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Evaluation of candidate harvest control rules for the tropical skipjack purse seine fishery.

SC12-MI-WP-06

R. Scott[1], G. M. Pilling, S. Brouwer and J. Hampton

[1]Oceanic Fisheries Programme, Secretariat of the Pacific Community

Contents

1 Executive Summary

1. The Parties to the Nauru agreement (PNA) requested that Pacific Community (SPC) evaluate a number of candidate harvest control rules (HCRs) for the tropical purse seine fishery for skipjack. Two harvest control rules, HCR1 and HCR2, have previously been evaluated by SPC and HCR1 is not considered in this report. HCR2 was retained for further evaluation along with 3 additional candidate HCRs (HCR3, HCR4 and HCR5).

	HCR Control Parameters			
	$SB/SB_{F=0}$	$SB/SB_{F=0}$	Catch (t)	Comments
HCR1	0.3	0.2	-	Not considered in this report
HCR2	0.4	0.2	-	-
HCR3	0.48	0.2	-	-
HCR4	0.48	0.2	-	Non-linear decline to control param 2
HCR5	0.48	0.2	1,400,000	Additional catch constraint

2. This document presents the results of preliminary analyses of the type required to evaluate HCRs. It:
   - outlines the 4 candidate HCRs that apply only to effort of fisheries within regions 2, 3 and 5 of the skipjack stock assessment and do not apply to archipelagic waters;
   - details preliminary analyses undertaken to assess their performance;
   - discusses further work required for more comprehensive testing; and
   - identifies some potential performance indicators to determine the relative performance of the HCRs in achieving the management objectives.
3. The primary objectives of the candidate HCRs as examined here are:
   - to maintain the stock at biomass levels close to the target reference point (TRP);
   - to have minimal risk of biomass falling below the LRP in the long term (20 years); and
   - to maintain stability in effort in the short to medium term (10 years).
4. The evaluations are based on 200 stochastic projections using the 2014 skipjack reference case assessment model, run over a 30 year period with three year management time steps and with two sources of uncertainty: future recruitments were determined using the distribution of estimated recruitments from the 2014 skipjack assessment for the years 2002:2011; and stock assessment uncertainty was added through a 10% error in the biomass at the end of each management period, prior to calculating allowable effort from the HCR.
5. Two effort creep scenarios were considered. One in which effort creep did not occur; and a second in which a 2% year on year increase in purse seine effective effort was applied over and above the effort level determined from the HCR.

6. The HCRs show broadly similar performance under zero effort creep conditions for most of the performance indicators; HCRs 2 and 4 perform marginally better in maintaining the stock around the TRP and effort around 2012 levels, while HCRs 3 and 5 are more likely to reduce fishing effort, particularly in the short-term.
7. Greater performance differences are apparent for the 2% effort creep scenario revealing a trade-off between maintaining adult biomass at the TRP and maintaining stability in effort in both the short- and longer-term.
8. The preferred HCR may therefore depend largely on the extent to which effort creep is considered to be occurring in the fishery and the length of time that the HCR is expected to be in place. HCRs 2 and 4 perform relatively well in the short-term in the absence of effort creep but can lead to reduced adult biomass if effort creep exists. HCRs 3 and 5 lead to larger effort reductions in the short-term but are better able to maintain adult biomass closer to the TRP if effort creep is occurring.

We invite WCPFC-SC to:

- Consider the technical approach used to evaluate the candidate HCRs.
- Note the range of uncertainties and alternative states of nature examined and consider what additional sources of uncertainty should be considered in future evaluations.
- Note the range of performance indicators developed in this analysis and consider which metrics are most informative and whether additional or alternative performance indicators should be developed.
- Note the potential importance of effort creep in determining the performance of the candidate HCRs.

2 Introduction

The Parties to the Nauru Agreement (PNA) requested that the Pacific Community (SPC) evaluate a range of specified candidate harvest control rules (HCRs) controlling purse seine fishing effort, designed to manage the Western and Central Pacific Ocean (WCPO) skipjack stock relative to agreed target and limit reference points. The results of those analyses were presented to the PNA in April 2016 and following subsequent discussions a number of modifications to the initial HCRs were proposed for further evaluation. Further background information on the initial HCRs is provided in Appendix A. The HCRs presented in this report represent the second iteration of this work following advice from the PNA. This document:

1. outlines four candidate HCRs put forward by the PNA;
2. details preliminary analyses undertaken to test their relative performance;
3. identifies some potential performance indicators; and
4. discusses further work that may be desired for more comprehensive testing;

The HCRs apply only to the effort of the tropical purse seine fishery EEZs and high seas. The tropical purse seine fishery is defined here as those fisheries in assessment regions 2, 3 and 5, excluding archipelagic waters but including high seas waters in regions 2 and 3. Throughout the evaluations, fishing has been assumed to remain constant for fisheries within archipelagic waters and in regions 1 and 4.

2.1 What are harvest control rules?

HCRs are pre-agreed and simulation tested management actions (e.g. the number of days that can be fished by a fishery) to be taken by a management body, that are designed to maintain the stock around a target reference point (TRP), while avoiding exceeding a limit reference point (LRP) and broadly achieve other specified management objectives to the extent possible. The target and limit reference points should be set at levels that are consistent with the long-term sustainability and profitability of the fishery and the resource (defined by agreed management objectives).

Simple HCRs can be described as an "if then" statement. For example "if the stock levels fall below a specified trigger then the level of fishing must be reduced by some predefined amount to return it to target levels". Managers should preferably agree in advance what measures should be taken to achieve the predefined reduction in fishing, such as effort limits, regional closures or gear restrictions.

2.2 Harvest Strategy Framework

CMM 2014-06 (WCPFC, 2014) outlines the necessary elements of a harvest strategy as having:

1. defined operational objectives, including timeframes, for the fishery or stock.
2. target and limit reference points for each stock;
3. acceptable levels of risk of not breaching limit reference points;
4. a monitoring strategy using best available information to assess performance against reference points;
5. decision rules (or HCRs) that aim to achieve the target reference point on average and aim to avoid the limit reference point with high probability; and
6. an evaluation of the performance of the proposed HCRs against management objectives, including risk assessment.

Elements of components 1, 2, 5 and 6 are addressed in this analysis. Component 4 is addressed separately in SC12-MI-WP04.

3 Management objectives and candidate harvest control rules

The primary objectives of the HCRs, as drawn from PNA management objectives, are to maintain the stock at biomass levels close to the agreed TRP (50% $\mathrm{SB}_{F=0}$) with minimal risk of falling below the LRP (20% $\mathrm{SB}_{F=0}$) over the long-term (20 to 30 years) and to maintain stability in effort in the short- to medium-term (next 10 to 15 years).

3.1 Candidate harvest control rules to be evaluated

The candidate HCRs designed by PNA parties and presented here (Table 1, Figure 1) represent the second iteration of HCR evaluations (note that HCR1 and HCR2 have previously been evaluated and that HCR1 is not considered in this report). The HCRs relate the allowable fishing effort to stock status but each has an alternative threshold biomass value at which effort reduction begins. Effort management, as determined by the HCRs, has been applied only to the tropical purse seine fishery (as defined above). Fishing effort in other areas was assumed to remain constant at 2012 effort levels (see Section 4.1).

Within each HCR, tropical purse seine effort was maintained at 2012 effort levels (effort scaler = 1) until such time as biomass declines to a biomass trigger point (control parameter 1). At biomass levels assessed to be below that trigger, effort progressively decreases to zero (control parameter 2, at which point only fisheries in archipelagic waters and in regions 1 and 4 would be operating).

Table 1: Control parameter settings for candidate harvest control rules considered in this report and previously. Control parameters (CP) are the trigger points for management action that determine the shape of the harvest control rule.

	CP1 $SB/SB_{F=0}$	CP2 $SB/SB_{F=0}$	CP3 Catch (t)	Comments
HCR1	0.3	0.2	-	Not considered in this report, see Appendix A
HCR2	0.4	0.2	-	-
HCR3	0.48	0.2	-	-
HCR4	0.48	0.2	-	Non-linear decline to control param 2
HCR5	0.48	0.2	1,400,000	Additional catch constraint

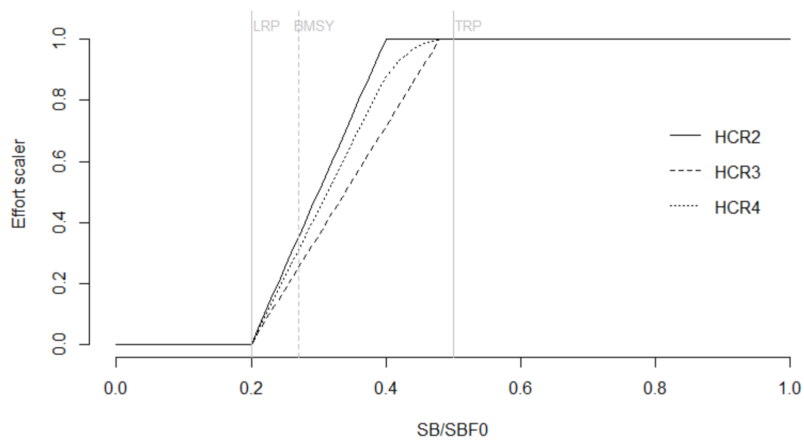


Figure 1: Candidate effort-based harvest control rules. Effort is maintained at 2012 effort levels for $SB/SB_{F=0}$ above some biomass trigger point (HCR2 = 0.4; HCR3 and HCR4 = 0.48). For HCR4 effort declines progressively. HCR5 is identical to HCR3 in form, but includes an additional catch level trigger. See main text for more information.

For the candidate HCRs considered here the biomass trigger is set to either 40% $SB_{F=0}$ (HCR2) or 48% $SB_{F=0}$ (HCRs 3, 4 and 5).

