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ICES Journal of Marine Science, 2023, **80**, 897–910
DOI: 10.1093/icesjms/fsad023
Advance access publication date: 20 February 2023
Original Article

Exploring balanced harvest as a potential strategy for highly exploited multispecies fisheries

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Balanced harvest (BH) proposes moderate fishing mortality rates across all species or sizes in proportion to productivity, serving as a possible strategy for ecosystem-based fisheries management. Fishing patterns in some developing countries (e.g. China, the largest producer of seafood) closely resemble BH, where catches have been highly diversified by unselective gears due to market demand for almost all species. In this study, we employed an OSMOSE ecosystem model developed for the Yellow Sea in China to investigate the potential occurrences and advantages of BH in this region with highly exploited multispecies fisheries. Simulations were carried out under four types of fishing scenarios, where various levels of fishing mortality rates for all species or specific functional groups were implemented. Results indicated that the occurrences of BH depended on fishing pressure and targeted functional groups, and that size-level BH was significantly correlated with biomass and yield for most species. In particular, varying fishing pressure for certain functional groups resulted in BH, which produced a high yield for specific species and ensured their biomass sustainability. We concluded that the benefits of BH could be potentially achieved by adjusting fishing pressure for certain functional groups based on the existing fishing pattern in over-exploited ecosystems.

Keywords: Balanced harvest, Ecosystem approach to fisheries, ecosystem model, multispecies fisheries, OSMOSE.

Introduction

Balanced harvest (BH) is defined as fishing pressure being spread across the widest possible range of trophic levels, sizes, and species at moderate fishing mortality rates in proportion to the natural productivity of each component in a marine ecosystem (Zhou *et al.*, 2010; Garcia *et al.*, 2012; Kolding *et al.*, 2016a; Zhou *et al.*, 2019). The primary goal of BH is to reduce fishing impacts on the structure of marine ecosystems while simultaneously maintaining or maximizing fishery yield (Garcia *et al.*, 2012; Kolding *et al.*, 2016b; Zhou *et al.*, 2019).

The BH strategy has attracted broad attention worldwide and has been investigated through modelling studies with size-based models, multispecies predation models, and whole ecosystem models (Garcia *et al.*, 2012; Law *et al.*, 2012, 2016; Jacobsen *et al.*, 2014; Kolding *et al.*, 2016b; Heath *et al.*, 2017; Zhou and Smith, 2017; Plank, 2018; Nilsen *et al.*, 2020). These studies indicated that BH can help preserve ecosystem structure, maintain relative abundances of different sizes and species, and increase fishery yield substantially (Garcia *et al.*, 2012; Law *et al.*, 2016; Kolding *et al.*, 2016b). Therefore, BH can be used as a potentially valuable strategy for ecosystem-based fisheries management (EBFM) (Garcia *et al.*, 2016; Zhou *et al.*, 2019).

As the world's largest producer of seafood, fisheries in China contribute to almost one-fifth of the global catch volume (Food and Agriculture Organization of the United Nations, 2016; Cao *et al.*, 2017; Szuwalski *et al.*, 2017) and are characterized by the complete retention of highly diversified catches using unselective fishing gears, without practising discarding (Szuwalski *et al.*, 2017, 2020; Kritzer *et al.*, 2022). Such a fishing pattern in China appeared to resemble BH; however, it is characterized by indiscriminate fishing and the depletion of high trophic level species, which is inconsistent with a major objective of BH to protect marine taxa that are large in body size but low in production (Szuwalski *et al.*, 2017; Zhou *et al.*, 2019; Burgess and Plank, 2020). To reverse the trend of increased ecological risks and fish stock depletion, environmental protection and ecocivilization have been increasingly proposed as essential elements of sustainable development in China, including clear support for the United Nations Sustainable Development Goals (Kuhn, 2016; Cao *et al.*, 2017; Kritzer *et al.*, 2022). Considering the size of Chinese fisheries and the unselective fishing practices, developing novel management methods in the next few decades rather than relying on strategies used by some developed countries has been emphasized in the recent assessment of global fisheries stocks so as to sustain fisheries biomass, stocks, and profits in China (Costello *et al.*, 2016; Cao *et al.*, 2017; Szuwalski *et al.*, 2020).

