Validation of a feedback harvest control rule in data-limited conditions for managing multispecies fisheries

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Abstract: Harvest control rules (HCRs) for sustainable fishery management have been developed for data-limited fish species for which stock assessments cannot be conducted. However, HCRs have largely not considered mixed-species catches, as when fishing-effort data are widely pooled for numerous minor species in a multispecies fishery. Presently, a feedback HCR has been successfully applied in Japanese fisheries management. By combining management strategy evaluation with a simulation to generate mixed-species data from a multispecies fishery that assume constant catchability (q) among species, the performance of this feedback HCR was evaluated and then compared with its performance using species-specific data. In most cases, the biomass was controlled over that needed for maximum sustainable yield (MSY) and the fishing effort was under the fishing mortality consistent with achieving MSY (F_{MSY}). However, for slow-growing species, the biomass might become lower than what is required to remain capable of producing MSY, even though fishing effort was controlled under F_{MSY}. The results show that the feedback HCR is appropriate for multispecies fisheries management where only mixed-species data are available but with special monitoring for slow-growing minor species.

Keywords: data-limited, feedback control, harvest control rule, management strategy evaluation, multispecies fisheries

Introduction

The majority of world fisheries are multispecies fisheries, where a multitude of species are exploited by the same or different gear simultaneously (Welcomme 1999, Möllmann et al. 2014). This situation may lead to the mortality of non-target species and over-exploitation. Several fisheries management approaches have been introduced to mitigate over-exploitation. However, fisheries management has largely used conventional single-species stock assessment models (Newman et al. 2018), which requires data of each species individually (Hilborn and Walters 1992, Cadrin and Dickey-Collas 2015). Consequently, it is impractical to manage each species individually using conventional stock assessment methods in a mixed or multispecies fishery (Shertzer and Williams 2008).

Especially in tropical regions, where many mixed or multispecies fisheries exist, accomplishing the assumptions of single-species stock assessments is difficult owing to the use of various types of gear and sympatric assemblages of abundant species (Johannes 1998, Welcomme 1999, Mace 2001). In these regions, fisheries management has been based on a scientific model designed for temperate regions, wherein maximum sustainable yield (MSY) is calculated for few key species, although the applicability of this model is limited in multispecies tropical/subtropical fisheries (Pomeroy 1995). Moreover, a lack of financial and technical support in species separation (Yuniarta et al. 2017) might also lead to failures to provide species-specific data.

Harvest control rules (HCRs), as algorithms to determine pre-agreed harvest management actions such as allowable biological catch (ABC) from catch statistics and biological information, are used for making a wide range of fisheries decisions, such as setting total allowable catch (TAC) (Deroba and Bence 2008, Punt 2010, Wiedenmann 2013, Kvamsdal et al. 2016). Recently, several HCRs have been evaluated across various uncertainties in stock dynamics through simulations based on management strategy evaluation (MSE), a technique used to mimic realistic conditions over various exploitation histories and diverse population characteristics (Butterworth 2007, De Oliveira et al. 2008, Carruthers et al. 2014, Punt et al. 2016, Wiedenmann et al. 2016).

The feedback HCR (Tanaka 1980) has garnered success and is now widely applied in Japanese fisheries management (Ichinokawa et al. 2017). The Fishery Agency of Japan introduced a TAC system in 1997 as the main instrument of fisheries management which is specialized for stocks where the biomass is not estimated (Matsuda et al. 2010, Makino 2011). The feedback HCR is one of Japanese harvest control rules that calculate scientific recommendations for annual catch quota (i.e., ABC) under a TAC system by taking the previous stock abundance index into consideration for the future catch. In the feedback strategy, the resource can be assumed as a control system with catch quota as an input and stock abundance index as an output. In this case, the catch quota is adjusted based on the stock abundance index (Magnusson 1992). Therefore, the feedback HCR designs ABC to stabilize the stock size and ensure continued utilization. The TAC system has proved effective in achieving decreases in the exploitation rate of the stocks, as compared with the stocks managed using other systems (Ichinokawa et al. 2017).

Some studies evaluated the robustness of the feedback HCR through several models that used single-stock data (Hurtado-Ferro et al. 2010, Hoshino et al. 2012, Ohshimo and Naya 2014, Ichinokawa et al. 2015), but none considered validating the robustness of the feedback HCR for a mixed-species fishery. Such validation would be a valued response to recent calls for fishery management approaches under data-limited conditions and applicable to most countries.

In the present study, the feedback HCR was considered as a prospective HCR in the context of mixed-species data from a multispecies fishery. The sensitivity of its performance over several scenarios of population dynamics was examined and then compared across other modified HCRs.

Materials and methods

Evaluation of the feedback HCR

To test the performance of the feedback HCR, a management strategy evaluation (MSE) was conducted over a range of scenarios covering fishes with various life histories and exploitation histories. An MSE that comprises operating, assessment, and management sub-models was developed. A single-species Schaefer production model was applied as an operating model (OM) to determine the population dynamics of a species. It is assumed that distribution of a species is sympatric and homogeneous in the fishing ground and that the fishing gear harvests a uniform portion of the fish in the fishing ground without species selectivity. As a caution, all results in this study hinge on constant catchability assumptions.

To imitate mixed-species conditions, an abundance index for a group of species was provided by using the total biomass of the species group. The feedback HCR was applied to determine a catch quota, and the catch amount in a multi-species fishery is assumed to be equal to the catch quota.

To compare the performance of the HCR between the mixed-species condition and the single-species condition, the single-species condition was developed by providing an abundance index for each separate species using the simulated biomass of each species. In this situation, the total catch was the total of the catch quotas for each species. The performance measures for a variety of HCR feedback factor values were also examined. To evaluate the uncertainty of the process error of the population dynamics and the measurement error of the abundance index, this process was repeated 1000 times for each scenario.

The feedback HCR evaluated in this study is called the ABC rule 2-1 in the Japanese TAC system (Fisheries Agency and Fisheries Research and Education Agency of Japan 2017) and was previously validated for single-species stock data (Hiramatsu 2004, Ohshimo and Naya 2014, Ichinokawa et al. 2015). The formulas used for the ABC rule 2-1 are as follows:

$$C_y = \delta_y \times \gamma_y \times C_{y-2} \quad (1)$$

$$\gamma_y = 1 + k\left(\frac{b_y}{\bar{I_y}}\right) \quad (2)$$

$$\bar{I_y} = \frac{1}{3}\left(I_{y-4} + I_{y-3} + I_{y-2}\right) \quad (3)$$

where C_y is the catch quota in year y, which equals to the catch amount for evaluating fisheries management strategies; δ_y is the weighing coefficient and the default values are set as 1.0, 1.0 and 0.8, denoting stock levels that are high, medium and low, respectively. The stock level is determined by the stock abundance index (I_y) in year at $y-2$ [1], using the thresholds made from the 33rd and 67th percentiles of the 20-year historical stock abundance index. Then, γ_y represents the trend of the stock abundance, when available, and this value comprises the weighted coefficient k (default 1.0); b_y is the regression coefficient of the stock abundance index I_{y-4}, I_{y-3}, I_{y-2}, against year; and $\bar{I_y}$ is the mean of I_{y-4}, I_{y-3} and I_{y-2}.

[1] see eq. 7 for the abundance index formula.

The coefficients δ and k are tuning parameters that adjust the response of the biomass-trend index on the ABC. In this study, different k values were applied to the alternative feedback HCRs. In a similar theoretical study, the coefficients k was named as the feedback gain between the index and future catch which was applied to ensure the existence and stability of the trend of stock abundance (Magnusson 1992). The value of feedback factor k reflects the sensitivity of the catch quota that is changed by the biomass trends. If k is too large, catch quota will greatly increase even when the biomass is slightly increasing, and vice versa, which may lead to high variability in catches due to random fluctuation in the biomass index.