HCR5 is identical to HCR3 in form, but includes an additional component in which effort is also reduced if catch exceeds some threshold level (control parameter 3). These measures are intended to promote greater long-term stability in catch and in particular to counter the effects of potential effort creep in the fishery. The effort reduction will apply if the catch for the tropical purse seine fishery (regions 2, 3 and 5, excluding archipelagic waters) exceeds 1.4 million tonnes for two consecutive years. In such an event, effort for the following year will be reduced proportionally by the extent that the average catch exceeds 1.4 million tonnes. For example, if the average catch in the previous two years was 1.54 million tonnes (i.e. 10% above the catch threshold), effort for the remaining years in the management period would be reduced by 10%. HCR5 computes the effort scaler corresponding to the biomass of the stock and the effort scaler corresponding to recent catch and selects the lower of the two.

The formulation of all 4 HCRs (HCRs 2, 3, 4 and 5, as they have been implemented) is shown in Figure 1, and the pseudo-code for the implementation of the catch constraint in HCR5 is given in Appendix C.

3.2 Performance indicators

Performance indicators (performance statistics) are summary statistics calculated from the simulation results that inform on the success of each HCR in achieving the management objectives. More than one performance measure may be required for each management objective. Table 2 identifies the indicators that have been used here to quantify the performance of the HCRs and to allow managers to identify those HCRs that best meet their objectives.

Performance indicator 1 measures the ability of the HCR to maintain the stock at or around the TRP and performance indicator 2 measures the risk of falling below the LRP. Performance indicator 3 is a measure of the overall annual variability in effort. The median inter-annual variation in effort ($I\bar{A}V$, calculated as per Equation 1) is close to 1 in the majority of cases, therefore the 5^{th} percentile has been used as a measure of the spread of the distribution of that variability.

$$I\bar{A}V = \frac{\sum_i \sum_y \frac{E_{i,y}}{E_{i,y-1}}}{(Y-1)I} \tag{1}$$

where : $E_{i,y}$ = Effort in year y and iteration i; Y = Number of years; I = Number of iterations

Performance indicators 4 and 8 are short- to medium-term measures of effort change in the fishery, and the ability of the HCR to maintain biomass around the TRP, repectively.

Performance indicators 5, 6 and 7 measure performance of the HCR in terms of catch, effort and CPUE in the last 10 years of the simulation period relative to 2012 values. These indicators identify

Table 2: Performance indicators.

PI	Year Range	Description
1	2042	Probability of falling below 50% $SB_{F=0}$ in the terminal year
2	2013:2042	Probability of falling below 20% $SB_{F=0}$ during the simulation period
3	2013:2042	The lower 5%ile of the inter-annual variation in effort
4	2013:2022	The lower 5%ile of the effort scaler in the first 10 years
5	2033:2042	Median catch in the last 10 years of the simulation period relative to 2012
6	2033:2042	Median effort in the last 10 years of the simulation period relative to 2012
7	2033:2042	Median CPUE in the last 10 years of the simulation period relative to 2012
8	2013:2022	Probability of falling below 50% $SB_{F=0}$ in the first 10 years

likely long-term status of the fishery as a consequence of the HCR.

4 Evaluation framework and assumptions

The evaluation is based on a relatively simple approach similar to that of Kell et al. (2013) that uses stochastic projections to project the stock status forwards in time with future effort levels that are determined from the HCR at specific management intervals. 200 projections were run over a 30 year period with 3 year management time steps (i.e. a management decision based on the HCR remains in place for 3 years before re-assessment of the stock and re-evaluation of management decisions).

The basis of the projections was the 2014 skipjack reference case assessment model (Rice et al., 2014) with future recruitments determined from the distribution of estimated recruitments for the most recent 10 years of the 2014 stock assessment prior to the terminal year (2002:2011). Catchability for each fishery was held constant, throughout the projection period, at 2012 levels.

4.1 Application of Effort Scalers

Effort management under the HCR evaluations was applied only to the tropical purse seine fishery. Fisheries in other areas have been maintained at 2012 catch and effort levels throughout the analysis. As such, effort scalers determined from the HCR have been applied only to the purse seine fleets operating in regions 2, 3 and 5 (from the 2014 assessment these correspond to fisheries 5, 6, 9, 10, 13 and 14) and excluding archipelagic waters (see Section 4.1.1).

Stock status is determined from the ratio of current adult biomass (ie the adult biomass in the year preceding the management year) to the average of stock status under zero fishing conditions for the period 2002:2011. Future effort levels determined from the HCR are applied from the year following the management year. In this way the evaluations reflect a two year time lag between evaluation of stock status and the implementation of management action. The illustration below shows, for each management cycle (1st, 2nd, 3rd, ...), the assessment and management year (**x**), the year for which stock status is estimated (o) and the years for which the management action will be applied (m).

Year	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	...
1st	o	**x**	m	m	m							
2nd				o	**x**	m	m	m				
3rd							o	**x**	m	m	m	
...										o	**x**	...

4.1.1 Archipelagic Waters

It has been assumed that the HCR will not apply to fishing activities within the archipelagic waters (AW) of regions 2, 3 and 5. The effort scaler resulting from the HCR has therefore been adjusted to take account of unchanged archipelagic fishing effort (which for the purpose of this analysis has also been assumed to remain constant at 2012 effort levels). This correction applies specifically to purse seine fleets operating in assessment Region 5.

The basis of the AW corrections and details of the calculations are given in Appendix B.

4.2 Uncertainty

We have considered only a limited range of uncertainty for these analyses. In part because of the limited time available to conduct the evaluations, but also because a broader discussion of the types and scale of uncertainty to be included has not yet taken place within WCPFC. We note the recommendations of the expert consultation workshop on MSE (SC12-MI-WP05, this session) with regards to characterising uncertainty and further discuss this in section 6.3 of this report.

The evaluations included two sources of uncertainty. The first represents process error through variability in future recruitment, the second represents a combination of model error and estimation error implemented by applying random noise to estimates of adult biomass, reflecting some level of uncertainty in MULTIFAN-CL assessment results.

For this analysis stochastic future recruitments have been generated using the deviates around the average stock-recruitment relationship curve taken from the most recent 10 year period of the 2014 stock assessment (2002 to 2011). The 2012 recruitment deviates were fixed in the assessment and are therefore not included.

Assessment uncertainty, in the context of this analysis, refers to the extent to which the final assessment model is truly representative of the stock being assessed. The evaluations include a 10% error [N(0,0.1)] in the estimated biomass in the last year of the three year projection, which is used to calculate the allowable effort from the HCR. This approach is considered to provide only a preliminary approximation of assessment uncertainty.

4.3 Robustness trials

In addition to the uncertainty underlying the stock assessment and future recruitment levels, the HCR must also be robust to so-called ‘alternative states of nature’. These are plausible biological and fishery scenarios that differ from those assumed for the stock assessment. For example, the form of the stock and recruitment relationship; the overall magnitude of natural mortality; the potential for hyperstability in CPUE; and the extent of effort creep in the fishery. The emphasis here is on the term plausible. The scenarios investigated should comprise a small realistic set of alternative states that cover the major sources of uncertainty. For the preliminary analyses presented in this paper we consider only a single robustness trial, for effort creep.

The effort creep scenario (based on early estimates developed by Tidd et al. (2015)) assumed a 2% year-on-year increase in purse seine effective effort, over and above the effort level determined from the HCR. This is just one assumption for effort creep and is used to illustrate the need for robustness testing. The effort creep increase was applied only to the tropical purse seine fishery governed by the HCR (ie. excluding those operating in the archipelagic waters of region 5, the Indonesian and Philippines fleets and the Japanese purse seine fleet operating in assessment Region 1).

5 Results

The performance of the four candidate HCRs, based upon the performance indicators identified in Table 2, is presented in Table 3 and a selection of plots are shown to graphically illustrate the results in terms of the overall trajectory of adult biomass (Figure 2), the relationship between adult biomass and yield (Figure 3) and the likely trajectory of effort (Figure 4). The performance indicators are summarised graphically in Figures 5, 6 and 7 to aid comparison.

Table 3: Metrics for each HCR for the performance indicators specified in Table 2 and for the two effort creep scenarios.

PI	Description	HCR2	HCR3	HCR4	HCR5
	Effort Creep = 0%				
1	P[SB_{2042} > 50% $SB_{F=0}$]	0.57	0.60	0.59	0.61
2	P[$SB_{2013:2042}$ > 20% $SB_{F=0}$]	1.00	1.00	1.00	1.00
3	5%ile AV Effort	1.00	0.88	0.97	0.88
4	5%ile Effort $scaler_{2013:2022}$	0.98	0.72	0.88	0.75
5	$\widehat{Catch}_{2033:2042}$	0.87	0.86	0.87	0.84
6	$\widehat{Effort}_{2033:2042}$	1.00	1.00	1.00	1.00
7	$\widehat{CPUE}_{2033:2042}$	0.86	0.84	0.85	0.84
8	P[$SB_{2013:2022}$ > 50% $SB_{F=0}$]	0.49	0.53	0.50	0.53
	Effort Creep = 2%				
1	P[SB_{2042} > 50% $SB_{F=0}$]	0.04	0.16	0.09	0.14
2	P[$SB_{2013:2042}$ > 20% $SB_{F=0}$]	1.00	1.00	1.00	1.00
3	5%ile AV Effort	1.00	0.77	0.90	0.78
4	5%ile Effort $scaler_{2013:2022}$	0.99	0.69	0.86	0.72
5	$\widehat{Catch}_{2033:2042}$	1.02	0.99	0.99	0.97
6	$\widehat{Effort}_{2033:2042}$	1.00	0.94	0.98	0.93
7	$\widehat{CPUE}_{2033:2042}$	1.01	1.03	1.01	1.04
8	P[$SB_{2013:2022}$ > 50% $SB_{F=0}$]	0.39	0.46	0.42	0.45

5.1 No Effort Creep

For the zero effort creep scenario the long-term performance of the various candidate HCRs was quite similar, and there were only small differences in the performance of the HCRs in the short and long-term. Throughout the evaluation period adult biomass remained on average at or close to the TRP with zero probability of falling below the LRP, and effort was generally maintained around 2012 effort levels.

