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Development and evaluation of a cpue-based harvest control rule for the southern and eastern scalefish and shark fishery of Australia

L. Richard Little[1]*, Sally E. Wayte[1], Geoffrey N. Tuck[1], Anthony D. M. Smith[1], Neil Klaer[1], Malcolm Haddon[1], André E. Punt[1,2], Robin Thomson[1], Jemery Day[1], and Mike Fuller[1]

[1]*CSIRO Marine and Atmospheric Research and Wealth from Oceans Flagship, GPO Box 1538, Hobart, Tasmania 7001, Australia*
[2]*School of Aquatic and Fishery Sciences, University of Washington, Box 355020, Seattle, WA 98195-5020, USA*

**Corresponding author: tel +61 3 6232 5006; fax +61 3 6232 5053; E-mail: rich.little@csiro.au*

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Many fishery management agencies are adopting harvest control rules (HCRs) to achieve harvest policies and management objectives. HCRs, however, often require data-intensive stock assessments to facilitate the harvest prescription. An HCR based on catch and catch per unit effort (cpue) was developed for the southern and eastern scalefish and shark fishery of Australia, for stocks that lack the data needed to conduct a full statistical catch-at-age assessment. The HCR produces a recommended biological catch and is characterized by two parameters, target cpue and target catch, both derived from historical data. Simulation tests showed that the HCR could guide the stock to the desired state from different initial levels of depletion. However, the selection of parameter values for the HCR was critical. Achieving fishery objectives was difficult when the target catch was a function of recent catch, rather than data from a pre-defined historical reference period. Problems may also arise when specifying the reference period on which the HCR parameters are determined. The cpue-based HCR is a valuable tool for managing fisheries where monitoring and assessment activities are relatively expensive, or in general, where data are scarce.

Keywords: Australia, cpue, harvest control rule, management strategy evaluation, simulation.

Introduction

Guidelines that aim to achieve broad fishery-management objectives are referred to as harvest policies. To implement such policies with output controls, harvest control rules (HCRs) are needed to prescribe the annual harvest as a function of stock status (Deroba and Bence, 2008).

The Australian federal government introduced a harvest policy for all fisheries under its jurisdiction in 2007 (DAFF, 2007; Smith *et al.*, 2009). These fisheries include the southern and eastern scalefish and shark fishery (SESSF), a multispecies, multigear fishery that is the main source of fresh fish to the Sydney and Melbourne markets. Catches are taken both inshore and offshore, bounded by Fraser Island (Queensland) in the north, around southeastern Australia, and west to the border of Western Australia. Management of the SESSF is based on a mixture of input and output controls, with more than 30 commercial stocks, species or species groups currently under quota management.

A formal harvest-strategy policy (HSP) was implemented for the SESSF in 2008 (DAFF, 2007; Rayns, 2007), with the goal of maximizing the economic output of the fishery. The HSP specifies processes for monitoring and assessing each stock managed under the quota system, as well as the HCRs that translate assessment results into management advice in the form of a recommended biological catch (RBC). A total allowable catch (TAC) is then calculated from the RBC, accounting for catches in the adjoining Australian states, anticipated discards, and incorporating a factor to account for the uncertainties in different types of stock assessment. The HCRs developed for the HSP ultimately aim to move the stock biomass to a target level where economic yield is maximized, B_{MEY}. A default proxy, 48% of the pre-exploitation biomass (the biomass before any fishing), represented as B_{48}, is used for the target biomass in the absence of alternatives provided by formal analyses (DAFF, 2007; note that we use B_{100} for the unexploited equilibrium biomass; other authors often express this as B_0). These HCRs also include a limit reference point (20% of the pre-exploitation biomass, B_{20}) below which the RBC is zero, targeted fishing is prohibited, and a rebuilding plan must be developed (DAFF, 2007). Rebuilding plans in the past have included monitoring and mitigation strategies to protect spawning aggregations, for example, and also a TAC for bycatches (AFMA, 2008).

