# Summary of TRL TAC setting process and development of Harvest Control Rules (HCR) for use under quota management

*Éva Plagányi, Darren Dennis, Roy Deng, Robert Campbell, Trevor Hutton*

CSIRO Oceans and Atmosphere

TRLRAG August 2016

## Table of Contents

## Summary

In response to a planned change to quota management of the Torres Strait rock lobster fishery, a number of changes in the development of harvest control rules (HCR) and the TAC setting process have been necessary to take into account changes in the methods used, as well as the survey frequency and timing, to achieve defined biological, economic and socio-cultural objectives of the lobster fishery. This document summarises further work towards developing an empirical Harvest Control Rule (HCR) for TRL, in response to a RAG recommendation that empirical HCRs be considered. The performance of alternative candidate empirical HCRs is compared and discussion proceed as to how it could be used as part of the TAC setting process. This document is a preliminary summary only discussing work in progress for discussion at the August 2016 TRLRAG meeting, and a final report will be prepared thereafter.

The 2015 stock assessment model is used as the operating model, together with 3 alternative versions of this model, collectively termed a Reference Set. The alternative Operating Models (OMs) include consideration of a lower stock-recruitment steepness parameter, changing the assumption of a hyperstable relationship between CPUE and stock abundance, and a more conservative recruitment scenario in which there is a 10% chance of recruitment being 75% the base level, and autocorrelation with the following year's recruitment determined by a (uniform) randomly generated probability. The technical specifications are summarised in this document. The performance of every HCR alternative candidate that is trialed is assessed by computing the median and average performance over 800 simulations, made up of 200 stochastic replicates of each of the 4 alternative Operating Models (OMs).

Simulations account for both observation area and implementation error, and a range of robustness trials conducted. Different implementation errors are set for each of the three sectors (TIB,TVH and PNG) based on historic performance, and sensitivity to these can be tested. The empirical HCRs trialed are based on all or some of the available indices of relative abundance, including preseason survey data (ages 1+ and 0+) and CPUE (TVH, TIB), with different weightings trialed, as well as different methods based on recent trends in these indices. Performance statistics for a number of candidate HCRs are compared, and show key trade-offs such as between catch, catch variability, risk of depletion and risk of closure of the fishery. Details of the alternative options and formulae used are provided, as well as suggestions for refining choice of the final HCR. Final tuning and refinements will be done in response to feedback from stakeholders, and alternative variants of these HCRs will be presented and discussed at the TRLRAG. The implications of the results for adjusting aspects of the Harvest Strategy will also be discussed.

The final choice of HCR will be determined by stakeholder preferences after considering the trade-offs between various key performance statistics. In general, there are several examples of HCRs that perform well across a range of alternative weightings accorded to the survey and CPUE information. The HCR candidates that use the log of the slope in these surveys generally perform better than HCRs not based on the log of the slope (particularly in terms of catch variability). Adaptive HCRs also outperform constant catch strategies which are shown to result in much higher risk of depletion except under very low average catch scenarios.

## Introduction – developing an empirical Harvest Control Rule (HCR) for the TRL fishery

The RAG recommended trialling the use of an empirical harvest control rule HCR, and this document summarises further progress in development of an approach. Empirical HCRs are considered a defensible approach given that have been shown to perform almost as well as model-based approaches (Punt et al. 2012; Rademeyer et al. 2007). Both model-based and empirical HCR's typically include free parameters that can be adjusted to tune their performance to achieve desired optimal trade-offs between performance statistics. Empirical harvest strategies have demonstrated the ability to achieve objectives such as reversing a decline in a population. However, they can suffer from a lack of information about the exact level at which the resource abundance will approach, as can aim for a target level, and hence additional analyses are required to determine how the target relates to specified reference levels.

Another potential disadvantage of empirical HCR's is that they can perform worse than model-based approaches in terms of the level of inter-annual variability in output recommendations (Butterworth and Punt 1999; Punt and Smith 1999). This is because model-based methods typically consider the behaviour of the resource over a long time period and, hence variability in forecasts is dampened, whereas empirical approaches typically estimate short-term trends, taking into account only data for the most recent years.

Given that large inter-annual variability in management recommendations can be problematic for many fisheries, this needs to be borne in mind in designing an empirical HS, but management strategy evaluation (MSE) can be used to simulation test beforehand the overall performance of the HS. Also, in the case of TRL, the resource is recruit driven and highly variable, and hence higher levels of inter-annual variability may be more acceptable. The performance of alternative HCRs is evaluated using performance measures that should ideally be based on both the most recent information, as well as consideration of trends over a longer period.

A further advantage of empirical approaches is that they are simple to develop and easily understood by all stake-holders. Furthermore, they are quick and easy to run and, hence many alternative simulations and scenarios can be tested quickly.

### Data inputs

We assume a HCR formula needs to be applied in early December (after the pre-season survey) of year *y* to set the final TAC for the following year *y+1*. We assume:

- Pre-season survey index for year *y;*
- Assume no mid-year survey index currently available, but can simulate future availability;
- Total catch for year *y* based on available estimates at end of October of year *y:* need total TIB, TVH, PNG catch
- CPUE TIB data for year *y*
- Standardized CPUE TVH index for year *y*
- Need to test robustness of approach to possibility that data not available in any year, as well as penalty (extra precaution) if data not available

In terms of an empirical rule, one approach could be to use both the pre-season survey index and CPUE, although with greater weighting applied to the pre-season survey. Also there is currently a big gap (no data for 2009-2013) in the pre-season index time series, so as a start one could try use a regression applied to the latest data plus 2005-2008 data. The CPUE trend information could then be used to scale up or down the more recent catch average (last 5 yrs), but use average of TVH and TIB CPUE trends, and finally applying a tuning parameter to weight the survey and CPUE adjustments.

### The Operating Model

The stock assessment model of Plaganyi et al. (2015) is used as the operating model OM (Appendix 1), and hence assumed to represent reality in terms of the underlying lobster population dynamics. A number of additional sensitivity tests will be run to capture some of the key uncertainties, and as described below a

Reference Set is used rather than a single model. A spatial operating model has also previously been developed as part of the MSE project (Plagányi et al. 2012; Plaganyi et al. 2013), but updating this model for use here wasn't possible given the tight timelines, and the amount of work needed to spatially disaggregate all the data in order to update the model. The latter model could usefully be applied in future to test sensitivity to an alternative structural representation.

The operating model is conditioned on data available up until October 2015. Although the mid-year surveys have currently been discontinued, the model is able to simulate the generation of future mid-year survey data in order to test candidate HCRs that include a mid-year survey.

A Reference Set (RS) (Rademeyer et al. 2007) comprising 4 different Operating Models OMs was constructed to include a sufficiently representative range of potential estimates of current population status and productivity, as follows:

OM1: Based on stock assessment model with *h=0.7*; and hyperstability parameters for CPUE TVH and TIB sectors set at *hyps1 = 0.75* and *hyps2 = 0.5* respectively;
OM2: More conservative steepness parameter *h=0.5* of the stock-recruitment function (*hyps1=0.75; hyps2=0.5*); Note the initial set of HCRs (Appendix 5) used *h=0.6*;
OM3: CPUE hyperstability parameters set to 1, i.e. *hyps1=1; hyps2 = 1 (h=0.7)*;
OM4: As in OM1 but testing sensitivity to more negative recruitment scenarios with possible autocorrelation. This is implemented by randomly forcing recruitment to be three-quarters of the usual level with 10% probability of this occurring in any year, and generating a random autocorrelation parameter $\rho$ for the following year, where $\rho$ determines the extent to which the recruitment in the second year is similar to that in the previous year, i.e.
Recruitment (year 2) = $\rho$ x recruitment(year1)+$(1-\rho)$ x recruitment(year2).

All model results are integrated across these four alternative models, with equal weight accorded to each, and 200 replicates of each OM, yielding a total of 800 projection scenarios over which results are integrated. An example of the difference in performance of an illustrative HCR (HCR10 – see below) across the four OMs is shown in Appendix 3. The historic trajectories are shown in Fig. 1.

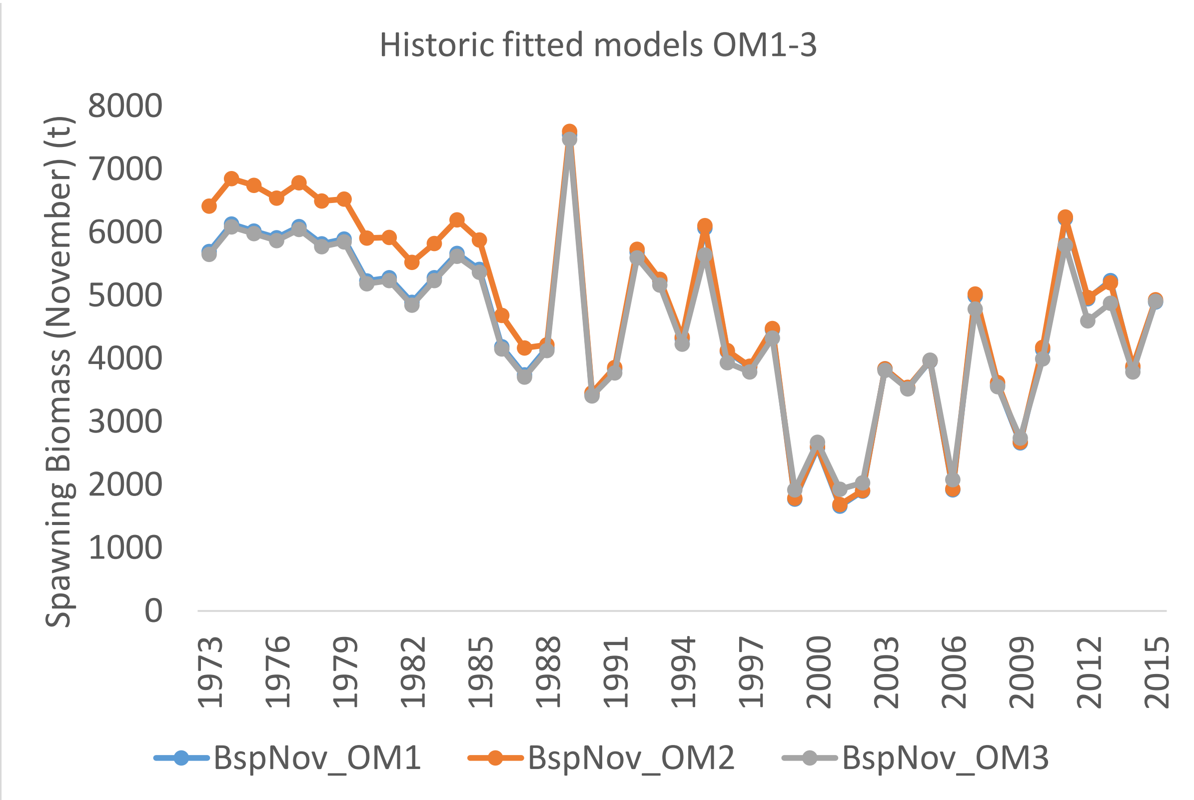



Fig. 1. Historic spawning biomass trajectories for alternative operating models 1 to 3

## Future Projections

"Future data" in the form of survey indices of abundance (pre-season 0+, 1+; mid-year 1+, 2+) and sector-specific CPUE series (TIB and TVH) are required by the Harvest Control Rule (HCR) to compute a TAC for each of the years in the projection period for each candidate rule tested. These abundance indices (CPUE and surveys) are generated from the OM, assuming the same error structures as in the past, as described below.

One of the issues that we need to take into consideration is that all the indices have a different number of years in the time-series. As the standard-deviation will be correlated with the scale of the index, we first ensure that all indices are on the same scale. Hence, we scaled the indices so that the mean is equal to 1 over the five common years (2005-2008 + 2014). We then calculated the standard-deviation for each index over all years for each index and then only the set of common years. This gives:

| | All-Yrs | Common |
|---|---|---|
| CPUE_TVH | 0.35 | 0.30 |
| CPUE_TIB | 0.19 | 0.10 |
| Pre-season 1+ | 0.38 | 0.38 |
| Mid-yr 1+ | 0.37 | 0.61 |
| Mid-yr 2+ | 0.52 | 0.53 |

As the common results are calculated over only 5 years this time-series is probably too small to get a good handle on variability (sigma), therefore we also take guidance from the All-Yrs results. The small variance for the TIB index has been noted before and is likely to be influenced by a high degree of hyper-stability probably due to fishers maintaining catch rates by, for example, fishing known aggregation points (such as rocky reefs) close to port and not fishing during periods of low abundance. The coarse scale of the effort data (day) upon which this time-series is based is also likely to influence this result – as may the fact that the sampling is not complete with substantial data gaps in some years. Some degree of hyper-stability may also be noted for the TVH index as again fishers will tend to fish known sites where lobsters have aggregated in the past – however, this fleet is more mobile and so will likely spend more time searching for high abundance sites and so the CPUE series may be closer to the variance in the true abundance (i.e. the hyper-stability is likely to be much less). This is somewhat indicated by the corroboration of the survey and CPUE indices. When computing the TAC for year *y*+1, CPUE data are assumed to be available to year *y*, but as these indices are based on all data available at the end of October, there may be an additional error if there is a delay in some of the data being submitted and analysed in time for that year's analyses. Hence, some additional variance is accounted for by scaling both the CPUE sigma values to 0.40 in the base-case.
The future CPUE data series are generated from model estimates for exploitable biomass and catchability coefficients.

Future survey data are generated from model estimates of mid-year (June) and pre-season (November) survey biomass. Log-normal error variance includes the survey sampling variance with the CV set equal to the average historical value, plus survey additional variance, estimated within the OM concerned from past data. For the TAC for year *y*+1, such data are available for year *y*.
To illustrate how the generation of future survey and CPU indices, with observation error added, compare with the model "true underlying " spawning biomass, an example from a single randomly selected replicate is shown in Figure 2.