Table 1 shows the feedback factor values used in this study. Furthermore, an abbreviation (1.0-1.0-1.0-0.8) was used to represent that k is 1.0, and δ is 1.0, 1.0 and 0.8, when stock levels are high, middle or low. Thus, the abbreviation 1.0-1.0-1.0-0.8 defines the default feedback HCR.

Management strategy evaluation

Operating models

The population dynamics in the operating model (OM) were based on a single-species production model for three species. Then, to simulate mixed-species data, the abundance index was calculated from the total biomass of the three species, though the population dynamics of each species were calculated independently. It is assumed that interspecific relationships among the species are negligible and that all the species exist in closed stocks.

Each model run was simulated for a total 51-year period, which was divided into a pre-management period and a management period, of 21 and 30 years, respectively.

For the pre-management period, the population dynamics are described as follows:

$$B_{i,y+1} = \left\{B_{i,y} + r_i \cdot B_{i,y}\left(1 - \frac{B_{i,y}}{K_i}\right)\right\}\hat{\varepsilon}_{i,y} - qX_sB_{i,y} \qquad (4)$$

where $B_{i,y}$ is the biomass of species *i* (*i* =1, 2, 3) in year *y*; r_i is the intrinsic growth rate of species *i*; K_i is the carrying capacity of species *i*; q is catchability; and X_s is fishing effort for each scenario *s* (*s* = 1, 2, 3) described below. As a cautionary note, catchability (q) was assumed to be uniform among species. In this situation, the distribution of a species is sympatric and homogeneous in the fishing ground, and the fishing gear harvests a constant portion of fish in the fishing ground without species selectivity. To express the process error of the population dynamics, a log-normal error $\hat{\varepsilon}$ was induced as follows:

$$\hat{\varepsilon}_{i,y} = \exp\left(\sigma_R \varepsilon_{i,y} - \frac{1}{2}\sigma_R^2\right) \quad (5)$$

where ε is a random number with standard normal distribution, and σ_R is the scale of variance for the process error.

To cover various changes in stock size in the pre-management period, three scenarios were considered, following the method of previous simulation studies (i.e., Hiramatsu 2004, Ohshimo and Naya 2014, Ichinokawa et al. 2015). Exploitation histories for the pre-management period were reflected in the value of the initial biomass (B_1) and the value of the terminal biomass (B_{21}), which was defined as either high (B_H), medium (B_M), or low (B_L) biomass at 75%, 50% and 30% of total carrying capacity, respectively. Three scenarios, $B_L – B_H$, $B_M – B_M$, and $B_H – B_L$, showed that the biomass changes from the initial biomass B_1 (left-hand side, Fig. 1) to the biomass at the end of the pre-management period B_{21} (right-hand side, Fig. 1), given the derived fishing mortalities $q \cdot X_s$ at 0.025, 0.133 and 0.233 for $B_L – B_H$, $B_M – B_M$, and $B_H – B_L$, respectively and supposing the deterministic model ($\sigma_R = 0$). However, since the simulation run was conducted with process errors, B_{21} might have various values that did not exactly correspond to B_H, B_M or B_L (Supplementary, Figs. S1–S3).

For the management period, the feedback HCR (eq. 1) was applied to calculate the annual catches as follows:

$$B_{i,y+1} = \left\{B_{i,y} + r_i \cdot B_{i,y}\left(1 - \frac{B_{i,y}}{K_i}\right)\right\}\hat{\varepsilon}_{i,y} - \frac{B_{i,y}}{\sum B_{i,y}} C_y \quad (6)$$

where the catch C_y is calculated by eq. 1 and 2 in the management period. In the multispecies HCR simulations, the pooled abundance index with measurement errors was given by:

$$I_y = \left(\frac{B_y + B_{y+1}}{2}\right) \exp\left(\sigma_I \eta - \frac{1}{2}\sigma_I^2\right) \quad (7)$$

where B_y is the biomass at the beginning of year y; η is a random number with a standard normal distribution; and σ_I is the scale of variance for the measurement error. The catch of each species in the total catch quota is allocated as proportional to the biomass of each species, which reflects a non-selective multi-species fishery.

To evaluate the robustness of the HCR, the magnitude for σ_R and σ_I was assumed as 0.2 for the default, as was applied in former studies (i.e., Hiramatsu 2004, Ohshimo and Naya 2014, Ichinokawa et al. 2015). Additionally, σ_I= 0.4 was tested, and the results are provided in Supplementary, Figs. S4, S5.

To accommodate diverse life histories, three types of species were assumed, with the intrinsic growth rate (*r*) ranging from 0.2 to 1.0, and the carrying capacity (*K*) ranging from 10 000 to 50 000, which are wider ranges than were included in previous studies to highlight uncertainty (see Table 2). Following the conventional Schaefer model, MSY and biomass at MSY (B_{MSY}) were calculated as $K/2$ and $rK/4$, respectively, while fishing mortality at MSY (F_{MSY}) was calculated as $\mathrm{MSY/B_{MSY}}$. To ensure robustness of the results related to the relationship between *r* and *K*, other scenarios are given in Supplementary, Tables S1a, S1b.

To compare the performance of the feedback HCR with mixed- and single-species data, simulations for the single-species data were also conducted. Catch was calculated for each species based on the species-specific index of abundance:

$$B_{i,y+1} = \left\{B_{i,y} + r_i \cdot B_{i,y}\left(1 - \frac{B_{i,y}}{K_i}\right)\right\}\hat{\varepsilon}_{i,y} - C_{i,y} \tag{8}$$

$$C_{i,y} = \delta_i \times \gamma_i \times C_{i,y-2} \tag{9}$$

$$\gamma_{i,y} \; = 1 + k\left(\frac{b_{i,y}}{\overline{I_{i,y}}}\right) \tag{10}$$

$$I_{i,y} = \left(\frac{B_{i,y} + B_{i,y+1}}{2}\right)\exp\left(\sigma_I \eta - \frac{1}{2}\sigma_I^2\right) \tag{11}$$

$$\overline{I_{i,y}} = \frac{1}{3}\left(I_{i,y-4} + I_{i,y-3} + I_{i,y-2}\right) \tag{12}$$

Performance measures

To evaluate the performance of the feedback HCR, a range of performance measures were calculated to meet a set of management objectives: prevention of overfishing, stock conservation, yield optimization, extinction avoidance, and catch stability (Deroba and Bence 2008, Wiedenmann 2013, Carruthers et al. 2014, Punt et al. 2016, Wiedenmann et al. 2016). The performance measures considered five aspects, as follows:

(1) The probability of overfishing (P_{OF}) as the proportion of years in which fishing mortality ($F_{i,y}$) exceeded F_{MSY} in the management period, where $F_{i,y}$ was calculated as $C_{i,y}/B_{i,y}$.
(2) Biomass status (B/B_{MSY}), as the average biomass over the last 10 years (B_{42}–B_{51}) relative to B_{MSY}.
(3) Yield status (C/MSY), as represented by the mean catch over the management period relative to MSY.

(4) Management failure, which was defined as the proportion of the simulations run where $C_{i,y} \geq B_{i,y}$ over 1000 simulation runs.

(5) The coefficients of variation (CV) for biomass and catch, which reflect the extent of the biomass and catch variability under the simulation; the CV was calculated as the ratio of the standard deviation to the mean.

These performance measures were compared between the mixed- and single-species data over the various combinations of scenarios and feedback factor values.