Each stock in the SESSF is assigned to one of four "Tiers" for assessment purposes under the HSP. The assessment Tiers have different levels of either quantity or quality of data. Therefore, assessments range from a fitted statistical catch-at-age model with high-quality (Tier 1) or low-quality (Tier 2) data, to analysis of catch curves (Tier 3) or catch per unit effort (cpue) data (Tier 4). Each Tier uses a different HCR to translate the estimated stock status into the RBC (Smith *et al*., 2008). The Tier 4 HCR presented here is currently applied to 13 stocks in the fishery.

The initial cpue-based HCR implemented in the SESSF for Tier 4 stocks (Smith *et al*., 2008) was unsuccessful because it did not have an explicit target cpue. This HCR tended to maintain *status quo*, resulting in virtually constant RBCs even when the stock was depleted. Several alternative methods for setting TACs using minimal amounts of data have been proposed (e.g. Kolody *et al*., 2009; MacCall, 2009; O'Neill *et al*., 2010). Methods such as those of Pope (1983), Shepherd (1991), Dichmont *et al*. (2006) and the North Pacific Fishery Management Council Tier 4 rule (NPFMC, 2001) require more information than is available for the Tier 4 stocks in the SESSF. In this paper, we outline a simple catch- and cpue-based HCR that includes cpue targets and limit reference points, using a simulation procedure known as management strategy evaluation (MSE) to evaluate the effectiveness of the HCR under a range of conditions (Smith *et al*., 1999).

Methods

The Tier 4 HCR sets the RBC using the formula

$$\text{RBC} = C_{\text{targ}} \max\left(\frac{\overline{\text{cpue}} - \text{cpue}_{\text{lim}}}{\text{cpue}_{\text{targ}} - \text{cpue}_{\text{lim}}}, 0\right), \quad (1)$$

where $\text{cpue}_{\text{targ}}$ is the target cpue, cpue_{lim} the limit cpue, $\overline{\text{cpue}}$ the average cpue observed over the past m years, and C_{targ} a catch target. Under this HCR, the RBC is zero if $\overline{\text{cpue}}$ is less than cpue_{lim}, then increases linearly to reach C_{targ} when $\overline{\text{cpue}}$ is at $\text{cpue}_{\text{targ}}$. Although no maximum RBC is specified, the SESSF has a management rule that the TAC cannot change by more than 50% from year to year. Also, the TAC does not change if the difference in the recommended value from that of the previous year is $<10\%$. This rule was instituted by the management agency, on advice from industry and scientists, with the intent of preventing inconveniently small incremental changes from year to year.

The Tier 4 HCR developed here uses cpue as the target indicator and is based on fishery-dependent logbook information, which includes only retained catches. Based on the state of this indicator, the HCR generates an RBC as a proportion of C_{targ}, which is based on total catch. The RBC is then translated into a TAC by removing expected discards, which are determined from a weighted average of discards estimated for the previous 4 years, with greater weighting on the most recent data.

Selection of HCR parameters

The parameters of the HCR are set assuming that cpue is proportional to stock abundance, using the following two rules.

(i) If a cpue series is available for the entire exploitation history of the fishery, then, assuming the stock was at unexploited equilibrium at the start of the fishery, the initial cpue, $\text{cpue}_{\text{init}}$, corresponds to B_{100}, and the other reference points are simply fractions of this level, i.e. $\text{cpue}_{\text{targ}} = 0.48\ \text{cpue}_{\text{init}}$, and $\text{cpue}_{\text{lim}} = 0.2\ \text{cpue}_{\text{init}}$, with C_{targ} set to the catches observed at $\text{cpue}_{\text{targ}}$.

(ii) If the cpue time-series does not go back to the start of fishing, $\text{cpue}_{\text{targ}}$ is set to the average cpue during a period of relative stability, i.e. one identified as desirable in terms of cpue, catches, and the status of the fishery. cpue_{lim} is 20/48 of this value. The value for C_{targ} is set to the average catch over the same period.

Most species in the SESSF fall under the second rule, and examination of fisheries data shows that for many species, cpue and catches were relatively stable and desirable during the period 1986–1995. We assumed that the stock biomass was also stable then. When applying the rule, therefore, we set $\text{cpue}_{\text{targ}}$ and C_{targ} to the average values from 1986 to 1995 (unless otherwise specified), under the assumption that the stock was close to B_{MEY} during that period.