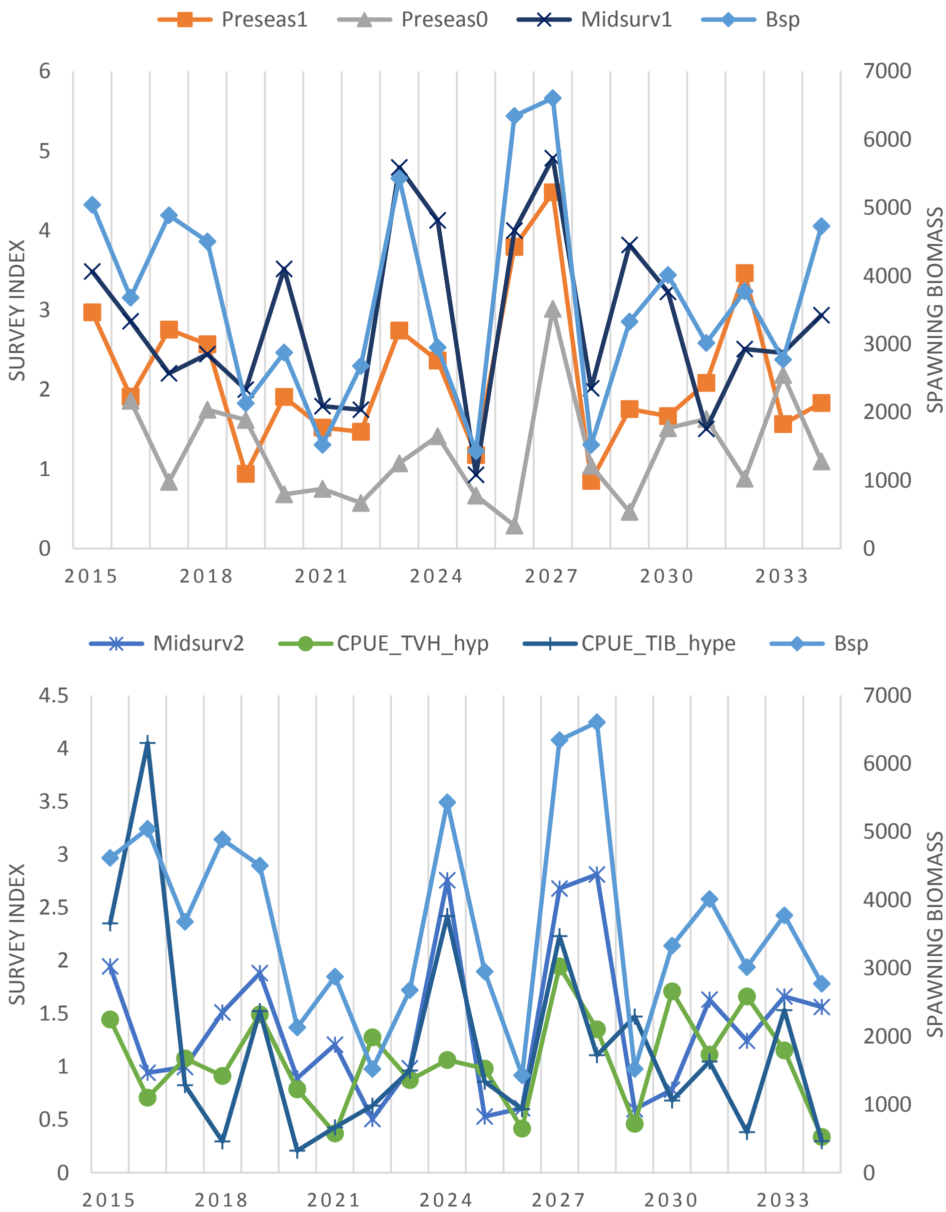



Fig. 2. Example from single replicate comparing the spawning biomass with model-generated future survey indices of relative abundance, with observation error added. The preseason 0+ index has been shifted a single year and the preseason 1+ and midyear survey 1+ shifted one year so they correspond with the prediction for spawning biomass. The CPUE (TIB) and CPUE (TVH) indices have been adjusted to account for the hyperstability parameters of 0.5 and 0.75 respectively used in the base-case model.

## Simulating TACs and actual catches

The total TAC recommended is divided in fixed proportions amongst the various sectors, with the following values used for the sector allocations: TIB: 38%, TVH: 29%, PNG: 33%

We include in this model implementation uncertainty which is defined as the difference between the model TAC recommendation and the actual catch that is taken in a year. It was considered important to include implementation uncertainty for a number of reasons: (a) observed substantial differences between the actual catches and the "dummy" TAC over the past decade, as well as in the performance of the three sectors relative to their "dummy" allocation (Table 4); (b) challenges in ensuring that under a quota management system each of the three sectors (TIB, TVH, PNG) will effectively monitor catches during the fishing season and ensure that fishing stops when the limit is reached; (c) uncertainty as to possible discard mortalities under quota management, which may be exacerbated during anomalously warm periods; (d) whether decision makers accept or change the scientific recommendation (no precedent for this scenario); (e) potential (unknown) catches of TRL in PNG demersal trawl fisheries targeting prawns; (f) unknown future changes in fishing operations.

In the initial simulations presented at the TRLRAG in March 2016, the relationship between the recommended TAC for year *y* ($TAC_y$) and the actual catch in year *y* ($C_y$) was modelled using the formula:

$$C_y = TAC_y \times e^{\varepsilon_y} \ , \ \ \varepsilon_y \sim N(0;\sigma^2)$$

where a value for σ (0.05) was selected based on comparison with past observations over the period 2006-2015. Sensitivity to alternative values of σ is also investigated.

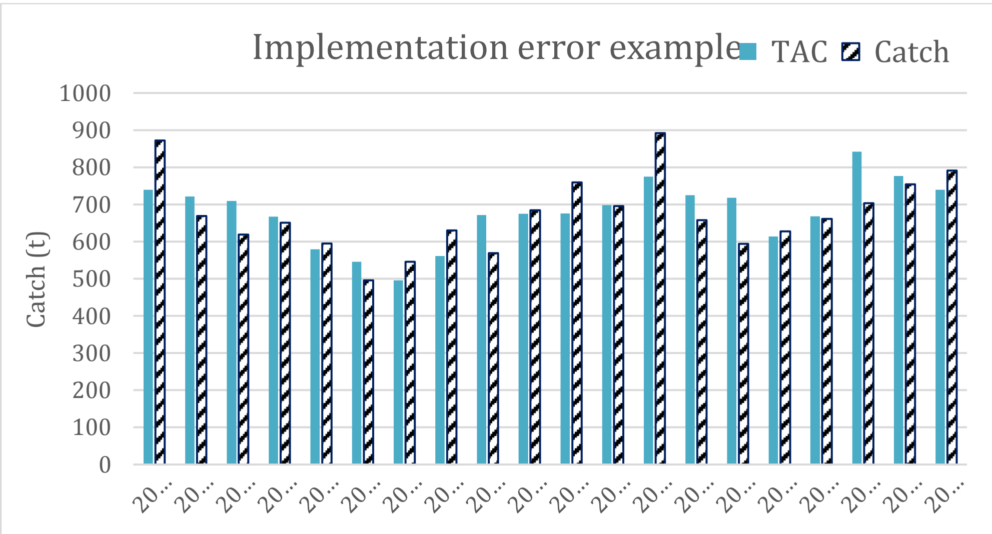
This has subsequently been changed to allow the use of different implementation error magnitudes for each of the three sectors based on recent observed catches, and hence base case values are set at σ(TIB) (0.06), σ(TVH) (0.04) and σ(PNG) (0.1). These values can be adjusted, for example, to simulate scenarios in which different sectors reduce the difference between total catch and the allocated catch based on the TAC.

An illustrative example from a single randomly selected model replicate is shown in Figure 3.

Table 4. Comparison of actual catches and dummy TAC for each of the years as shown

| Year | TiB | TVH | PNG | TS_Total | Aus_TAC | Catch as % of TAC |
|---|---|---|---|---|---|---|
| 2004 | 211 | 481 | 182 | 874 | | |
| 2005 | 345 | 545 | 228 | 1118 | | |
| 2006 | 143 | 135 | 142 | 420 | 471 | 89% |
| 2007 | 267 | 269 | 228 | 764 | 842 | 91% |
| 2008 | 207 | 100 | 221 | 528 | 751 | 70% |
| 2009 | 135 | 91 | 161 | 387 | 450 | 86% |
| 2010 | 182 | 279 | 293 | 754 | 853 | 88% |
| 2011 | 201 | 503 | 165 | 869 | 803 | 108% |
| 2012 | 151 | 370 | 174 | 695 | 964 | 72% |
| 2013 | 127 | 362 | 108 | 597 | 871 | 69% |
| 2014 | 132 | 273 | 261 | 666 | 616 | 108% |
| 2015 | 151 | 152 | 416* | 719 | 769 | 93% |

- Recent updated catch (previous estimate was 192t) still to be confirmed by TRLRAG



| Year | Catch | Catch_TIB | Catch_TVH | Catch_PNG | TAC-Catch_actual | TAC |
|---|---|---|---|---|---|---|
| 2015 | 860.326 | 322.688 | 238.254 | 299.384 | -91.3262 | 769 |
| 2016 | 741.626 | 283.353 | 219.54 | 238.733 | 38.673 | 780.299 |
| 2017 | 668.417 | 256.438 | 201.122 | 210.857 | 64.0464 | 732.464 |
| 2018 | 710.379 | 270.427 | 207.388 | 232.565 | 11.7605 | 722.14 |
| 2019 | 698.723 | 265.005 | 201.202 | 232.516 | -12.0248 | 686.698 |
| 2020 | 582.892 | 223.013 | 173.483 | 186.396 | 38.6679 | 621.56 |
| 2021 | 644.757 | 243.179 | 182.001 | 219.577 | -41.1621 | 603.595 |
| 2022 | 599.696 | 225.854 | 168.423 | 205.419 | -45.1733 | 554.522 |
| 2023 | 550.313 | 211.53 | 166.875 | 171.908 | 64.58 | 614.893 |
| 2024 | 705.677 | 267.884 | 203.877 | 233.916 | -6.49961 | 699.177 |
| 2025 | 768.477 | 289.408 | 215.794 | 263.276 | -58.1303 | 710.347 |
| 2026 | 679.866 | 258.415 | 197.348 | 224.102 | 1.59127 | 681.457 |
| 2027 | 756.608 | 284.356 | 210.969 | 261.282 | -69.0552 | 687.553 |
| 2028 | 712 | 272.452 | 212.04 | 227.508 | 48.4021 | 760.402 |
| 2029 | 629.369 | 242.28 | 192.034 | 195.055 | 84.918 | 714.287 |
| 2030 | 708.714 | 268.889 | 204.342 | 235.484 | -9.99769 | 698.717 |
| 2031 | 582.965 | 221.702 | 169.557 | 191.706 | 4.23174 | 587.197 |
| 2032 | 556.773 | 214.215 | 169.493 | 173.065 | 71.467 | 628.24 |
| 2033 | 742.493 | 282.749 | 217.042 | 242.702 | 14.6933 | 757.186 |
| 2034 | 712.088 | 269.206 | 202.685 | 240.197 | -31.8324 | 680.255 |

Fig. 3. Example of model output for a single replicate, showing the difference between the TAC and the actual catch when assuming implementation error, and example values for individual sectors from a single replicate (from 200) for OM1.

## Candidate HCRs considered

We focused on empirical approaches for the reasons elaborated above. Hence, the HCRs tested are model-free, increasing or decreasing the TAC in response to the magnitude of recent trends in CPUE and survey estimates. Further details are provided in Appendices 3-5.

A range of alternatives were tested that included different combinations of all available indices of abundance, including options that accorded zero weight to some abundance series. Four different kinds of HCRs were tested as follows:

(1) Constant Catch
(2) Slope - Based on a simple fixed slope parameter applied to the preseason survey indices;
(3) Regression – Based on the slope of a regression line that is fitted each year to the past *n* (n=5 in base-case) survey data points, and similarly for CPUE where included, and multiplied by either a fixed average historical catch (average of past 5 years in base-case) or the average of the previous 5 year's catch.
(4) Log Regression – As above, except that the slope is computed based on the natural logarithm of the survey and CPUE indices in an attempt to decrease inter-annual variability.

In all these cases, an additional option can be included to cap the maximum catch (1000 t in base-case), and if preferred, to also set the minimum catch (not implemented in base-case).

Following feedback from the TRLRAG, the basic form of HCR rule being tested is as follows, and uses the preseason survey 1+ and 0+ indices, both CPUE indices, taking natural logarithms of the slopes, an upper catch limit, and using weightings as follows:

$$TAC_{y+1} = wt\_s1 \cdot \left(1 + s_y^{presurv,1}\right) \cdot \bar{C}_{y-4,y} + wt\_s2 \cdot \left(1 + s_y^{presurv,0}\right) \cdot \bar{C}_{y-4,y}$$
$$+ wt\_c1 \cdot \left(1 + s_y^{CPUE,TVH}\right) \cdot \bar{C}_{y-4,y} + wt\_c2 \cdot \left(1 + s_y^{CPUE,TIB}\right) \cdot \bar{C}_{y-4,y}$$

or if $TAC_{y+1}$ > 1000t, $TAC_{y+1}$ = 1000.

where

$\bar{C}_{y-4,y}$ is the average achieved catch during the past 5 years, including the current year i.e. from year *y*-4 to year *y*,

$s_y^{presurv,1}$ is the slope of the logarithms of the preseason survey 1+ abundance index, based on the 5 most recent values;

$s_y^{presurv,0}$ is the slope of the logarithms of the preseason survey 0+ abundance index, based on the 5 most recent values;

$s_y^{CPUE,TVH}, s_y^{CPUE,TIB}$ is the slope of the logarithms of the TVH and TIB CPUE abundance index, based on the 5 most recent values;

wt_s1, wt_s2, wt_c1, wt_c2 are tuning parameters that assign relative weight to the preseason 1+ (wt_s1) and 0+ (wt_s2) survey trends compared with the CPUE TVH (wt_c1) and TIB (wt_c2) trends;

Examples of some of the range of alternative weightings tested are shown in Table 5.

Table 5. Alternative combinations of survey and CPUE indices to inform alternative HCRs

| Code | Preseas1+ | Preseas0+ | Midyr1+ | Midyr2+ | CPUE_TVH | CPUE_TIB | Historic Catch |
|---|---|---|---|---|---|---|---|
| Constant catch | X | X | X | X | X | X | X |
| Preseas | ✓ | X | X | X | X | X | ✓ |
| Preseas_CPUE | ✓ | X | X | X | ✓ | ✓ | ✓ |
| Preseas_0_1_slope | ✓ | ✓ | X | X | X | X | ✓ |
| Preseas_CP_0_1 | ✓ | ✓ | X | X | ✓ | ✓ | ✓ |
| Preseas_0_1_ave | ✓ | ✓ | X | X | X | X | ✓ |
| Preseas_CP_0_1_ave | ✓ | ✓ | X | X | ✓ | ✓ | ✓ |
| Preseas_Mid_CP | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

| Description | Preseason survey 1+ | Preseason survey 0+ | CPUE_TVH | CPUE_TIB | Examples |
|---|---|---|---|---|---|
| | wt_s1 | wt_s2 | wt_c1 | wt_c2 | HCRs |
| Only survey | 1 | 0 | 0 | 0 | HCR4-7 |
| High wt to survey | 0.8 | 0.1 | 0.05 | 0.05 | HCR9 |
| | 0.7 | 0.2 | 0.05 | 0.05 | RHCR6 |
| equal wt to 0+ and CPUE | 0.7 | 0.1 | 0.1 | 0.1 | RHCR7 |
| | 0.6 | 0.1 | 0.15 | 0.15 | HCR8; RHC |
| higher weight to 0+ surve | 0.6 | 0.3 | 0.05 | 0.05 | RHCR3 |
| less weight to survey | 0.5 | 0.1 | 0.2 | 0.2 | RHCR8 |
| No survey, only CPUE | 0 | 0 | 0.5 | 0.5 | HCR12 |
| | | | | | |

## Adding survey trigger and limit reference points

The TRLRAG **agreed** to the following reference points for the fishery:

- $B_0$ is the model-estimate of spawning stock biomass in 1973 (start of the fishery).
- $B_{TARG}$ is the agreed proxy for $B_{MEY}$, $B_{TARG}$ = 0.65.
- $B_{THRES}$ is the agreed "threshold" biomass level below which more stringent rules for calculating the TAC apply, $B_{THRES}$ = 0.48.
- $B_{LIM}$ is agreed to be half of $B_{TARG}$, $B_{LIM}$ = 0.32.
- If the limit reference point ($B_{LIM}$) is triggered two years out of the most recent three year period, then the fishery is closed.
- $F_{TARG}$ is the model-estimated level of fishing mortality that keeps the stock around $B_{TARG}$, $F_{TARG}$ = 0.15.

