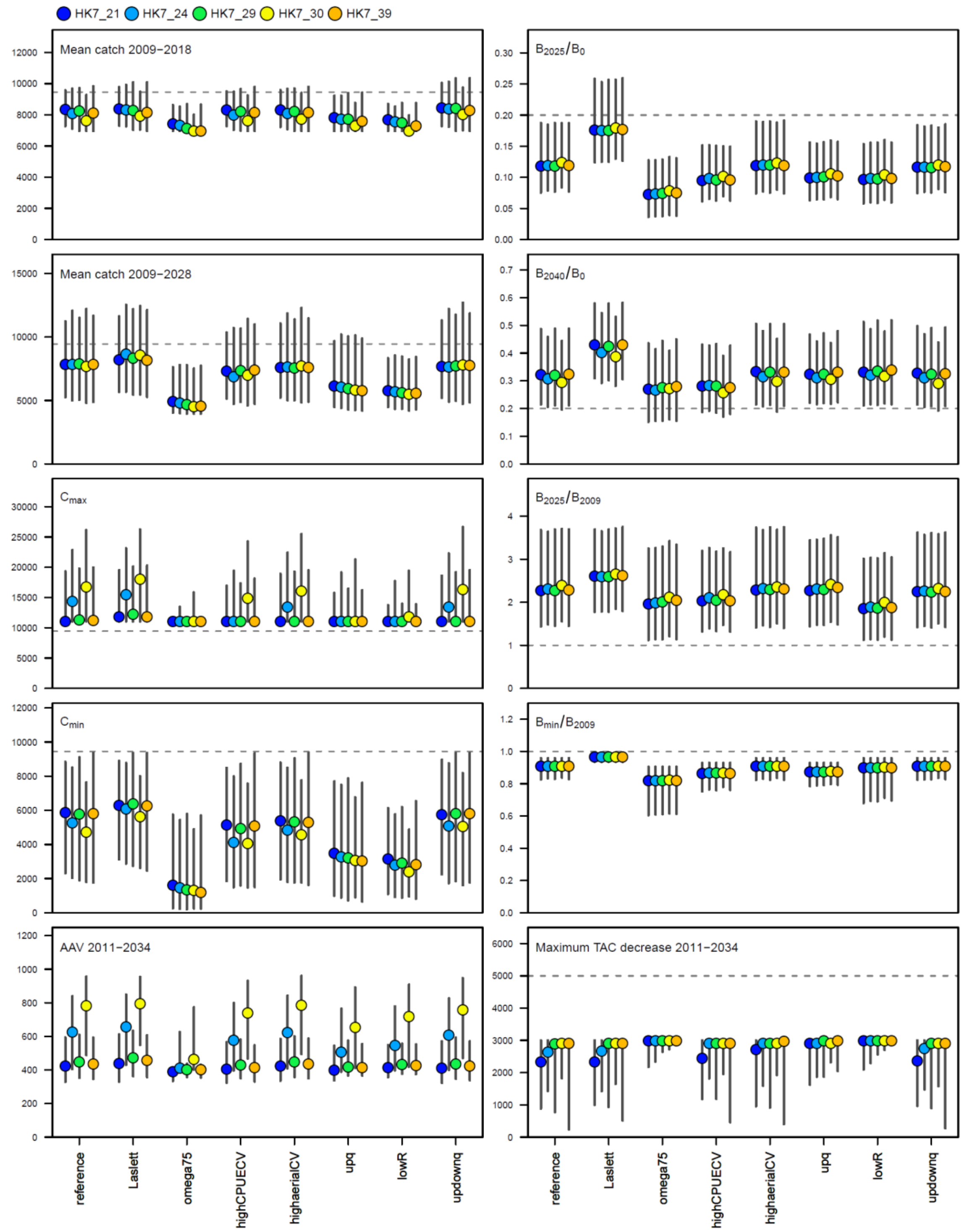
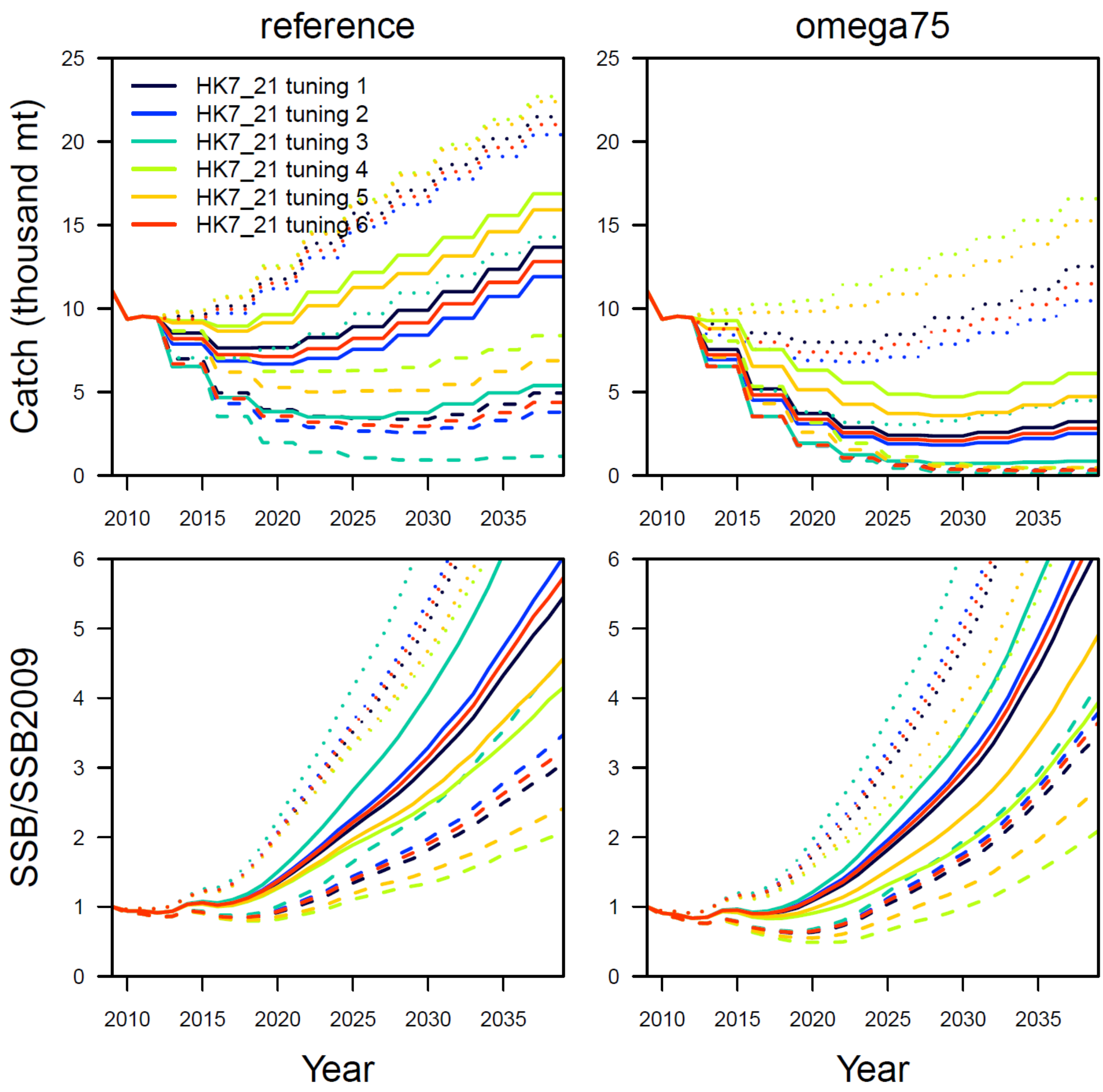


Fig. 3. Time trajectory plot for catch and stock biomass for the reference set and the omega75 robustness trial, showing the median (solid), higher 10 percentile (dot) and lower 10 percentile (dash) for ***HK7_21*** tuned to ***the different tuning options***.



Appendix 1

HK6

The original HK6 ("Hiroyuki Kurota ver. 6") determines a TAC from two candidate TACs calculated using the CPUE trend for age 4+ over the most recent years (δTAC^{cpue}), and using the AS (aerial survey) index over the most recent years (δTAC^{aerial}). This MP then chooses the minimum of the two candidate TACs. The change of TAC is specified as:

$$\delta TAC_{y+1}^{cpue} = \begin{cases} 1+k_1\lambda & \lambda < 0 \\ 1+k_2\lambda & \lambda \geq 0 \end{cases}$$

$$\delta TAC_{y+1}^{aerial1} = \begin{cases} m_{\max} & \frac{1}{\tau_{as}} \sum_{i=y-\tau_{as}}^{y-1} \ln\left(I_i^{AS}\right) > l_{\max} \\ a \times \left(\frac{1}{\tau_{as}} \sum_{i=y-\tau_{as}}^{y-1} \ln\left(I_i^{AS}\right) \right) + b & l_{\min} \leq \frac{1}{\tau_{as}} \sum_{i=y-\tau_{as}}^{y-1} \ln\left(I_i^{AS}\right) \leq l_{\max} \\ m_{\min} & \frac{1}{\tau_{as}} \sum_{i=y-\tau_{as}}^{y-1} \ln\left(I_i^{AS}\right) < l_{\min} \end{cases}$$

$$TAC_{y+1} = TAC_y \times \min\left(\delta TAC_{y+1}^{cpue},\ \delta TAC_{y+1}^{aerial1}\right)$$

where

λ is the slope of the regression of *ln* (I_i^{CPUE}) against year (from y - τ_{cpue} - 1 to y - 2),

k_1, k_2 are control parameters,

I_i^{AS} is the aerial survey index in year y,

τ_{as} is the time-period over which the mean of the AS index is calculated,
m_{max}, m_{min}, l_{max}, l_{min} are control parameters (l_{min} is used as a tuning parameter), and
a, b are parameters related to m_{max}, m_{min}, l_{max}, l_{min} to provide a continuous rule.

Appendix 2

Fig. A1-a. Time trajectory plot for catch and stock biomass for the reference set and the omega75 robustness trial, showing the median (solid), higher 10 percentile (dot) and lower 10 percentile (dash) for the different MPs depending on ***the time period to estimate CPUE slope.***

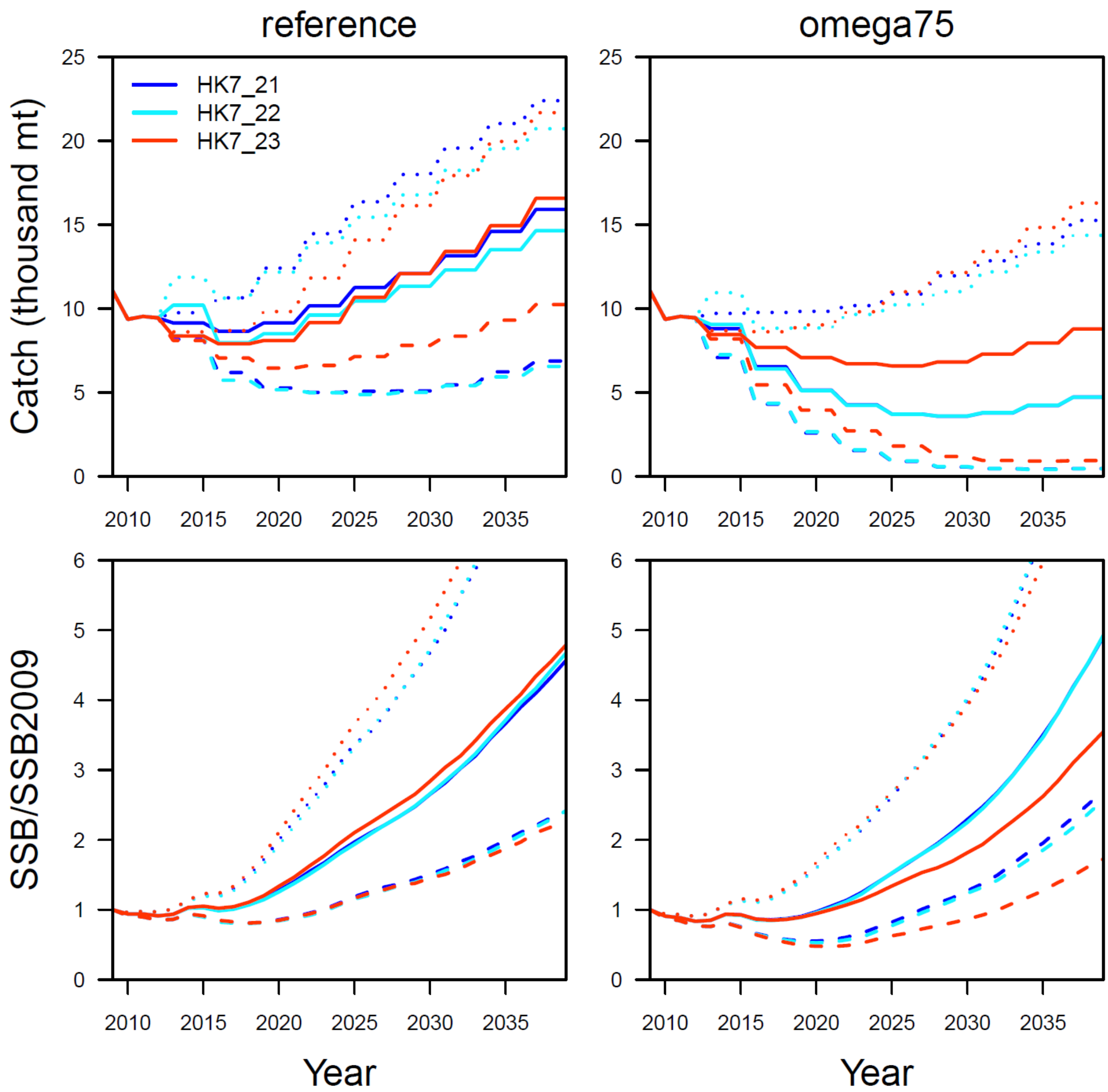


Fig. A1-b. Comparison of MP performance for the reference set and the robustness trials, showing the median and 10 percentiles for the different MPs depending on ***the time period to estimate CPUE slope.***