Results

Performance measures of the default feedback HCR

The results present the performance of the default feedback HCR with mixed-species data and with single-species data, for three species, under three different scenarios, and for given different exploitation histories in the pre-management period (Table 3). The 20 trajectories of biomass and catch are depicted to illustrate performance of the feedback HCR under three scenarios $B_L – B_H$, $B_M – B_M$ and $B_H – B_L$ (Supplementary, Fig. S1–S3). As an example, in the $B_M – B_M$ scenario, with both mixed- and single-species data, the biomass values of species 2 and 3 were generally above B_{MSY} (1.59–1.76 B_{MSY}), while the catch was consistently below MSY (0.31−0.53 MSY). In contrast, the patterns for species 1 were unfavorable, as biomass was generally below B_{MSY} (0.87−0.89 B_{MSY}) and the catch was occasionally above MSY (P_{OF} = 0.35–0.37).

Evaluation of the default HCR across the different scenarios in a Kobe-plot (Fig. 2) showed that the level of fishing mortality, with both the mixed- and single-species data, was generally below the overfishing threshold (below F/F_{MSY}), except for species 1 under scenario $B_H – B_L$ with mixed-species data. However, for catch status (Fig. 3), the default HCR showed that in all cases the catch was below *MSY*.

Comparing the performance of the default HCR between the single- and mixed-species data showed that for most cases the performances of the two types of data were similarly scattered; however, minor differences in the performance measures were noted for species 1. The B/B_{MSY} of species 1 showed the same trend with single-species data and mixed-species data under scenario $B_H - B_L$ (0.31 and 0.27, respectively) and under scenario $B_M - B_M$ (0.89 and 0.87, respectively). However, the catch status of species 1 in scenario $B_M - B_M$ showed that mixed-species data produced a slightly higher *C*/MSY (0.56) than that with single-species data (0.45) (Table 3).

Under the heavy-exploitation scenario $B_H - B_L$, the P_{OF} of species 1 was nearly twice as low with the single-species data than it was with the mixed-species data (0.49 vs 0.83). In terms of the management failure measure for the same species, the single-species data generated failure as high as 0.44, whereas no failures occurred using the mixed-species data. However, for species 3 these two measures performed similarly with the single- and mixed-species data but for species 2 slight differences were evident (P_{OF} =0.13 and 0.05, respectively; Failure = 0.07 and 0.00, respectively) (Table 3).

Across the scenarios, the total *C*/MSY displayed similar ranges with the single- and mixed-species data, at 0.13–0.44 and 0.14–0.47, respectively. Similar performance with the single- and mixed-species data also occurred for total B/B_{MSY}, as evident in the ranges 0.73–1.72 and 0.74–1.70, respectively. Concerning the P_{OF} for the total species, no overfishing was observed when applying either data type. However, in terms of the total management failure measure, the single-species data produced more failures (0–0.48) than did the mixed-species data (0.01) (Table 3).

To explore the robustness of the results with different life-history scenarios, the three species were given various *r* and *K* values (Figs. 2, 3; Supplementary, Figs. S4–S7). Changes of *K* and *r* show similar results for biomass, catch, and fishing mortality status. However, an increase in r would distribute the biomass above B/B_{MSY} in all cases, and thus put fishing mortality under the overfishing threshold, including for species 1 under scenarios $B_H – B_L$ and $B_M – B_M$, and for the total species under scenario $B_H – B_L$, which had previously resulted in overfished stock status (Fig. 2) under the original set of parameter values (Table 2).

Performance measures of the alternative feedback HCRs

To ensure robust performance of the default feedback HCR, alternative versions were compared by modifying the feedback factor values k (Fig. 4; Supplementary, Tables S2–S5). In terms of biomass status, the feedback HCR responded similarly to the changes of k with the mixed-species data, but with the single-species data the changes acted to increase the biomass ratio as $k > 1$ ($k = 2.5$), especially for species 1 under scenarios $B_H – B_L$ and $B_M – B_M$, with ranges of 0.29–0.68 and 0.76–1.12, respectively. In most cases, the CV in biomass showed that there was no difference in performance with changes of the parameter k, except for species 1 with single-species data and under the heavy-exploitation scenario, which attained high data dispersion of about 0.68 as $k > 1$ ($k = 1.5$). Across the modified feedback HCRs, the heavy-exploitation scenario revealed lower biomass than in the two other critical scenarios. These conditions were also reflected in the total biomass condition.

The whole-catch performance roughly showed that the difference in k did not influence the value of C/MSY. A similar performance resulted with the mixed- and single-species data, except for species 1 with mixed-species data, which produced a 0.1-higher yield than that with the single-species data under scenario

$B_M - B_M$. However, the catch dispersion with single-species data showed that an increase in parameter *k* (*k* > 1) would enlarge the catch data dispersion, leading to poorer model fitness, especially for species 1 under scenario $B_H - B_L$ at $k = 2.5$ (0.75). Conversely, with mixed-species data, the model fitness performed relatively similar with changes of *k* and was widely distributed below 0.50, except for species 1, which produced a CV slightly above 0.50 under the heavy-exploitation scenario.

Generally, across the different *k* parameters, the P_{OF} of the feedback HCRs scattered similarly, with values below 20%, except for the slow-growing species 1. For that species, overfishing occurred more often under the heavy-exploitation scenario (reaching about 80%) than occurred under the other scenarios. Nonetheless, overfishing became less frequent once $k > 1.5$ for species 1 with the single-species data. However, over the various results across the different species, exploitation histories, and types of data, a state of frequent overfishing was not detected for the total fish community.

The other critical performance was in model failures of some adjusted *k* parameters in the default feedback HCR, which performed similarly for both the single- and mixed-species data. For each species, the performance of the failure measure acted differently, such that no failure was observed for the typically fast-growing species 3 across the modified *k* parameters. However, failure occurred more often for species 1 and 2, reaching 60% and 20%, respectively, when $k < 1.5$. The model failures for species 1 were similarly reflected for the total fish community.

Discussion

In the present study, alternative feedback HCRs were evaluated with mixed-species data, and over a range of scenarios, to determine the robustness of the HCR and its effectiveness in attaining a set of management objectives. Previous studies have explored the development and testing of evaluation methods for HCRs for managing data-limited fisheries (Carruthers et al. 2014, Dowling et al. 2015b, Jardim et al. 2015). While Dichmont et al. (2012) published a reference of evaluating HCRs for fisheries with mixed-species data, to our knowledge, no previous validation for reference comparison has been published to evaluate any HCRs for mixed-species fisheries. Therefore, the present study attempted to accomplish fisheries management under a default HCR, which complies with data-limited and mixed-species conditions. A straightforward validation of mixed-species data was generated by comparing the default feedback HCR and its alternates in terms of their performances with single-species data, which have been validated previously (Ohshimo and Naya 2014, Ichinokawa et al. 2015). Under these circumstances, an ideal HCR would be a tool for limiting the frequency of overfishing, maintaining biomass, and generating more stable catches for mixed-species stocks—goals that were reflected in the five performance measures.

Catchability (q) is the value that might substantially influence simulation results, which reflects the efficiency of a fishery or the vulnerability of fish to fishing gear or fishing strategies. For this simulation, catchability was assumed to be uniform among species, therefore to be cautioned that all results hinge on constant catchability assumption. However, in some actual fisheries, the assumption for constant catchability may not be always satisfactory as it will vary based on abundance, fish behavior, population dynamics, fishing strategy and environmental conditions (Yamakawa et al. 1994, Maunder et al. 2006). On the other hand, changes in q would also generate additional uncertainty in the catch rate as an index of stock abundance, if q actually varied over time (Jul-Larsen et al. 2003). The interpretation of catchability can be different depending on how population units are chosen (Arreguín-Sánchez 1996). In this model, catchability was represented as a part of fishing mortality ($q. X$) units to express the number of fish caught in the population. This suggests that the fishing effort is considered uniformly distributed and of constant quality, and the population size is considered constant. Therefore, to obtain an index of total biomass where survey catchability is assumed uniform among species, effort standardization can be applied beforehand. As standardization aims to control species targeting and dynamics of the fleet or population (Squires and Vestergaard 2015).