Risk statistics produced show that under some circumstances, the resource may drop below reference points such as $Bsp = 0.48K$ and/or $Bsp = 0.32K$. A method is therefore needed to reduce the probability of the resource dropping to low levels, and to move it instead to remain around the target biomass level (the resource naturally fluctuates around this level). However, if a stock assessment is not conducted every year, then the status of the resource relative to $K$ is not known, and it is necessary to use proxies instead. Hence, for example, one can compare historic survey indices of abundance with periods of low abundance in the past (e.g. 2001) to derive and test use of survey-indices-based trigger and limit reference points. As the preseason survey is the primary and most reliable index, a suggested method was trialed here based on only the preseason 1+ index in the current year, and with initial settings of trigger and limit survey reference points of 1.25 and 0.8 respectively. The limit survey reference point is a proxy for Blim and represents the lower limit below which the fishery should be closed in accordance with the Commonwealth harvest strategy guidelines. The trigger reference point represents the points below which smaller TACs should be set in order to allow the resource to recover back to the target level. Hence a hockey-stick type rule could be implemented, as shown in Figure 4. For preseason 1+ survey indices above the trigger reference point, the TAC is fixed at the value recommended using the HCR as above. However if the survey index for the current year is less than the trigger limit, then the TAC decreases linearly from the trigger to the limit reference point, and are set at zero once the limit reference point is surpassed.

Sensitivity to an alternative version with a higher trigger is investigated, with the trigger set at 1.5.

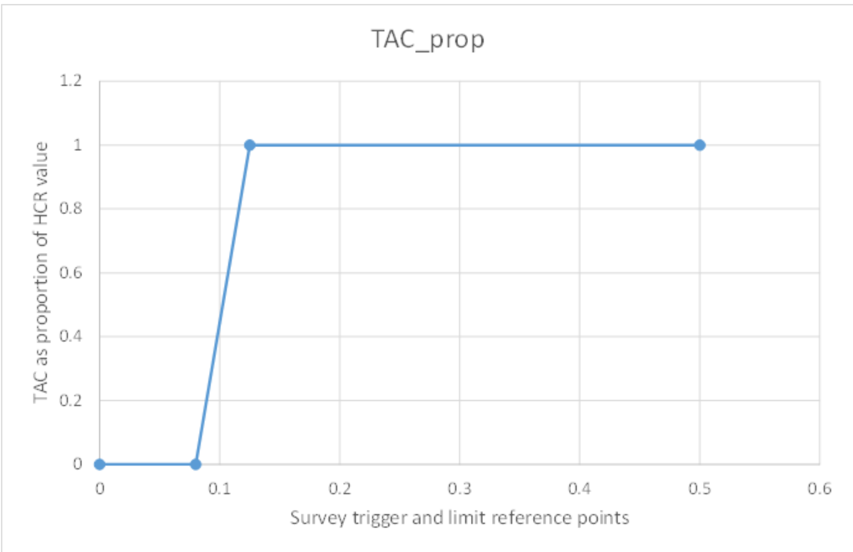



Fig. 4. Example of a Hockey-stick type control rule for modifying the recommended TAC based on survey trigger and limit reference points.

## Management Objectives

There are several objectives identified for the TRL fishery as follows:

- To maintain the spawning stock at levels that meet or exceed the level required to produce the maximum sustainable yield.
- In accordance with the TS Treaty, to protect the traditional way of life and livelihood of Traditional Inhabitants, particularly in relation to their traditional fishing for TRL.
- To provide for the optimal utilisation, co-operative management with Queensland and PNG and for catch sharing to occur with PNG.
- To optimise the value of the fishery
- To monitor interactions between the prawn and lobster fisheries.
- To maintain appropriate controls on fishing gear allowed in the fishery so as to minimise impacts on the environment.
- To promote economic development in the TS area with an emphasis on providing the framework for commercial opportunities for Traditional Inhabitants and to ensure that the opportunities available to all stakeholders are socially and culturally appropriate for the TS and the wider Queensland and Australian community

In terms of developing a HCR, we focus on the first four of these objectives. Building on previous agreements during TRLRAG meetings to deal with the extremely high observed variability in the fishery, we use as a target an average fishing mortality of 0.15 because this level is demonstrated to correspond to a sustainable level that also provides good catch rates.

Candidate HCRs are evaluated to ensure that they do not pose unacceptable risk to the spawning biomass. Given that the new harvest strategy is still under development, and iterative feedback from stakeholders is needed to finalise choice of risk statistics, some alternative options are presented for consideration by the TRLRAG and TRLWG. Quantifying the risk to the resource under alternative HCRs assists in the final selection of a HCR which meets the objectives of low risk of depleting the spawning biomass as well as ensuring that potential economic gains are not lost due to an overly conservative approach.

Detailed bio-economic information for the different fishery sectors (Hutton et al. in press), as well as socio-cultural considerations (Plaganyi et al. 2013; Van Putten et al. 2013a; van Putten et al. 2013b) have previously been presented, but is beyond the scope of this study to comprehensively update. Instead only simple economic information is presented for each scenario to assess how well it meets economic objectives, using as a proxy catch per sector and total value of the fishery. In addition, projected future catch rates for the TVH and TIB sectors are used as a proxy for economic performance, and an additional consideration relates to the inter-annual variability in catch.

## Performance Statistics

The following performance statistics, were computed for each candidate harvest control rule (HCR). Projections were conducted over 20 years and 200 replicates of each of the 4 OMs, ie total of 800 simulations. The same set of random numbers were used in testing all HCR candidates. In each case the median and 75$^{th}$ and 25$^{th}$ percentiles were computed, and the range of values also shown for the full projection period given that there is a lot of inter-annual variability in stock biomass. Examples of individual trajectories (worm plots) are also presented.

### *Resource status-related*

- $B^{sp}_{2034} / B^{sp}_{2015}$ the expected median spawning biomass at the end of the projection period, relative to the current 2015 level.

- $B^{sp}_{2034} / B^{sp}_{1973}$ the expected median spawning biomass at the end of the projection period, relative to the starting (1973) level (used as a proxy for K).
- Risk of depletion: percentage of all individual runs that ended below (a) 32% and (b) 48% of K.

### *Utilisation-related*

- Average catch: $\overline{C} = \frac{1}{20}\sum C_y$ over 2015 to 2034.
- Catch variability $\frac{1}{20}\sum {C_y}/{\overline{C}}$
- Implementation error – difference between TAC and actual catch over the projection period

### *Additional statistics*

- Average annual value ($ million) per sector (TVH, TIB) computed as the landed weight of each species multiplied by current average market prices. This does not account for costs of monitoring and adaptive management
- Projected future CPUE for the TVH and TIB sectors
- Projected average fishing mortality proportion

The preferred key statistics identified by the TRLRAG were (1) $B^{sp}_{2034} / B^{sp}_{2015}$; (2) Average Catch; (3) Average Catch Variability (AAV) and ($) average fishing proportion, and these key variables are highlighted in the outputs produced.

## Tuning and designing HCR with stakeholder input

- Try alternatives and present trade-offs to stakeholders to select preferred HCR (eg trade-off to ensure high average annual catch but low risk of depletion of lobster population)
- Tuning pars include: weighting of pre-season data vs TIB CPUE, TVH CPUE; no. of yrs to compute slope over, catch multipliers in decision rule, slope regression (eg using logarithm)
- Can impose constraint on the extent TAC can vary, or set maximum and minimum values
- Can add an exceptional circumstances clause (eg seagrass die back or sand incursion)

The advice of the TRLRAG and TRLWG is sought as to preferred choice of a HCR for the TAC setting process.

## Results

The Performance Statistics for a range of HCRs which performed reasonably are shown in the attached Figures. For all statistics, values shown are the median of the 100 replicates, together with the $75^{th}$ and $25^{th}$ percentiles (i.e. the rectangles encompass 50% of all outcomes) as well as the range of values. As requested by the TRLRAG, the full set of results are presented in Appendices 5-7 and further results will be provided on request.

Overall summary plots are shown to compare the performance of a range of HCRs in terms of selected key performance statistics: resource status: the end of projection period (2034) spawning biomass relative to the start (1973) spawning biomass; average fishing proportion and fishery performance based statistics, namely average catch and catch variability. Key risk statistics include the proportion of times the spawning biomass drops below 20%, 32% or 48% of the 1973 starting value (assumed to be *K*), as well as the probability of closure of the fishery. The initial results set in Appendix 5 and results in Appendix 6 evaluate the risk of a potential fishery closure but do not actually set TACs to zero in the simulations. This is done instead in the set of "closure" HCRs shown in Appendix 7 as this aspect needs to be discussed by the TRLRAG. Additional Sensitivity results will also be presented at the TRLRAG.

For each HCR, there are a large number of performance statistics output for consideration by stakeholders, and hence a smaller set of key variables is plotted to show: (a) total catch per year (t); (b) total spawning biomass (t) per year; (c) fishing mortality proportion per year; (d) proportion of times spawning biomass drops below 32%, below 48% and the annual average variability in catch; (e) two randomly drawn (from 100) individual catch and (f) spawning biomass trajectories, which are examples of plausible future outcomes, noting that the median projections shown are not representative of a single plausible outcome but represent the "average" of future plausible outcomes.

Three additional sets of results are available for each HCR:

(1) Biomass-related (t) – (a) shows the median projected spawning biomass trajectory; (b) relative spawning biomass depletion; (c) projected spawning biomass relative to the equivalent no-fishing trial; (d) the projected fishing mortality proportion; (e) the projected annual CPUE (TIB) and (f) CPUE (TVH) catch rate performance;
(2) Catch-related – (a) total projected catch (t); (b) TIB catch; (c) TVH catch; (d) PNG catch; (e) total beach price ($ mil); and (f) difference between TAC and actual catch;
(3) Projected survey indices (of relative abundance with error added) – (a) pre-season survey 1+; (b) pre-season survey 0+; (c) mid-year survey 1+; (d) mid-year survey 2+; (e) future CPUE (TVH) and (f) future CPUE (TIB).

In general (Figs 1-15), there are several examples of HCRs that perform well across a range of alternative weightings accorded to the survey and CPUE information. The HCR candidates that use the log of the slope in these surveys generally perform better than HCRs not based on the log of the slope (particularly in terms of catch variability). Adaptive HCRs also outperform constant catch strategies which are shown to result in much higher risk of depletion except under very low average catch scenarios.

Future work will modify and further tune the preferred HCR or set of HCRs in response to feedback from stakeholders, and will include further robustness testing. In addition, results are not presented here for examples using the midyear survey assuming that these surveys may be continued in the future. Future work will thus look at both including additional survey information, as well as the possibility of some data not being available to inform the HCR, and this will usefully inform the settings for a tiered harvest strategy approach that accounts for the different risk-catch-cost trade-offs of different stock assessment and monitoring options. This approach will guide future decisions on research and data collection investment for the fishery.

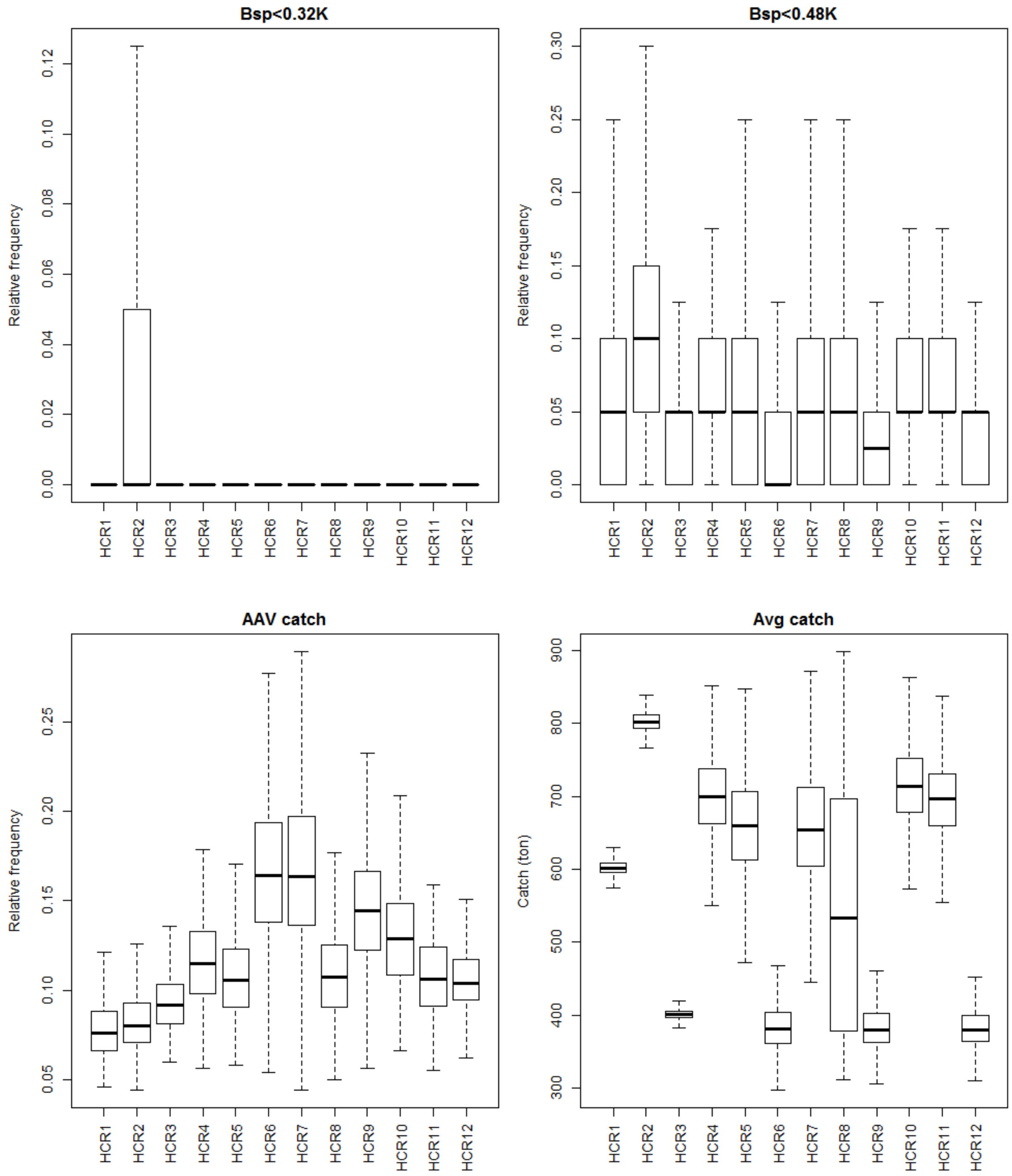



Fig. 5. Comparison of some key performance statistics for initial HCR set HCR1-12.