Evaluation of alternative HCRs

MSE is an approach used widely for evaluating HCRs (Punt *et al*., 2001, 2005). It attempts to account not only for the uncertainty in the underlying dynamics of fish populations, but also for that associated with the methods and data used to assess and prescribe management actions (Smith *et al*., 1999). The MSE approach involves evaluating the entire management process from data collection, analysis, and stock assessment to the application of HCRs that rely on these analyses, using Monte Carlo simulation where parameters or data values are sampled from appropriate probability distributions. The result is the distribution of possible outcomes associated with a particular management strategy (Haddon, 2001). MSE is, therefore, designed to explore, as realistically as possible, the consequences of potential management options for a fishery.

An MSE model has been developed for the SESSF (Wayte, 2009), consisting of an operating model that represents the real world, and an associated assessment model that measures or estimates the state of the stock represented in the operating model and provides results to a decision procedure such as an HCR, all within a simulation framework. The technical specifications of the SESSF operating and assessment models are given in Fay *et al*. (2009). The operating model consists of an age-structured population dynamics model. For the evaluation of the Tier 4 HCR, the assessment model works by analysing past and future cpue data generated based on the biomass in the underlying operating model.

Each simulation for a given stock has two parts. The first involves historical data to set the starting conditions for future projections. This is achieved by fitting the operating model to the real historical data for the stock concerned. The second part projects the population into the future, from these starting conditions, by setting future catches derived with the HCR, which is informed by the cpue generated from the operating model. Multiple projections are conducted to account for various sources of stochastic error. Process error from annual recruitments is captured by lognormally sampling from an underlying Beverton–Holt stock–recruitment relationship:

$$N_{s,0,t} = 0.5\left(\frac{4hR_0S_t}{S_0(1-h)+S_t(5h-1)}\right)e^{\varepsilon_t - 0.5\sigma_R^2} \quad \varepsilon_t \sim N(0, \sigma_R^2), \quad (2)$$

where $N_{s,a,t}$ is the number of fish of sex s and age a at the start of year t, ε_t the recruitment residual for year t, h the steepness of the stock–recruitment relationship, S_t the spawning biomass at time t (S_0 is the spawning biomass at pre-exploitation equilibrium when recruitment equals R_0), and σ_R the standard deviation of the logarithm of recruitment about the expected value from the stock–recruitment relationship (Haltuch *et al.*, 2008).

Observation error is incorporated in the projection period based on the relationship between cpue and biomass:

$$\text{cpue}_t^f = q^f B_t^f \mathrm{e}^{\eta^f - 0.5\sigma_f^2} \quad \eta^f \sim N(0, \sigma_f^2), \tag{3}$$

where cpue_t^f is the cpue in the operating model for fleet *f* during year *t*, $\sigma_f^2 = \ln(1 + cv_f^2), \text{cv}_f$ is the coefficient of variation of the cpue observation error for fleet *f*, q^f the catchability coefficient for fleet *f* (cv_f and q^f are estimated when the operating model is fitted to the real historical data), and B_t^f the retainable vulnerable biomass for fleet *f* in the middle of year *t*:

$$B_t^f = \sum_s \sum_L w_{L,s} \varphi_L^f V_L^f \sum_a \Phi_{L,s,a} N_{s,a,t} \mathrm{e}^{-0.5M}, \tag{4}$$

where $w_{L,s}$ is the weight per fish of sex *s* in length class *L*, φ_L^f the fraction of the catch of animals in length class *L* retained by fleet *f*, V_L^f the gear selectivity by fleet *f* on fish in length class *L*, $\Phi_{L,s,a}$ the proportion of fish of sex *s* and age *a* that are in length class *L*, and *M* the instantaneous rate of natural mortality. Observation error therefore directly influences the relationship between stock biomass and cpue used in the HCR.

In reality, because the cpue data used for Tier 4 HCRs are based on fishery-dependent logbook information, which includes only retained catches, and because SESSF stocks can be fished by several fleets simultaneously, the outputs from a cpue standardization (Maunder and Punt, 2004) are actually used as inputs in the HCR, because standardization accounts for differences among vessels, fishing grounds, etc. However, we did not perform a cpue standardization in the MSE analyses, but instead used the simulated cpue from the fleet with the largest catch over the most recent five years. After the TAC is determined from the RBC, the share allocated to each fleet is based on its proportion of the total catch over the most recent 5 years.