The equilibrium yield and biomass plot (Figure 3, left panel) shows the stock achieving a stable equilibrium close to the TRP (ie. all of the green points are clustered around the intersection of the equilibrium yield curve and the line denoting the TRP). This indicates that, under the assumption of zero effort creep, 2012 effort levels are, as previously evaluated, an appropriate long-term management measure for maintaining the stock at the TRP (given the level of uncertainty assumed in this analysis). Notably, for all HCRs, long-term catch is reduced resulting in an approximate 15% reduction in CPUE[2] from 2012 levels (Table 3, performance indicator 5).

Overall, HCRs 2 and 4 performed slightly better in terms of maintaining effort around 2012 levels (Figure 4; see also performance indicators 1 and 8 in Table 3). Greater differences between the various HCRs were apparent in the short-term variation in effort where HCRs 2 and 4 called for fewer reductions in effort (see Figure 4 and Table 3, performance indicator 4) and maintained effort at or closer to 2012 levels in the short-term compared with HCRs 3 and 5. There were small differences between HCRs for the remaining performance indicators.

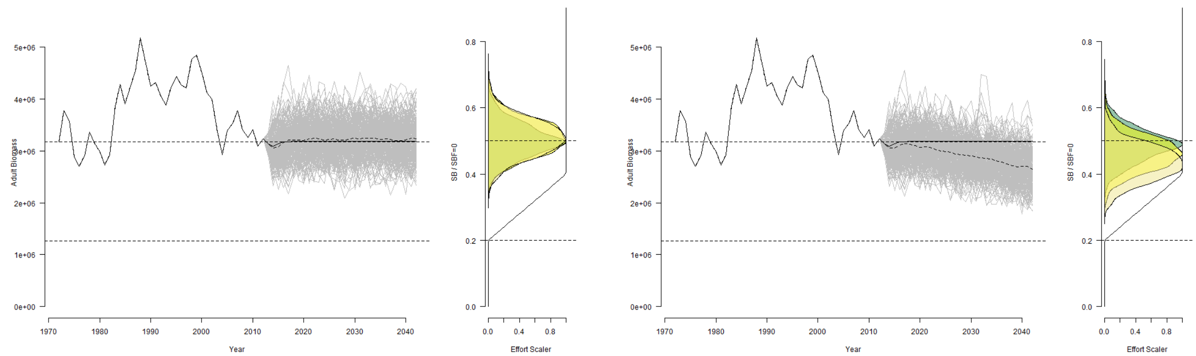
5.2 2% Effort Creep

Larger differences in performance of the HCRs were evident for the 2% effort creep scenario for which the results show a clear trade-off between maintaining the stock around the TRP and maintaining stability in effort. None of the HCRs were able to keep adult biomass at the TRP on average, in the face of effort creep. HCRs 3 and 5, the two HCRs that call for slightly larger reductions in effort as the stock falls below 48% $SB_{F=0}$, were more successful at maintaining adult biomass at higher levels than HCRs 2 and 4. However, this was achieved at the cost of greater progressive effort reductions over time (Figure 4).

The reductions in fishing effort resulting from HCRs 3 and 5 lead to only small reductions in catch (relative to 2012 values) and consequently CPUE increases more for HCRs 3 and 5 (3% and 4% respectively) than for HCRs 2 and 4 (Table 3, performance indicator 7), although it should be noted that the relative differences in CPUE between HCRs are very small.

The equilibrium yield and biomass plot (Figure 3, right panel) shows the stock is not in a state of stable equilibrium. The green points move progressively along the yield curve from right to left as

[2]Calculations based on estimated catch and underlying effort under HCR. We note potential uncertainty in actual purse seine CPUE with changes in stock size.



(a) No effort creep (b) 2% effort creep

Figure 2: Results of evaluations of HCR2 showing adult biomass as projected from a 30 year deterministic forecast (solid black line) and from 200 iterations of the HCR (grey lines) for runs assuming a) no effort creep, and b) effort creep at 2% per annum. The dashed line shows median biomass from the 200 iterations. The plot to the right shows the density distribution of estimated adult biomass during the first (2013:2022, green), second (2023:2032, yellow) and third (2033:2042, khaki) decades of the projection period along with the effort scaler corresponding to the HCR. Horizontal dotted lines indicate adult biomass correspondng to the TRP and LRP (50% and 20% $SB_{F=0}$ respectively) as calculated from the 2014 assessment.

the stock size progressively declines. This pattern is apparent to a greater or lesser extent for all four HCRs and indicates that the effort reductions derived from all the candidate HCRs are not sufficient to maintain the stock at the TRP given 2% effort creep.

5.3 The effect of the catch control in HCR5

The additional control in HCR5, that reduces fishing effort when tropical purse seine catches exceed 1.4 million tonnes for two consecutive years, has little or no impact on the performance indicators under the zero effort creep scenario since catch above the 1.4 million tonne threshold are very rarely achieved (Table 4) unless fishing effort was increased beyond 2012 levels.

For the 2% effort creep scenario the incidence of high catch in consecutive years is substantially increased, although to a lesser extent under HCR5 as that HCR explicitly reduces effort in that situation. Although the incidence of high catch was reduced, HCR5 resulted in slightly lower terminal adult biomass than HCR3 with little or no change in overall effort levels as measured by the performance indicators.

Comparative results from individual iterations in which the effort reduction due to high catches was triggered (Figure 8) show that catch in the following year is reduced to a greater extent under HCR5 when compared with HCR3 and adult biomass levels are correspondingly slightly higher, but that the difference persists for only a brief period before the trajectories of both adult biomass and catch converge again under the two HCRs.

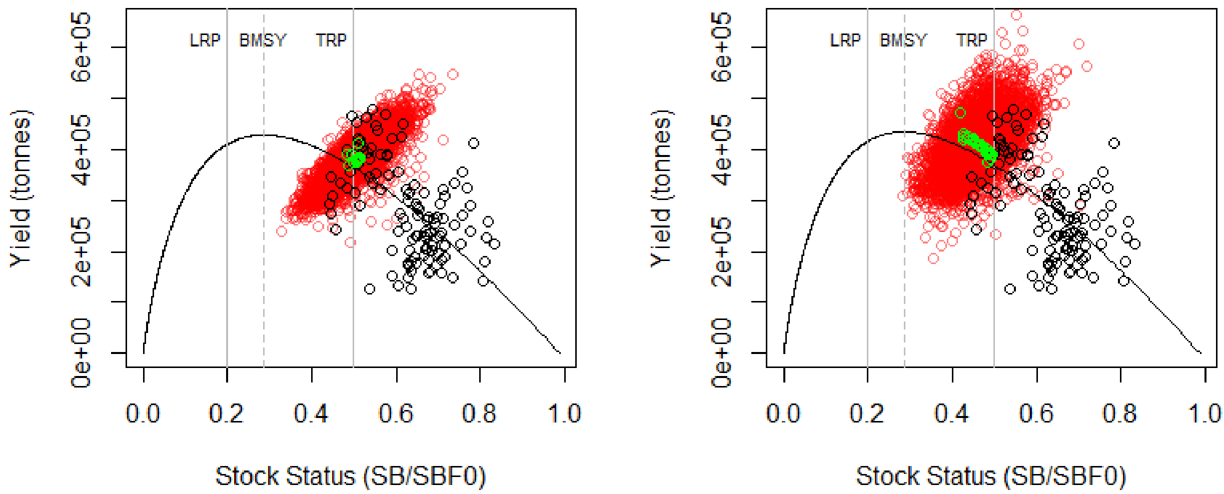


Figure 3: Skipjack equilibrium yield and biomass plots for HCR2 with zero effort creep (left) and 2% effort creep (right). Solid line shows the theoretical equilibrium yield for a given stock status. Black points show the historical yield and biomass pairs for the period 1983 to 2012. Red points show the projected yield and biomass pairs for the 200 simulations and green points show the quarterly median values for the simulation period (2013:2042).

Table 4: Probability of tropical purse seine catch exceeding 1.4 million tonnes in two consecutive years during the projection period (a value of 0.05, for example, indicates a 5% probability (1 in 20) that this will happen once during the 30 year projection period).

Effort Creep	HCR2	HCR3	HCR4	HCR5
0%	0.045	0.035	0.050	0.030
2%	0.985	0.860	0.885	0.620

Although there are no clear benefits in terms of either adult biomass or fishing effort resulting from the catch control, the incidence of consecutive high catch is reduced for HCR5 under both effort creep scenarios (Table 4), which may have other benefits not captured here.