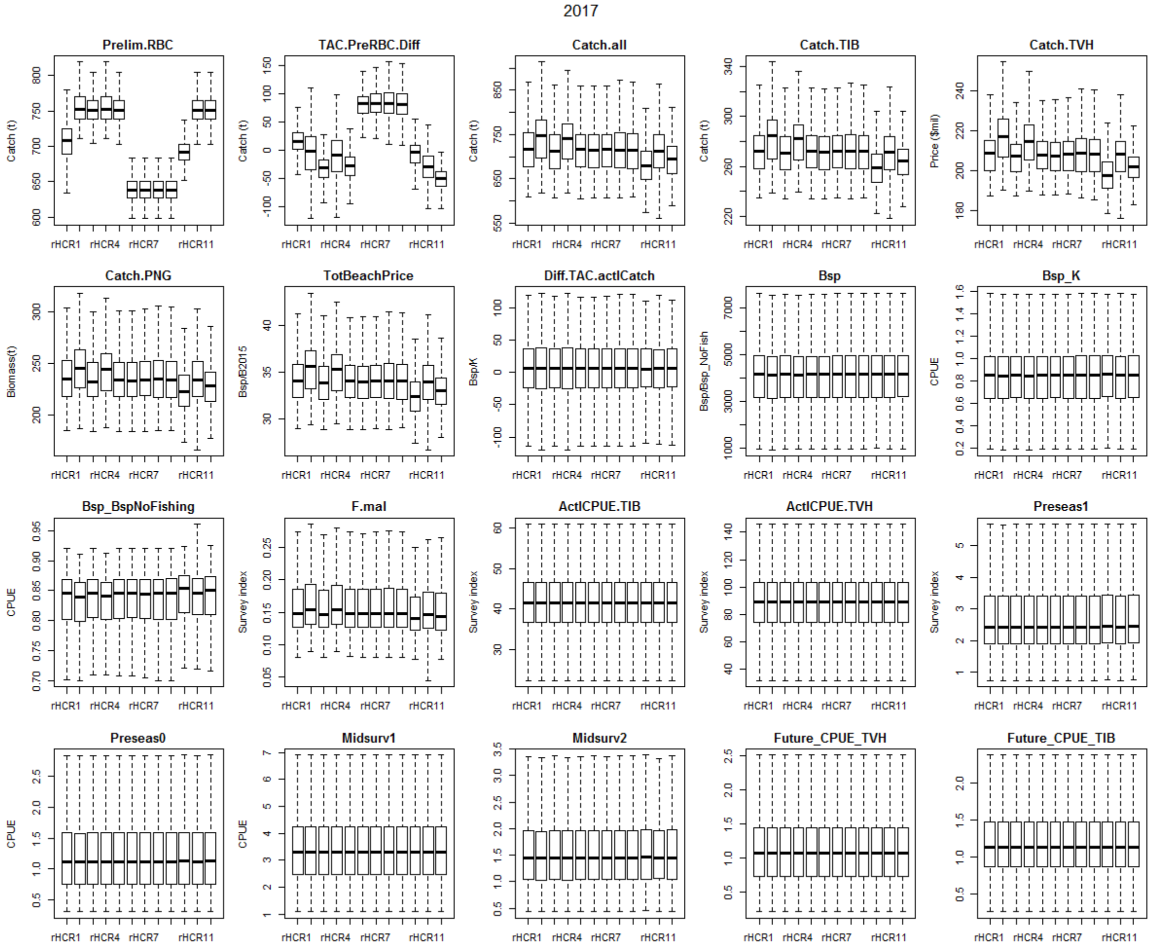



Fig. 6. Comparison of performance statistics for initial HCR set HCR1-12.

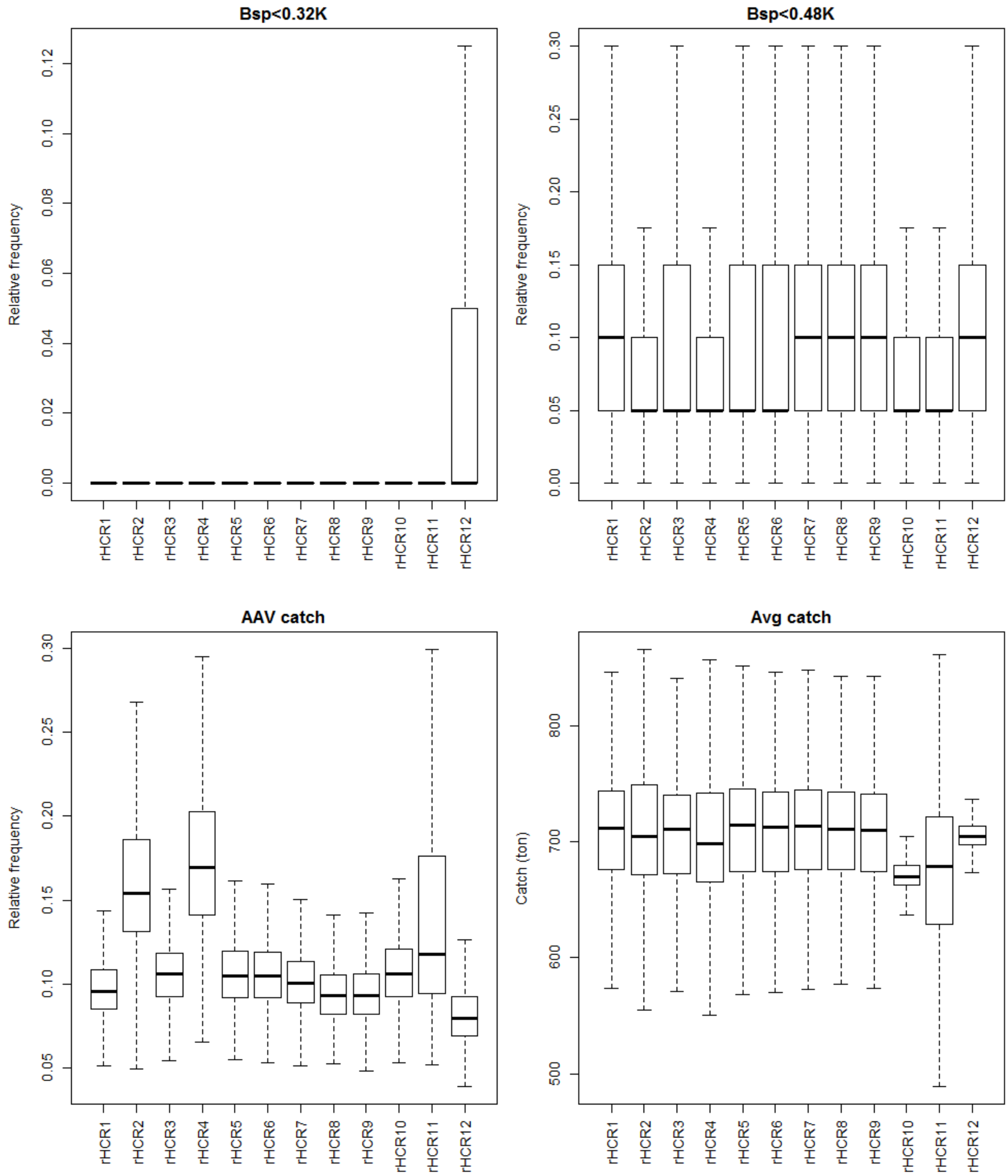



Fig. 7. Comparison of some key performance statistics for revised HCR set rHCR1-12.

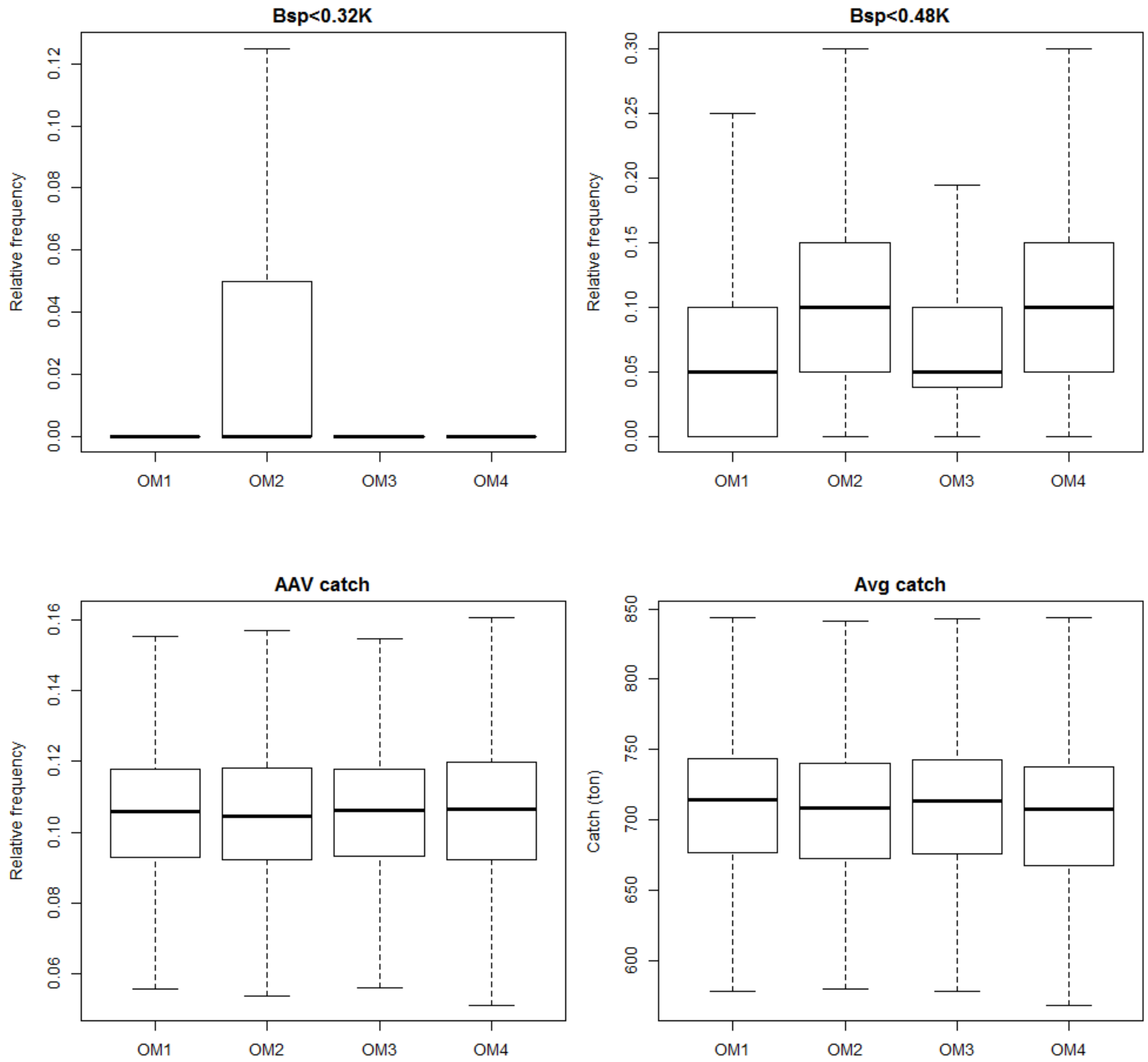



Fig. 8. Comparison of performance of the four Operating Models OM1-4 using rHCR3.