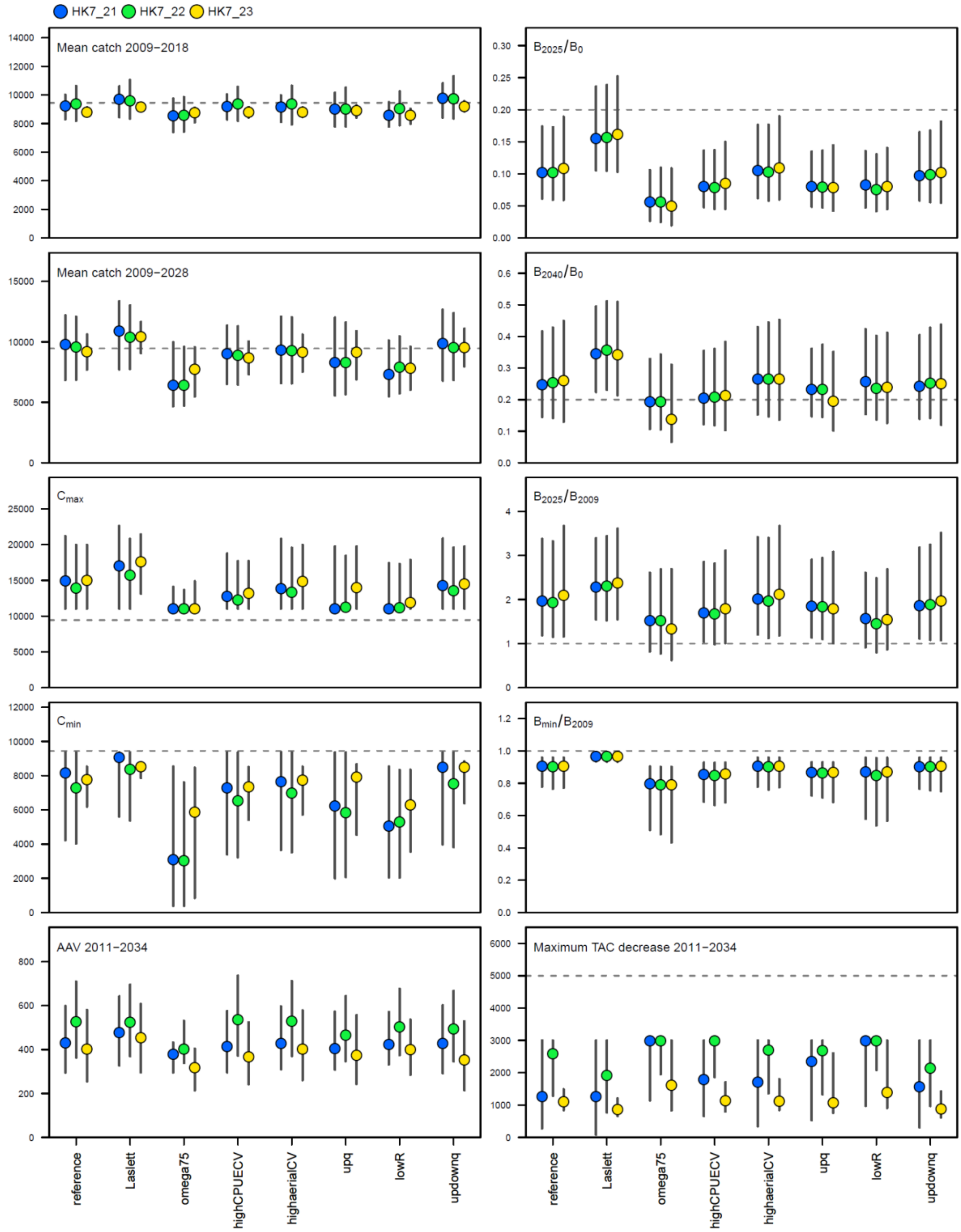


Fig. A2-a. Time trajectory plot for catch and stock biomass for the reference set and the omega75 robustness trial, showing the median (solid), higher 10 percentile (dot) and lower 10 percentile (dash) for the different MPs in relation to ***k_1-k_2* (responsiveness to CPUE slope)**

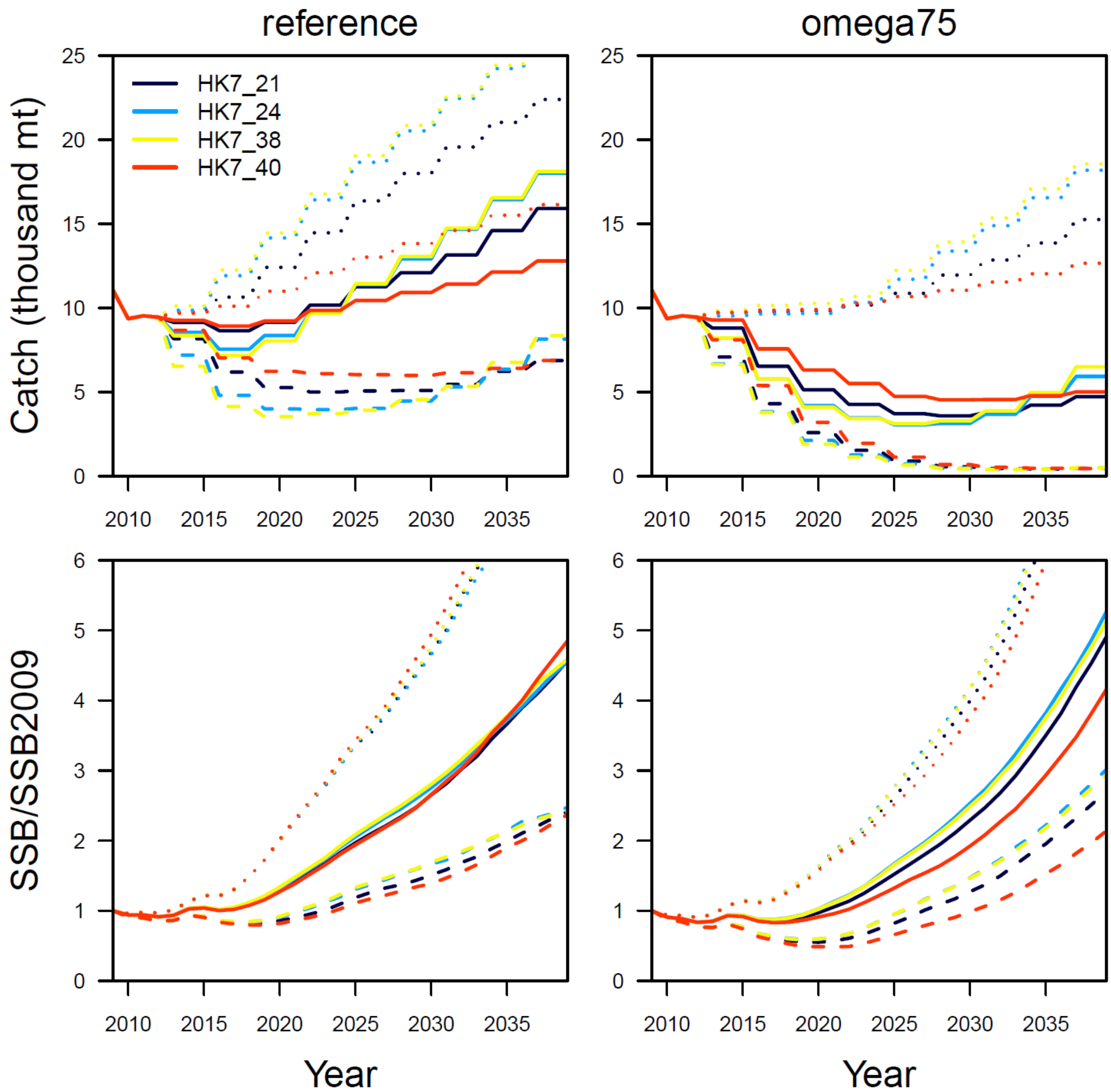


Fig. A2-b. Comparison of MP performance for the reference set and the robustness trials, showing the median and 10 percentiles for the different MPs in relation to ***k_1-k_2* (responsiveness to CPUE slope).**

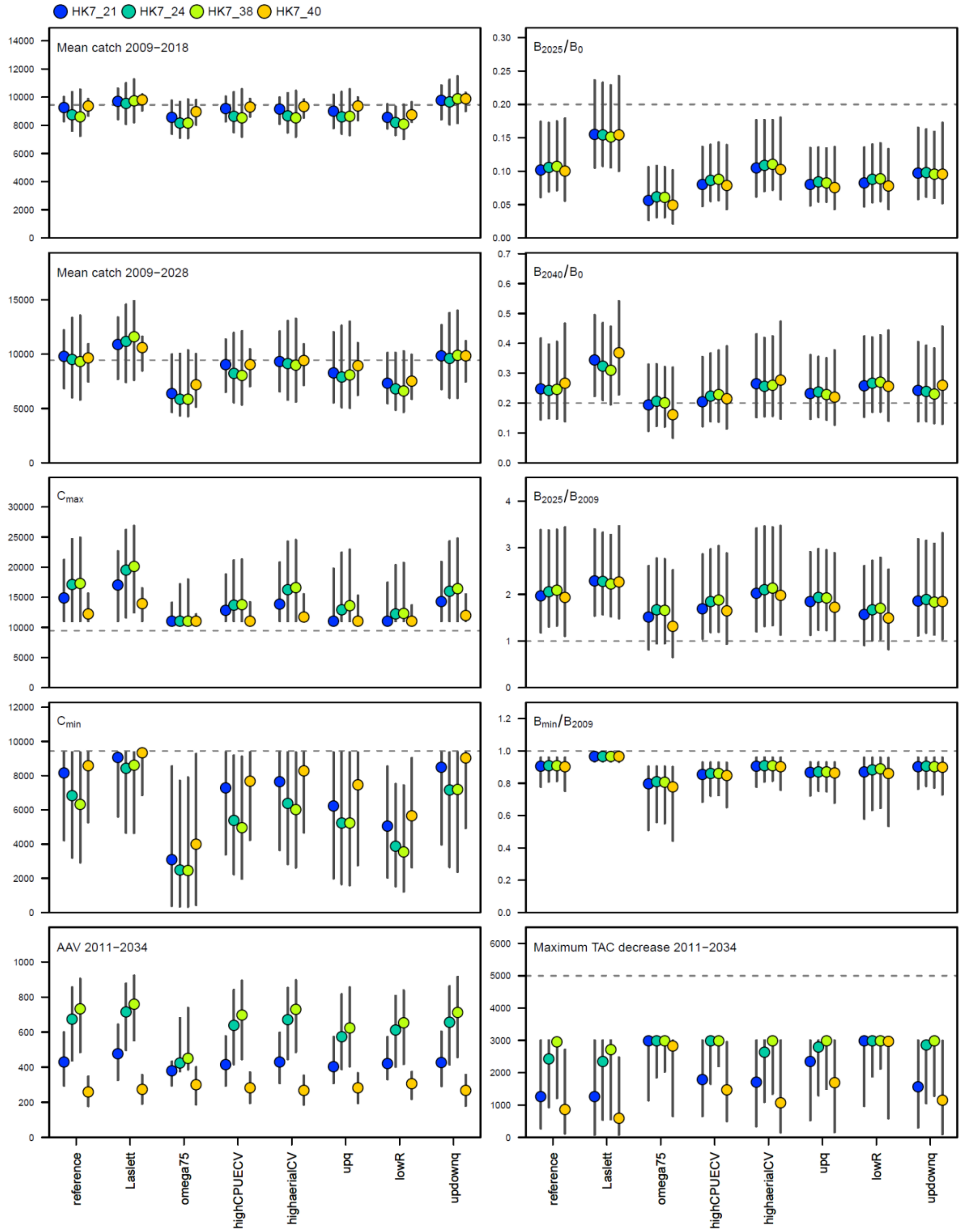


Fig. A3-a. Time trajectory plot for catch and stock biomass for the reference set and the omega75 robustness trial, showing the median (solid), higher 10 percentile (dot) and lower 10 percentile (dash) for the different MPs in relation to ***the AS index options.***