By taking the constant catchability assumption, fisheries are characterized by multiple species which are subject to the relatively non-selective nature of fishing gears and the homogenous mixing of the fish stock (Murawski et al. 1983, Murawski 1991). Thus, deploying gears to different areas in a certain unit will result in a similar species composition since the fish are homogeneously distributed and have the same probability of being caught by the gears (Hoggarth et al. 2006). However, it is highlighted that the application of a constant coefficient is valid only for the conditions under individuals with similar catchability or the same quality of fishing effort (Arreguín-Sánchez 1996). A tropical purse seine fishery might be an example. In the case of the 2017 Indian Ocean Tuna Commission, including skipjack in the purse seine log-set (PSLS) CPUE provided no evidence of changes in its catchability over time (Kolody and Jumppanen 2018).

Across the scenarios observed for the default feedback HCR, the type of exploitation scenario considerably influenced the performance measures. The heavier the exploitation of the fishery, the poorer the performance of each feedback HCR. Under the riskiest scenario, $B_H - B_L$, the performance of the default feedback HCR produced the highest probability of overfishing, the least catch productivity, and the lowest biomass availability.

In most cases, the biomass performances, with both the mixed- and single-species data, indicated that the default HCR could maintain or rebuild high stock biomass for some life histories, with the exception of species 1, a typically slow-growing and long-lived species, which responded differently. The catch performances also showed that the default HCR could generate a less-risk low-level yield (below the potential yield) since the fishing mortality was considerably conservative (below overfishing threshold). These results correspond to other evaluation studies that stated that the more conservative HCR would be compatible for meeting a set of long-term management objectives (Punt et al. 2008, Kleisner et al. 2013, Wiedenmann et al. 2016). The performances of these two parameters showed that there was a trade-off between biomass status and catch status. In a real-life fishery where effective management regulations exist, this trade-off will respond to a decline in stocks by trying to decrease the catch to gradually rebuild the biomass (Kleisner et al. 2013). Therefore, future impact assessments should further consider these two performance measures to improve the applicability of the feedback HCR. In addition, the confirmation of historical fishing pressures is recommended, as the results here revealed that given relatively low initial exploitation, the performance measures of the default feedback HCR with either mixed- or single-species data were similar for each individual species.

The exploration of five different values of k is a validation of feedback factor value that adjusts the trend of biomass indices on the default feedback HCR formula. Ohshimo and Naya (2014) suggested setting k lower to avoid the risk of a high catch CV and higher frequency of management failures. However, those are not the only objectives of management because managers should also try to achieve optimum yields. If an HCR has the capacity to balance the trade-offs between all management objectives, the P_{OF} level should be somewhat less than 0.5 across all scenarios (Wiedenmann et al. 2016). From this study, it was shown that increasing k would worsen the model fitness, which would be undesirable in terms of stability of the fishery, even though it would lead to the projection of higher stock size and catch. Setting a lower k, however, would cause a higher frequency of management failures. In terms of the occurrence of overfishing, no positive outcome was demonstrated through modification of parameter k. Thus, aside from the results of k modification, the default HCR appears to be robust enough to deal with most management objectives, thus there was insufficient reason to recommend a change to the default HCR.

Comparing the performance of different k values between the single- and multi-species data showed that the mixed-species data had less sensitivity to k than did the single-species data. Changes in k would not affect all performances measures for mixed-species data. Conversely, for slow-growing species under single-species data, the biomass ratio increased as $k > 1$, and lower levels of failure and diminished overfishing occurred as $k \geq 1.5$. This situation might be too risky for minor slow-growing species since the total biomass estimation in the fishery would depend on the other major moderate- and fast-growing species. In this case, it is fair to assert that slow-growing species in a single-species fishery would be better managed separately, by applying the modified feedback HCR with $k = 1.5$, otherwise, the estimation of biomass for slow-growing species would be overestimated.

Concerning on the performance comparison of the default feedback HCR with the single-species and mixed-species data indicated that in most cases, both applications performed frequently comparable over four measures, but will be critical under the riskiest scenario, $B_H - B_L$, where the slow-growing species has a probability of overfishing that is doubled with the multi-species application yet its management failure occurred nearly 50% higher with the single-species application. However, it needs to be cautioned that the similar results of both applications might be due to the assumption of the current framework which is centered on a uniform catchability across species. Moreover, diverse combinations of life history traits might result in different performances, particularly for growth rate parameter –as it performed riskier for the slow-growing species than for other species. For the implementation of the feedback HCR in a real fishery, realistic catchability and life history traits can be applied for further simulations, which might cause diverse findings for all performance measures.

Other studies also indicated that unselective fisheries, as occurred in the multi-species application, might have an advantage for conserving biomass of each species, since mixed-species fisheries cannot target the declined species (Hollowed et al. 2000, Iriondo et al. 2012, Gaichas et al. 2017). However, careful monitoring should be focused on the minor species, as it is easiest to disappear in the multi-species body, and in such situation, the unselective assumption might be violated (Gaichas et al. 2017).

The default feedback HCR explored in this study runs on an original set of *r* and *K* parameter values, as we assumed that *r* and *K* are inversely related. However, in some circumstances, the results may be sensitive to different parameter values. Therefore, we included two additional scenarios (Supplementary, Tables S1a, S1b) to cover a range of life-history characteristics. The results showed the default feedback HCR was less sensitive to the diverse biomass production (*K*) but receptive to low intrinsic rates of increase (*r*) (Supplementary, Figs. S6–S9). Growth characteristics certainly have a critical effect on population dynamics and fisheries management, since for some mixed-species fisheries, fast-growing species mostly support higher estimations of MSY than do slow-growing species (Murua et al. 2017). Therefore, in this circumstance, since the fishing impact levels could be diverse for certain species and different biomass-level scenarios, special monitoring should be considered, particularly for slow-growing minor species, which may display lower biomass and a higher frequency of being overfished when compared with other species.

In this study, implementation error was excluded as a source of error because the purpose was not to characterize the management performance with a given stock, but merely to focus on the performance of the feedback HCR. Consideration of implementation error might reveal remarkable patterns of the control rule's performance if the purpose is to evaluate a management system for a specific fishery (Wiedenmann et al. 2016).

In practice, the feedback HCR as a short-term management approach might be relevant for management in regions with multispecies fisheries where only mixed-species data are available. Uncertainties that may cause future impacts to fisheries, if not convincingly handled, could severely degrade the fishery resources, such as depleting the stocks. Such fisheries require short-term tactical fisheries management that can also continuously protect a fishery from unacceptable or undesirable changes to stock size and yield (Anonymous 2015, Yuniarta et al. 2017).

Particular HCRs (reviewed in Deroba and Bence 2008) have specific functions, such as maximizing yield or profits, minimizing the risk of overexploitation by maintaining biomass above the MSY threshold, minimizing the stock's recovery time, or minimizing the variability of the yield and profits. Accordingly, this feedback HCR might not be credited as an optimal harvest policy for some data-limited fisheries as compared with some HCRs already reviewed in other studies (Wiedenmann 2013, Carruthers et al. 2014, Dowling et al. 2015a, Newman et al. 2015). However, the feedback HCR described here presents an initial step toward sustainably managing multispecies fisheries while contending with data-limited conditions. Future improvements to species-specific data availability will allow application of more sophisticated and optimal HCRs. The results of this work may be used as a simulation-based reference to expand use of the default feedback HCR to handle not only single-species fisheries but also mixed-species fisheries.