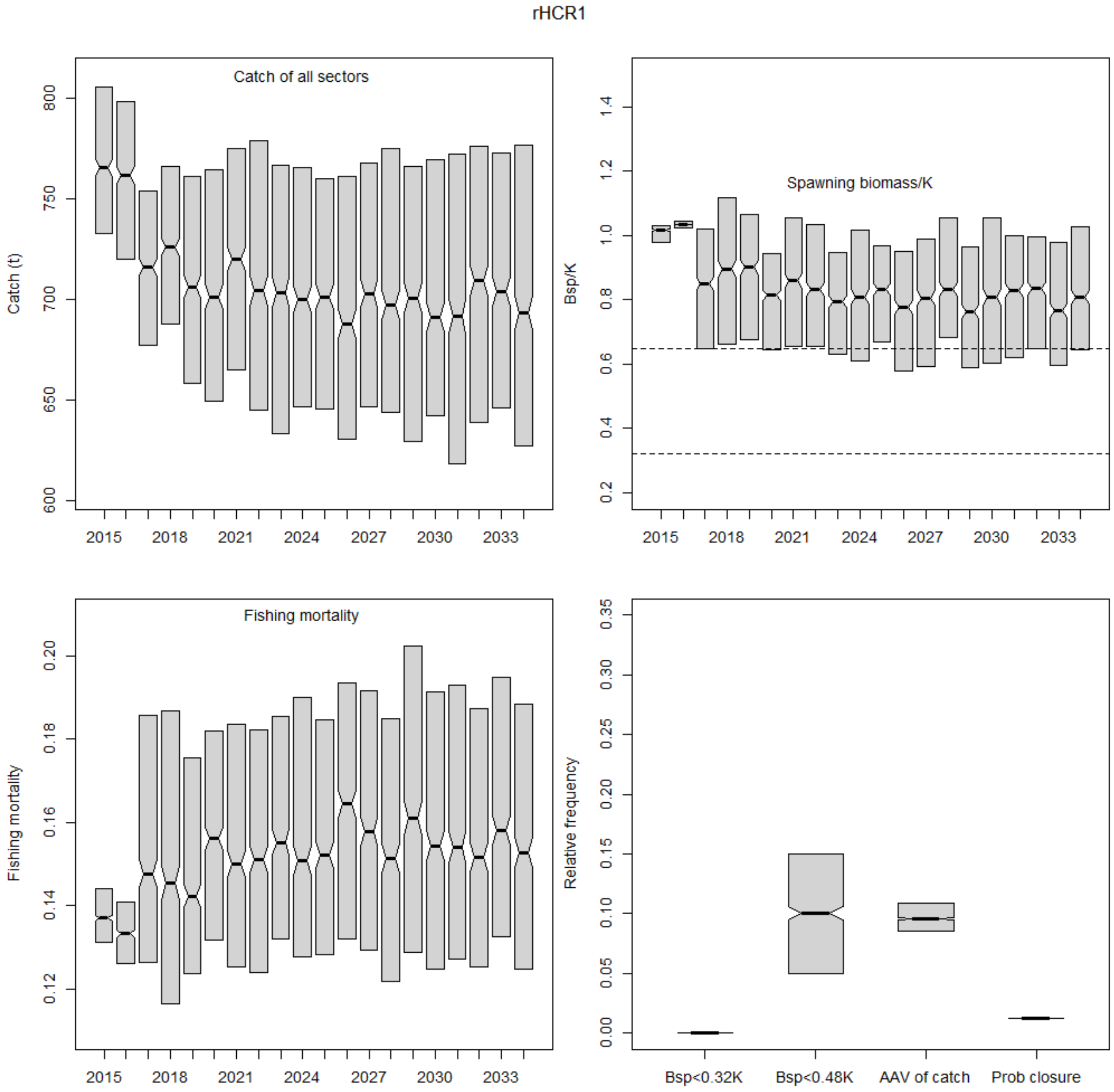



Fig. 9. Key performance statistics for rHCR1

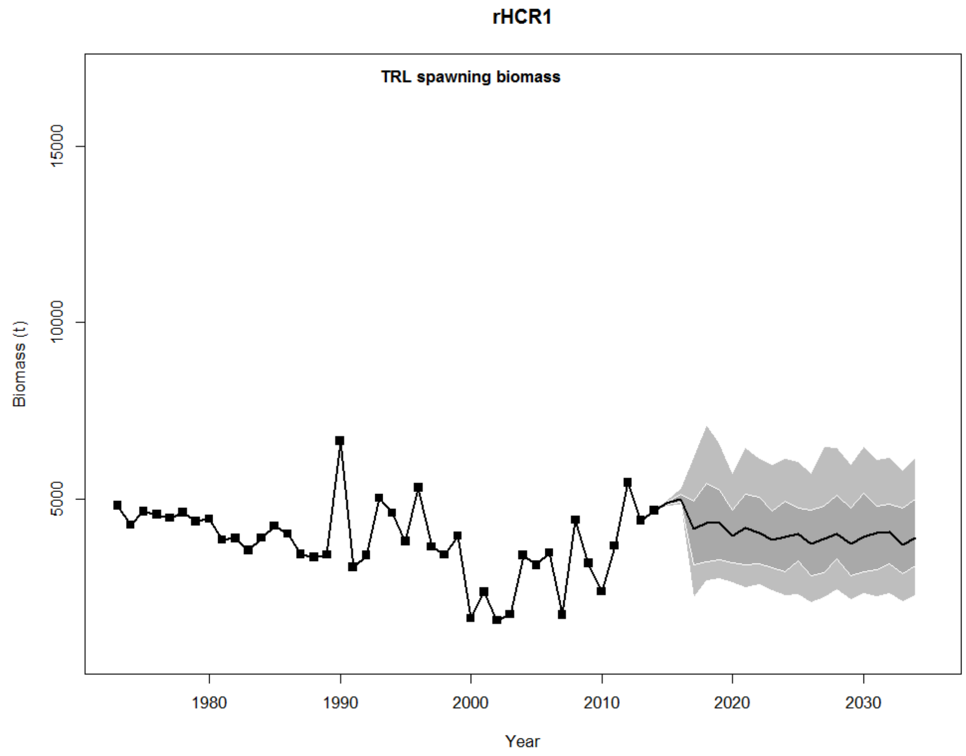



Fig. 10. Comparison between historic and projected biomass under rHCR1

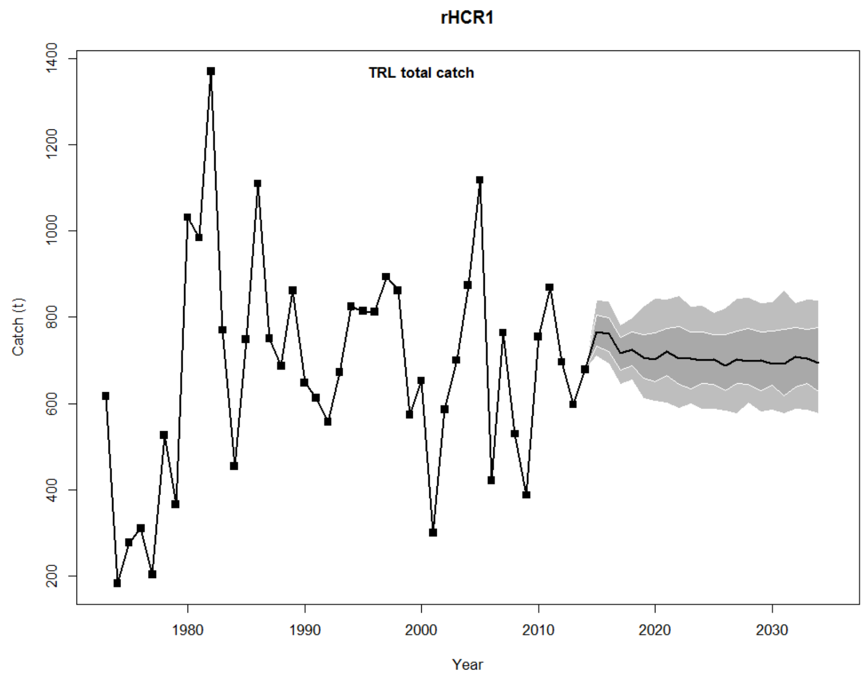



Fig. 11. Comparison between historic and projected catch under rHCR1

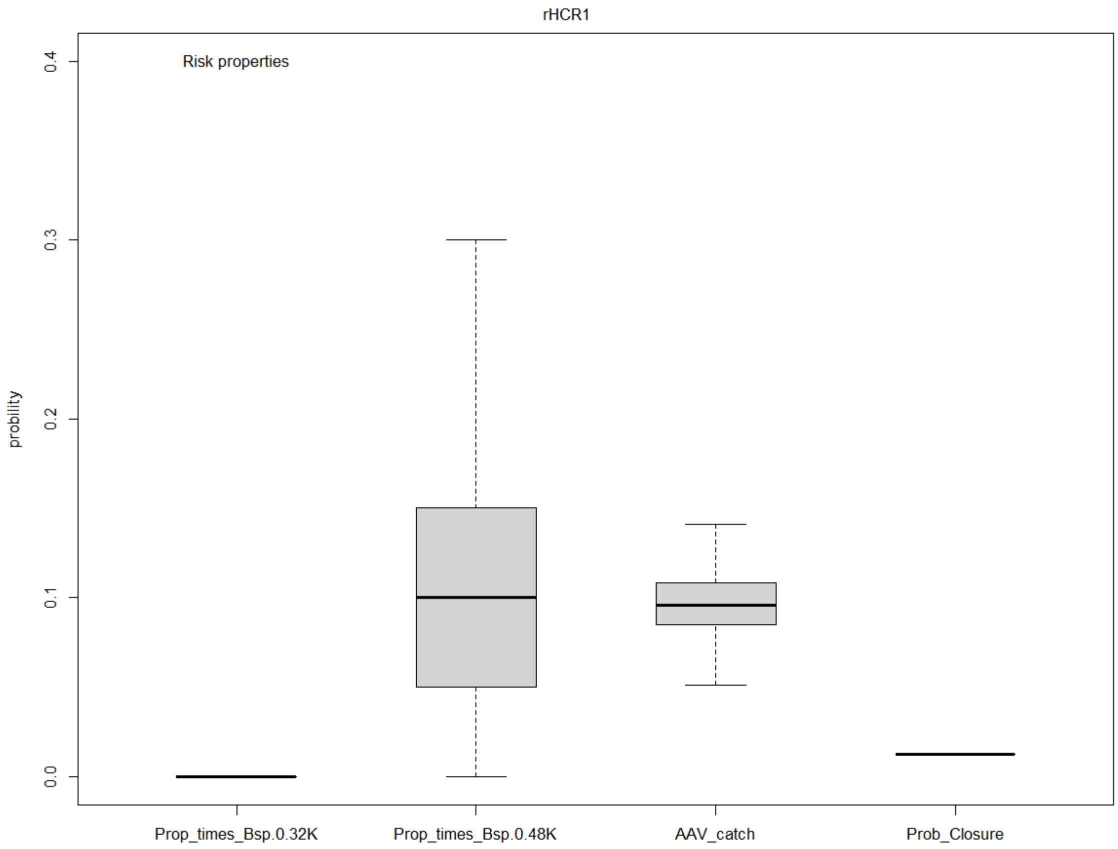


Fig. 12. Risk properties summary under rHCR1

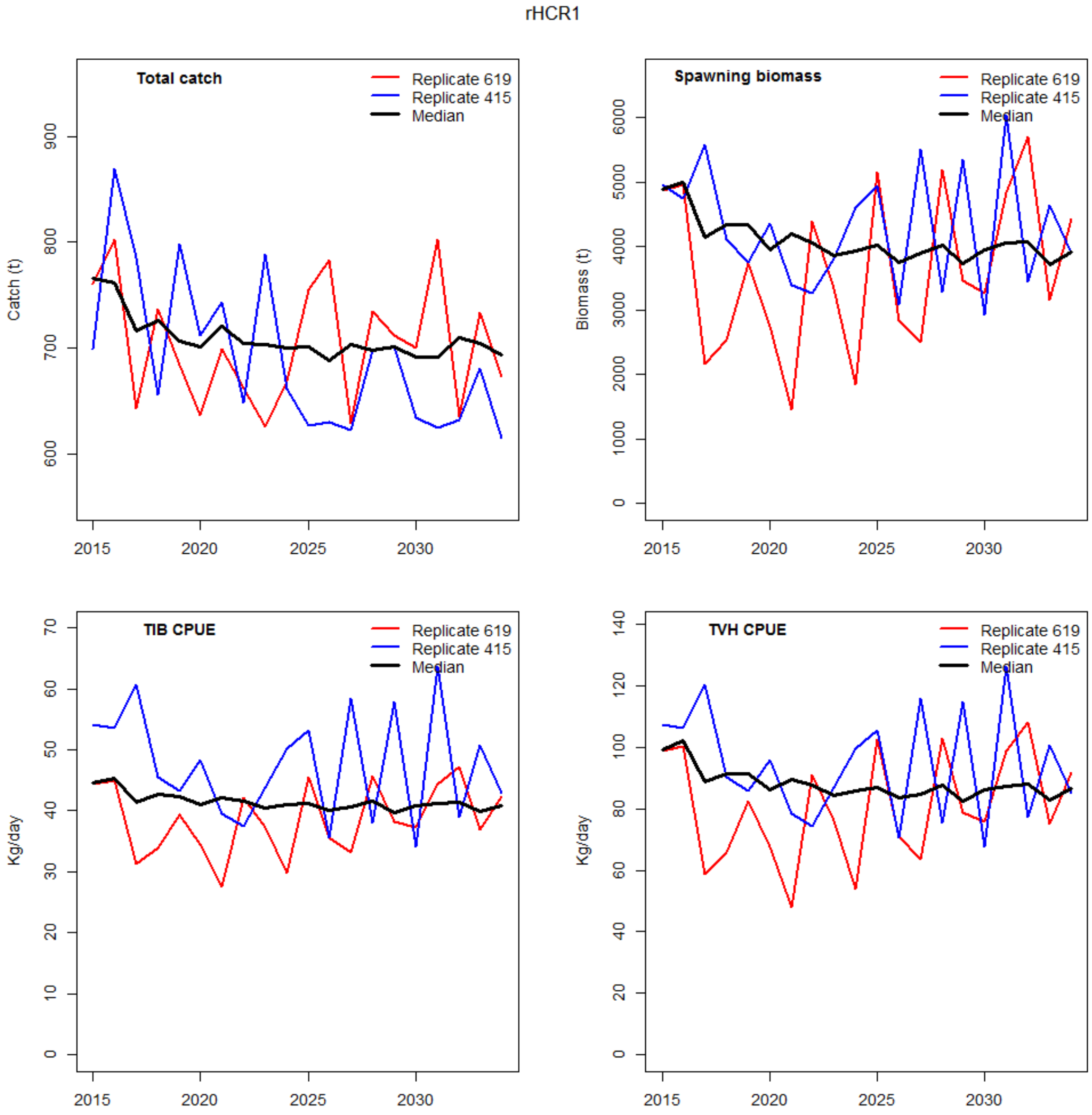



Fig. 13. Example showing median values and 2 random replicates under rHCR1

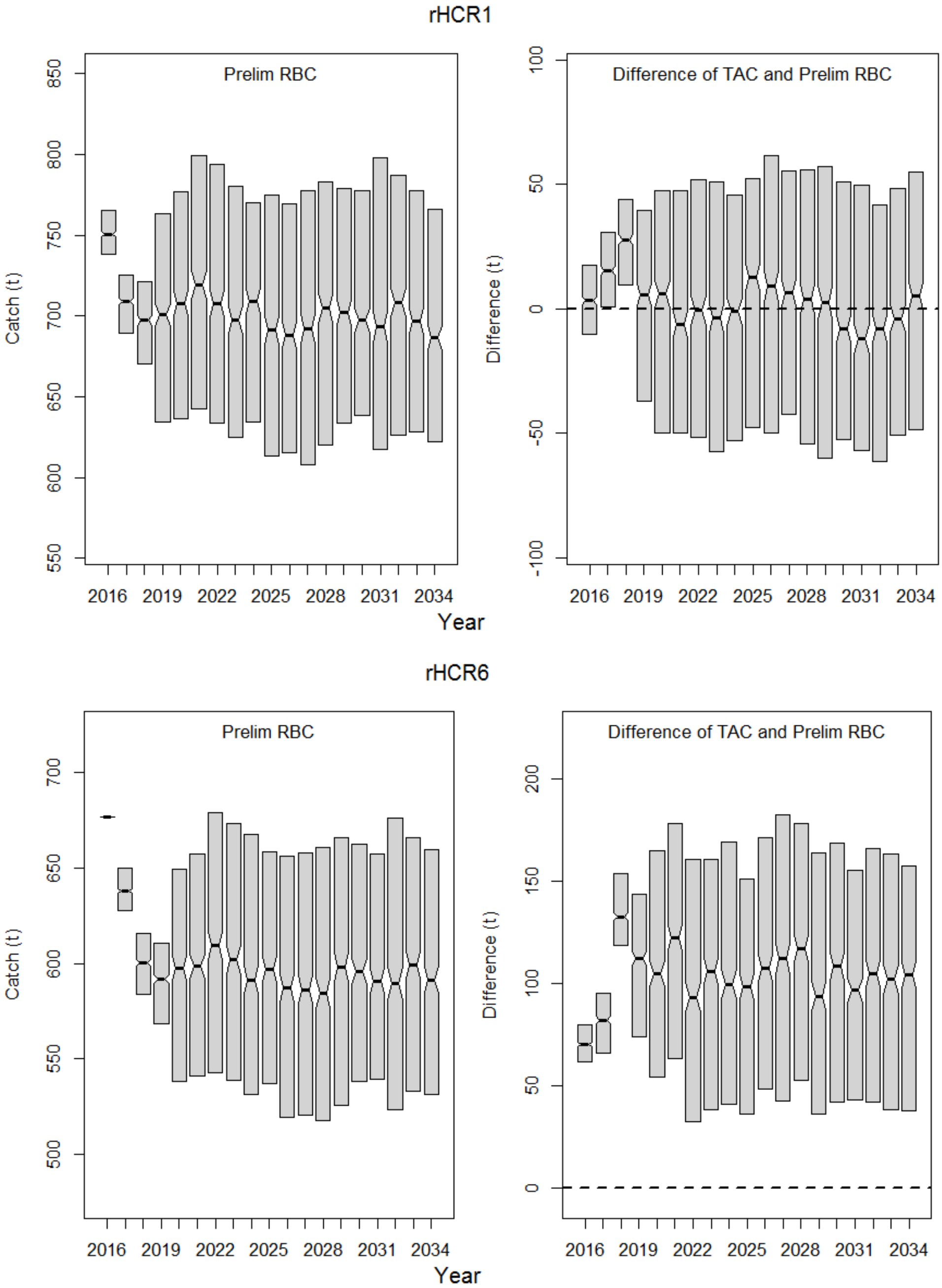



Figure 14. Examples of performance of forecast TAC when tuned to be similar to the final TAC value (top with tuning par = 1) or below the final TAC (lower panel with tuning parameter = 0.85).