Simulated populations are based on the biology and fishery characteristics of tiger flathead (*Neoplatycephalus richardsoni*) and school whiting (*Sillago flindersi*). Tiger flathead is an important species in the SESSF, achieving maximum lengths around 60 cm, and ages of 20 years. It is found mainly at depths of 40–100 m and is a major component of the fishery in terms of yield, profitability, and effort. It has been targeted historically by four fleets: steam trawlers (1915–1961), Danish seiners (1921–present), diesel otter trawlers off NSW and Victoria (1971–present) and off Tasmania (1985–present; Klaer, 2007). We chose to examine the effects of implementing this HCR on tiger flathead because we know the stock dynamics on which the underlying operating model was based and could therefore test decision procedures based on the HCRs for all four Tiers.

The Tier 4 HCR for school whiting was evaluated because that species has greater uncertainty in the stock dynamics, given it is a small (15–20 cm), fast-growing, fecund species with a maximum age of ~5 years and has highly variable recruitment. Consequently, school whiting display variable cpue and catches. Since records began in 1947, the species has been caught by two fleets: Danish seiners and otter trawlers (Day, 2007). The HCR was parametrized for both stocks, unless otherwise stated, by identifying the period 1986–1995 as producing a sustainable yield at a relatively constant cpue.

Projections started in 2007 (the last year in which an actual stock assessment of both species was performed and could be used to parametrize the operating model) and continued for 80 years to highlight any transient dynamics caused by the HCR. Ten scenarios were performed, each replicated 100 times (Table 1). These examined the implications of changing the historical reference period for the HCR parameters from 1986–1995 to 1998–2002, the implications of calculating C_{targ} based on the average catch in a historical reference period, or on the average for the most recent 4 years, and the effect of starting the projection at different stock-status levels. Scenario 4 mimics the cpue-based HCR that was initially chosen for Tier 4 stocks (Smith *et al.*, 2008) by calculating C_{targ} as the average of the most recent 4 years of catches. Values for C_{targ} are reported in Table 1. The values for $\text{cpue}_{\text{targ}}$ are not reported because they vary among simulations as a result of observation error. The coefficient of variation (cv_f) for the observation error was 0.2 for tiger flathead and 0.3 for school whiting.

The state of the stock when the HCR was first applied was selected so that the spawning biomass was in turn equal to, below, or above the target level (Table 1). These constraints were implemented by adjusting the recruitment residuals for the 9 years before the start of the projection period, which preserved the historical dynamics of the populations as much as possible.

Table 1. Ten scenarios examined which differ according to species, initial conditions of the projection period, parameters of the HCR (including historical period), and the catch target, C_{targ}.

		Historical period from which			
Scenario	**Species**	**$\text{cpue}_{\text{targ}}$ is calculated**	**C_{targ} is calculated**	**Initial conditions relative to B_{48}**	**C_{targ} (t)**
1	Tiger flathead	1986–1995	1986–1995	At target	2 177
2	Tiger flathead	1986–1995	1986–1995	Below target	2 177
3	Tiger flathead	1986–1995	1986–1995	Above target	2 177
4	Tiger flathead	1986–1995	Average over most recent four years	Below target	Variable
5	Tiger flathead	1998–2002	1998–2002	Below target	3 238
6	School whiting	1986–1995	1986–1995	At target	1 864
7	School whiting	1986–1995	1986–1995	Below target	1 864
8	School whiting	1986–1995	1986–1995	Above target	1 864
9	School whiting	1986–1995	Average over most recent four years	Below target	Variable
10	School whiting	1998–2002	1998–2002	Below target	1 539

Results

The results of the projections are summarized by time-trajectories (medians, 2.5 percentile, and 97.5 percentile for the projection period) of spawning biomass relative to B_{100}, cpue relative to $cpue_{targ}$, and catches. Scatterplots of cpue and RBC relative to the target levels show whether the reference period catches align with the targets specified from the HCR.

Tiger flathead

Ideally, the average biomass during the reference period for $cpue_{targ}$ should equal the harvest-policy objective B_{48}. However, the operating model showed an average biomass for 1986–1995 (Figure 1a, shaded area) slightly higher than B_{48} (Figure 1a, grey line). The cpue and the catch targets (Figure 1b and c, blue dashed lines) were within the range specified for the reference period (Figure 1b and c, shaded area).