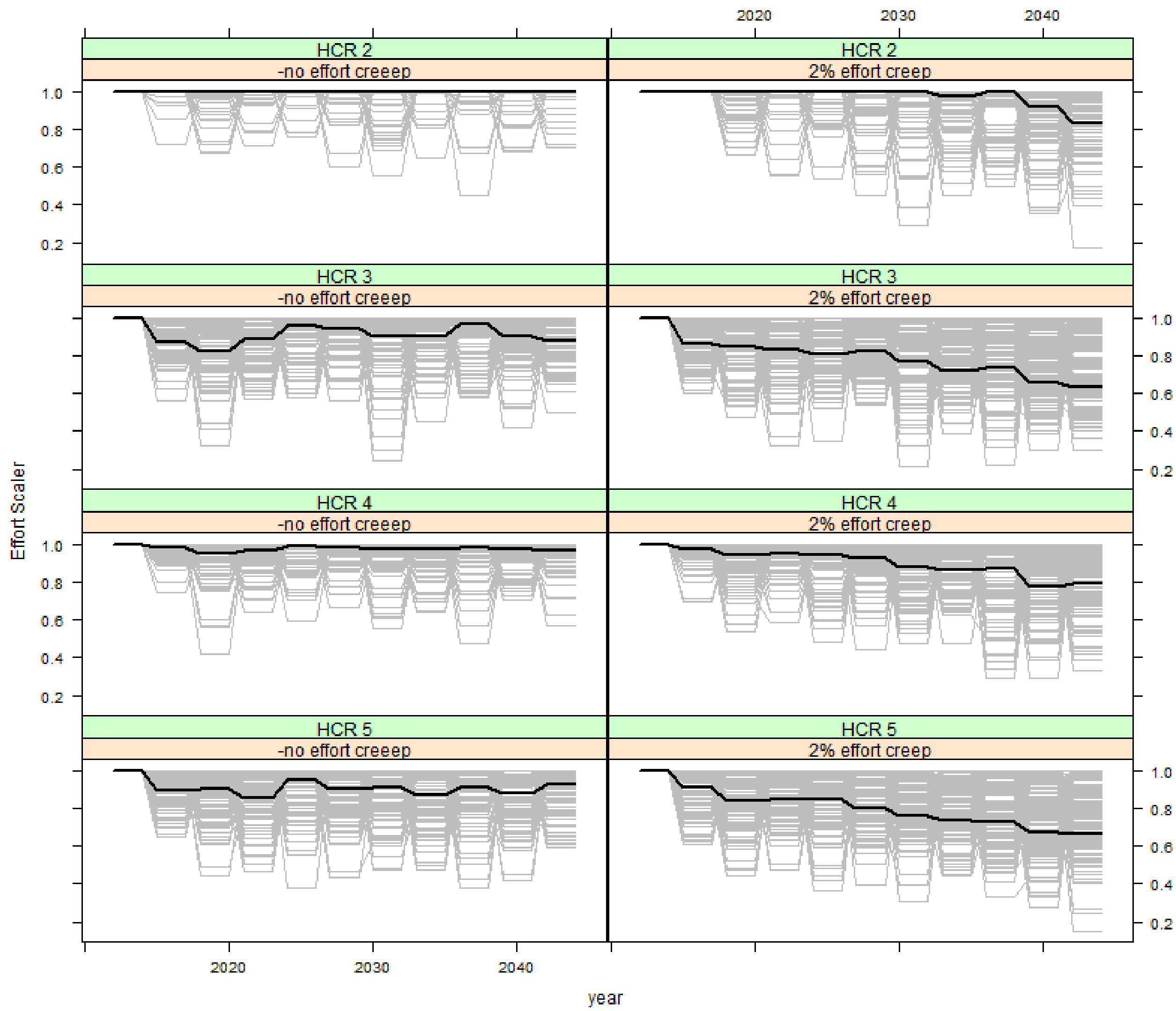


Figure 4: Effort scalers determined by HCRs 2 to 5 (rows) with either 0 or 2% effort creep (left and right columns respectively). Grey lines show the individual effort scalers for each of the 200 iterations. Black lines show the lower 20th percentile of effort scalers i.e. for a given year there is an 80% chance that the effort scaler will be at or above the black line.

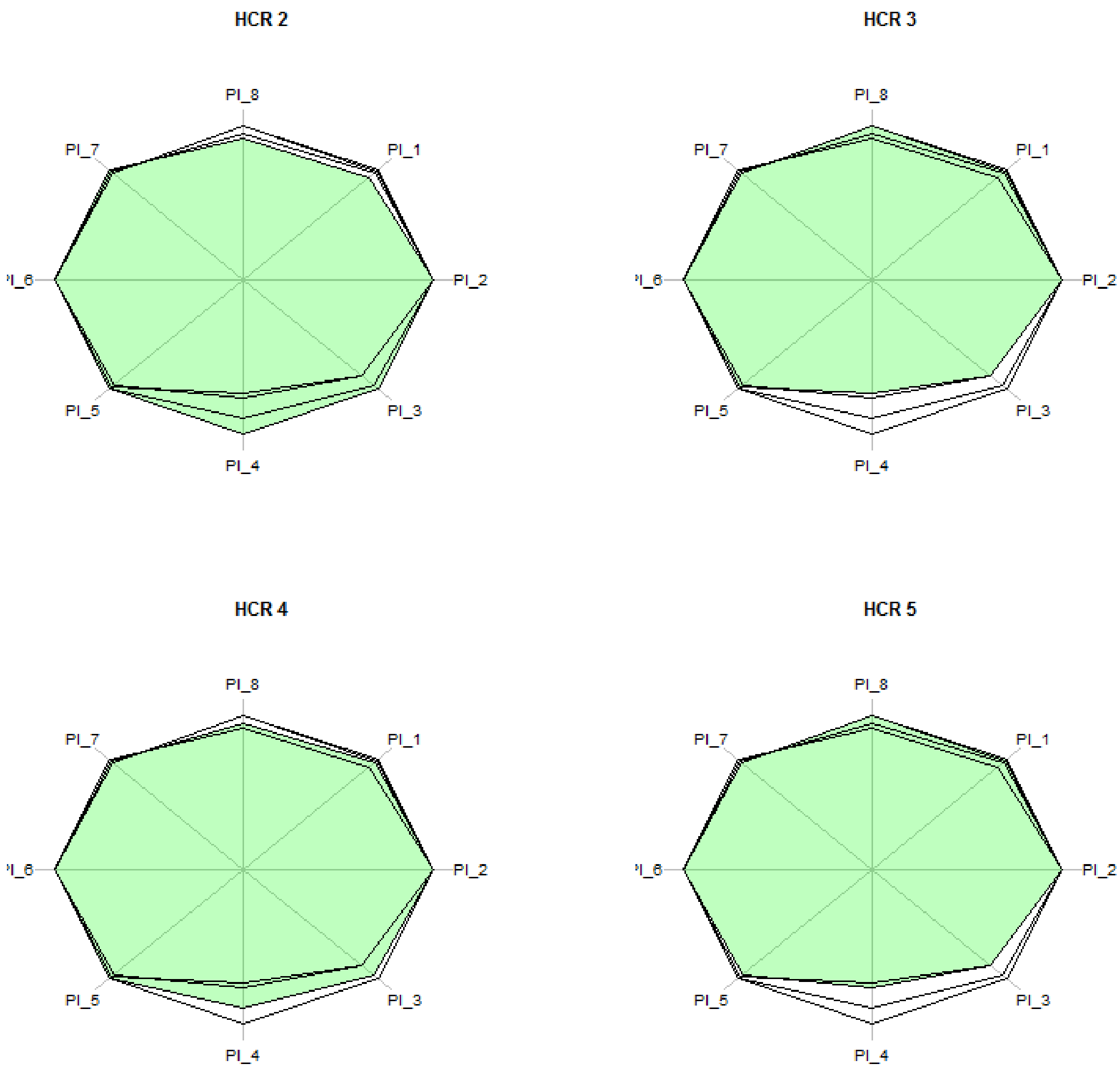


Figure 5: Comparative plots of performance indicators for HCRs 2 to 5 under the no effort creep scenario. The polygon corresponding to the HCR is shaded green with results for the other 3 HCRs shown as unshaded polygons. Points towards the centre of the polygon represent less desirable outcomes. PI 1 to 8 correspond to the performance indicators listed in Table 2.

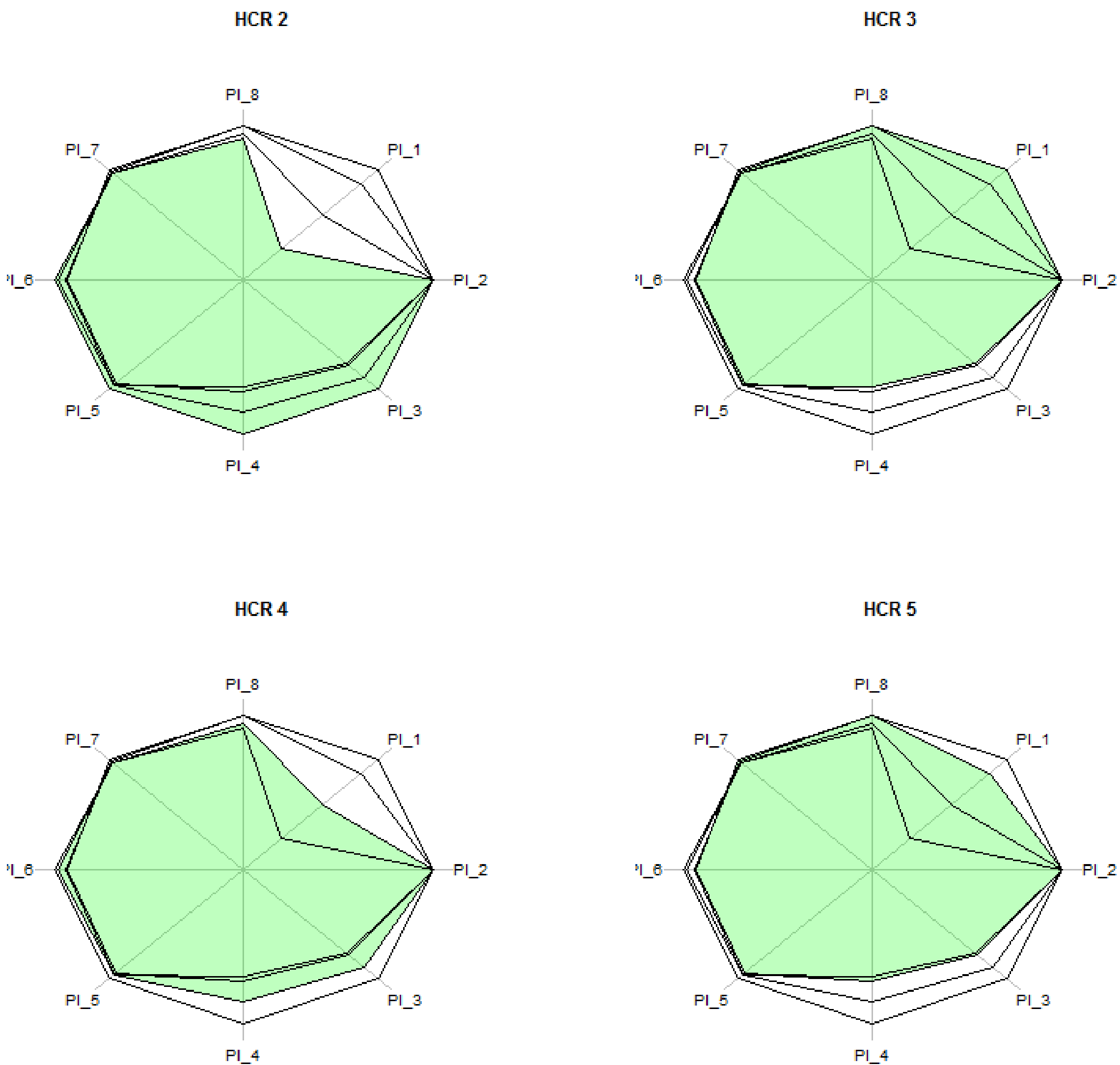


Figure 6: Comparative plots of performance indicators for HCRs 2 to 5 under the 2% effort creep scenario. The polygon corresponding to the HCR is shaded green with results for the other 3 HCRs shown as unshaded polygons. Points towards the centre of the polygon represent less desirable outcomes. PI 1 to 8 correspond to the performance indicators listed in Table 2.