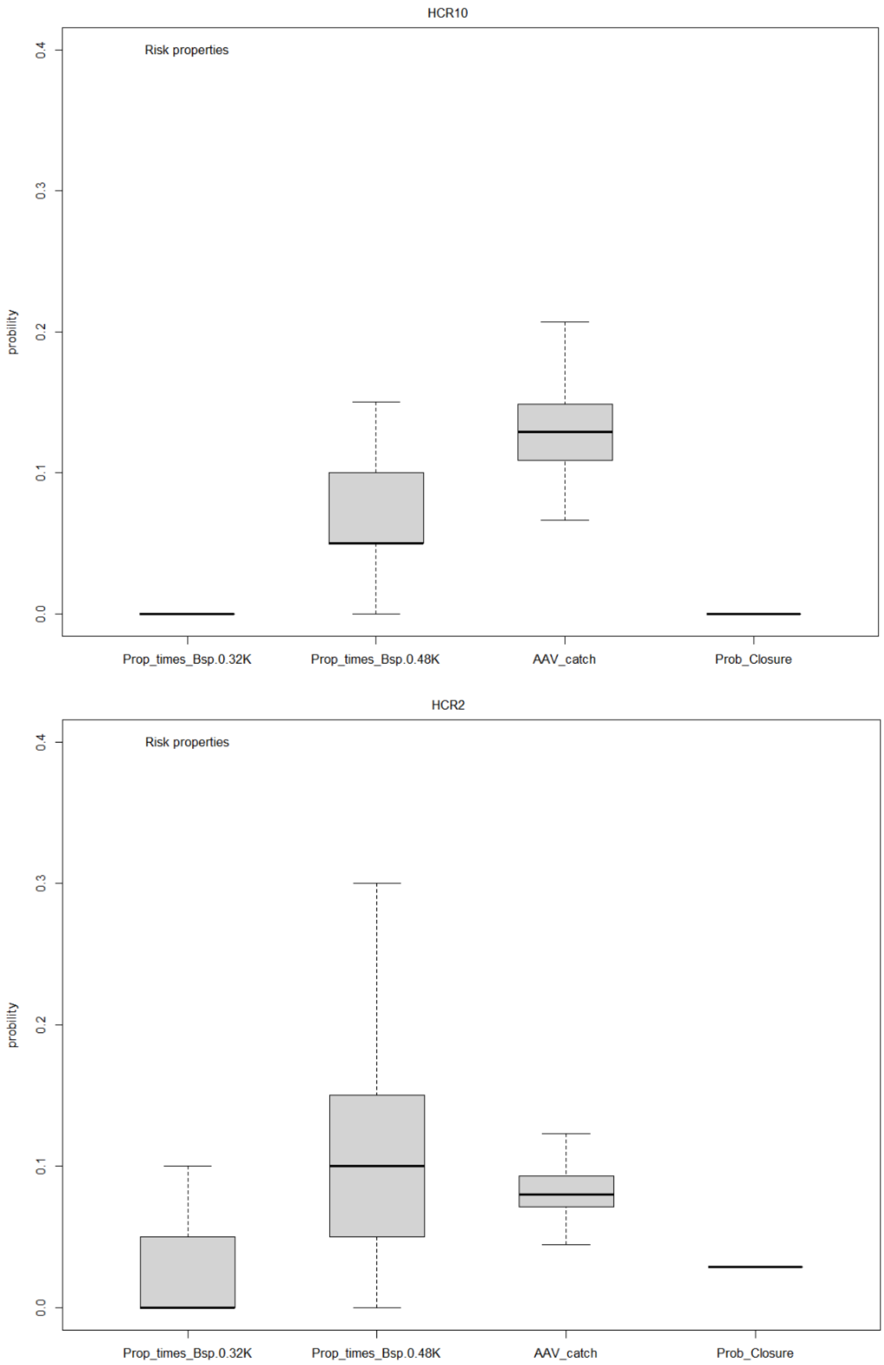



Figure 15. Comparison of risk under adaptive (top and non-adaptive or constant scenario (below).

## Acknowledgements

This research project was co-funded by the Australian Fisheries Management Authority and CSIRO. Thanks to Nokome Bentley, Trophia, for suggestions and inputs during the HCR development process, and to all stakeholders for valuable feedback.

## References

Baranov, T. On the question of the biological basis of fisheries. Nauchnyi Issledovatelskii Ikhtiologicheskii Institut Isvestia 1 (1): 81–128. Reports from the Division of Fish Management and Scientific Study of the Fishing Industry](English translation by WE Ricker, 1945 Mimeographed); 1918

Beverton, R.; Holt, S. On the dynamics of exploited fish populations. UK Ministry of Agriculture and Fisheries Investigations (Ser 2). 19; 1957

Butterworth, D.S.; Punt, A.E. Experiences in the evaluation and implementation of management procedures. Ices J Mar Sci. 56:985-998; 1999

Fournier, D.A.; Skaug, H.J.; Ancheta, J.; Ianelli, J.; Magnusson, A.; Maunder, M.N.; Nielsen, A.; Sibert, J. AD Model Builder: using automatic differentiation for statistical inference of highly parameterized complex nonlinear models. Optimization Methods and Software. 27:233-249; 2012

MacFarlane, J.; Moore, R. Reproduction of the ornate rock lobster, Panulirus ornatus (Fabricius), in Papua New Guinea. Mar Freshwater Res. 37:55-65; 1986

Moore, R.; Macfarlane, J.W. Migration of the Ornate Rock Lobster, Panulirus-Ornatus (Fabricius), in Papua-New-Guinea. Aust J Mar Fresh Res. 35:197-212; 1984

Phillips, B.; Palmer, M.; Cruz, R.; Trendall, J. Estimating growth of the spiny lobsters Panulirus cygnus, P. argus and P. ornatus. Mar Freshwater Res. 43:1177-1188; 1992

Pitcher, C.R.; Skewes, T.D.; Dennis, D.M.; Prescott, J.H. Estimation of the Abundance of the Tropical Lobster Panulirus-Ornatus in Torres Strait, Using Visual Transect-Survey Methods. Mar Biol. 113:57-64; 1992

Plagányi, É.; Deng, R.; Dennis, D.; Hutton, T.; Pascoe, S.; van Putten, I.; Skewes, T. An integrated Management Strategy Evaluation (MSE) for the Torres Strait Tropical Rock Lobster Panulirus ornatus fishery. CSIRO/AFMA Final Project Report; 2012

Plaganyi, E.E.; van Putten, I.; Hutton, T.; Deng, R.A.; Dennis, D.; Pascoe, S.; Skewes, T.; Campbell, R.A. Integrating indigenous livelihood and lifestyle objectives in managing a natural resource. P Natl Acad Sci USA. 110:3639-3644; 2013

Pope, J. An investigation of the accuracy of virtual population analysis using cohort analysis. ICNAF Research Bulletin. 9:65-74; 1972

Punt, A.E.; McGarvey, R.; Linnane, A.; Phillips, J.; Triantafillos, L.; Feenstra, J. Evaluating empirical decision rules for southern rock lobster fisheries: A South Australian example. Fish Res. 115:60-71; 2012

Punt, A.E.; Smith, A.D.M. Harvest strategy evaluation for the eastern stock of gemfish (Rexea solandri). Ices J Mar Sci. 56:860-875; 1999

Rademeyer, R.; Butterworth, D.; Plagányi, É. A history of recent bases for management and the development of a species-combined Operational Management Procedure for the South African hake resource. African Journal of Marine Science. 30:291-310; 2008

Rademeyer, R.A.; Plaganyi, E.E.; Butterworth, D.S. Tips and tricks in designing management procedures. Ices J Mar Sci. 64:618-625; 2007

Trendall, J.; Bell, R.; Phillips, B. Growth of the spiny lobster, Panulirus ornatus, in the Torres Strait. Proc Workshop on Pacific Inshore Fisheries, South Pacific Commission: Noumea; 1988

Van Putten, I.; Deng, R.; Dennis, D.; Hutton, T.; Pascoe, S.; Plaganyi, E.; Skewes, T. The quandary of quota management in the Torres Strait rock lobster fishery. Fisheries Manag Ecol. 20:326-337; 2013a

van Putten, I.; Lalancette, A.; Bayliss, P.; Dennis, D.; Hutton, T.; Norman-Lopez, A.; Pascoe, S.; Plaganyi, E.; Skewes, T. A Bayesian model of factors influencing indigenous participation in the Torres Strait tropical rocklobster fishery. Mar Policy. 37:96-105; 2013b

# APPENDIX 1 – Operating Model - Stock Assessment Equations

## Introduction

Torres Strait rock lobsters emigrate in spring and breed during the subsequent summer (November-February) (MacFarlane and Moore 1986; Moore and Macfarlane 1984). Therefore, the number of age 2+ lobsters at the middle of the breeding season (December) should represent the size of the spawning stock (Figure A-0-1). A schematic summary timeline underlying the new Integrated model is presented in Figure A-0-1. To simplify computations, the new model assumes catches, migration and spawning occur at discrete times, with quarterly updates to the dynamics of each age class. Catches of 2+ individuals are assumed taken as a pulse at midyear, with individuals migrating out of the Torres Straits at the end of the third quarter, and a spawning biomass being computed at the end of the year. Catches of 1+ lobsters are assumed taken at the end of the third quarter, when a proportion of this age class have grown large enough to be available to fishers.

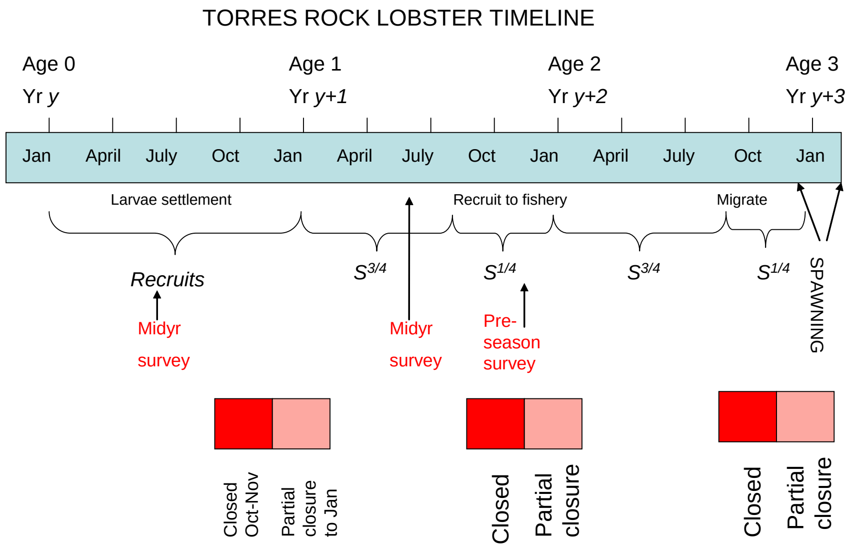



**Figure A-0-1. Summary timeline for Torres Strait Rock Lobster model.**

*P. ornatus* is an unusually fast growing lobster and hence analyses are expected to be sensitive to changes in assumption regarding growth rate (length vs age) and mass-at-length. Previous modelling studies used the Trendall et al. (1988) relationship:

$$CL_m = 177\left(1 - e^{-0.386(m/12 - 0.411)}\right)$$

where *CL* is carapace length (mm) and *m* is age in months for aspects of the computations. However, after converting length to mass using the morphometric relationship:

TOTWT=0.00258*(CL^2.76014)

the Trendall et al (1988) relationship translates into average individual masses that are less than the observed average mass of lobsters caught in the fishery. The Integrated model thus uses the Phillips et al. (1992) male growth relationship:

$$CL = L_\infty \left(1 - e^{-kt}\right)$$

where $L_\infty = 165.957 \quad mm$;
$\kappa = -0.0012$; and
$t$ is age in DAYS.

## The Integrated Fishery Model

An age-structured model of the Torres Strait rock lobster population dynamics was developed and fitted to the available abundance indices by maximising the likelihood function. The model equations and the general specifications of the model are described below, followed by details of the contributions to the log-likelihood function from the different sources of data available. Quasi-Newton minimization is used to minimize the total negative log-likelihood function (the package AD Model Builder$^{TM}$ (Fournier et al. 2012) is used for this purpose.

## Lobster population dynamics

### *Numbers-at-age*

The resource dynamics are modelled by the following set of population dynamics equations:

$$N_{y+1,1} = R_{y+1} \qquad 1$$

$$N_{y+1,a+1} = \left(N_{y,a}\, e^{-3M_a/4} - C_{y,a}\right) e^{-M_a/4} \qquad \text{for } a=1 \qquad 2$$

$$N_{y+1,a+1} = \left(N_{y,a}\, e^{-M_a/2} - C_{y,a}\right) e^{-M_a/2} \qquad \text{for } a=2 \qquad 3$$

where

$N_{y,a}$ is the number of lobsters of age $a$ at the start of year $y$ (which refers to a calendar year),

$R_y$ is the recruitment (number of 1-year-old lobsters) at the start of year $y$,

$M_a$ denotes the natural mortality rate on lobsters of age $a$,

$C_{y,a}$ is the predicted number of lobsters of age $a$ caught in year $y$, and

$m$ is the maximum age considered (taken to be 3).

These equations simply state that for a closed population, with no immigration and emigration, the only sources of loss are natural mortality (predation, disease, etc.) and fishing mortality (catch). They reflect Pope's form of the catch equation (Pope 1972) (the catches are assumed to be taken as a pulse at midyear for the 2+ class and at the start of the third quarter for the 1+ class) rather than the more customary Baranov form (Baranov 1918) (for which catches are incorporated under the assumption of steady continuous fishing mortality). Pope's form has been used in order to simplify computations.

*Recruitment*

The number of recruits (i.e. new 1-year old lobsters – it is simpler to work with 1- rather than 0-year old lobsters as recruits) at the start of year *y* is assumed to be related to the spawning stock size (i.e. the biomass of mature lobsters) by a modified Beverton-Holt stock-recruitment relationship (Beverton and Holt 1957), allowing for annual fluctuation about the deterministic relationship:

$$R_y = \frac{\alpha B^{sp}_{y-1}}{\beta + \left(B^{sp}_{y-1}\right)} e^{(\varsigma_y - (\sigma_R)^2/2)} \qquad 4$$

where

$\alpha, \beta$ are spawning biomass-recruitment relationship parameters,

$\varsigma_y$ reflects fluctuation about the expected recruitment for year *y*, which is assumed to be normally distributed with standard deviation $\sigma_R$ (which is input in the applications considered here); these residuals are treated as estimable parameters in the model fitting process. Estimating the stock-recruitment residuals is made possible by the availability of catch-at-age data, which give some indication of the age-structure of the population.

$B^{sp}_y$ is the spawning biomass at the start of year *y*, computed as:

$$B^{sp}_y = w^{st}_3 \cdot N_{y,3} \qquad 5$$

where

$w^{st}_3$ is the mass of lobsters of age 3 (i.e. in December during the spawning season).