The HCR maintained the biomass and cpue close to their respective target levels when the initial population was B_{48} (scenario 1, Figure 1). However, the median biomass tended to be slightly $>B_{48}$ (Figure 1a), whereas the median cpues and catches (Figure 1b and c) were slightly below their target levels because this combination of catch and cpue (biomass) represented an equilibrium condition in the operating model. The RBC and cpue values across all years and replicates clustered symmetrically around the target levels (Figure 1d).

The HCR also guided the biomass and catch rates close to the target levels when the biomass started the projection period $<B_{48}$ (scenario 2, Figure 1e). The projected catches were initially lower for scenario 2 than for scenario 1, which allowed the spawning biomass and catch rates to recover quickly, slightly overshooting the target, but eventually stabilizing close to target levels. The long-term catches were about the same (2000 t) for scenarios 1 and 2 (Figure 1c and g). The HCR could also guide the biomass towards the target level when it was initially $>B_{48}$ (scenario 3, Figure 1), by setting relatively high RBCs (Figure 1k) at the start of the projection period.

The HCR used for scenario 4 (Table 1) was similar to the Tier 4 HCR adopted for the SESSF during the years 2005–2007, in that C_{targ} was determined as the average catch in the 4 years before setting the RBC. Consequently, C_{targ} changed slowly over time and tracked recent TACs, but with a lag (Figure 1o). When large