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References

Anonymous. 2015, October. Marine Fisheries Management Plan of Thailand: A National Policy for Marine Fisheries Management (2015–2019). Department of Fisheries Ministry of Agriculture and Cooperatives, Thailand.

Arreguín-Sánchez, F. 1996. Catchability: a key parameter for fish stock assessment. Rev. Fish Biol. Fish. **6**(2): 221–242. doi:10.1007/BF00182344.

Butterworth, D.S. 2007. Why a management procedure approach? Some positives and negatives. ICES J. Mar. Sci. **64**(4): 613–617. doi:10.1093/icesjms/fsm003.

Cadrin, S.X., and Dickey-Collas, M. 2015. Stock assessment methods for sustainable fisheries. ICES J. Mar. Sci. **72**(1): 1–6. doi:10.1093/icesjms/fsu228.

Carruthers, T.R., Punt, A.E., Walters, C.J., MacCall, A., McAllister, M.K., Dick, E.J., and Cope, J. 2014. Evaluating methods for setting catch limits in data-limited fisheries. Fish. Res. **153**: 48–68. doi:10.1016/j.fishres.2013.12.014.

Deroba, J.J., and Bence, J.R. 2008. A review of harvest policies: Understanding relative performance of control rules. Fish. Res. **94**(3): 210–223. doi:10.1016/j.fishres.2008.01.003.

Dichmont, C., Deng, R., Punt, A., Venables, W., and Hutton, T. 2012. From input to output controls in a short-lived species: The case of Australia's Northern Prawn Fishery. Mar. Freshw. Res. **63**: 727–739. doi:10.1071/MF12068.

Dowling, N.A., Dichmont, C.M., Haddon, M., Smith, D.C., Smith, A.D.M., and Sainsbury, K. 2015a. Empirical harvest strategies for data-poor fisheries: A review of the literature. Fish. Res. doi:10.1016/j.fishres.2014.11.005.

Dowling, N.A., Dichmont, C.M., Haddon, M., Smith, D.C., Smith, A.D.M., and Sainsbury, K. 2015b. Guidelines for developing formal harvest strategies for data-poor species and fisheries. Fish. Res. **171**(Supplement C): 130–140. doi:10.1016/j.fishres.2014.09.013.

Fisheries Agency and Fisheries Research and Education Agency of Japan. 2017. Marine fisheries stock assessment and evaluation for Japanese waters (fiscal year 2016/2017).

Gaichas, S.K., Fogarty, M., Fay, G., Gamble, R., Lucey, S., Smith, L., and Prellezo, H. editor: R. 2017. Combining stock, multispecies, and ecosystem level fishery objectives within an operational management procedure: simulations to start the conversation. ICES J. Mar. Sci. **74**(2): 552–565. doi:10.1093/icesjms/fsw119.

Hilborn, R., and Walters, C.J. (*Editors*). 1992. Quantitative Fisheries Stock Assessment: Choice, Dynamics and Uncertainty. Springer US.

Hiramatsu K. 2004. Evaluation of the ABC decision rule by the operating model approach. Nippon Suisan Gakkaishi **70**(6): 879–883.

Hoggarth, D.D., Abeyasekera, S., Arthur, R., Beddington, J.R., Burn, R.W., Halls, A., Kirkwood, G.P., McAllister, M.K., Medley, P., Mees, C., Parkes, G., Pilling, G., Wakeford, R., and Welcomme, R. 2006. Stock assessment for fishery management.

Hollowed, A.B., Bax, N., Beamish, R., Collie, J., Fogarty, M., Livingston, P., Pope, J., and Rice, J.C. 2000. Are multispecies models an improvement on single-species models for measuring fishing impacts on marine ecosystems? ICES J. Mar. Sci. **57**(3): 707–719. doi:10.1006/jmsc.2000.0734.

Hoshino, E., Milner-Gulland, E.J., and Hillary, R.M. 2012. Bioeconomic adaptive management procedures for short-lived species: A case study of Pacific saury (Cololabis saira) and Japanese common squid (Todarodes pacificus). Fish. Res. **121**–**122**(Supplement C): 17–30. doi:10.1016/j.fishres.2012.01.007.

Hurtado-Ferro, F., Hiramatsu, K., and Shirakihara, K. 2010. Allowing for environmental effects in a management strategy evaluation for Japanese sardine. ICES J. Mar. Sci. **67**(9): 2012–2017. doi:10.1093/icesjms/fsq126.

Ichinokawa, M., Okamura, H., and Kurota, H. 2017. The status of Japanese fisheries relative to fisheries around the world. ICES J. Mar. Sci. **74**(5): 1277–1287. doi:10.1093/icesjms/fsx002.

Ichinokawa, M., Okamura, H., Kurota, H., yukami, R., Tanaka, H., Shibata, Y., and Ohshimo, S. 2015. Searching for optimum management procedures by quantifying management objectives for Japanese domestic fishery stocks without stock biomass estimation. Nippon SUISAN GAKKAISHI **81**(2): 206–218. doi:10.2331/suisan.81.206 [In Japanese].

Iriondo, A., García, D., Santurtún, M., Castro, J., Quincoces, I., Lehuta, S., Mahévas, S., Marchal, P., Tidd, A., and Ulrich, C. 2012. Managing mixed fisheries in the European Western Waters: Application of Fcube methodology. Fish. Res. **134–136**: 6–16. doi:10.1016/j.fishres.2012.07.019.

Jardim, E., Azevedo, M., and Brites, N.M. 2015. Harvest control rules for data limited stocks using length-based reference points and survey biomass indices. Fish. Res. **171**(Supplement C): 12–19. doi:10.1016/j.fishres.2014.11.013.

Johannes, R.E. 1998. The case for data-less marine resource management: examples from tropical nearshore finfisheries. Trends Ecol. Evol. **13**(6): 243–246. doi:10.1016/S0169-5347(98)01384-6.

Jul-Larsen, E., Kolding, J., Overå, R., Nielsen, J.R., and Zwieten, P.A.M. 2003. Management, co-management or no management? Major dillemas in southern African freshwater fisheries. 1. Synthesis report. *In* FAO Fisheries Technical Paper. No. 426/1. Rome.

Kleisner, K., Zeller, D., Froese, R., and Pauly, D. 2013. Using global catch data for inferences on the world's marine fisheries. Fish Fish. **14**(3): 293–311. Wiley/Blackwell (10.1111). doi:10.1111/j.1467-2979.2012.00469.x.

Kolody, D., and Jumppanen, P. 2018. Indian ocean skipjack purse seine catchability trends estimated from bigeye and yellowfin assessments. Available from http://www.iotc.org/documents/WPTT/20/32 [accessed 10 January 2018].

Kvamsdal, S.F., Eide, A., Ekerhovd, N.-A., Enberg, K., Gudmundsdottir, A., Hoel, A.H., Mills, K.E., Mueter, F.J., Ravn-Jonsen, L., Sandal, L.K., Stiansen, J.E., and Vestergaard, N. 2016. Harvest control rules in modern fisheries management. Elem Sci Anth **4**(0). doi:10.12952/journal.elementa.000114.

Mace, P.M. 2001. A new role for MSY in single-species and ecosystem approaches to fisheries stock assessment and management. Fish Fish. **2**(1): 2–32. doi:10.1046/j.1467-2979.2001.00033.x.