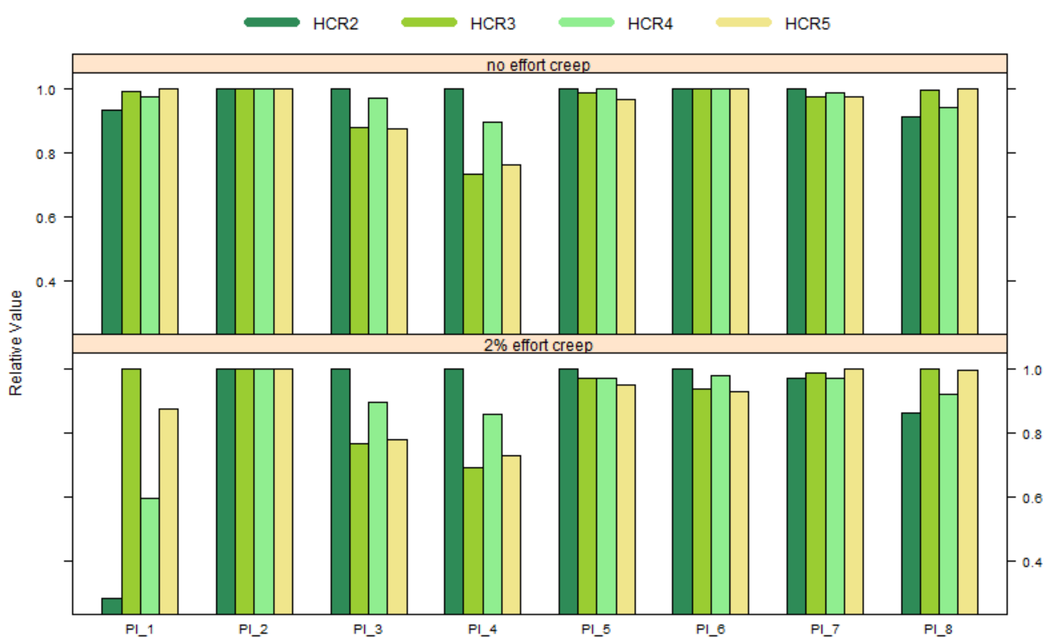
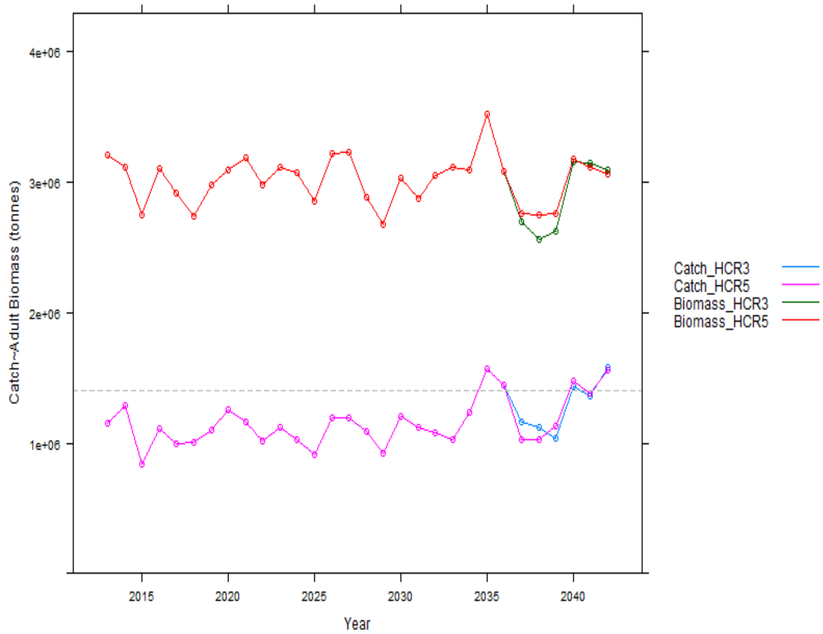
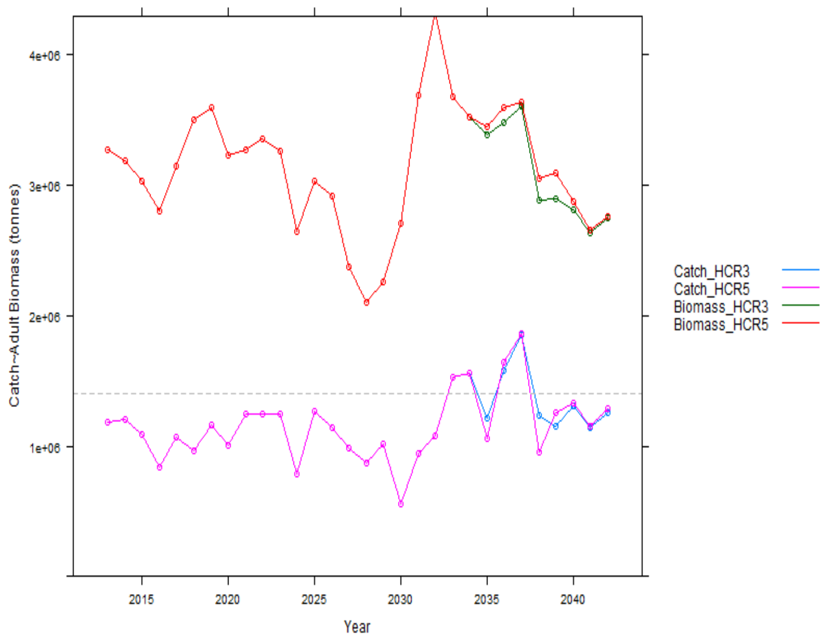


Figure 7: Relative performance indicators for HCRs 2 to 5 under zero effort creep and 2% effort creep scenarios. PI 1 to 8 correspond to the performance indicators listed in Table 2.



(a) iteration 4



(b) iteration 75

Figure 8: Adult biomass and catch from individual iterations (for the effort creep scenario) in which assessment uncertainty has been set to zero showing the catch and adult biomass trajectories resulting from HCR3 and HCR5. Horizontal dotted line denotes the catch limit threshold of 1.4 million tonnes.

6 Discussion

6.1 Identification of the "best" harvest control rule

This study presents preliminary analyses to test the potential performance of four candidate HCRs. Throughout the analysis a number of approximations and simplifying assumptions have been made which would, we suggest, benefit from more thorough examination before a definitive verdict can be passed on the potential performance of the HCRs.

A key factor in the decision of the "best" HCR could be the length of time that it is expected to be in place before an alternative HCR is implemented. Of the options evaluated here, the HCRs that perform better in the long-term, in terms of maintaining biomass around the TRP, perform less well in the short-term, in terms of maintaining current effort levels.

In the short-term, and in the absence of effort creep:

- HCRs 2 and 4 perform well in terms of maintaining effort around 2012 effort levels (performance indicator 4) but less well at maintaining biomass around the TRP (performance indicator 8).
- HCRs 3 and 5 maintain biomass very slightly above the TRP at the expense of reduced effort.

In the short-term, and with effort creep occurring:

- The general pattern is similar to the zero effort creep scenario, however, none of the HCRs manage to maintain biomass around the TRP and the scale of effort reduction is increased.
- HCR 2 is able to maintain effort very close to 2012 effort levels throughout the first 10 years, although this results in significant reductions in adult biomass away from the TRP, due to the increase in effective effort.

In the long-term:

- HCRs 2 and 4 are better able to maintain effort around 2012 effort levels for both effort creep scenarios.
- It is difficult to identify a best performing HCR in terms of terminal biomass. Under zero effort creep conditions all HCRs achieve a terminal biomass slightly above the TRP and under 2% effort creep biomass is, on average, well below the TRP for all HCRs.
- Similarly, there is very little variation among HCRs in median catch, effort or CPUE in the last 10 years of the simulation (ie. all four HCRs perform similarly well or badly depending on the effort creep scenario).

Ultimately, the basis for selecting the final HCR has to be clear to all stakeholders. A recommended approach is to focus on a few key performance indicators whose results are combined over the range of 'states of nature' examined (e.g. all operating models included in the 'core set' of runs (Rademeyer et al., 2007)); see also 6.3).

We note that the process of identifying candidate HCRs that meet objectives can take considerable time. The approach taken by the Commission for the Conservation of Southern Bluefin Tuna (CCSBT) to identify a final procedure was to evaluate a large number of candidate HCRs and identify the key elements of the best performing candidates and then combine them to develop further HCRs (Hillary et al., 2015). This approach was also employed by the International Whaling Commission.

6.2 Choosing and interpreting performance indicators

Figures 5, 6 and 7 show the relative performance of the candidate HCRs as determined from the performance indicators (Table 2). Some of the indicators show zero (or minimal) variation for the different HCRs because all of the HCRs performed equally well (or badly) with regard to that particular metric. In some cases the choice of the best performing HCR is based on very small differences in the performance indicators. To some extent this is because the the candidate HCRs under consideration are themselves very similar.

An unexpected result of this evaluation is that HCR3 appears to outperform HCR5 in terms of performance indicator 1 (probability of falling below $\mathrm{SB}_{F=0}$ in the final year). This is surprising since it might be assumed that the additional effort reductions associated with HCR5 would maintain the stock at higher biomass levels. A recent expert consultation workshop on MSE (SC12-MI-WPXX, this session) noted several issues regarding the development of performance indicators, some of which may of particular relevance to performance indicator 1. The workshop recommended using the same random deviates for each HCR evaluation to ensure that each evaluation is directly comparable with others and is repeatable. Whilst we have adopted this approach for the random recruitment deviates used in the evaluations we did not do so for the assessment error. As such the apparent difference in performance indicator 1 between HCR3 and HCR5 may be due to differences in the random numbers drawn for each evaluation. This may be compounded by the fact that performance indicator 1 is calculated over just one year (the terminal year). Performance indicators that are averaged over a period of years and are calculated from simulations using a consistent set of random deviates across evaluations are likely to provide more robust and directly comparable results.