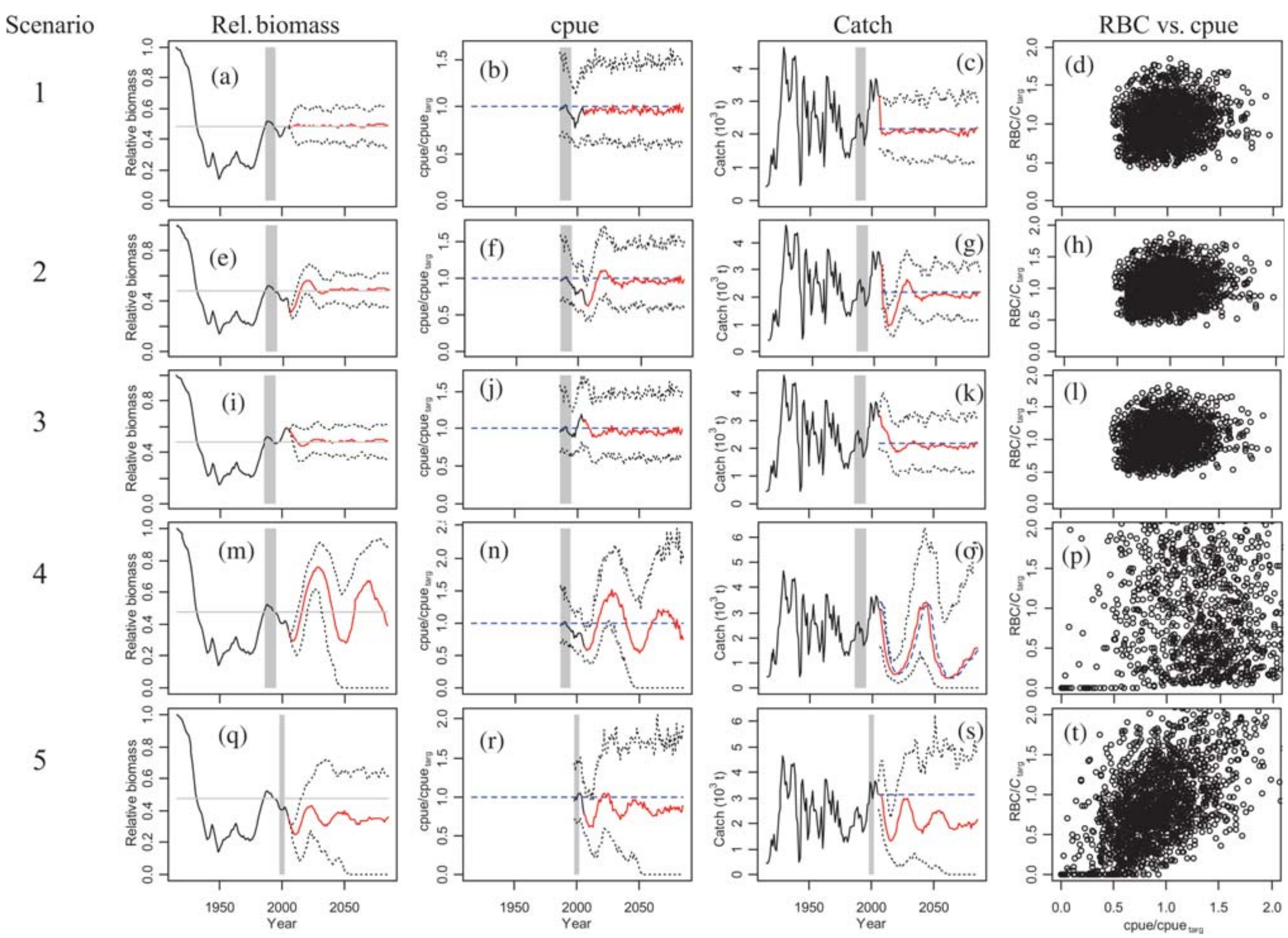

Figure 1. MSE results for scenarios 1–5, tiger flathead: historical fit (black lines) and median projected trajectory (in red) with 2.5 and 97.5 percentiles (dotted lines) of (a, e, i, m, and q) relative biomass in the operating model and the implicit objective of the HCR (grey line), (b, f, j, n, and r) catch rates, and (c, g, k, o, and s) catches. The blue dashed lines in panels (b, f, j, n, and r) and (c, g, k, o, and s) indicate the target levels, determined as the average during the reference period (shaded area). (d, h, l, p, and t) RBC and cpue values relative to their target levels in the last 20 years of projection.