Magnusson, K.G. 1992. A feedback and probing strategy to regulate harvesting from a renewable resource. Math. Med. Biol. **9**: 43–65. doi:10.1093/imammb/9.1.43.

Makino, M. 2011. Fisheries Management in Japan. doi:10.1007/978-94-007-1777-0.

Matsuda, H., Makino, M., Tomiyama, M., Gelcich, S., and Carlos Castilla, J. 2010. Fishery management in Japan. Ecol. Res. **25**(5): 899–907. doi:10.1007/s11284-010-0748-5.

Maunder, M.N., Sibert, J.R., Fonteneau, A., Hampton, J., Kleiber, P., and Harley, S.J. 2006. Interpreting catch per unit effort data to assess the status of individual stocks and communities. ICES J. Mar. Sci. **63**(8): 1373–1385.doi:10.1016/j.icesjms.2006.05.008.

Möllmann, C., Lindegren, M., Blenckner, T., Bergström, L., Casini, M., Diekmann, R., Flinkman, J., Müller-Karulis, B., Neuenfeldt, S., Schmidt, J.O., Tomczak, M., Voss, R., and Gårdmark, A. 2014. Implementing ecosystem-based fisheries management: from single-species to integrated ecosystem assessment and advice for Baltic Sea fish stocks. ICES J. Mar. Sci. **71**(5): 1187–1197. doi:10.1093/icesjms/fst123.

Murawski, S. 1991. Can We Manage Our Multispecies Fisheries? Fisheries **16**(5): 5–13. Wiley-Blackwell. doi:10.1577/1548-8446(1991)016<0005:CWMOMF>2.0.CO;2.

Murawski, S., M. Lange, A., Sissenwine, M., and K. Mayo, R. 1983. Definition and Analysis of Multispecies Otter-Trawl Fisheries Off the Northeast Coast of the United-States. ICES J. Mar. Sci. **41**: 13–27. doi:10.1093/icesjms/41.1.13.

Murua, H., Rodriguez-Marin, E., Neilson, J.D., Farley, J.H., and Juan-Jordá, M.J. 2017. Fast versus slow growing tuna species: age, growth, and implications for population dynamics and fisheries management. Rev. Fish Biol. Fish. **27**(4): 733–773. doi:10.1007/s11160-017-9474-1.

Newman, D., Berkson, J., and Suatoni, L. 2015. Current methods for setting catch limits for data-limited fish stocks in the United States. Fish. Res. **164**: 86–93. doi:10.1016/j.fishres.2014.10.018.

Newman, S.J., Brown, J.I., Fairclough, D. V., Wise, B.S., Bellchambers, L.M., Molony, B.W., Lenanton, R.C.J., Jackson, G., Smith, K.A., Gaughan, D.J., Fletcher, W. (Rick) J., McAuley, R.B., and Wakefield, C.B. 2018. A risk assessment and prioritisation approach to the selection of indicator species for the assessment of multi-species, multi-gear, multi-sector fishery resources. Mar. Policy **88**(Supplement C): 11–22. doi:10.1016/j.marpol.2017.10.028.

Ohshimo, S., and Naya, M. 2014. Management Strategy Evaluation of Fisheries Resources in Data-poor Situations Using an Operating Model Based on a Production Model. Japan Agric. Res. Q. JARQ **48**(2): 237–244. doi:10.6090/jarq.48.237.

De Oliveira, J.A.A., Kell, L.T., Punt, A., Roel, B.A., and Butterworth, D.S. 2008. Managing without best Predictions: The Management Strategy Evaluation Framework. *In* Advances in Fisheries Science. *Edited by* A. Payne, J. Cotter, and T. Potter. Blackwell Publishing Ltd., Oxford, UK. pp. 104–134.

Pomeroy, R.S. 1995. Community-Based and Co-Management Institutions for Sustainable Coastal Fisheries. Ocean Coast. Manag. **27**: 143–162. doi:10.1016/0964-5691(95)00042-9.

Punt, A.E. 2010. Harvest control rules and fisheries management. *In* Handbook of Marine Fisheries Conservation and Management. *Edited by* R.Q. Grafton, R. Hilborn, D. Squires, M. Tait, and M. Williams. Oxford University Press, Oxford, New York. pp. 582–594.

Punt, A.E., Butterworth, D.S., Moor, C.L., Oliveira, D., A, J.A., and Haddon, M. 2016. Management strategy evaluation: best practices. Fish Fish. **17**(2): 303–334. doi:10.1111/faf.12104.

Punt, A.E., Dorn, M.W., and Haltuch, M.A. 2008. Evaluation of threshold management strategies for groundfish off the U.S. West Coast. Fish. Res. **94**(3): 251–266. doi:10.1016/j.fishres.2007.12.008.

Shertzer, K.W., and Williams, E.W. 2008. Fish assemblages and indicator species: reef fishes off the southeastern United States. Fish. Bull. **106**(3): 257–269.

Squires, D., and Vestergaard, N. 2015. Productivity growth, catchability, stock assessments, and optimum renewable resource use. Mar. Policy **62**: 309–317. doi:10.1016/j.marpol.2015.07.006.

Tanaka, S. 1980. A Theoretical Consideration on the Management of a Stock-Fishery System by Catch Quota and on Its Dynamical Properties. Nippon Suisan Gakkaishi **46**(12): 1477–1482. doi:10.2331/suisan.46.1477.

Welcomme, R.L. 1999. A review of a model for qualitative evaluation of exploitation levels in multi-species fisheries. Fish. Manag. Ecol. **6**(1): 1–19. doi:10.1046/j.1365-2400.1999.00137.x.

Wiedenmann, J. 2013. An Evaluation of Harvest Control Rules for Data-Poor Fisheries. North Am. J. Fish. Manag. **v. 33**(4): 845–860. doi:10.1080/02755947.2013.811128.

Wiedenmann, J., Wilberg, M., Sylvia, A., and Miller, T. 2016. An evaluation of acceptable biological catch (ABC) harvest control rules designed to limit overfishing. Can. J. Fish. Aquat. Sci. **74**(7): 1028–1040. doi:10.1139/cjfas-2016-0381.

Yamakawa, T., Matsumiya, Y., Nishimura, M., and Ohnishi, S. 1994. Expanded DeLury's Method with Variable Catchability and its Application to Catch-Effort Data from Spiny Lobster Gillnet Fishery. Fish. Sci. **60**(1): 59–63. doi:10.2331/fishsci.60.59.

Yuniarta, S., van Zwieten, P.A.M., Groeneveld, R.A., Wisudo, S.H., and van Ierland, E.C. 2017. Uncertainty in catch and effort data of small- and medium-scale tuna fisheries in Indonesia: Sources, operational causes and magnitude. Fish. Res. **193**: 173–183. doi:10.1016/j.fishres.2017.04.009.

Table 1. The feedback factor values for the default feedback harvest control rule (HCR) (case marked with an asterisk) and the alternative HCRs used in this study. The abbreviation 1.0-1.0-1.0-0.8 signifies that *k* is 1.0, and *δ* is 1.0, 1.0 and 0.8, corresponding to high, middle and low stock levels.

Case	k	δ_{high}	δ_{middle}	δ_{low}	Abbreviation
1	0.5	1.0	1.0	0.8	0.5-1.0-1.0-0.8
2*	1.0	1.0	1.0	0.8	1.0-1.0-1.0-0.8
3	1.5	1.0	1.0	0.8	1.5-1.0-1.0-0.8
4	2.0	1.0	1.0	0.8	2.0-1.0-1.0-0.8
5	2.5	1.0	1.0	0.8	2.5-1.0-1.0-0.8

Table 2. Set of parameter values for the three species in the multispecies fishery.