6.3 Next steps: Characterising uncertainty

The modelling framework employed in this analysis falls short of what would be required by a full MSE (Punt et al., 2014). The same assessment model has been used both to represent the underlying population and to generate the inputs (estimates of stock status) that feed into the

HCR. The assessment model settings for steepness, recruitment variability, selection patterns and other key assumptions are mirrored precisely in the underlying population. As a consequence an important source of potential uncertainty related to model error cannot be explicitly considered. Our evaluations have included a 10% error in the terminal biomass estimates in order to introduce some variability as a consequence of potential model error. However, this approach will likely underestimate the true uncertainty in some situations and takes no account of potential bias in assessment quantities. A more rigorous approach would be to separate the fishery dynamics (biological, economic, etc.) from the assessment and management process by partitioning the modelling framework into distinct operating model and management procedure components. The report of the expert consultation workshop on MSE (SC12-MI-WP05, this session) provides further information on approaches for conducting more comprehensive evaluations of candidate HCRs.

In effect we have considered only a single operating model here, one that is based on the reference case stock assessment and only a minimal set of robustness tests (with and without effort creep). As work progresses on the development of a harvest strategy approach for this fishery it will be necessary to identify a core set of operating models that more fully represent the most important sources of uncertainty along with a more comprehensive set of robustness tests (Rademeyer et al., 2007).

Effort creep is identified as one of the key factors impacting on the performance of the candidate HCRs. We have considered a single effort creep scenario in which effective effort increases annually by 2%. Over the course of the 20 year evaluation period this leads to a dramatic increase in effective effort. Even if effort creep in recent years has been high it is not clear that it will continue at the same rate indefinitely. Similarly effort creep has been assumed to apply at a constant annual rate. Given the influence of effort creep on the performance of the HCR it would be useful to get a better understanding of how and where it operates (eg. which fleet components are most affected? Is it a sporadic or continuous process? Can it be linked to specific technological developments? etc.).

7 Conclusions

The HCRs show broadly similar performance under zero effort creep conditions for most of the performance indicators although HCRs 3 and 5 are more likely to reduce fishing effort particularly in the short-term. Greater performance differences are apparent for the 2% effort creep scenario (Figure 6) revealing a trade-off between maintaining adult biomass at the TRP (performance indicator 1) and maintaining stability in effort in both the short- and longer-term (performance indicators 3&4).

The choice of HCR will depend largely on the extent to which effort creep is considered to be occurring in the fishery and the length of time that the HCR is expected to be in place. HCRs 2 and 4 perform relatively well in the short-term in the absence of effort creep but can lead to reduced adult biomass if effort creep exists. HCRs 3 and 5 lead to larger effort reductions in the short-term but are better able to maintain adult biomass closer to the TRP if effort creep is occurring.

We invite WCPFC-SC to:

- Consider the technical approach used to evaluate the candidate HCRs.
- Note the range of uncertainties and alternative states of nature examined and consider what additional sources of uncertainty should be considered in future evaluations.
- Note the range of performance indicators developed in this analysis and consider which metrics are most informative and whether additional or alternative performance indicators should be developed.
- Note the potential importance of effort creep in determining the performance of the candidate HCRs.

8 Acknowledgements

This work was funded by WCPFC and by the European Union through their funding support for the WCPFC "Simulation testing of reference points". Support was also received from the Pew Charitable Trusts. We are grateful to the PNA Parties for constructive discussions in developing the candidate harvest control rules.

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A Previous formulations of HCRs for evaluation

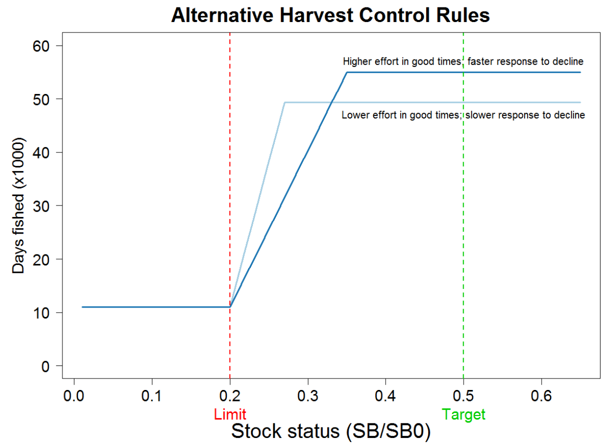


Figure 9: Two initial simple Harvest Control Rules. Based on the outcome of the stock assessment, future fishing effort (days fished) is determined from the lines above. Both rules have been designed to keep the stock around the target reference point level on average.

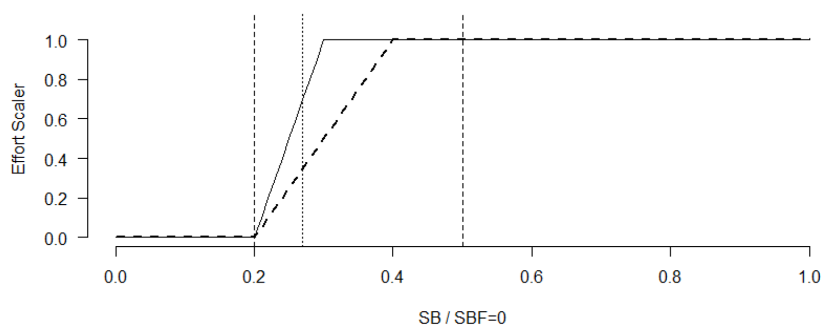


Figure 10: Subsequent proposed effort based harvest control rules. HCR1 (solid black line) sets effort equal to 2012 effort for stock biomass greater than 30% SBF=0 with effort declining to zero between 30% and 20% SBF=0. HCR2 (dashed line) follows a similar structure except that effort declines to zero between 40% and 20% SBF=0. Vertical dashed lines show the LRP (20% SBF=0) and TRP (50% SBF=0). Vertical dotted line indicates 27% SBF=0 corresponding to the biomass at MSY.

B Archipelagic Waters Correction

The archipelagic waters (AW) correction is based on the fishing effort figures reported in WCPFC-12-2015-IP02(rev1), Table 1 and the total 2012 purse seine effort for assessment Region 5 (summed over quarters) taken from the assessment input files prior to effort standardisation. The effort correction is a simple scaler based on the proportion of 2012 fishing effort inside and outside AWs (Eqn.2).

$$S_5 = \frac{S_{HCR} * E_{EEZ-AW} + E_{AW}}{E_{EEZ-AW} + E_{AW}} \tag{2}$$

where :

S_5	adjusted effort scaler to be applied in Region 5
S_{HCR}	effort scaler determined from the harvest control rule
E_{EEZ-AW}	fishing effort outside of AWs in 2012
E_{AW}	fishing effort inside AWs in 2012

Figure 11 illustrates the total effort trajectory for the tropical purse seine fishery in region 5 given a hypothetical continuous 20% effort reduction over a period of 20 management cycles. It shows that the overall effort for region 5 decreases to the AW effort level as the proportion of fishing effort outside of AWs declines to zero.

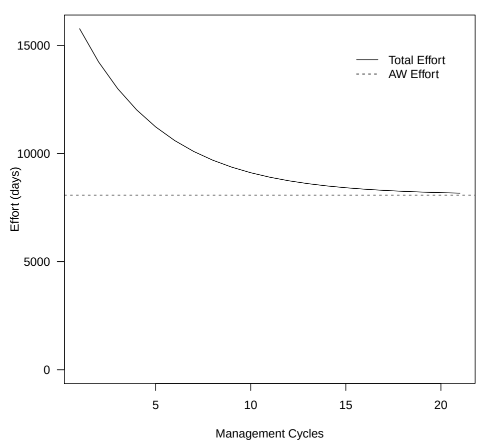


Figure 11: Archipelagic waters: Effort trajectory for Region 5 given a continuous 20% effort reduction over 20 management cycles. Effort progressively reduces to the baseline AW effort level.

C Pseudo-code for application of the catch based effort control

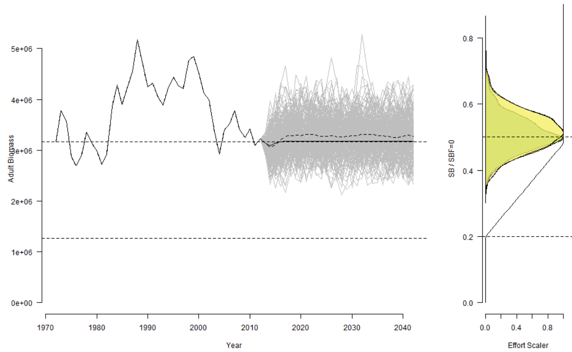
Harvest control rule 5 is based on a 'standard' biomass dependent effort scaler that is calculated and applied on a three year basis, similar to HCRs 2, 3 and 4, but in addition the rule includes an effort reduction that applies when catch by tropical purse seine fishery exceeds an upper threshold for two consecutive years. When triggered, the effort reduction is applied to the immediate following year. In this manner the catch control on fishing effort is not restricted to the three year management period but can apply in any year within the management period.