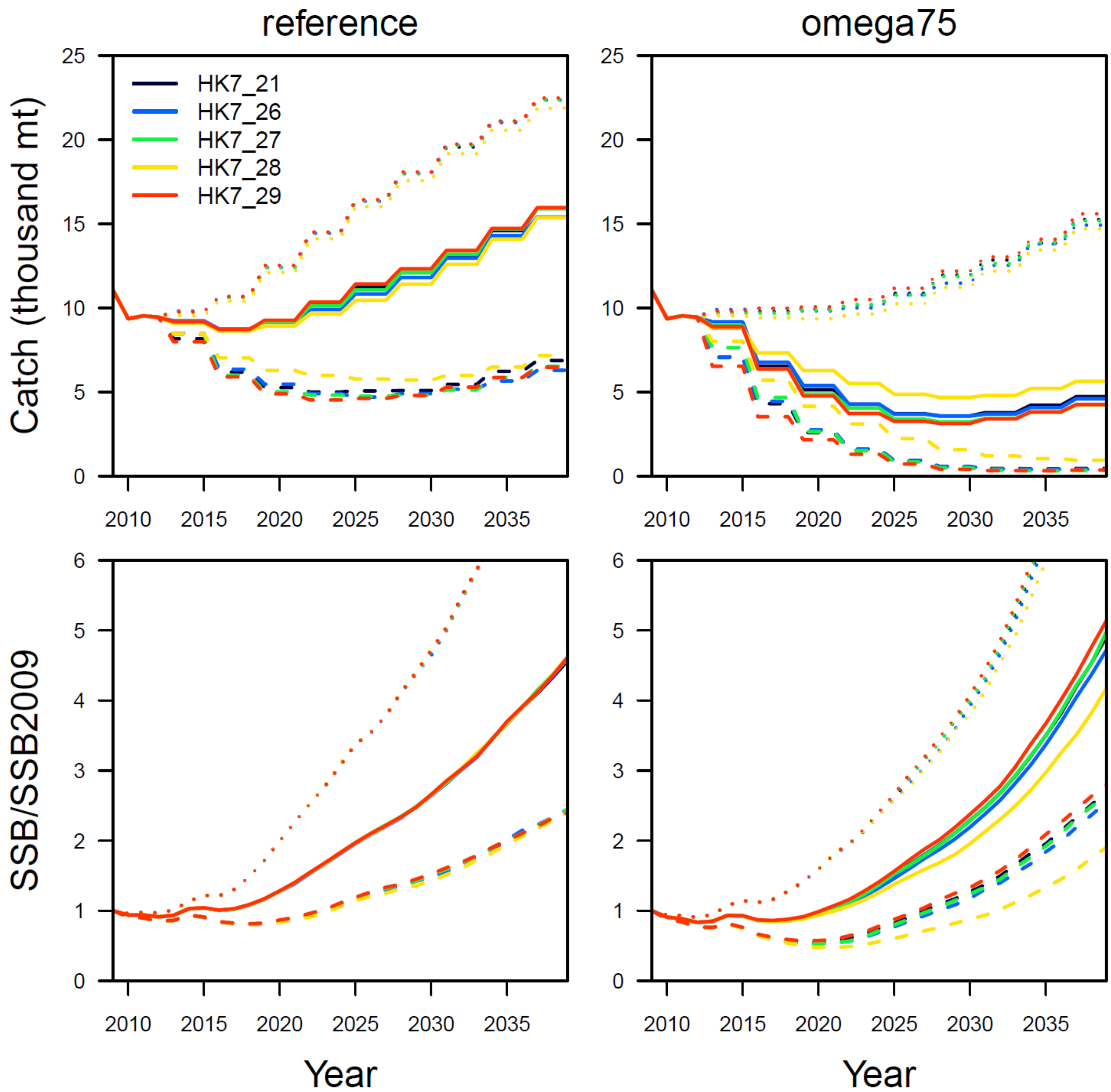


Fig. A3-b. Comparison of MP performance for the reference set and the robustness trials, showing the median and 10 percentiles for the different MPs in relation to ***the AS index options.***

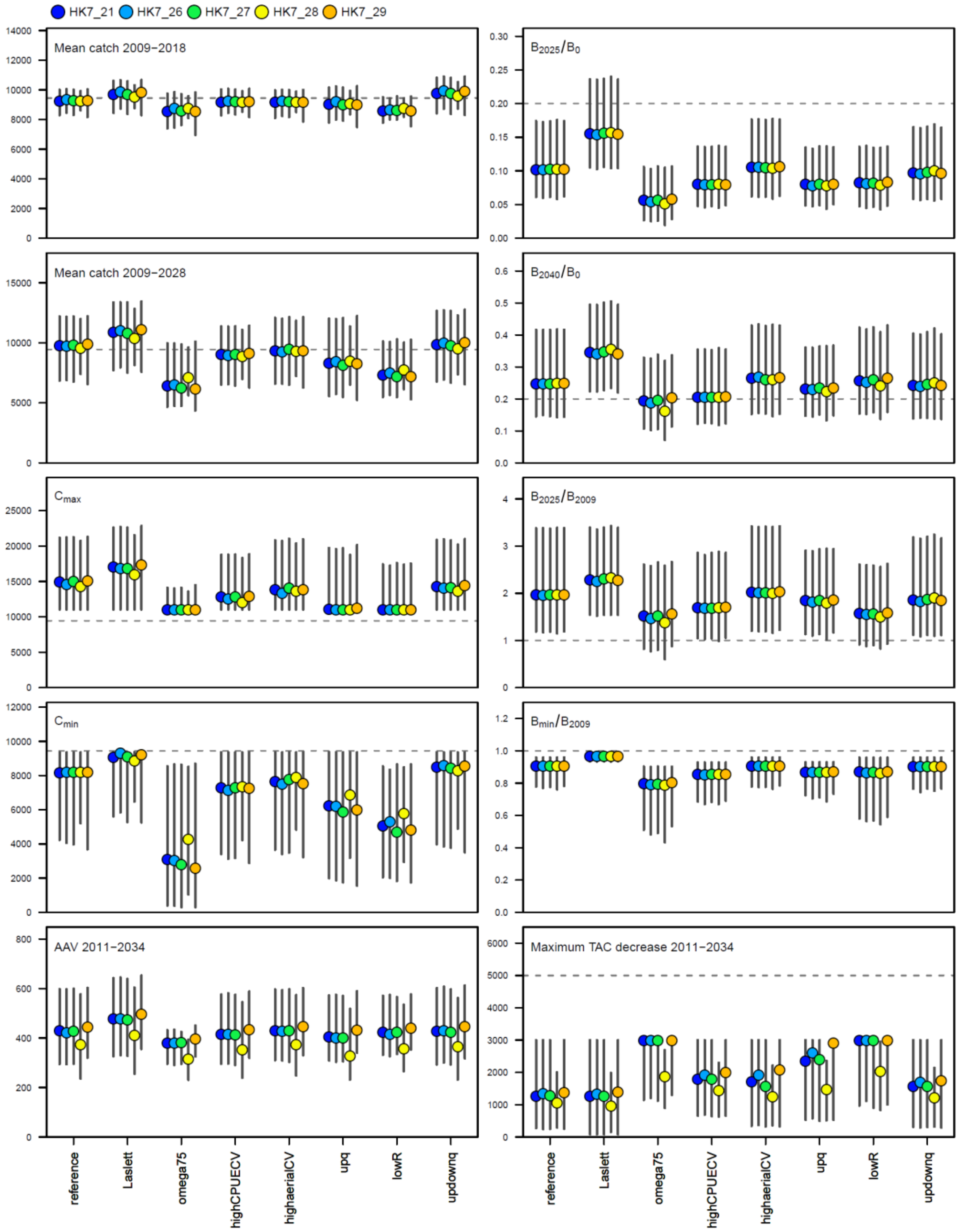


Fig. A4-a. Time trajectory plot for catch and stock biomass for the reference set and the omega75 robustness trial, showing the median (solid), higher 10 percentile (dot) and lower 10 percentile (dash) for the different MPs in relation to ***the power function options.***

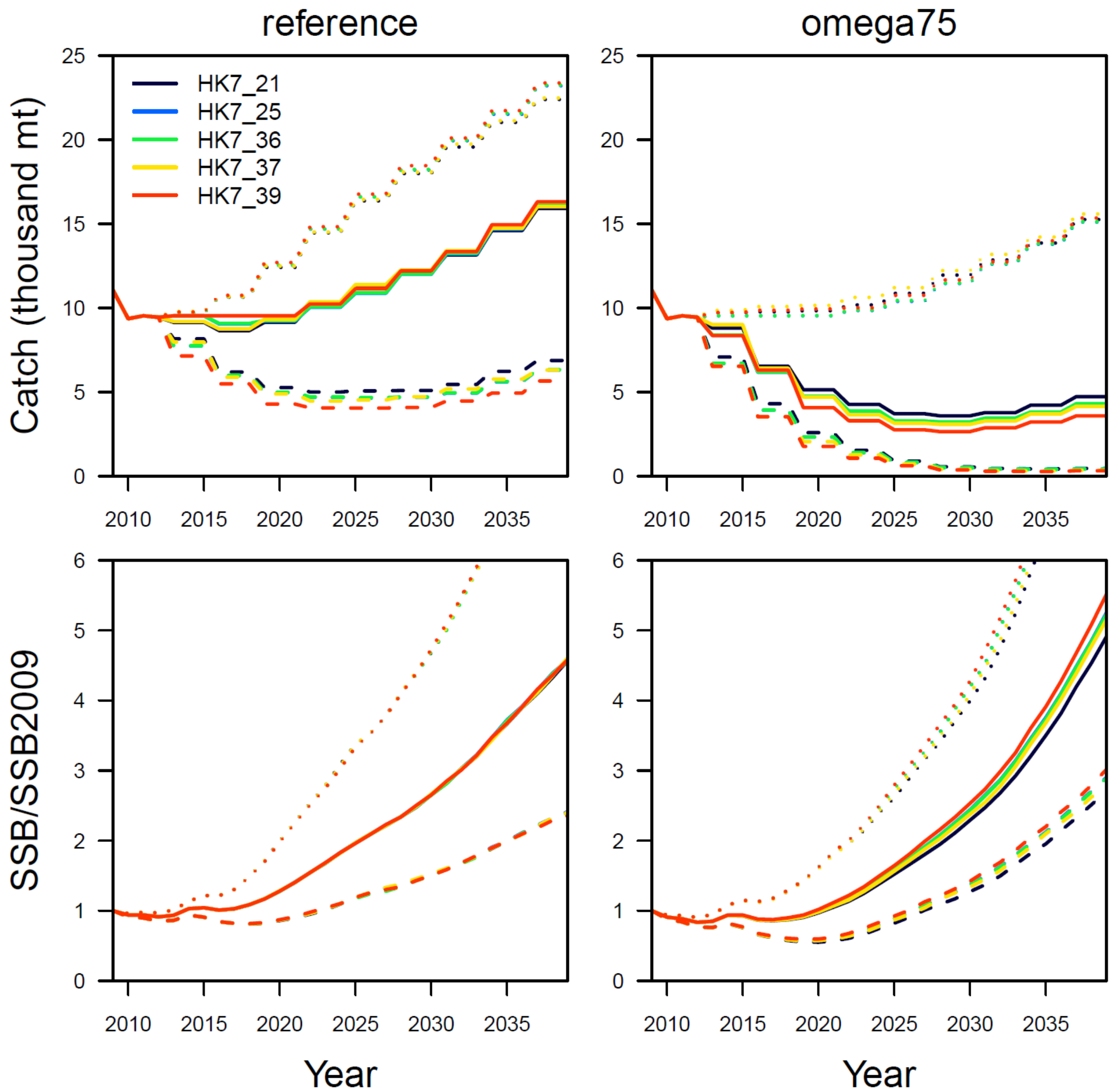


Fig. A4-b. Comparison of MP performance for the reference set and the robustness trials, showing the median and 10 percentiles for the different MPs in relation to ***the power function options.***