Parameter	Definition	Species 1	Species 2	Species 3
r	Intrinsic growth rate	0.2	0.5	1
K	Carrying capacity	50 000	20 000	10 000
MSY	Maximum sustainable yield	2 500	2 500	2 500
B_{MSY}	Biomass produced at the MSY level	25 000	10 000	5 000
F_{MSY}	Fishing mortality in achieving MSY	0.1	0.25	0.50

Table 3. Results of performance measures (probability of overfishing [P_{OF}], yield status [C/MSY], biomass status [B/B_{MSY}], and management failure [Failure]) when applying the default feedback harvest control rule to three species (slow-growing [Sp. 1], medium-growing [Sp. 2], and fast-growing [Sp. 3]), with mixed-species data and single-species data, under three critical biomass-trend scenarios: $B_H – B_L$, $B_M – B_M$, and $B_L – B_H$.

Scenario	Performance measures	Mixed-species results				Single-species results			
		Sp. 1	Sp. 2	Sp. 3	Total	Sp. 1	Sp. 2	Sp. 3	Total
$B_H – B_L$	P_{OF}	0.83	0.05	0.00	–	0.49	0.13	0.01	–
	C/MSY	0.23	0.66	0.45	0.45	0.12	0.59	0.50	0.43
	B/B_{MSY}	0.27	1.44	1.67	0.74	0.31	1.33	1.66	0.73
	Failure	0.00	0.00	0.01	0.01	0.44	0.07	0.01	0.48
$B_M – B_M$	P_{OF}	0.37	0.00	0.00	–	0.35	0.01	0.00	–
	C/MSY	0.56	0.53	0.31	0.47	0.45	0.53	0.33	0.44
	B/B_{MSY}	0.87	1.60	1.76	1.16	0.89	1.59	1.74	1.17
	Failure	0.00	0.00	0.01	0.01	0.07	0.00	0.01	0.07
$B_L – B_H$	P_{OF}	0.00	0.00	0.00	–	0.00	0.00	0.00	–
	C/MSY	0.24	0.12	0.06	0.14	0.20	0.11	0.06	0.13
	B/B_{MSY}	1.62	1.82	1.85	1.70	1.64	1.84	1.88	1.72
	Failure	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.00

Fig. 1. Biomass status, catch status, and fishing mortality under three critical biomass-trend scenarios during the pre-management period: $B_H - B_L$, $B_M - B_M$, and $B_L - B_H$.

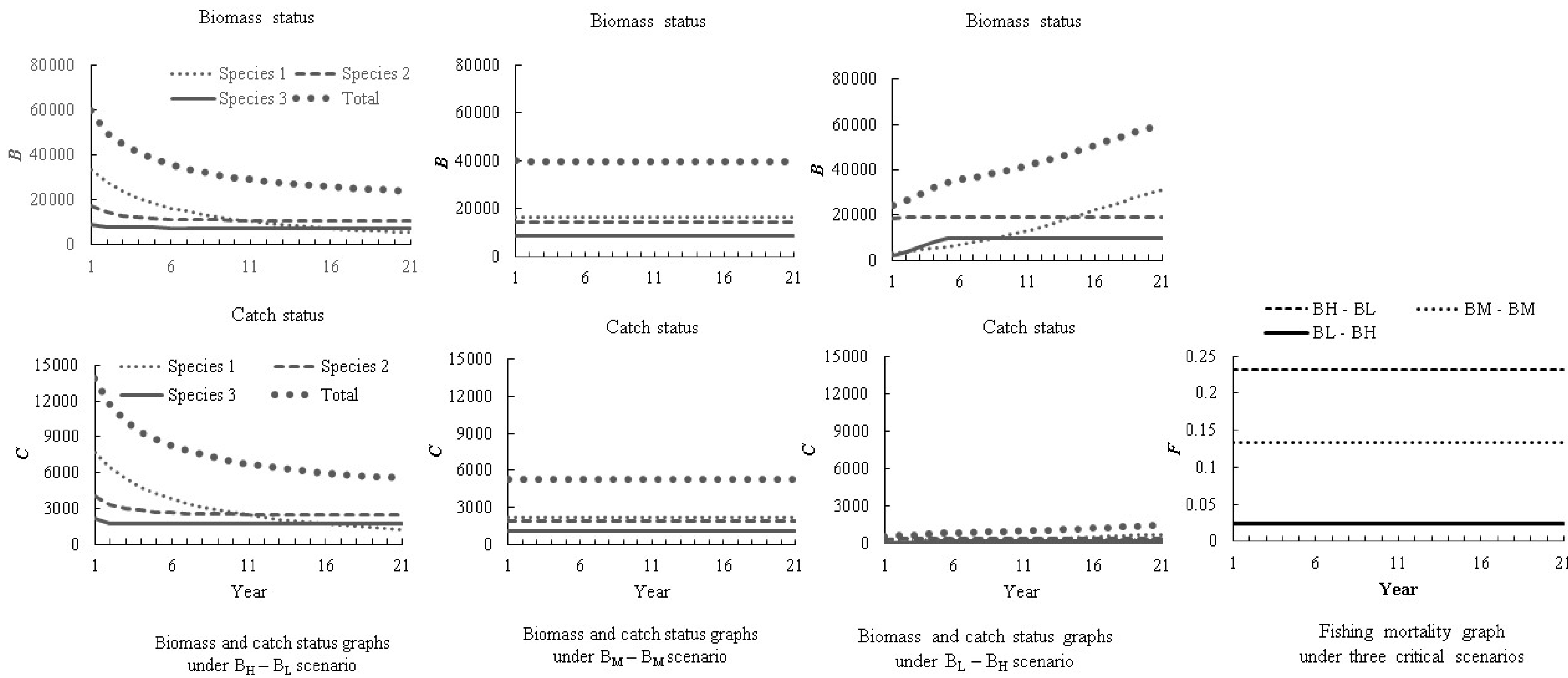

Fig. 2. Kobe-plot for the last management year, after applying the default feedback harvest control rule (denoted by the abbreviation 1.0-1.0-1.0-0.8), to mixed-species data (dark colors) and single-species data (pale colors), under three critical biomass-trend scenarios. Blue circles, green squares and orange triangles indicate species 1, 2 and 3, respectively. The filling type of the points denotes the type of biomass-trend scenario, with solid, pattern and band used for scenarios $B_H - B_L$, $B_M - B_M$ and $B_L - B_H$, respectively. The solid line indicates the overfishing threshold, while the dashed line defines the overfished line.