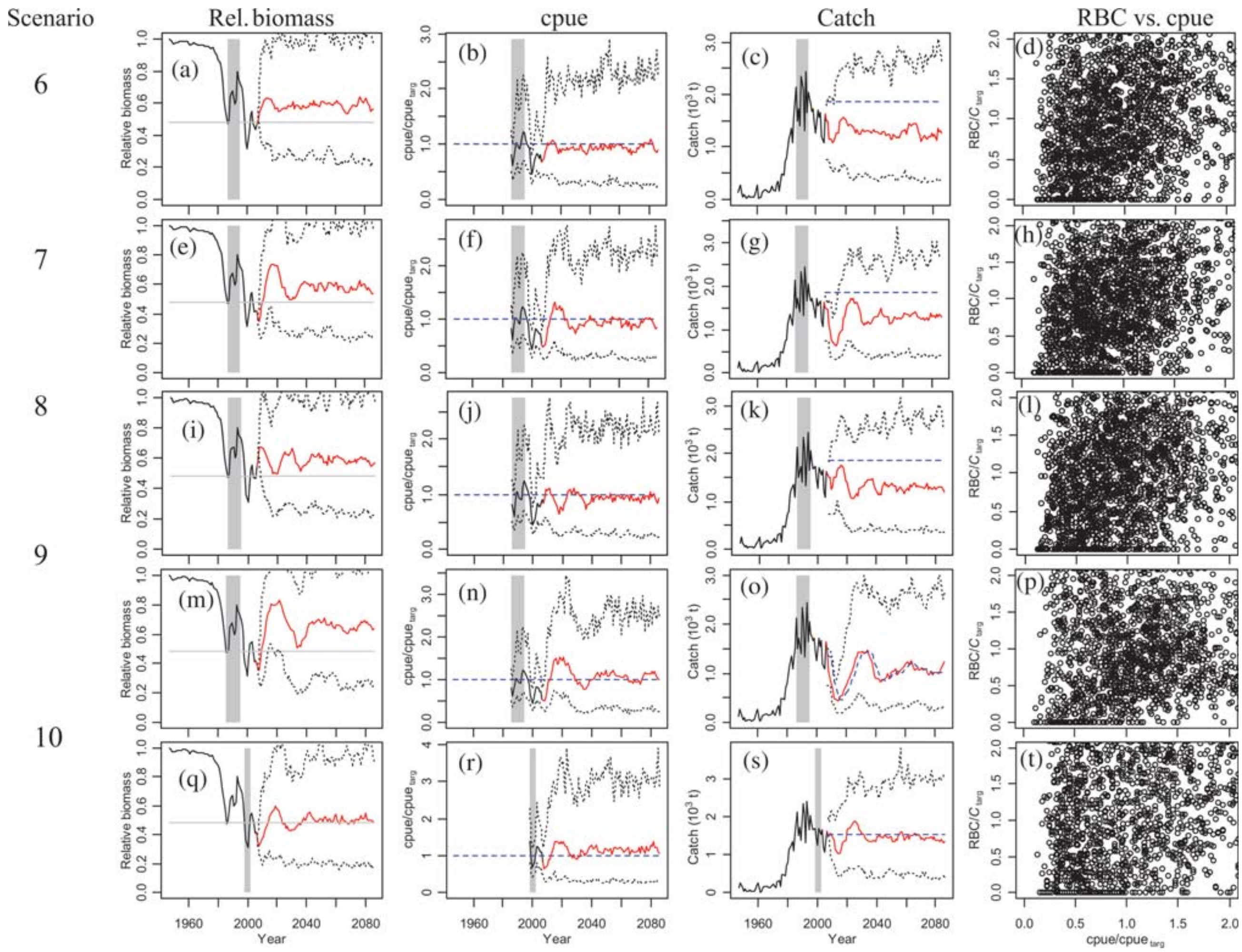

Figure 2. MSE results for scenarios 6–10, school whiting: historical fit (black lines) and median projected trajectory (in red) with 2.5 and 97.5 percentiles (dotted lines) of (a, e, i, m, and q) relative biomass in the operating model and the implicit objective of the HCR (grey line), (b, f, j, n, r) catch rates, and (c, g, k, o, s) catches. The blue dashed lines in panels (b, f, j, n, and r) and (c, g, k, o, and s) indicate the target levels, determined as the average during the reference period (shaded area). (d, h, l, p, and t) RBC and cpue values relative to their target levels in the last 20 years of projection.

catches are needed in 2025 to bring the cpue closer to the target (Figure 1n), the catches and C_{targ} are at their lowest in the cycle (Figure 1o), and the response is inadequate under such conditions. This HCR, therefore, was unable to achieve management objectives (Figure 1m); the RBC was high for many of the projections relative to C_{targ} (Figure 1o), because C_{targ} was allowed to change.

The relative biomass that resulted when the HCR was parametrized with data from the reference period 1998–2002 (shaded areas in Figure 1q) did not match B_{48} (grey line in Figure 1q). There is an obvious cyclic pattern in the projected cpue (Figure 1r), and neither the median cpue nor the median catches achieve the target levels, indicating that the selected $cpue_{targ}$ and C_{targ} are inconsistent with the dynamics of the operating model for the stated reference period. The cyclic behaviour appears to dampen, as a result of time-lags in the 4-year averaging of cpue for the HCR, and the response of the operating model to the RBC. A dampened oscillation is also seen to a lesser degree in Figure 1g, where the catches overshoot the targets by a lesser amount and settle more quickly than in Figure 1s.

School whiting

The average biomass during the reference period for school whiting (Figure 2a, shaded area) is $>B_{48}$ (Figure 2a, grey line). For scenario 6, the projected biomass, cpue, and catch (Figure 2a–c) varied widely, unsurprisingly because the biomass fluctuations of school whiting can be greater than those of tiger flathead (school whiting have higher natural mortality and greater variation in recruitment; Day, 2007; Klaer, 2007). The HCR stabilized the median cpue of the stock close to $cpue_{targ}$ (Figure 2b), but the median catch was well below C_{targ} (Figure 2c), although the initial biomass was equal to the target (Figure 2a). The greater variability in the catch and cpue for school whiting than for tiger flathead is evident in the relationship between the RBC and the cpue (Figure 2d).