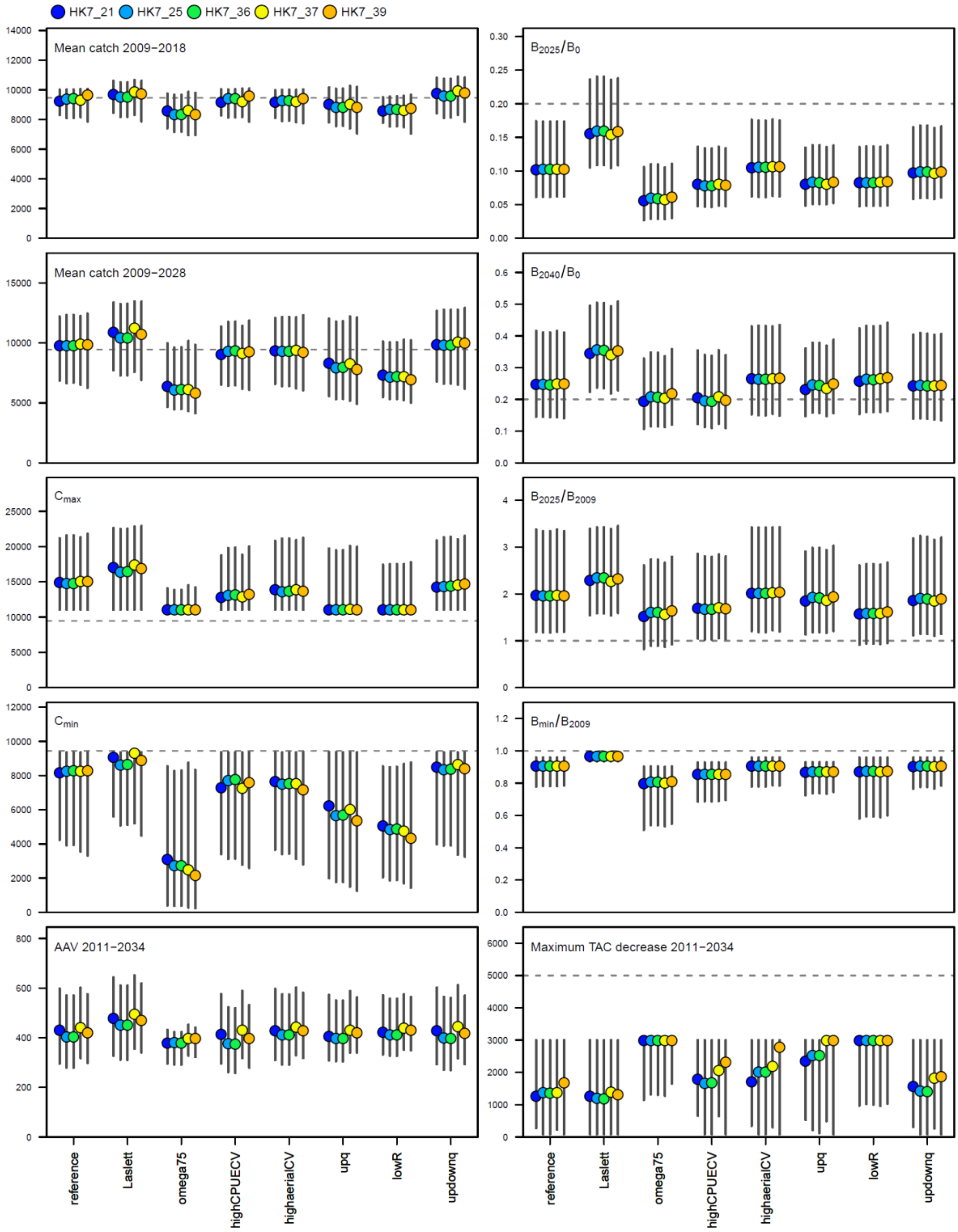


Fig. A5-a. Time trajectory plot for catch and stock biomass for the reference set and the omega75 robustness trial, showing the median (solid), higher 10 percentile (dot) and lower 10 percentile (dash) for the different MPs in relation to ***the combination methods.***

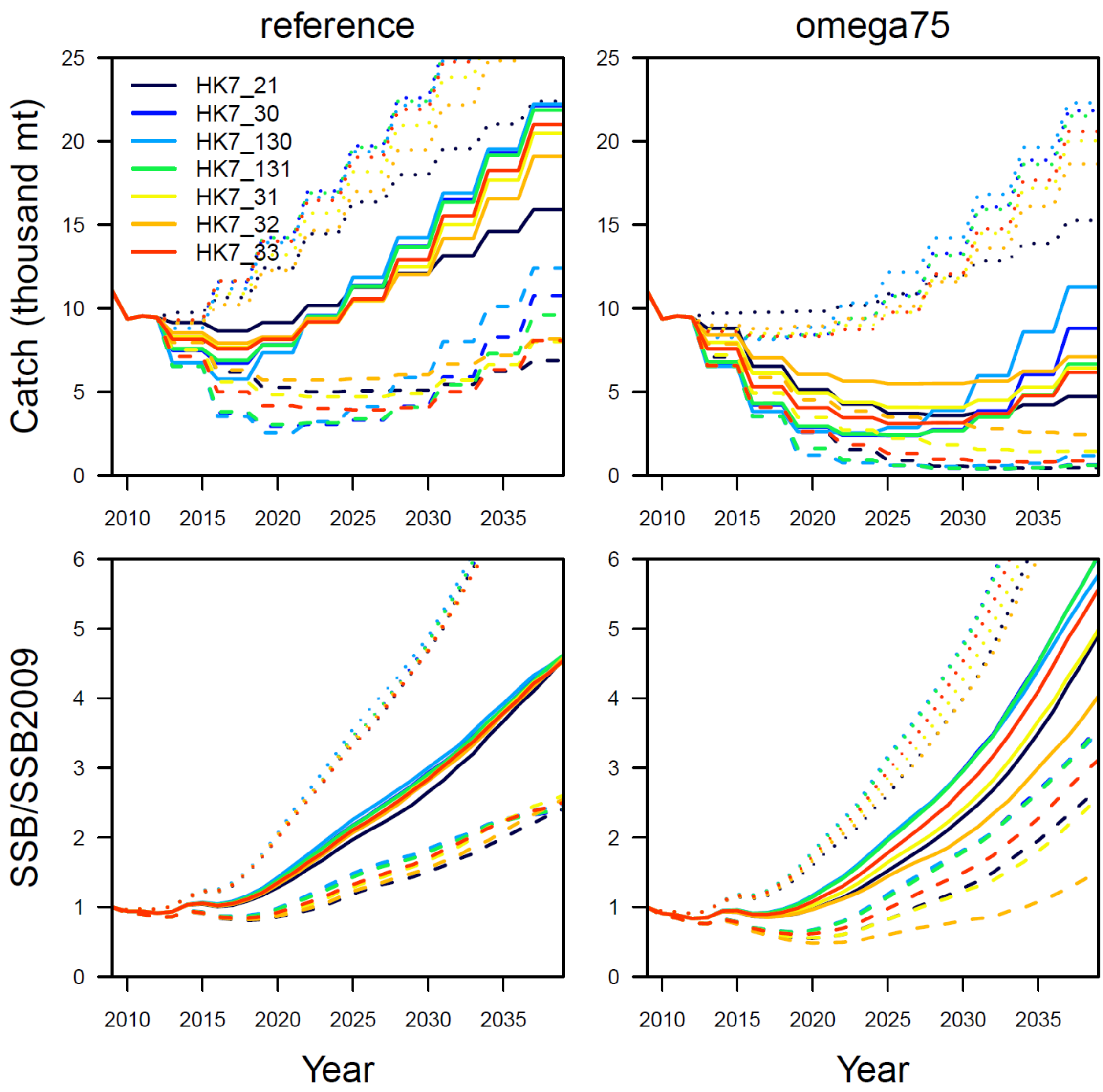


Fig. A5-b. Comparison of MP performance for the reference set and the robustness trials, showing the median and 10 percentiles for the different MPs in relation to ***the combination method.***

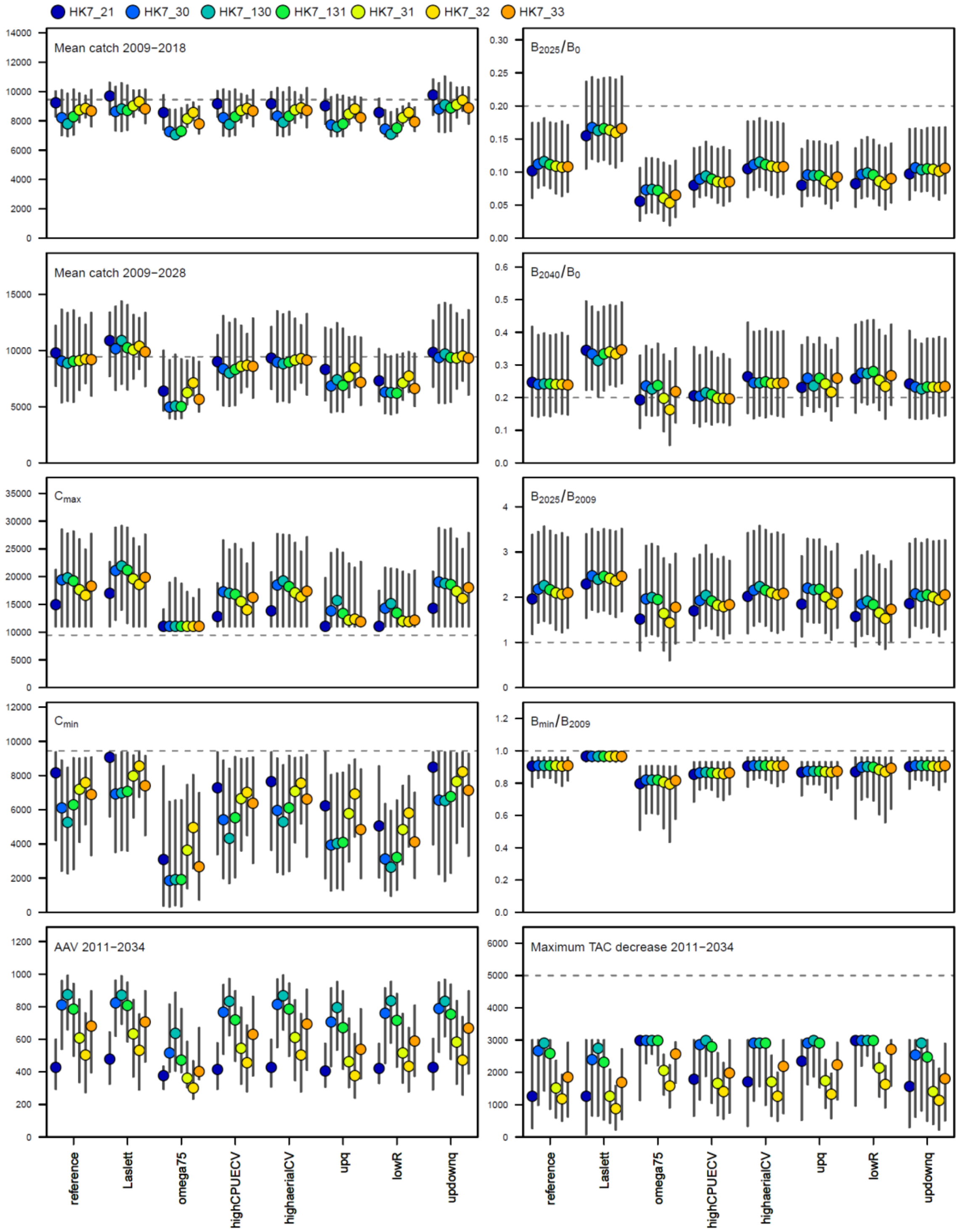
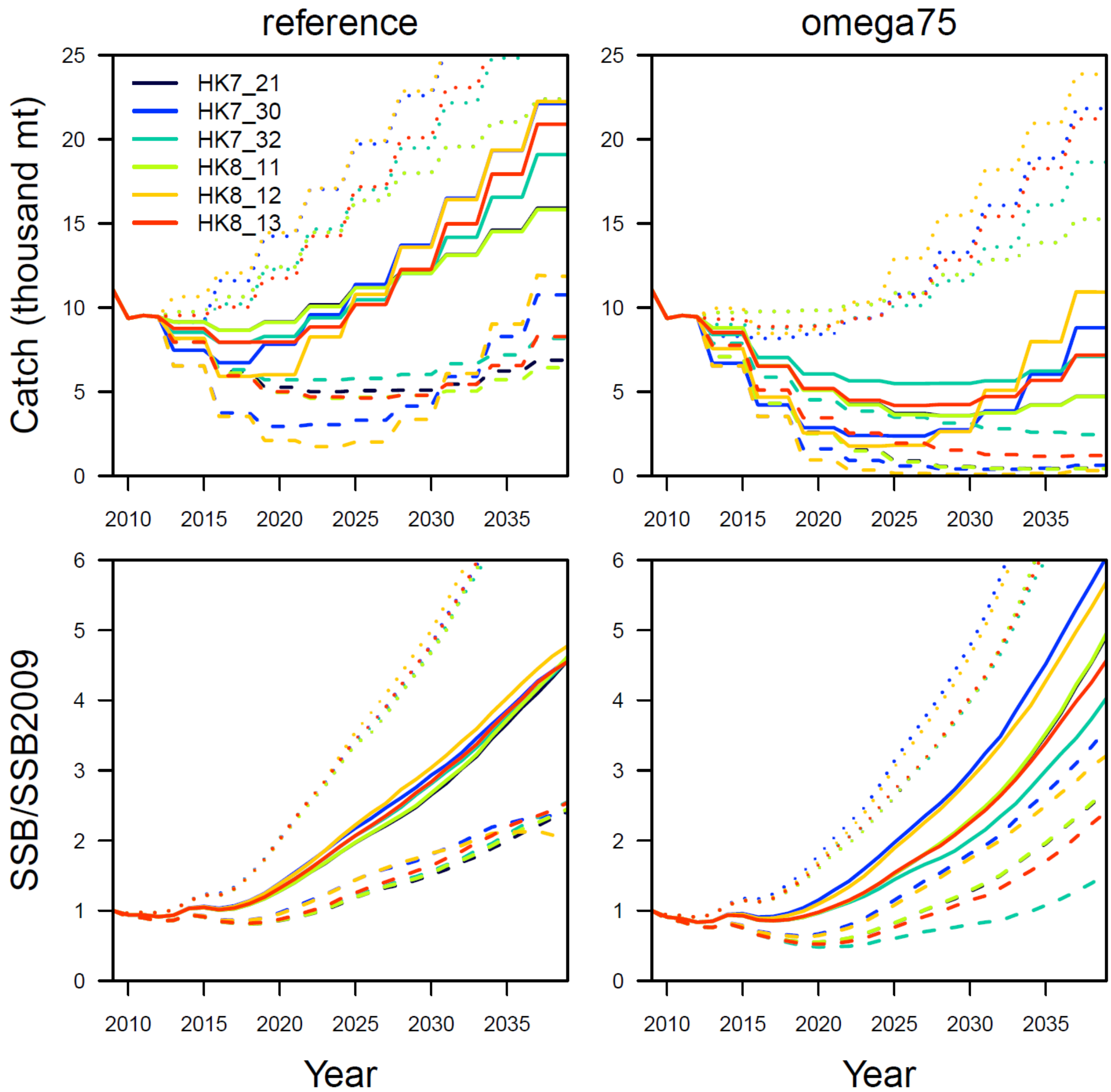