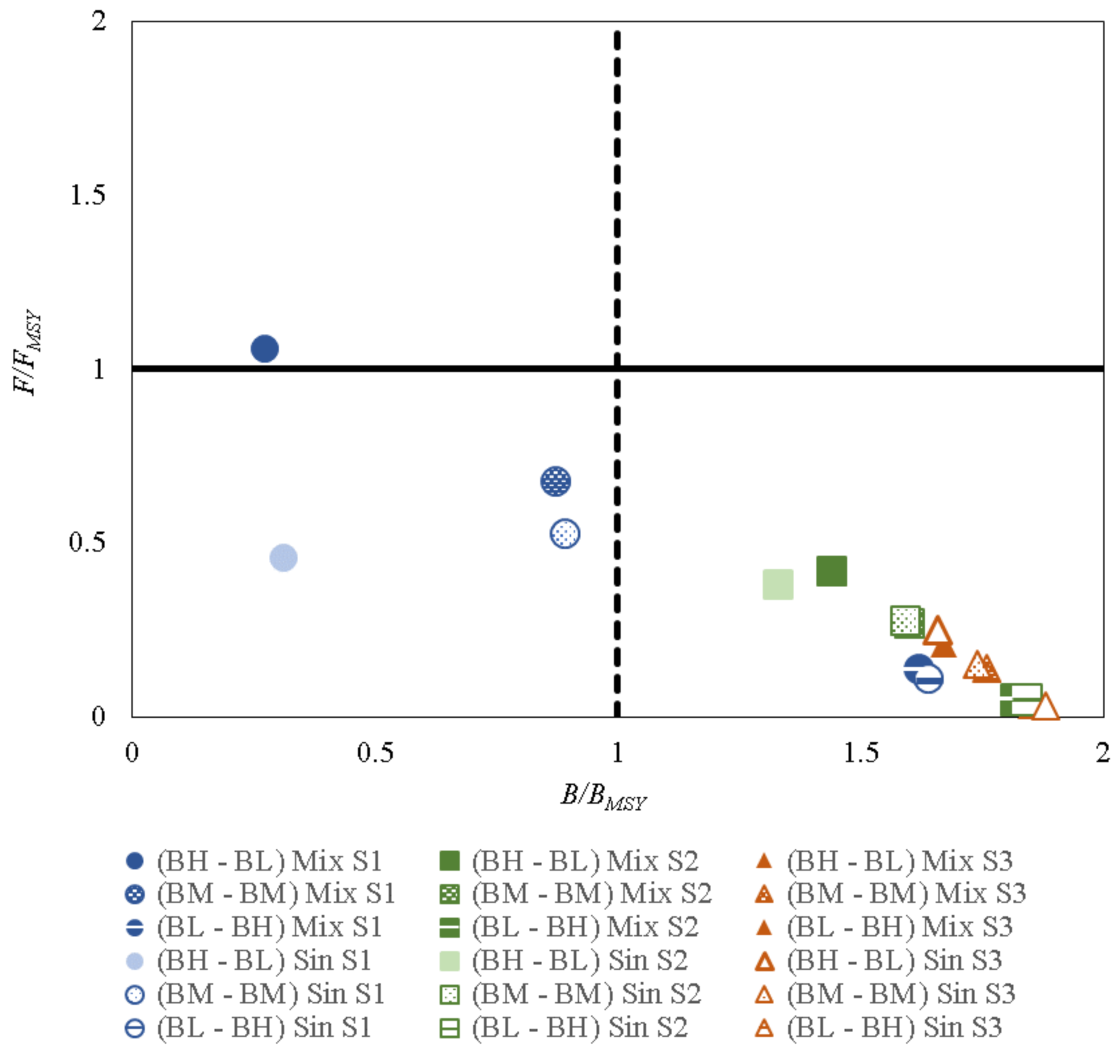

Fig. 3. Biomass and catch status performance of the default feedback harvest control rule (denoted by the abbreviation 1.0-1.0-1.0-0.8), to mixed-species data (dark colors) and single-species data (pale colors), under three critical biomass-trend scenarios. Blue circles, green squares, orange triangles and black diamonds indicate species 1, 2, 3 and the total species, respectively. The filling type of the points denotes the type of biomass-trend scenario, with solid, pattern and band used for scenarios $B_H – B_L$, $B_M – B_M$ and $B_L – B_H$, respectively. The solid line indicates the MSY level, while the dashed line defines the overfished line.

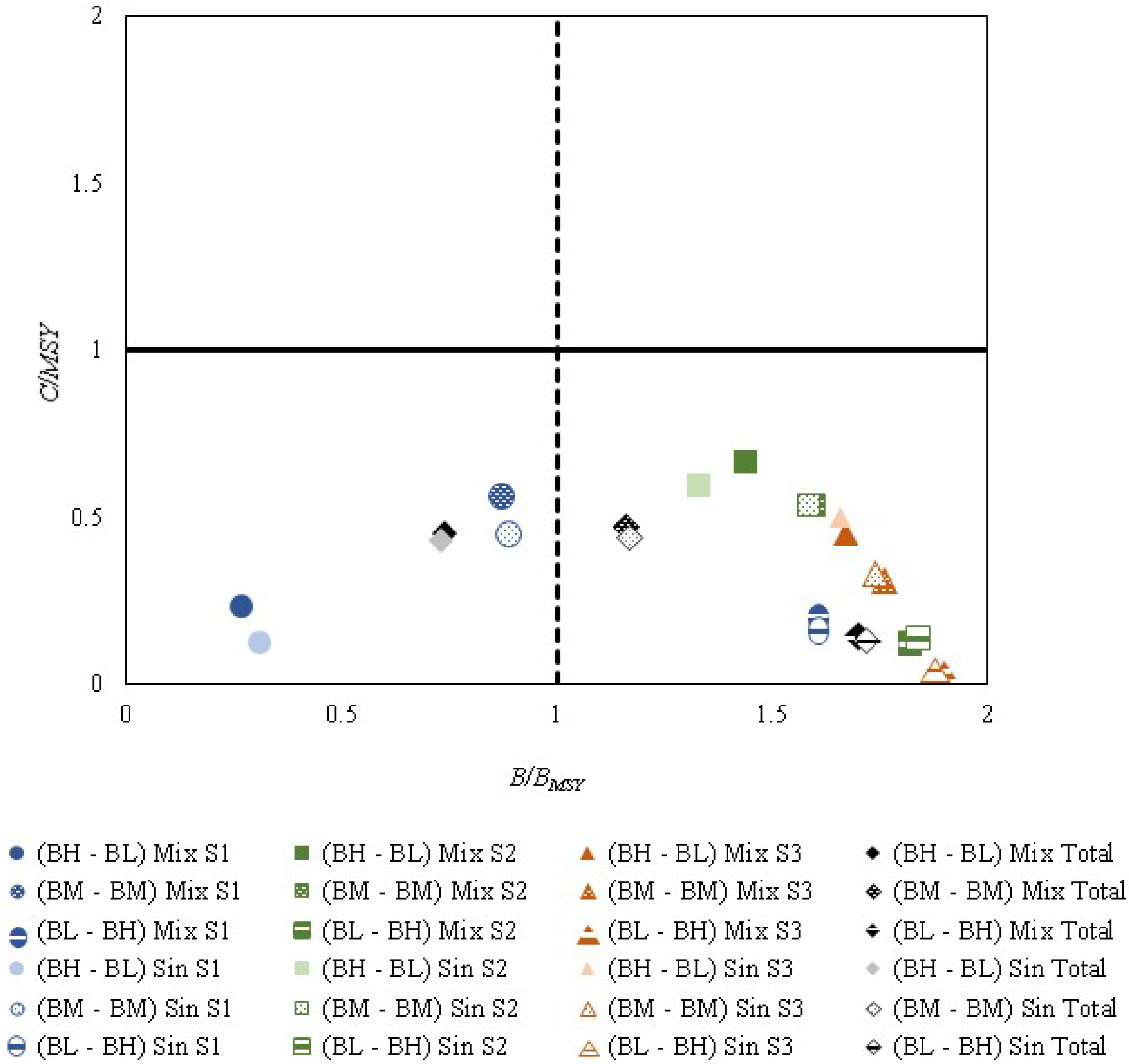

Fig. 4. Performance measures of the alternative feedback harvest control rules (HCRs), created by modifying the adjusting parameter *k*, with mixed-species data (black points) and single-species data (white points), under three critical biomass-trend scenarios ($B_H - B_L$, $B_M - B_M$, and $B_L - B_H$, denoted by circles, squares and triangles, respectively). The x-axis is the various *k*-modified feedback HCRs, and the y-axis is the performance measures, namely biomass status, coefficient of variation (CV) for the biomass, catch status, CV for the catch, probability of overfishing and management failure.