The results in scenario 7 were similar to those for scenario 6 (Figure 2). The main difference was the dampened cyclic pattern in catch and cpue attributable to the time-lag in the cpue averaging in the HCR, and the response of the stock (compare, for example, the cpue values at the start of the projection period in

Figure 2f with those for Figure 2b). The results for the scenario where C_{targ} was set to the average of the catches in the 4 years before setting the RBC (scenario 9) were similar to those for tiger flathead, although the oscillations were smaller (Figure 2o). In scenarios 7, 8, and 9, the HCR failed to guide the biomass to the target level mainly because the reference points ($cpue_{targ}$, C_{targ}) did not correspond to an equilibrium of the operating model. Scenario 10 (Figure 2) shows that the HCR can be expected to guide the school whiting stock to the desired state (despite considerable variability) if the reference period is changed so that the target cpue (Figure 2r, grey line) matches the biomass in the reference period (Figure 2r, shaded area).

Discussion

HCRs are being used increasingly by fishery managers around the world (Punt, 2006). One disadvantage of HCRs is the need for extensive data collection and analysis (Butterworth, 2007). Roel and De Oliveira (2007) compared HCRs that require different quantities of data in the management of western horse mackerel *Trachurus trachurus* and found that all required considerable information and detailed analysis. Similar to our approach, O'Neill *et al.* (2010) developed and simulation-tested a simple empirical HCR combining catch rates with survey results. In contrast, our cpue-based HCR does not require as much information, rather just fishery-dependent catch and cpue data.

The key components of our HCR are the parameters $cpue_{targ}$ and C_{targ}. The relationship between these parameters is critical. For example, they must correspond to a stable equilibrium point, or $cpue_{targ}$ and C_{targ} cannot be achieved simultaneously, and the cycling pattern evident in some of the figures would be expected. Miscalculating this relationship is very likely, especially for a stock which has only been fished down, with no period of stable catches and cpue. In this situation, a depletion-corrected average catch (MacCall, 2009) could be used to parametrize the HCR. The relationship between the target biomass and $cpue_{targ}$ is also important because the SESSF HSP has the former as B_{MEY}, assumed to be B_{48} in the absence of better data (DAFF, 2007). B_{48} was "known" in our simulations, so we could determine whether the stock fluctuated about this level. The HCR failed to achieve the B_{48} goal when the biomass in the reference period (shaded areas in the figures) did not correspond to the target biomass (grey line in the figures), as in scenarios 5 and 6. There are no formal abundance statistical estimates of Tier 4 stocks, so whether the B_{48} goal is achieved is unknown. Further economic analyses could lead to a refined cpue target that could better satisfy the economic goals in a more evidence-based manner.

Identifying when the HCR is failing would be useful. For example, revision of the parameter values would be indicated if the average long-term cpue and RBC recommendations did not equate with $cpue_{targ}$ and C_{targ}. Therefore, if the RBC recommendations were consistently above C_{targ}, this would suggest that the target cpue is not consistent with the target catch and that either $cpue_{targ}$ would need to be increased or C_{targ} reduced.

The Tier 4 HCR in the SESSF may not provide the ideal management advice required for the HSP, but it has an important role in the absence of better data. Its weakness is the reliance on fishery-dependent cpue values and catches as the sole sources of information. Catch-rate series are often noisy and may not reflect relative abundance, particularly for short-lived, highly variable species such as school whiting, or deep, densely schooling species such as oreos (*Pseudocyttus* spp., *Neocyttus* spp., *Allocyttus* spp.) and orange roughy (*Hoplostethus atlanticus*). One option for dealing with highly variable cpue series in the Tier 4 HCR would be to increase the period over which $\overline{cpue}$ is calculated, which should reduce the annual variability in the RBC. Alternatively, if the assumption that cpue is proportional to abundance is wrong, a cpue-based HCR may not be appropriate. Instead, an HCR based on catch-curve analysis (e.g. Wayte and Klaer, 2010) might perform better, assuming that it is possible to obtain the required age- or length-composition data.

We have presented a simple cpue-based HCR. The method requires at least some exploitation history to specify the HCR parameters. This HCR is being applied in the multispecies SESSF to stocks that have insufficient data to conduct a statistical catch-at-age assessment. It may also be applicable to other small-scale or data-poor fisheries, where monitoring and assessment activities are expensive (Campbell *et al.*, 2007; Dowling *et al.*, 2008; Dichmont and Brown, 2010). The MSE approach has shown the possible consequences of implementing this HCR under a range of conditions.

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