Fig. A6-a. Time trajectory plot for catch and stock biomass for the reference set and the omega75 robustness trial, showing the median (solid), higher 10 percentile (dot) and lower 10 percentile (dash) for the different MPs in relation to ***the addition of a CPUE target**.**



* HK8_11 showed the almost same behavior as HK7_21. This is considered to be because the tuning was not successful to incorporate information from the CPUE target. Results of HK8_14 and HK8_15 were close to those of HK8_12 and HK8_14, respectively.

Fig. A6-b. Comparison of MP performance for the reference set and the robustness trials, showing the median and 10 percentiles for the different MPs in relation to ***the addition of a CPUE target.***

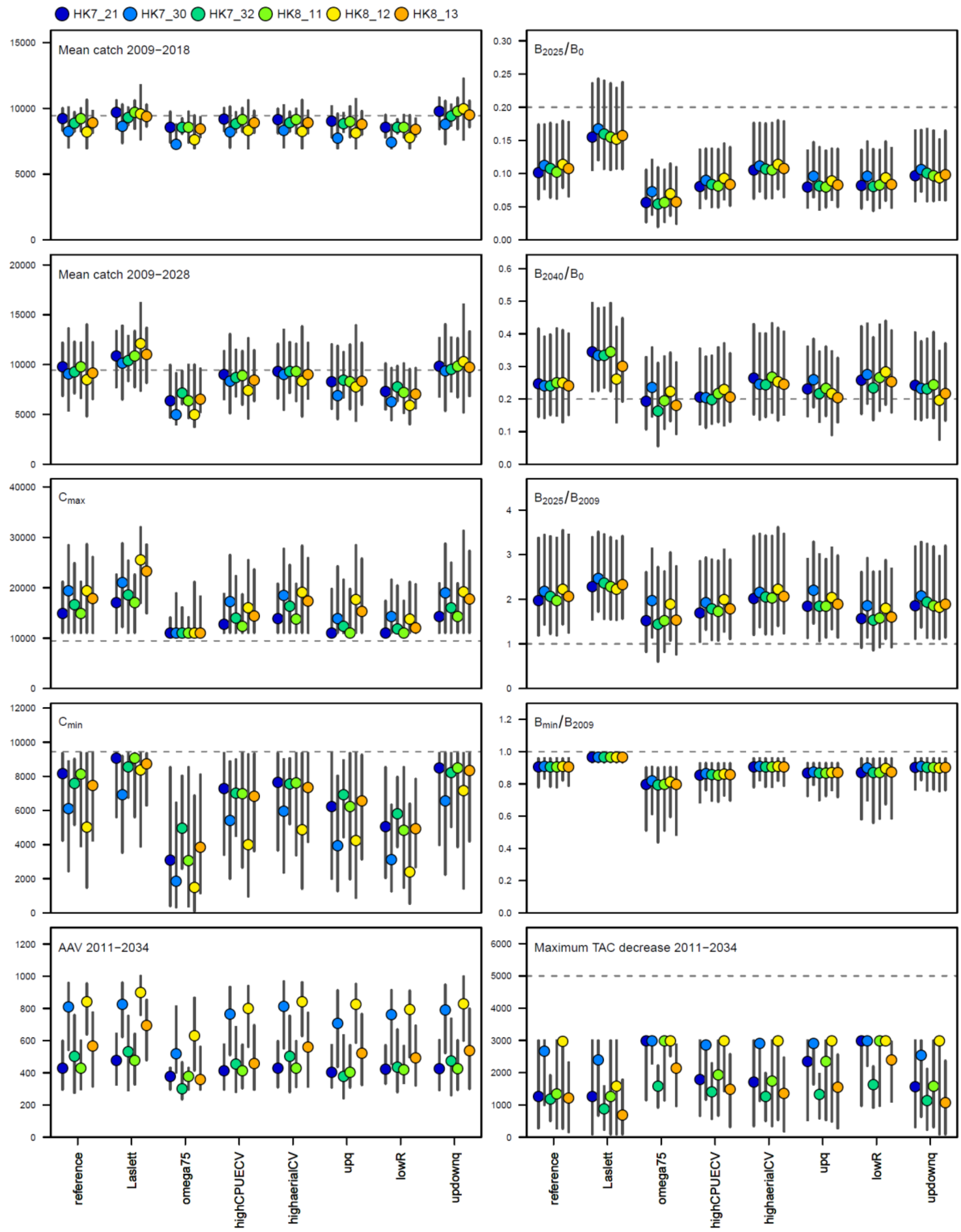


Fig. A7-a. Time trajectory plot for catch and stock biomass for the reference set and the omega75 robustness trial, showing the median (solid), higher 10 percentile (dot) and lower 10 percentile (dash) for the base case HK7 and ***HK6***.

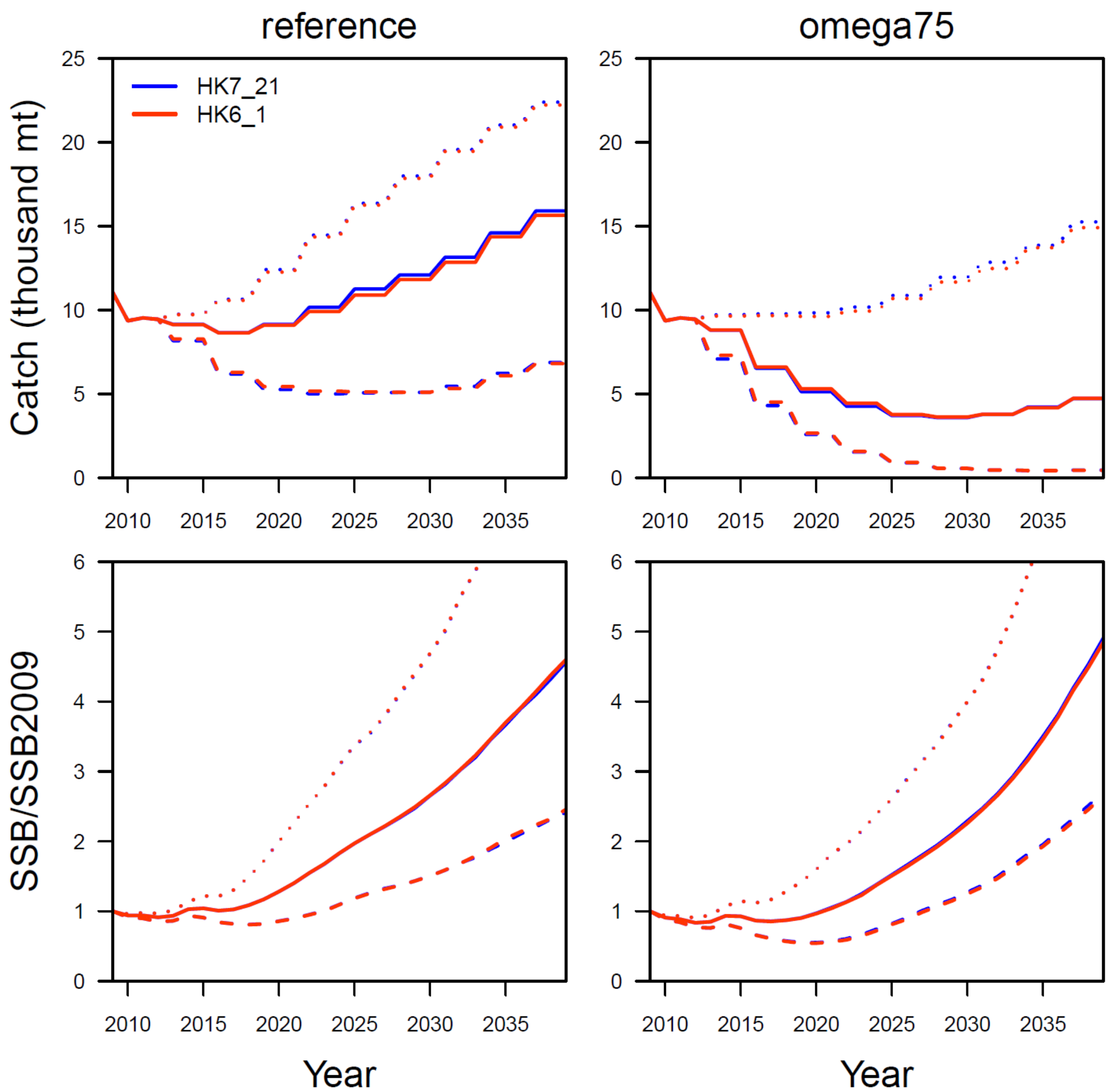


Fig. A7-b. Comparison of MP performance for the reference set and the robustness trials, showing the median and 10 percentiles for the base case HK7 and ***HK6***.