The pseudo-code for the application of HCR5 is as follows:

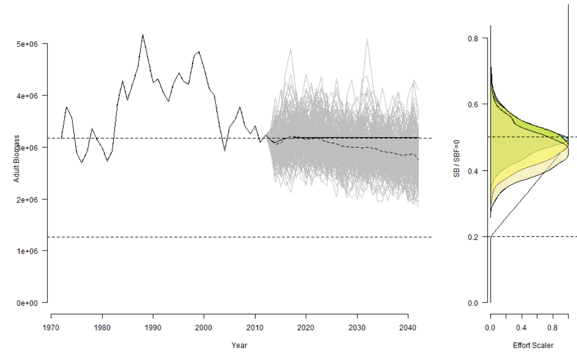
Algorithm 1 HCR5

```
procedure
top:
    for each iteration do
        set effort scalers to 2012 values for all future years
        read new simulated recruitment values from file
        for each management period do
            yy ← management year
            Run MFCL projection with existing effort scalers
            ab ← stock status in yy-1
            Check1 ← tropical P-S catch in yy-1 and yy > catch limit
            Calculate new effort scaler (given ab and tropical P-S catch)
            Update frq file with new effort for yy+1 to yy+3
            Re-run MFCL projection
            Check2 ← tropical P-S catch in yy and yy+1 > catch limit
            Check3 ← tropical P-S catch in yy+1 and yy+2 > catch limit
            if Check2 then
                Update frq with new effort for yy+2 and yy+3
                Re-run MFCL projection
                Check3 ← tropical P-S catch in yy+2 and yy+3 > catch limit
            if Check3 then
                Update frq with new effort for yy+3
        Next management period
    Next iteration
```

D Additional Plots and Figures

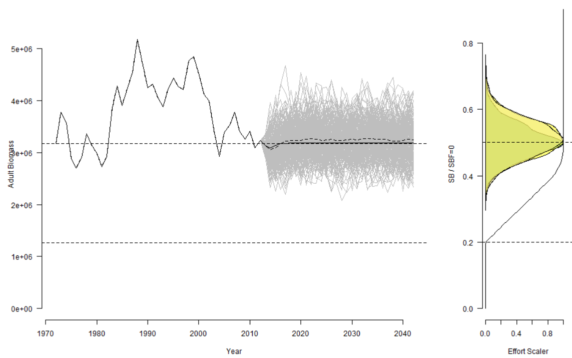


(a) No effort creep

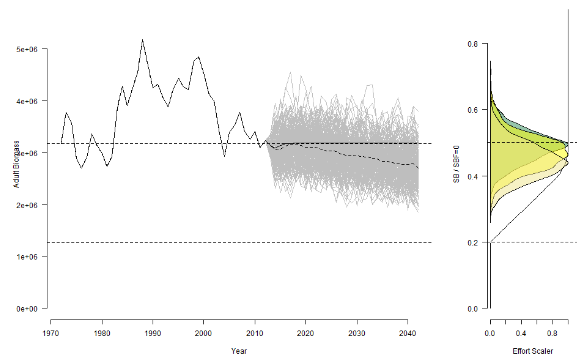


(b) 2% effort creep

Figure 12: HCR3: as for Figure 2.

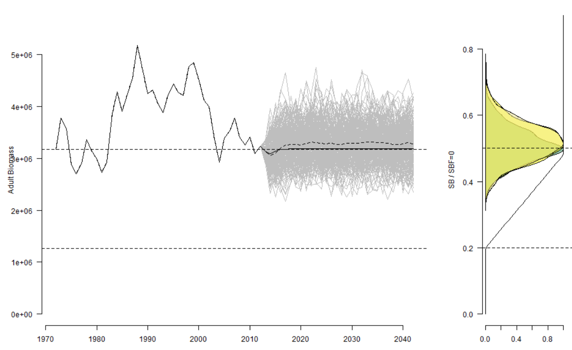


(a) No effort creep

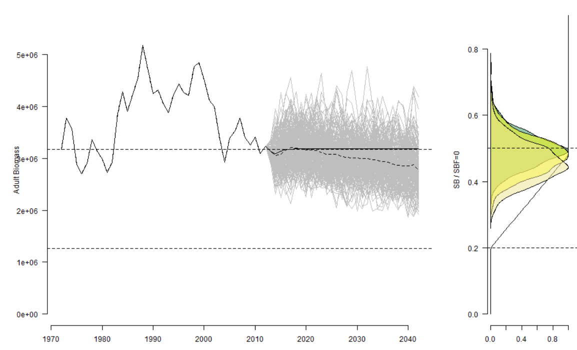


(b) 2% effort creep

Figure 13: HCR4: as for Figure 2.



(a) No effort creep



(b) 2% effort creep

Figure 14: HCR5: as for Figure 2.

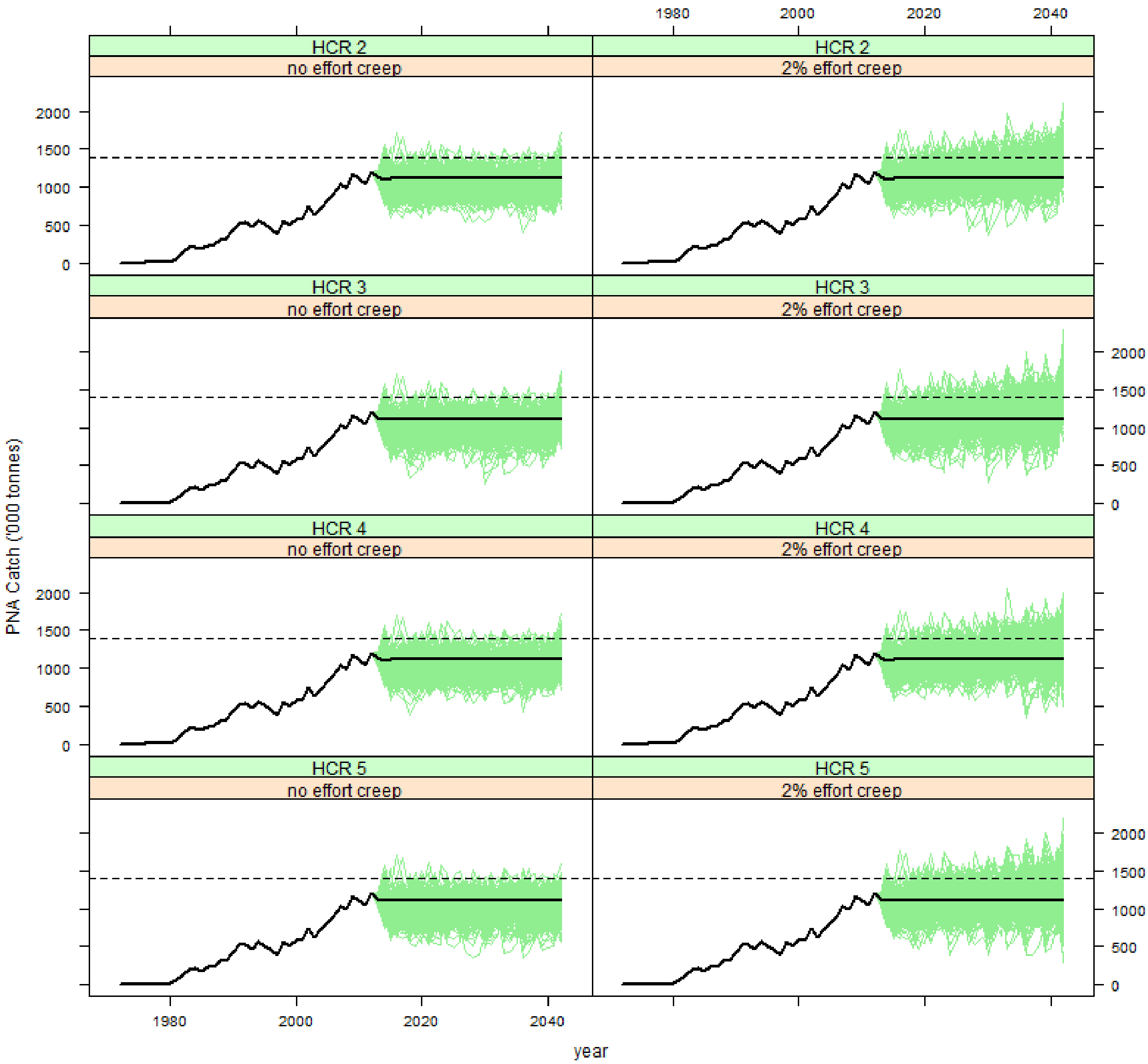


Figure 15: Observed catch for the tropical purse seine fishery (black line) for the period 1972 to 2012 and predicted catch (green lines) for each of the HCR (rows) and effort creep (columns) scenarios. tropical purse seine catch is calculated as the sum of catches by purse seine vessels in assessment regions 2, 3 and 5. Note that this currently includes AW.