In order to work with estimable parameters that are more meaningful biologically, the stock-recruitment relationship is re-parameterised in terms of the pre-exploitation equilibrium spawning biomass, $K^{sp}$, and the "steepness", *h*, of the stock-recruitment relationship, which is the proportion of the virgin recruitment that is realized at a spawning biomass level of 20% of the virgin spawning biomass:

$$\beta = \frac{\left(K^{sp}\right)^{\gamma}\left(1 - 5h0.2^{\gamma}\right)}{5h - 1} \qquad 6$$

and

$$\alpha = \frac{\beta + \left(K^{sp}\right)^{\gamma}}{SPR_{virg}} \qquad 7$$

where

$$SPR_{virg} = w^{st}_3 N^{virg}_3 \qquad 8$$

with

$$N^{virg}_1 = 1 \qquad 9$$

$$N^{virg}_a = N^{virg}_{a-1} e^{-M_{a-1}} \quad \text{for } 2 < a \le m \qquad 10$$

*Total catch and catches-at-age*

The catch by mass in year *y* is given by:

$$C_y = w_1^{land} N_{y,1} e^{-3M_a/4} S_{y,1} F_y^{1+} + w_2^{mid} N_{y,2} e^{-M_a/2} S_{y,2} F_y^{2+} \qquad 11$$

Where

$w_a^{land}$ denotes the mass of lobsters of age *a* that are landed at the end of the third quarter,

$w_a^{mid}$ denotes the mid-year mass of lobsters of age *a*,

$S_{y,a}$ is the commercial selectivity (i.e. vulnerability to fishing gear) at age *a* for year *y*; and

$F_y$ is the fished proportion (of the 1+ and 2+ classes) of a fully selected age class.

The model estimate of the exploitable ("available") component of biomass is calculated by converting the numbers-at-age into mass-at-age (using the individual weights of the 1+ lobsters assumed landed at the end of the third quarter, and the 2+ lobsters assumed landed at midyear):

$$B_y^{ex,1+} = w_1^{land} S_{y,1} N_{y,1} e^{-3M_a/4} \qquad 12$$

$$B_y^{ex,2+} = w_2^{mid} S_{y,2} N_{y,2} e^{-M_a/2} \qquad 13$$

and hence:

$$B_y^{ex} = B_y^{ex,1+} + B_y^{ex,2+} \qquad 14$$

The  model computes the catch by mass separately for the trawling sector, which is assumed to target 2+ lobsters only. The exploitable component of biomass for this sector is thus based on Equation (13) only and assumes full selectivity of the 2+ age group.

The model estimates of the midyear numbers of lobsters are:

$$N_y^{mid} = N_{y,1} e^{-M_1/2} + \left(N_{y,2}\, e^{-M_2/2} - C_{y,2}\right) \qquad 15$$

i.e.

$$N_{y,1}^{mid} = N_{y,1} e^{-M_1/2} \qquad 16$$

$$N_{y,2}^{mid} = N_{y,2}\, e^{-M_2/2} - C_{y,2} \qquad 17$$

Similarly, the model estimate of numbers for comparison with the Pre-Season November survey are as follows:

$$N_{y,1}^{pre} = \left(N_{y,1} e^{-3M_1/4} - C_{y,1}\right) e^{-M_1/6} \qquad 18$$

$$N^{pre}_{y,2} = N^{mid}{}_{y,2}\, e^{-5M_2/12} \quad - \tag{19}$$

The proportion of the 1+ and 2+ age classes harvested each year ( $F_y^{1+}$ ) are given respectively by:

$$F_y^{1+} = C_y^{1+} \;/\; B_y^{exp,1+} \tag{20}$$

$$F_y^{2+} = C_y^{2+} \;/\; B_y^{exp,2+} \tag{21}$$

where $C_y^{1+}$ and $C_y^{2+}$ are the catch by mass in year *y* for age classes 1 and 2, such that:

$$C_y^{1+} = p_{y,1+} C_y \tag{22}$$

and

$$C_y^{2+} = (1 - p_{y,1+}) C_y \tag{23}$$

with $p_{y,1+}$ representing the 1+ proportion of the total catch.

Given different fishing proportions for the two age classes, the numbers-at-age removed each year from each age class can be computed from:

$$C_{y,1} = S_{y,1} F_y^{1+} N_{y,1} e^{-3M_a/4} \quad \text{for } a = 1\text{, and} \tag{24}$$

$$C_{y,2} = S_{y,2} F_y^{2+} N_{y,2} e^{-M_a/2} \quad \text{for } a = 2 \tag{25}$$

The fully selected fishing proportion (*F*) is related to the annual fishing mortality rate (*F**) as follows:

$$1 - F = e^{-F^*} \tag{26}$$

### *Initial conditions*

Although some exploitation occurred before the first year for which data are available for the lobster stock, this is considered relatively minor and hence the stock is assumed to be at its pre-exploitation biomass level in the starting year and hence the fraction ( $\theta$ ) is fixed at one in the analysis described here:

$$B^{sp}_{y_0} = \theta \cdot K^{sp} \tag{27}$$

with the starting age structure:

$$N_{y_0,a} = R_{start} N_{start,a} \quad \text{for } 1 \le a \le m \tag{28}$$

where

$$N_{start,1} = 1 \tag{29}$$

$$N_{start,a} = N_{start,a-1} e^{-M_{a-1}} \quad \text{for } 2 \le a \le m-1 \tag{30}$$

## The (penalised) likelihood function

Model parameters are estimated by fitting to survey abundance indices, commercial and survey catch-at-age data as well as standardised CPUE data. A penalty function is included to permit estimation of residuals about the stock-recruitment function. Contributions by each of these to the negative of the log-likelihood (- $\ell nL$ ) are as follows.

### *Survey abundance data*

The same methodology is applied for the midyear and pre-season surveys, except that for the former there are indices for both the total 1+ and 2+ numbers, whereas for the pre-season the fit is only to the 1+ lobsters as most of the older lobsters will have migrated out of the region by November. The likelihood is calculated assuming that the observed midyear (and pre-season) survey abundance index is log-normally distributed about its expected value:

$$I_y^i = \hat{I}_y^i \exp\left(\varepsilon_y^i\right) \quad \text{or} \quad \varepsilon_y^i = \ell n\left(I_y^i\right) - \ell n\left(\hat{I}_y^i\right) \qquad 31$$

where

$I_y^i$ is the scaled survey abundance index for year *y* and series *i*,

$\hat{I}_y^i = \hat{q}_s \widehat{N}_y^{survey}$ is the corresponding model estimate, where $\hat{N}_y^{survey}$ is the model estimate of midyear numbers, given by equation 16 and 17 for the midyear survey, and for the pre-season survey it is given by equation 18.

$\hat{q}_s$ is the constant of proportionality (catchability) for the survey, and

$\varepsilon_y^i$ from $N\left(0, \left(\sigma_y^i\right)^2\right)$.

The contribution of the survey data to the negative of the log-likelihood function (after removal of constants) is then given by:

$$-\ell n\, L^{Surv} = \sum_i \sum_y \left[\ell n\left(\sigma_y^i\right) + \left(\varepsilon_y^i\right)^2 / 2\left(\sigma_y^i\right)^2\right] \qquad 32$$

where $\left(\sigma_y^s\right)^2 = \ln\left(1 + \left(CV_y\right)^2\right)$ and the coefficient of variation ( $CV_y$ ) of the resource abundance estimate for year *y* is input.
The survey catchability coefficient $\hat{q}_s$ is estimated by its maximum likelihood value:

$$\ell n\, \hat{q}_s = 1/n_i \sum_y \left(\ln I_y^i - \ln N_y^{ex}\right) \qquad 33$$

### *Commercial catches-at-age*

The contribution of the catch-at-age data to the negative of the log-likelihood function under the assumption of an “adjusted” lognormal error distribution is given by:

$$-\ell n\, L^{CAA} = \sum_y \sum_a \left[\ell n\left(\sigma_{com} / \sqrt{p_{y,a}}\right) + p_{y,a}\left(\ell n\, p_{y,a} - \ell n\, \hat{p}_{y,a}\right)^2 / 2\left(\sigma_{com}\right)^2\right] \qquad 34$$

where

$p_{y,a} = C_{y,a} / \sum_{a'} C_{y,a'}$ is the observed proportion of lobsters caught in year *y* that are of age *a*,

$\hat{p}_{y,a} = \hat{C}_{y,a} / \sum_{a'} \hat{C}_{y,a'}$ is the model-predicted proportion of lobsters caught in year *y* that are of age *a*, where

$$\hat{C}_{y,1} = N_{y,1}\, e^{-3M_a/4}\, S_{y,1}\, F_y^{1+} \qquad 35$$

$$\hat{C}_{y,2} = N_{y,2}\, e^{-M_a/2}\, S_{y,2}\, F_y^{2+} \qquad 36$$

and

$\sigma_{com}$ is the standard deviation associated with the catch-at-age data, which is estimated in the fitting procedure by:

$$\hat{\sigma}_{com} = \sqrt{\sum_y \sum_a \left(\ell n\, p_{y,a} - \ell n\, \hat{p}_{y,a}\right)^2 / \sum_y \sum_a 1} \qquad 37$$

The same approach is applied when fitting to the historic catch proportion data.

### *Survey catches-at-age*

The survey catches-at-age are incorporated into the negative of the log-likelihood in an analogous manner to the commercial catches-at-age, assuming an adjusted log-normal error distribution (equation 25) where:

$p_{y,a} = C_{y,a}^{surv} / \sum_{a'} C_{y,a'}^{surv}$ is the observed proportion of lobsters of age *a* in year *y*,

$\hat{p}_{y,a}$ is the expected proportion of lobsters of age *a* in year *y* in the survey, given by:

$$\hat{p}_{y,a} = N_{y,a} \Big/ \sum_{a'=1}^{2} N_{y,a} \qquad 38$$

### *Benchmark Survey Estimates of Absolute Abundance*

The absolute abundance of lobsters is estimated by fitting to data from two benchmark mid-year surveys. The total 2002 population estimate, together with 95% confidence interval, was $T_{89}$ = 9.0 (±1.9) million lobsters and for 1989, $T_{89}$ = 14.0 (±2.9) million lobsters (Pitcher et al. 1992). The 2+ year class was estimated at 1.77 (±0.38) million in 2002, and the 1+ year-class was at 5.2 (±1.5) million.

The approach is similar to that described above for the survey relative abundance index. The contribution of the survey data to the negative of the log-likelihood function (after removal of constants) is then given by:

$$-\ell \text{n}\, L^{Bench} = \ell \text{n}\left(\sigma_{89}\right) + \left(\varepsilon_{89}\right)^2 / 2\left(\sigma_{89}\right)^2 + \ell \text{n}\left(\sigma_{02}\right) + \left(\varepsilon_{02}\right)^2 / 2\left(\sigma_{02}\right)^2 \qquad 39$$

where $\varepsilon_{89} = \ell \text{n}\left(T_{89}\right) - \ell \text{n}\left(\hat{N}_{1989,1}^{mid} + \hat{N}_{1989,2}^{mid}\right)$;

$\varepsilon_{02} = \ell \text{n}\left(T_{02}\right) - \ell \text{n}\left(\hat{N}_{2002,1}^{mid} + \hat{N}_{2002,2}^{mid}\right)$; and

$(\sigma_y)^2 = \ln(1+(CV_y)^2)$ and the two coefficients of variation ($CV_{89}$ and $CV_{02}$) are input.

*Stock-recruitment function residuals*

The stock-recruitment residuals are assumed to be log-normally distributed and serially correlated. Thus, the contribution of the recruitment residuals to the negative of the (now penalised) log-likelihood function is given by:

$$-\ell nL^{pen} = \sum_{y=y1+1}^{y2}\left[\left(\frac{\lambda_y - \rho\lambda_{y-1}}{\sqrt{1-\rho^2}}\right)^2 \Big/ 2\sigma_R^2\right] \qquad 40$$

where

$\lambda_y = \rho\lambda_{y-1} + \sqrt{1-\rho^2}\,\varepsilon_y$ is the recruitment residual for year *y*, which is estimated for year *y*1 to *y*2 (see equation 4),

$\varepsilon_y$ from $N(0,(\sigma_R)^2)$,

$\sigma_R$ is the standard deviation of the log-residuals, which is input, and

$\rho$ is the serial correlation coefficient, which is fixed at 0 in base-case runs.

In the interest of simplicity, equation 40 omits a term in $\lambda_{y1}$ for the case when serial correlation is assumed ($\rho \neq 0$), which is generally of little quantitative consequence to values estimated.

The analyses conducted in this paper have however all assumed $\rho = 0$.

## Model parameters

Natural mortality:

Natural mortality ($M_a$) is generally taken to be age independent and is estimated in the model fitting process.

In sensitivity tests where age-dependence is admitted, it is taken to have the form:

$$M_a = \mu_1 + \mu_2 / a \qquad 41$$

Fishing selectivity-at-age:

The commercial selectivity is taken to differ over the 1973-2002 and 2002+ periods. Full selectivity of the 2+ class is assumed, with a separate selectivity parameter being estimated for each period for the 1+ class.