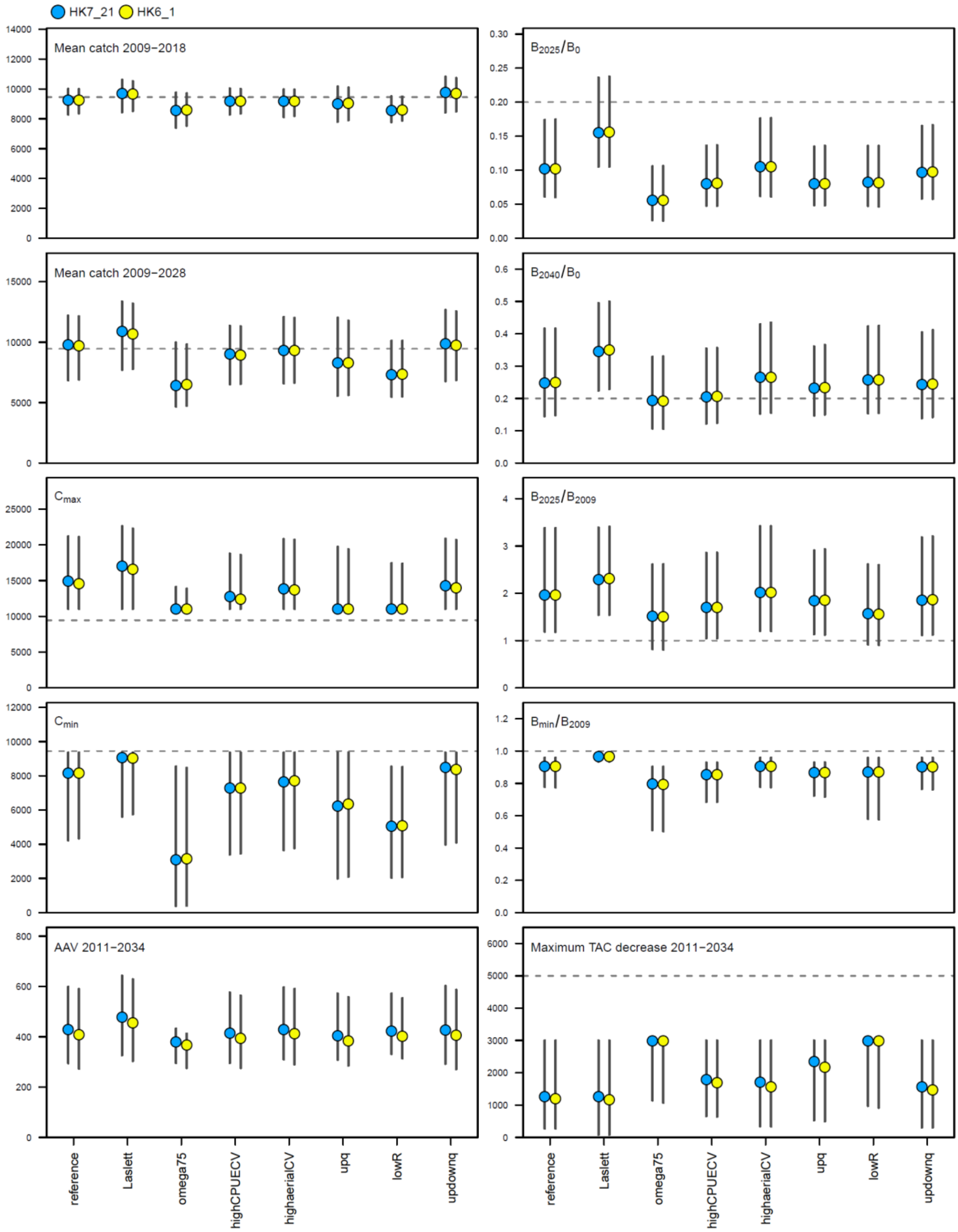


Fig. A8-a. Time trajectory plot for catch and stock biomass for the reference set and the omega75 robustness trial, showing the median (solid), higher 10 percentile (dot) and lower 10 percentile (dash) for the different MPs in relation to ***the maximum TAC change.***

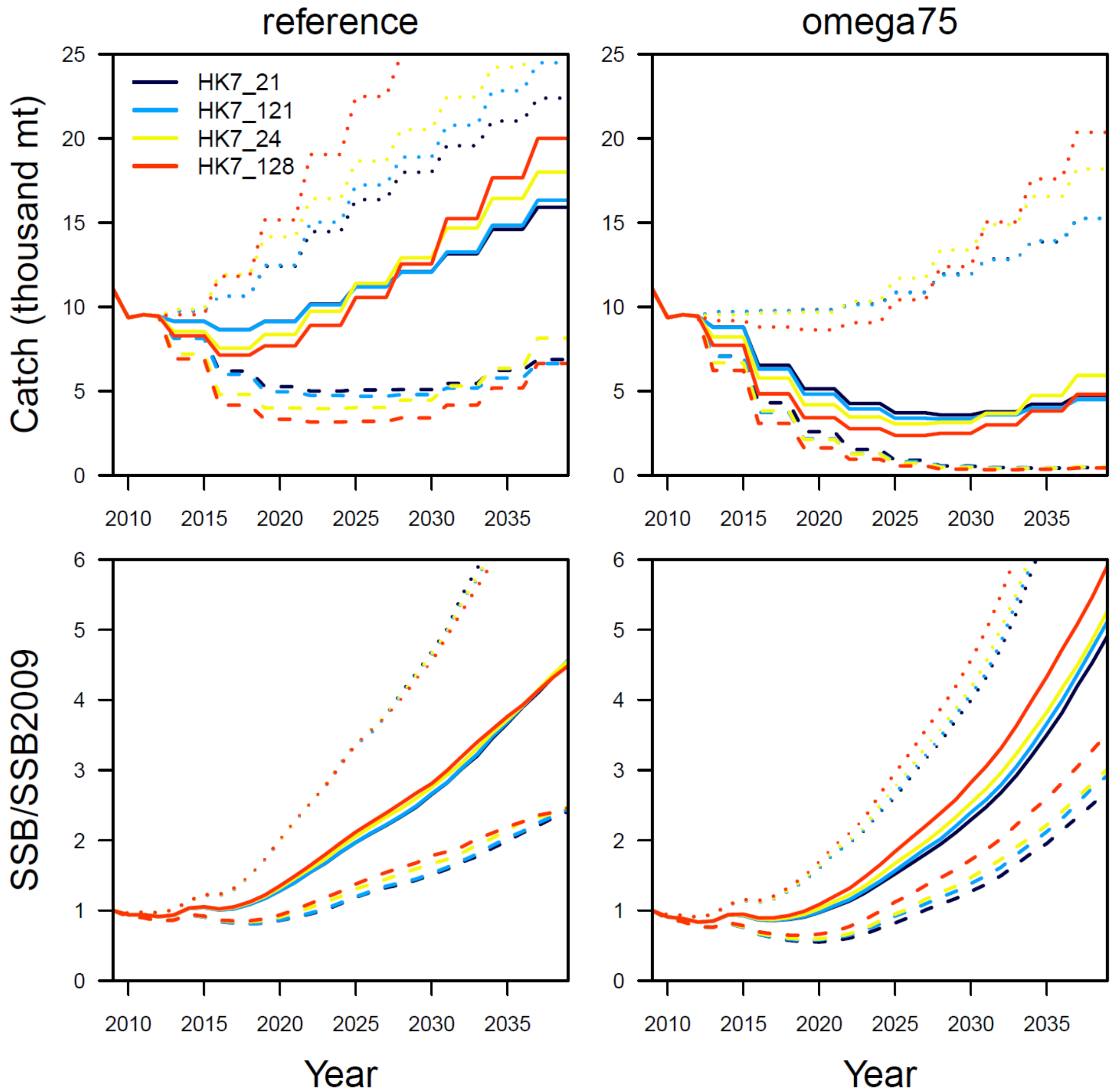


Fig. A8-b. Comparison of MP performance for the reference set and the robustness trials, showing the median and 10 percentiles for the different MPs in relation to ***the maximum TAC change.***

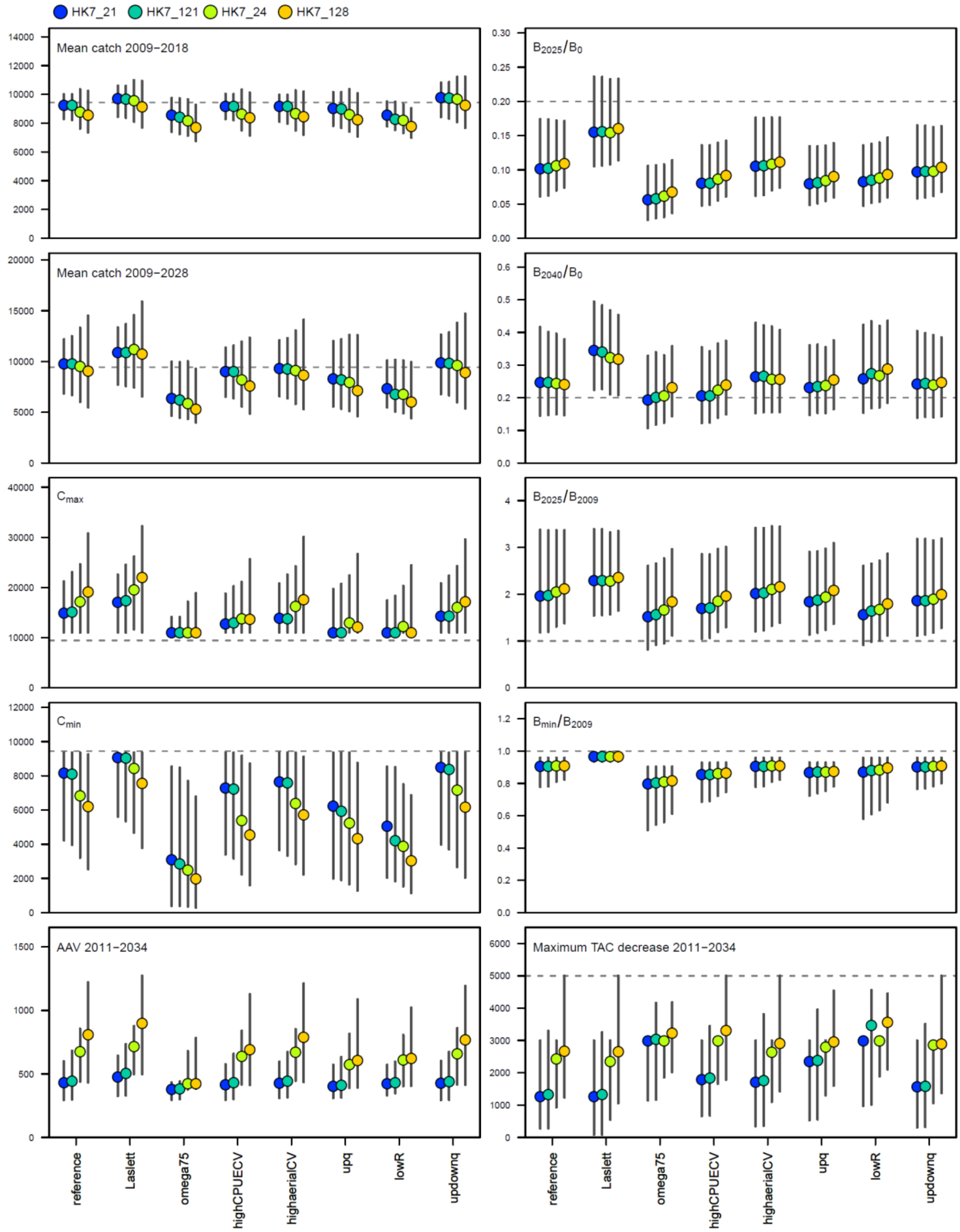


Fig. A9-a. Time trajectory plot for catch and stock biomass for the reference set and the omega75 robustness trial, showing the median (solid), higher 10 percentile (dot) and lower 10 percentile (dash) for the different MPs in relation to ***the implementation time lag.***

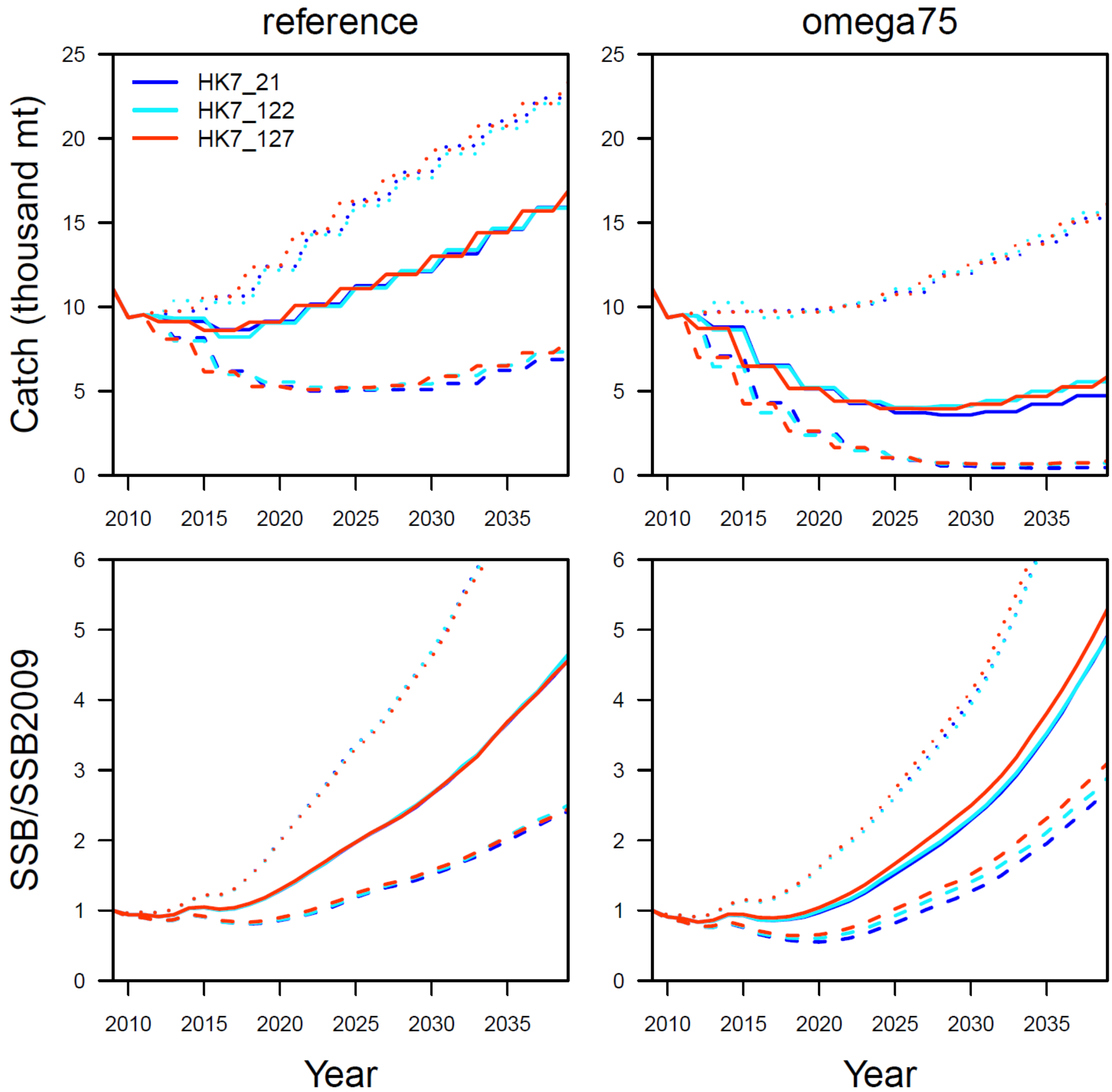


Fig. A9-b. Comparison of MP performance for the reference set and the robustness trials, showing the median and 10 percentiles for the different MPs in relation to ***the implementation time lag.***