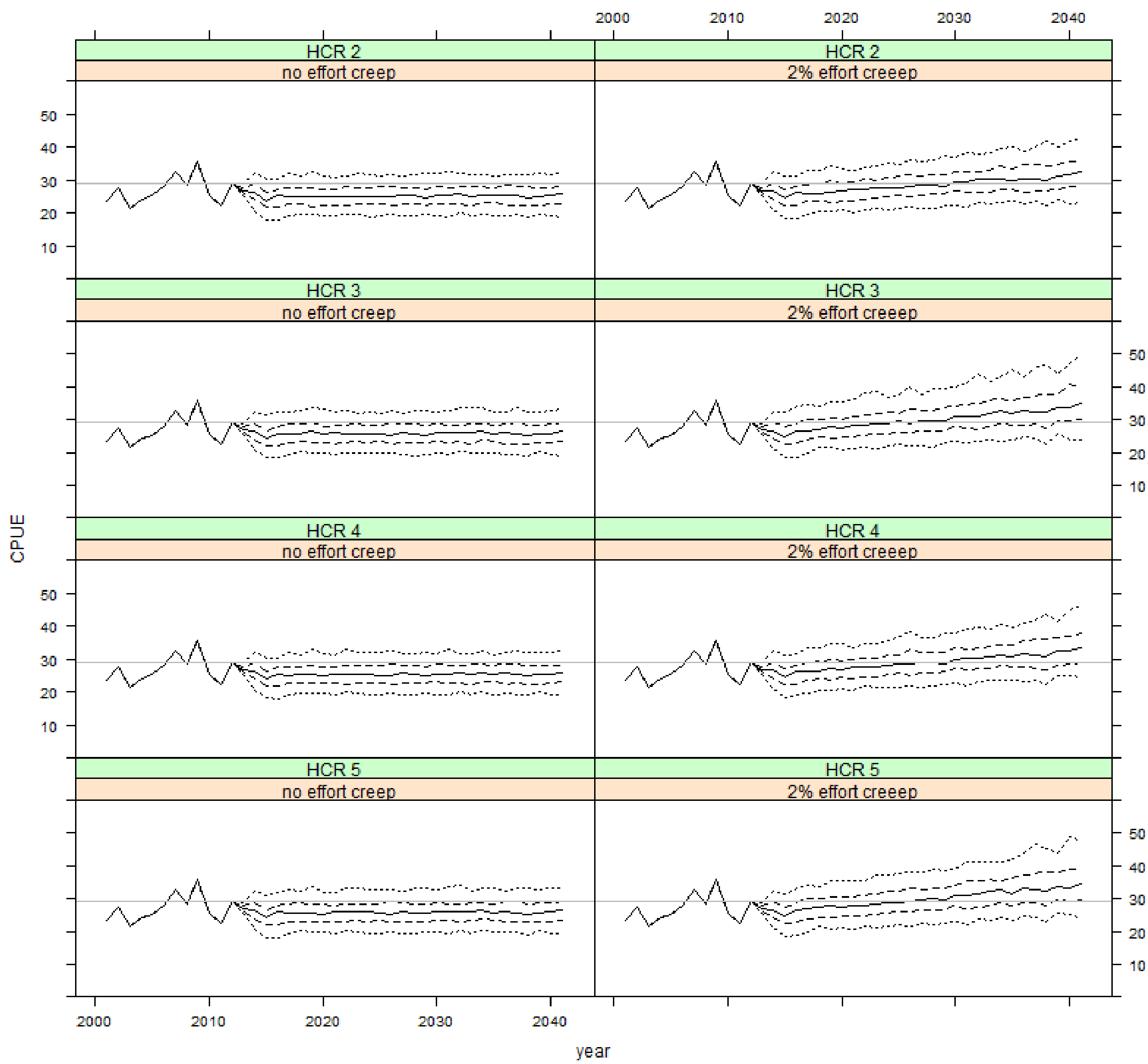


Figure 16: Observed CPUE for the period 2001 to 2012 and predicted CPUE for each of the HCR (rows) and effort creep (columns) scenarios. Predicted CPUE shows the 5^{th} and 95^{th} percentiles (dotted), 25^{th} and 75^{th} percentiles (dashed) and 50^{th} percentiles (solid). The horizontal grey line illustrates the 2012 CPUE level.

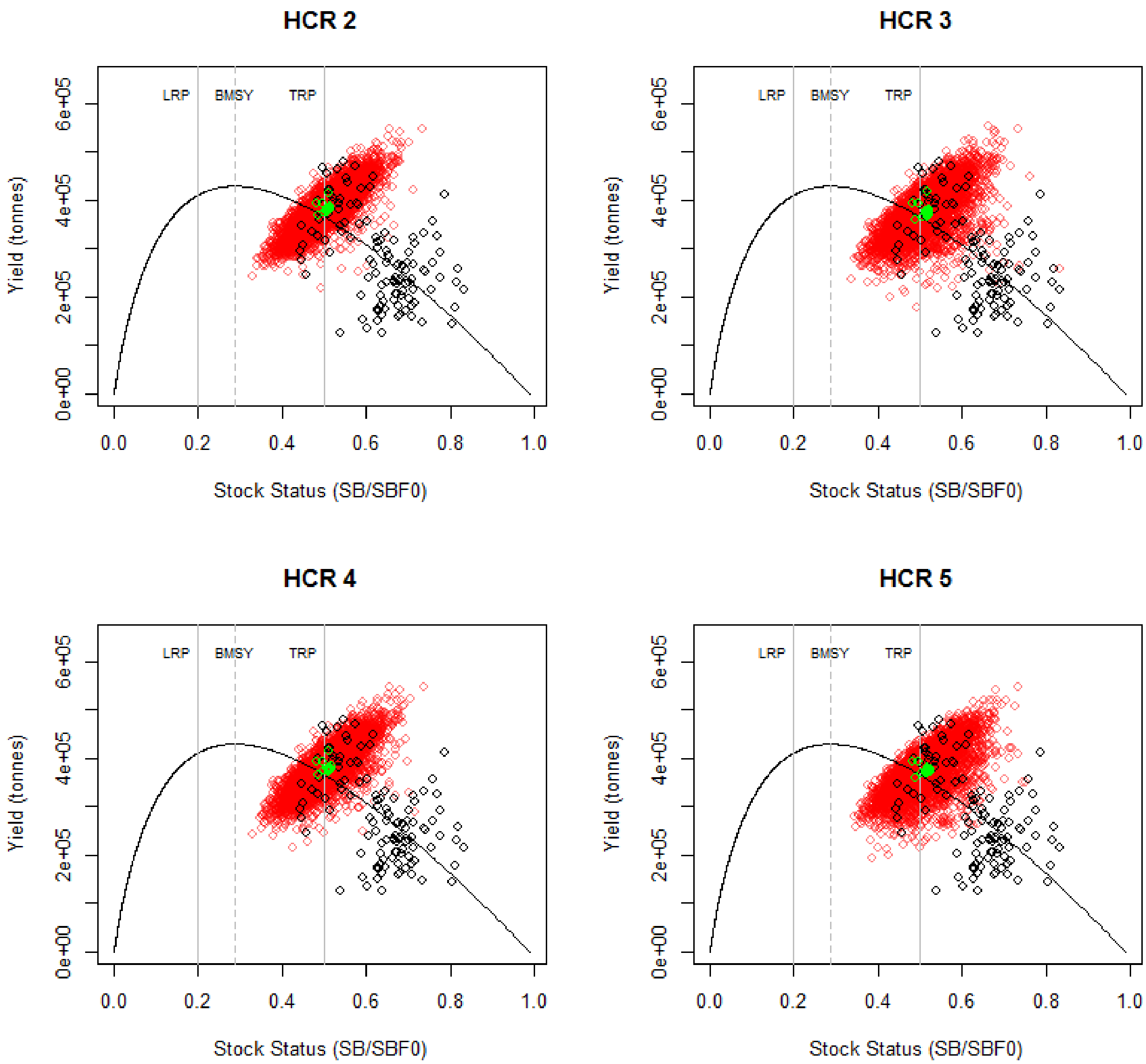


Figure 17: Equilibrium yield and biomass curves. As for Figure 3 but showing HCRs 2 to 5 for the zero effort creep scenario.

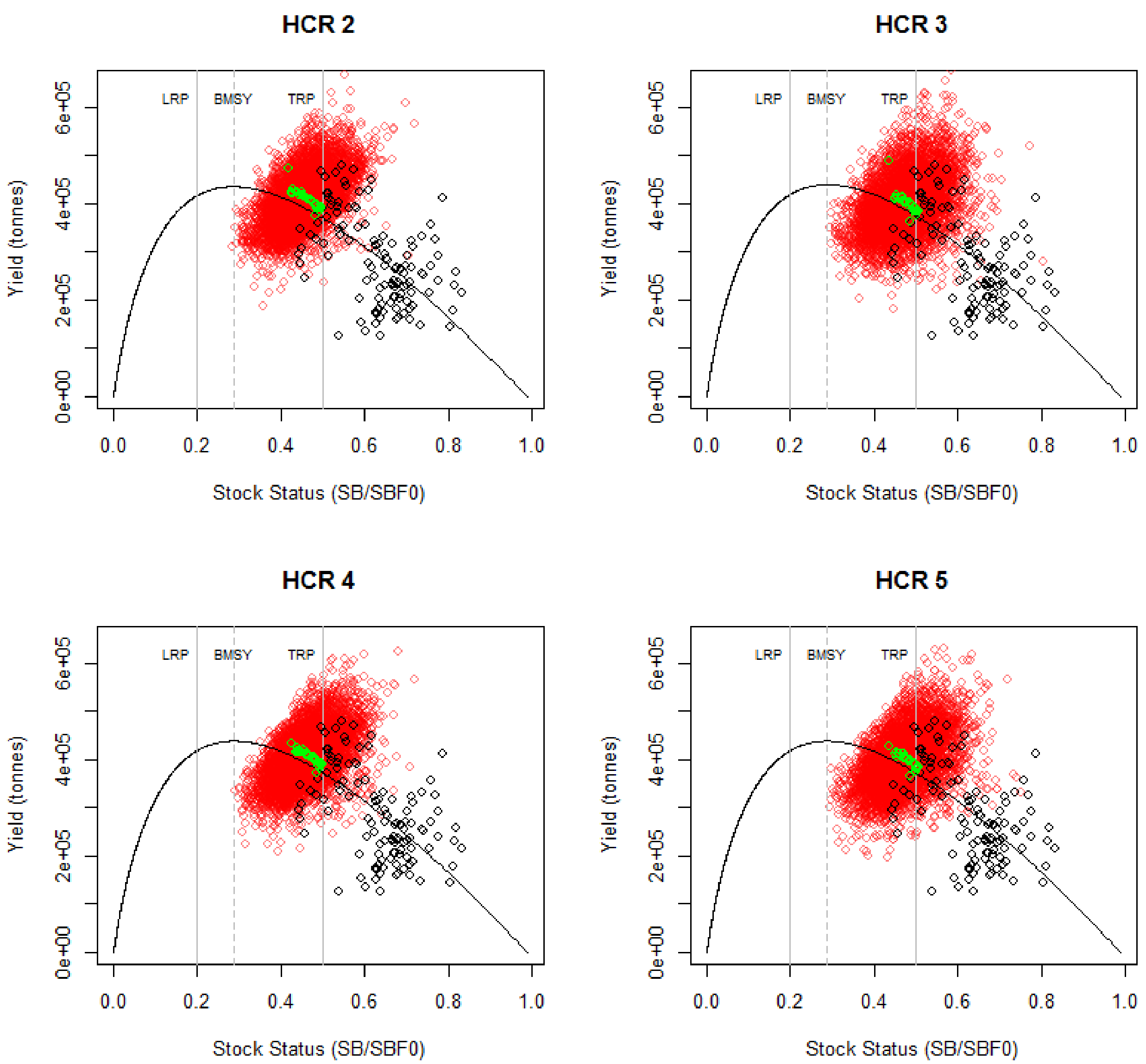


Figure 18: Equilibrium yield and biomass curves. As for Figure 3 but showing HCRs 2 to 5 for the 2% effort creep scenario.