## Table A1.1. Operating Models OM1-OM3 base estimates and settings for future projections

**OM1 : -lnL = -163.083**

| Parameter | OM1 Value | Units | Source |
|---|---|---|---|
| *B(1973)$^{sp}$(tons)* | 5696 | t | model estimate |
| *M* | 0.69 | $y^{-1}$ | model estimate |
| *h* | 0.70 | - | fixed model input |
| *Sel (age 1+) TIB,TVH 1973-1988* | 0.43 | - | stock assessment; relative to full selectivity of 2+ |
| *Sel (age 1+) TIB,TVH 1989-2001* | 0.16 | - | stock assessment; relative to full selectivity of 2+ |
| *Sel (age 1+) TIB,TVH post2002* | 0.02 | - | stock assessment; relative to full selectivity of 2+ |
| *Sel (age 1+) trawling* | 0.00 | - | stock assessment; relative to full selectivity of 2+ |
| Recruitment residuals sigma | 0.50 | - | fixed input based on stock assessment model |
| *Recruitment residuals (1985-2014)* | 30 parameters | | model estimates |
| Future recruitment residual sigma_out | 0.32 | | model output estimate |
| Catchability coefficient $q_f$ (TVH) | 1.86E-03 | - | model estimate; hyperstability fixed at 0.75 |
| Catchability coefficient $q_f$ (TIB) | 1.63E-02 | - | model estimate; hyperstability fixed at 0.5 |

**OM2 – *h*=0.5; -lnL = -162.815 (ns)**

| Parameter | OM2 Value | Units | Source |
|---|---|---|---|
| *B(1973)$^{sp}$(tons)* | 5187 | t | model estimate |
| *M* | 0.69 | $y^{-1}$ | model estimate |
| *h* | 0.70 | - | fixed model input |
| *Sel (age 1+) TIB,TVH 1973-1988* | 0.43 | - | stock assessment; relative to full selectivity of 2+ |
| *Sel (age 1+) TIB,TVH 1989-2001* | 0.16 | - | stock assessment; relative to full selectivity of 2+ |
| *Sel (age 1+) TIB,TVH post2002* | 0.02 | - | stock assessment; relative to full selectivity of 2+ |
| *Sel (age 1+) trawling* | 0.00 | - | stock assessment; relative to full selectivity of 2+ |
| Recruitment residuals sigma | 0.50 | - | fixed input based on stock assessment model |
| *Recruitment residuals (1985-2014)* | 30 parameters | | model estimates |
| Future recruitment residual sigma_out | 0.32 | | model output estimate |
| Catchability coefficient $q_f$ (TVH) | 1.86E-03 | - | model estimate; hyperstability fixed at 0.75 |
| Catchability coefficient $q_f$ (TIB) | 1.63E-02 | - | model estimate; hyperstability fixed at 0.5 |

**OM3 – *hyps*=1; -lnL = -157.197**

| Parameter | OM3 Value | Units | Source |
|---|---|---|---|
| *B(1973)$^{sp}$(tons)* | 4741 | t | model estimate |
| *M* | 0.69 | $y^{-1}$ | model estimate |
| *h* | 0.70 | - | fixed model input |
| *Sel (age 1+) TIB,TVH 1973-1988* | 0.43 | - | stock assessment; relative to full selectivity of 2+ |
| *Sel (age 1+) TIB,TVH 1989-2001* | 0.16 | - | stock assessment; relative to full selectivity of 2+ |
| *Sel (age 1+) TIB,TVH post2002* | 0.02 | - | stock assessment; relative to full selectivity of 2+ |
| *Sel (age 1+) trawling* | 0.00 | - | stock assessment; relative to full selectivity of 2+ |
| Recruitment residuals sigma | 0.50 | - | fixed input based on stock assessment model |
| *Recruitment residuals (1985-2014)* | 30 parameters | | model estimates |
| Future recruitment residual sigma_out | 0.32 | | model output estimate |
| Catchability coefficient $q_f$ (TVH) | 2.33E-04 | - | model estimate; hyperstability fixed at 1.0 |
| Catchability coefficient $q_f$ (TIB) | 2.67E-04 | - | model estimate; hyperstability fixed at 1.0 |

## APPENDIX 2 – The TRL HCR preliminary specifications

Four different kinds of HCRs were tested as follows:

(1) Constant catch scenarios are also shown for comparison
(2) Slope - Based on a simple fixed slope parameter applied to the preseason survey indices;
(3) Regression – Based on the slope of a regression line that is fitted each year to the past *n* (n=5 in base-case) survey data points, and similarly for CPUE where included, and multiplied by either a fixed average historical catch (average of past 5 years in base-case) or the average of the previous 5 year's catch.
(4) Log Regression – As above, except that the slope is computed based on the natural logarithm of the survey and CPUE indices in an attempt to decrease inter-annual variability.

In all these cases, an additional option can be included to cap the maximum catch (1000 t in base-case), and if preferred, to also set the minimum catch (300 t in base-case).

The formulae options for computing the TAC recommendation are as follows:

(1) Constant Catch

$$TAC_{y+1} = \bar{C} \quad \text{where } \bar{C} \text{ is a fixed average catch (t)} \qquad (1)$$

(2) Simple slope

$$TAC_{y+1} = \mu \cdot \left( \lambda^{pre1} \cdot I_y^{pre1} \Big/ \overline{I^{pre1}} + (1-\lambda^{pre1}) \cdot I_y^{pre0} \Big/ \overline{I^{pre0}} \right) \qquad (2)$$

Where

$TAC_y$ is the total TAC recommended for year *y*,

$\mu$ is a slope parameter based on historic survey data, obtained by comparing the slope of the relationship between catch and the survey index; results presented here fix the value at 600;

$\lambda^{pre1}$ is a tuning parameter that assigns weight to the preseason 1+ survey compared with the 0+ survey (if the value is set at 1, then only the 1+ survey data are used)

$I_y^{pre1}, \overline{I^{pre1}}$ are respectively the preseason 1+ survey index in year *y*, and the average value;

$I_y^{pre0}, \overline{I^{pre0}}$ are respectively the preseason 0+ survey index in year *y*, and the average value.

This formulation could be extended to include the midyear survey and/or CPUE indices.

(3) Regression slope

$$TAC_{y+1} = \lambda \cdot \left(1+s_y^{surv}\right) \cdot \bar{C}_{05\_08} + (1-\lambda) \cdot \left(1+s_y^{CPUE}\right) \cdot \bar{C}_{y-5,y-1} \quad (3)$$

where

$\bar{C}_{05\_08}$ is the average achieved catch during 2005 to 2008 (corresponding to the availability of preseason survey data),

$\bar{C}_{y-4,y}$ is the average achieved catch during the past 5 years, including the current year i.e. from year *y*-4 to year *y*,

$\lambda$ is a tuning parameter that assigns weight to the preseason trend compared with the CPUE trends, preliminary value is 0.7 to reflect greater precision of preseason index,

$s_y^{surv}$ is a measure of the past trend in the preseason survey abundance index as available to use for calculations for year *y*, and including the original 4 survey years, and

$s_y^{CPUE}$ is the average of the recent past trend in both the TVH and TIB CPUE abundance index as available to use for calculations for year *y*.

The trend measures are computed from the preseason survey 1+ index ( $I_y^{surv,1+}$ ), the standardized TVH CPUE ( $I_y^{CPUE,TVH}$ ), and TIB CPUE ( $I_y^{CPUE,TIB}$ ) indices, by computing the slope of the recent indices, or first computing the logarithm of the indices and then applying a linear regression:

- linearly regress $\ln I_y^{surv,1+}$ *vs* year *y*' for $y' = 2005$ to $2008$ and also including from $y' = y - p$ to $y' = y$, where *p* is the number of preseason surveys since 2014, to yield a regression slope value $s_y^{surv}$,
- linearly regress $\ln I_y^{CPUE,TVH}$ *vs* year *y*' for $y' = y - n$ to $y' = y$ (or y-1), to yield a regression slope value $s_y^{CPUE,TVH}$, where *n* is the length of the period considered for this regression, use standardized CPUE (see Fig. 2),
- linearly regress $\ln I_y^{CPUE,TIB}$ *vs* year *y*' for $y' = y - n$ to $y' = y$ (or y-1), to yield a regression slope value $s_y^{CPUE,TIB}$, still to decide if use nominal or std TIB CPUE

An average CPUE slope value is then computed as follows:

$$s_y^{CPUE} = \left( \frac{s_y^{CPUE,TVH}}{2} + \frac{s_y^{CPUE,TIB}}{2} \right) \qquad (2)$$

Alternative weightings can also be explored.

The tuning parameter, $\lambda$, is a measure of how responsive the HCR is to change in trend in the preseason survey versus CPUE data.

*TAC change constraints*

For all the HCR versions tested, it is possible to add additional constraints to limit inter-annual variability in the TAC. Hence an upper limit and lower limit are used in some scenarios, with base-case values set as follows:

$C^{\max} = 1000$

$C^{\min} = 300$

Alternative values could be tested, or a formulation whereby the TAC is constrained to increase or decrease by no more than a given percentage from year to year.

## APPENDIX 3 - Example of application of illustrative HCR to set 2015 TAC

Aug 2014 assessment model TAC prelim recommendation:  894t

June 2015 AFMA report update assessment including 2014 Preseason survey: 769t

Assuming applied HCR in Dec 2014 with survey + CPUE data for 2014 available: **707t**

(other settings λ=0.7; use TAC2014 as catch for 2014; std TVH CPUE; nominal TIB CPUE (with missing value for 2013))

Table A4.1. Original Worked example of HCR for calculating TAC for 2015.

| | Slope estimate | Average Catch (t) applied | (1+slope)*Catch | □*catch |
|---|---|---|---|---|
| Preseason survey | 0.0383 | 708 | 735.1 | 514.6 |
| TVH CPUE | -0.1 | | | |
| TIB CPUE | -0.081 | | | |
| Ave CPUE slope | -0.0905 | 706.6 | 642.7 | 192.8 |
| TAC for 2015 | | | | 707.4 |

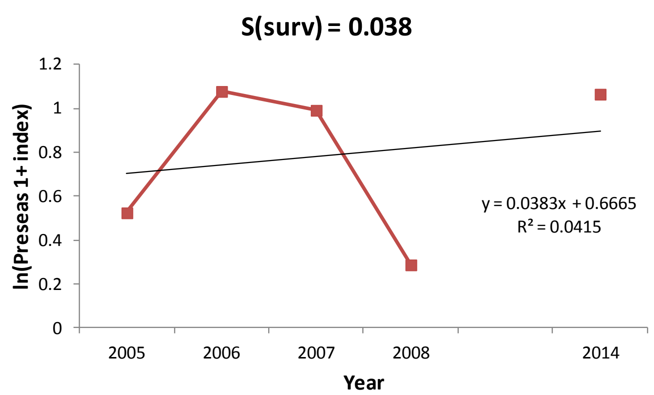



Fig. 1. Regression of natural logarithm of preseason survey index (1+ numbers) against year, to estimate survey slope estimate as shown. In HCR application, regression would be updated every year to take into account additional year's survey.

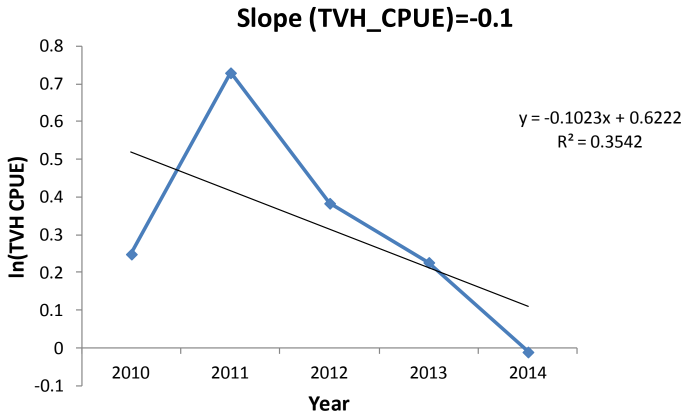



Fig. 2. Regression of natural logarithm of (Main effects model) TVH CPUE index against year, to estimate first CPUE slope estimate as shown. In HCR application, regression would be shifted forwards one year every year to focus on last 5 years.

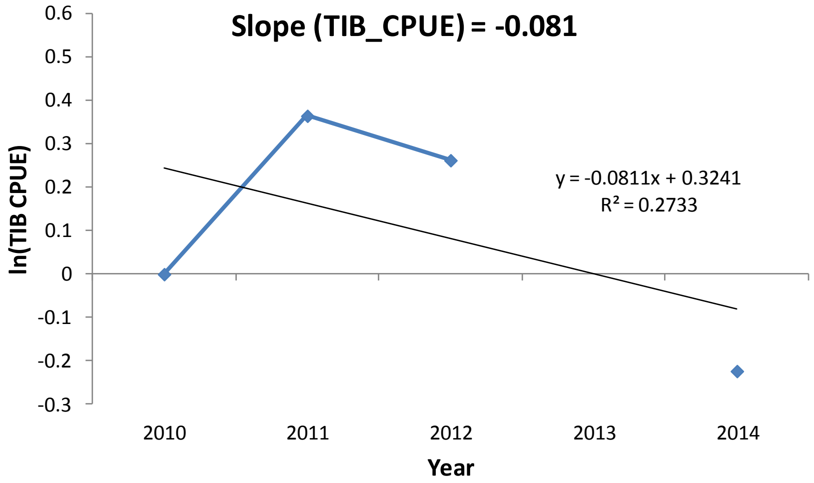



Fig. 3. Regression of natural logarithm of nominal TIB CPUE index against year, to estimate second CPUE slope estimate as shown. In HCR application, regression would be shifted forwards one year every year to focus on last 5 years.

## APPENDIX 4 – Guidelines for consideration under Exceptional Circumstance

The extract below is based on (Rademeyer et al. 2008)

**Preamble**

The pre-agreed HCR formulae for computing the TAC is based on pre-agreed resource monitoring data inputs. This combination of formulae and data will have been simulation tested to ensure anticipated performance that is adequately robust given inevitable scientific uncertainties about data and models of the resource dynamics and fishery. However, occasionally "Exceptional Circumstances" can arise which may indicate the need for recommendations to deviate from the outputs of the HCR, or necessitate bringing a more comprehensive review forward.

On a number of occasions below, the text requires judgements to be made of whether an effect is "appreciable" (for example, whether an abundance survey result is *appreciably* outside the range predicted in the simulation tests used in selecting the OMP). Such judgements are the province of the TRLRAG.

### 1. Metarule Process

Metarules can be thought of as "rules" which pre-specify what should happen in unlikely, exceptional circumstances when application of the TAC generated by the HCR is considered to be highly risky or highly inappropriate. Metarules are not a mechanism for making small adjustments, or 'tinkering' with the TAC from the HCR.

While the broad circumstances that may invoke the metarule process can be identified, it is not always possible to pre-specify the data that may trigger a metarule.

Examples of what might constitute an exceptional circumstance in the case of [hake] include, but are not necessarily limited to:

- Survey estimates of abundance that are appreciably outside the bounds predicted in the HCR testing.
- CPUE trends that are appreciably outside the bounds predicted in the HCR testing.
- Anomalous environmental conditions.

The primary focus for concluding that exceptional circumstances exist is if the population assessment/indicator review process provides results appreciably outside the range of simulated population and/other other indicator trajectories considered in HCR evaluations. Similarly, if there are regulatory changes likely to effect appreciable modifications to outcomes predicted in terms of the assumptions used for projections in the HCR evaluations, or changes to the nature of the data collected for input beyond those for which allowance may have been made in those evaluations, this would constitute grounds for concluding that exceptional circumstances exist in the context of continued application of the current HCR.

IF the TRLRAG agrees that exceptional circumstances exist, the severity of the exceptional circumstances needs consideration and a pre-agreed "Process for Action" could be followed.

For example, if the risk is to the resource, action could include at least an x% decrease in the TAC output by the HCR (or fishery closure), depending on severity.

If the risk is to socio-economic opportunities within the fishery, action could include at least a y% increase in the TAC output by the HCR, depending on severity.

The procedure for regular review and potential revision of the HCR is the process for updating and incorporating new data, new information and knowledge into the management procedure, including the operating models (OMs) used for testing the procedure.  This process is likely to occur every 3 years, but can be initiated at any time if there is sufficient reason for this.

If a stock assessment is conducted every three years, a process such as the following could be followed:

- Conduct an in depth stock assessment and review population, fishery and related ecosystem indicators, and any other relevant data or information on the population, fishery and ecosystem.
- On the basis of this, determine whether the assessment (or other) results are outside the ranges for which the HCR was tested (note that evaluation for exceptional circumstances could be carried out in parallel with this process), and whether this is sufficient to trigger a review/revision of the HCR.

- Review whether enough has been learnt to appreciably improve/change the operating models (OMs), or to improve the performance of the HCR, or to provide new advice on tuning level (chosen to aim to achieve management objectives).
- On the basis of this, determine whether the new information is sufficient to trigger a review/revision of the HCR.

**Reference**

Rademeyer, R.; Butterworth, D.; Plagányi, É. A history of recent bases for management and the development of a species-combined Operational Management Procedure for the South African hake resource. *African Journal of Marine Science*. 30:291-310; 2008

## APPENDIX 5 Results – initial set

## APPENDIX 6 Further Results – revised HCRs