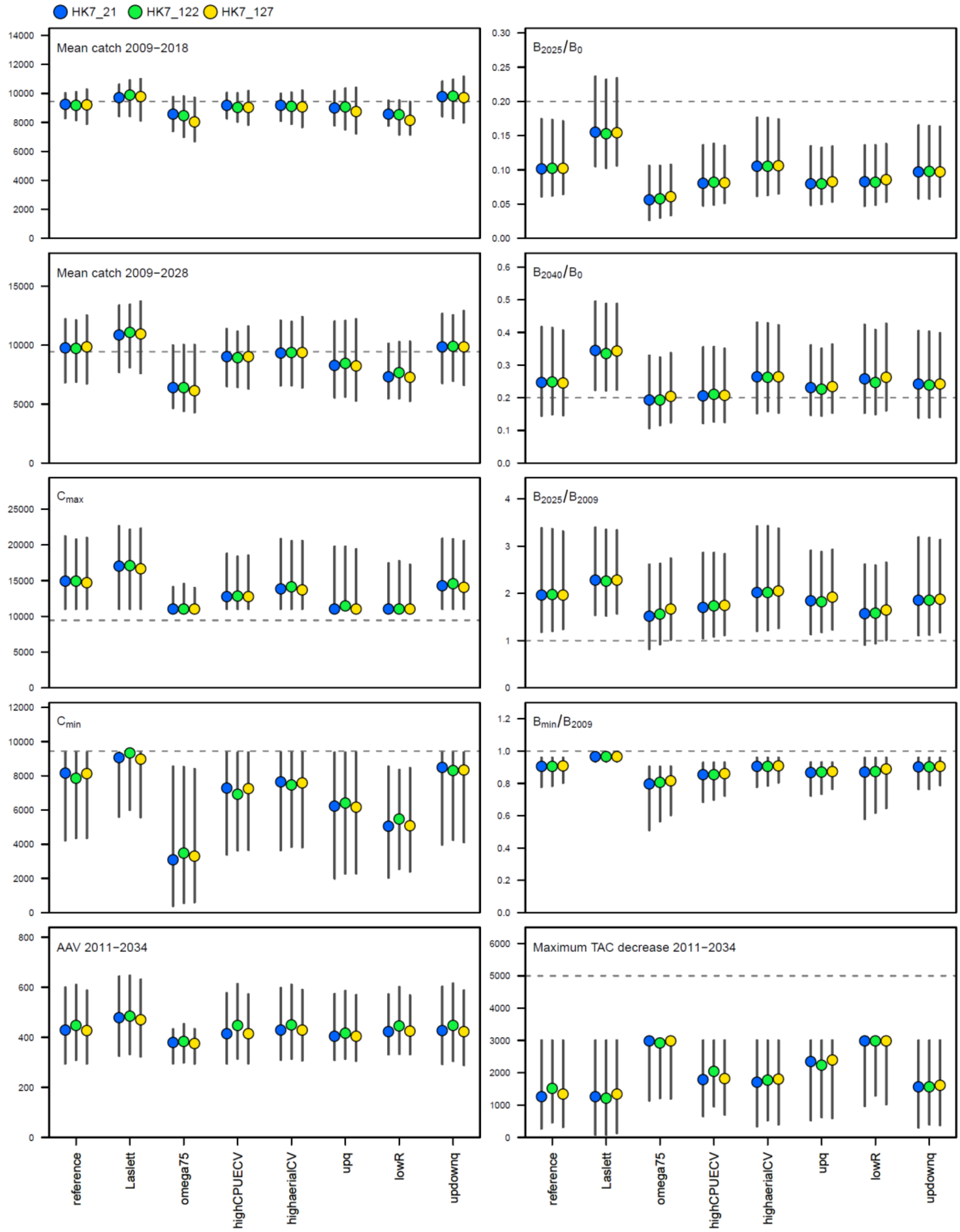


Fig. A10-a. Time trajectory plot for catch and stock biomass for the reference set and the omega75 robustness trial, showing the median (solid), higher 10 percentile (dot) and lower 10 percentile (dash) for the different MPs in relation to ***the frequency of TAC change***.

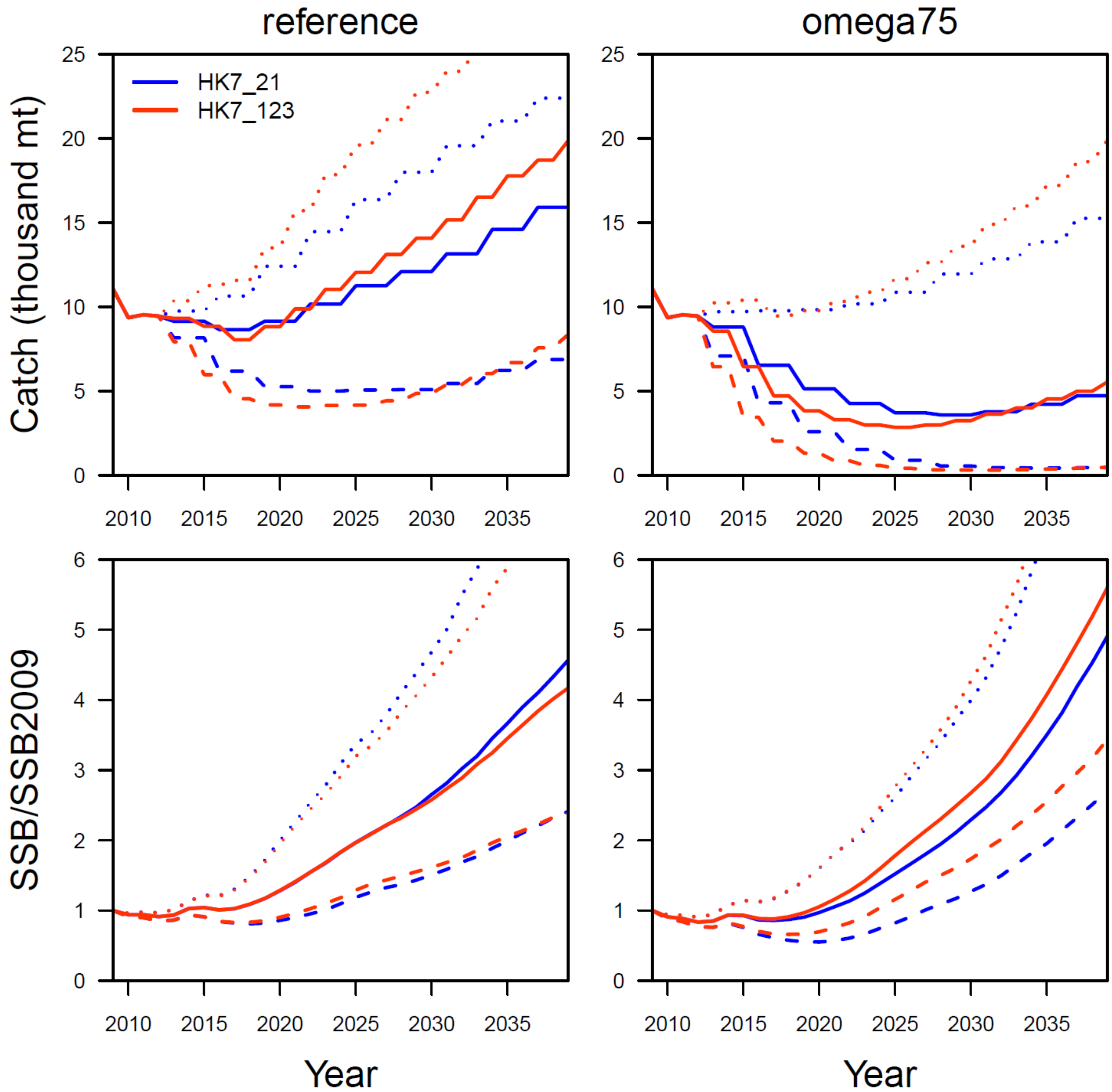


Fig. A10-b. Comparison of MP performance for the reference set and the robustness trials, showing the median and 10 percentiles for the different MPs in relation to ***the frequency of TAC change***.

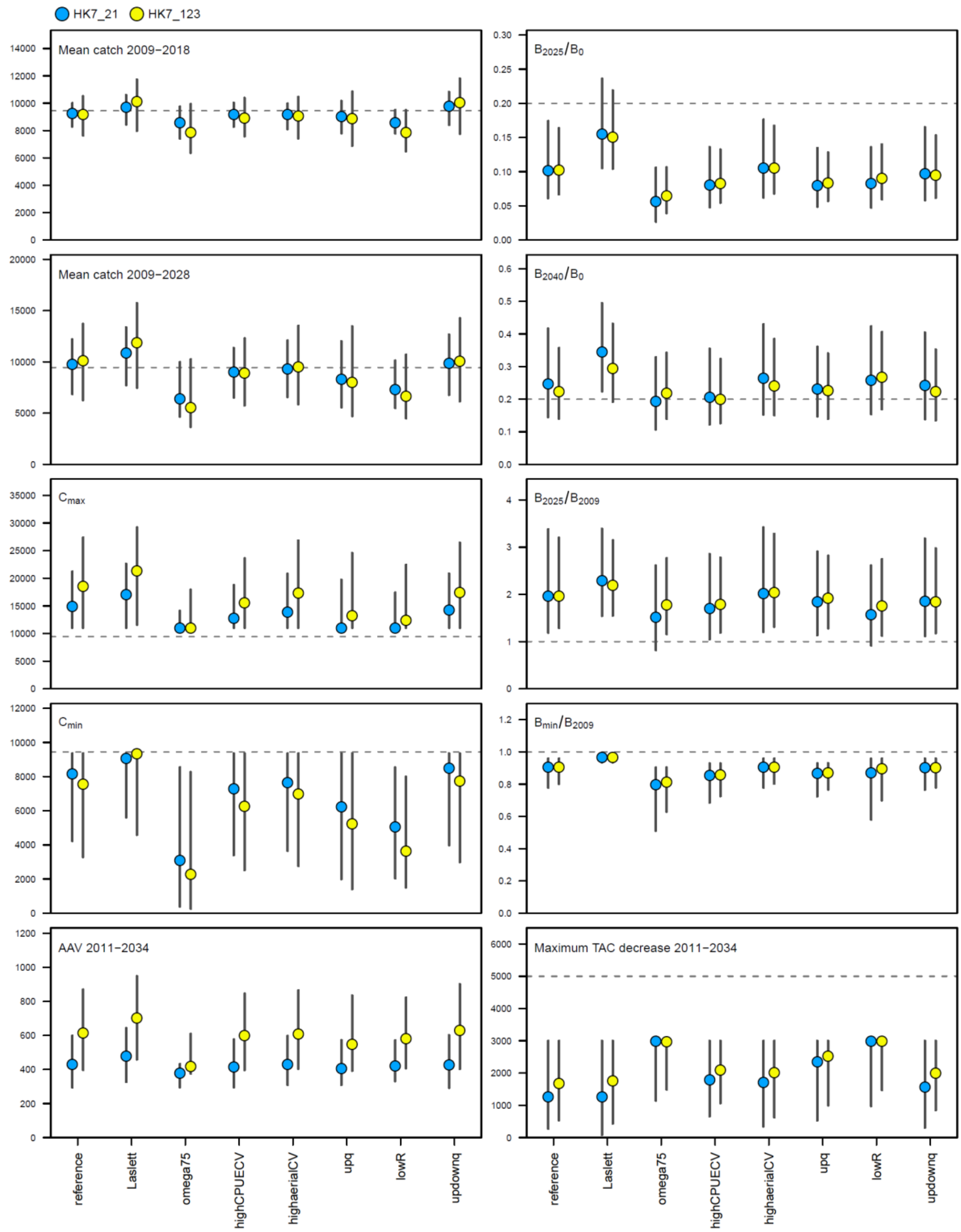


Fig. A11-a. Time trajectory plot for catch and stock biomass for the reference set and the omega75 robustness trial, showing the median (solid), higher 10 percentile (dot) and lower 10 percentile (dash) for the different MPs in relation to ***the quota allocation***.

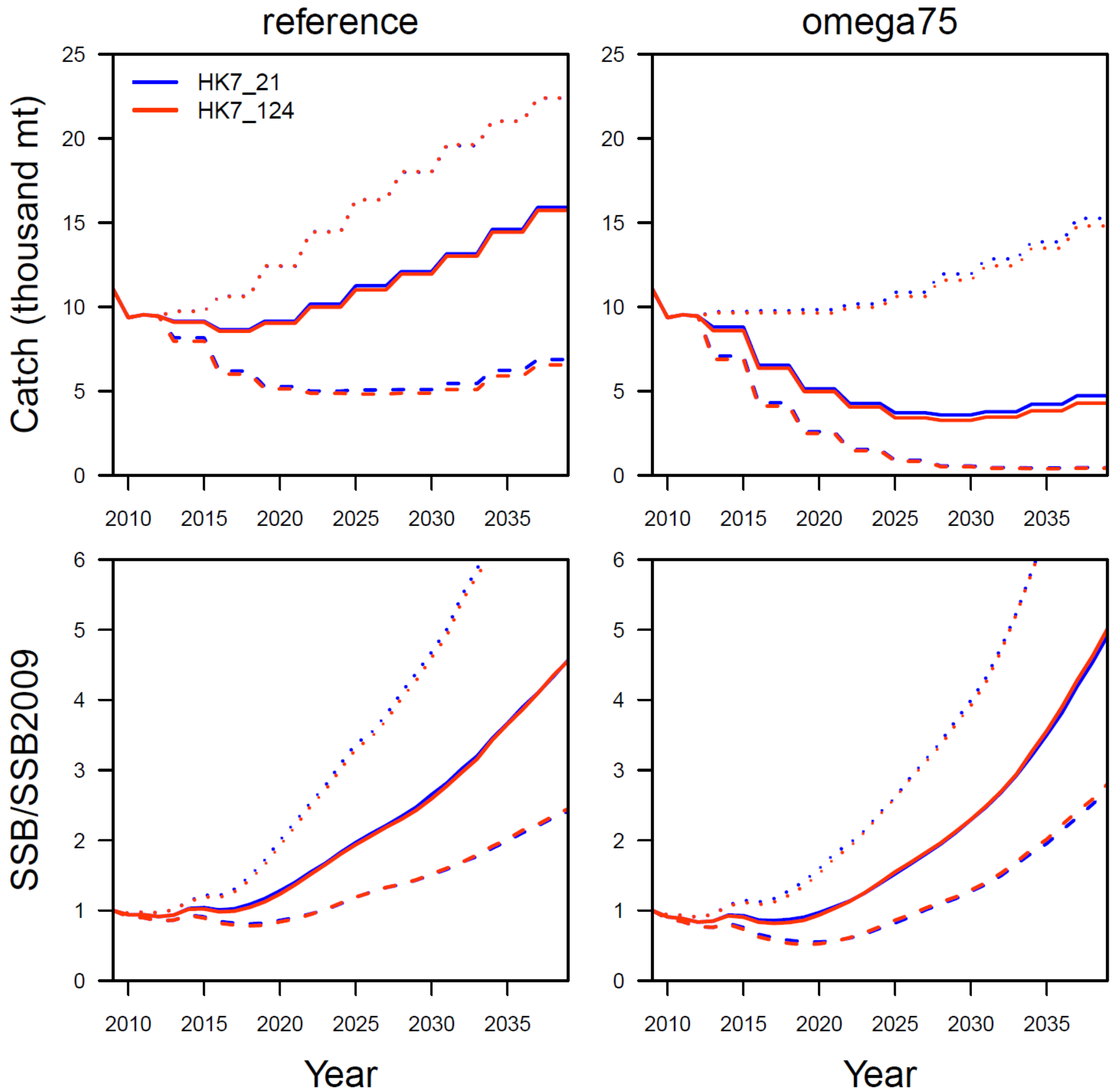


Fig. A11-b. Comparison of MP performance for the reference set and the robustness trials, showing the median and 10 percentiles for the different MPs in relation to ***the quota allocation***.

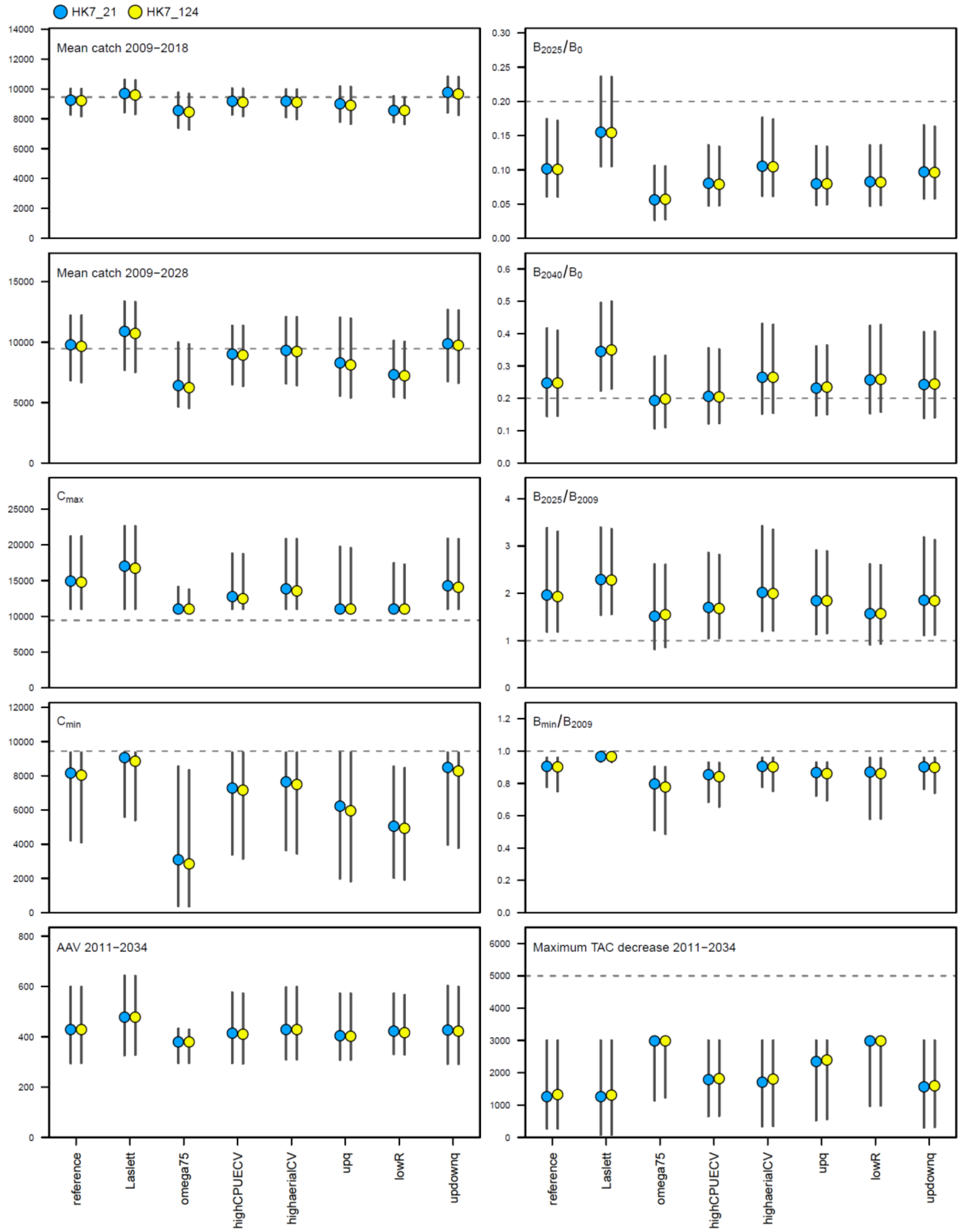


Fig. A12-a. Time trajectory plot for catch and stock biomass for the reference set and the omega75 robustness trial, showing the median (solid), higher 10 percentile (dot) and lower 10 percentile (dash) for the different MPs in relation to ***the tuning parameter***.

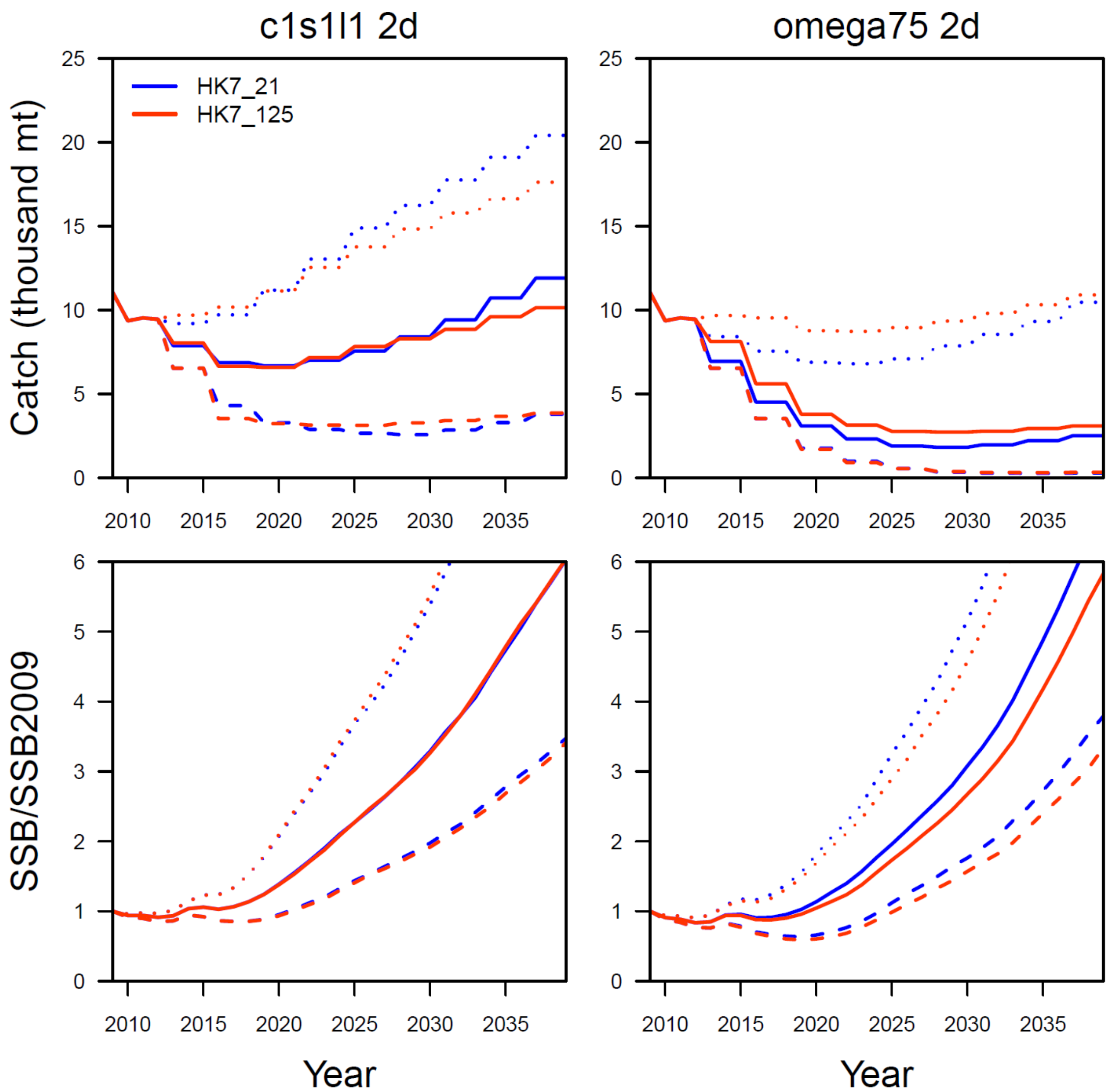


Fig. A12-b. Comparison of MP performance for the reference set and the robustness trials, showing the median and 10 percentiles for the different MPs in relation to ***the tuning parameter***.