In this study, we used an ecosystem modelling approach to explore BH as a potential strategy for intensive multispecies fisheries in the China Seas. Specifically, we employed an individual-based multispecies ecosystem modelling

Received: 14 December 2022; **Revised:** 26 January 2023; **Accepted:** 1 February 2023

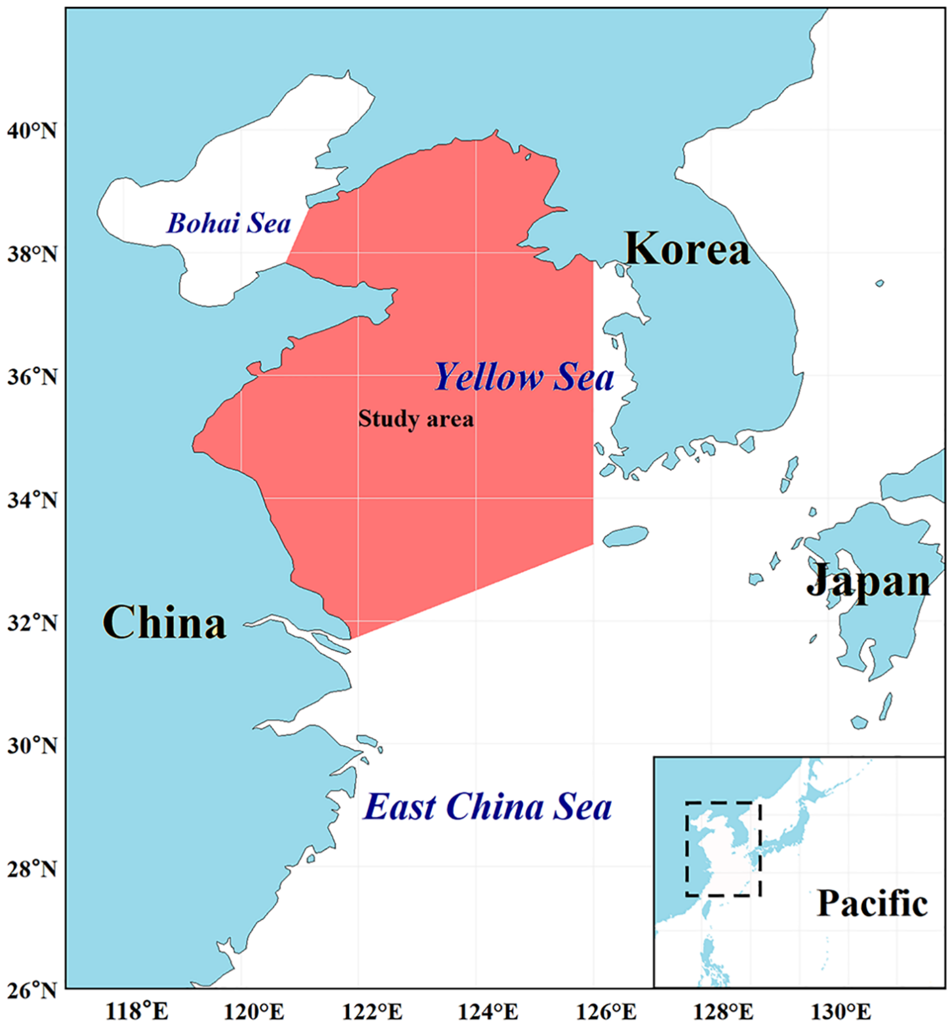

Figure 1. The study area for the OSMOSE-YS model in the Yellow Sea (light red area).

platform OSMOSE (Object-oriented Simulator of Marine Ecosystems; Shin and Cury, 2001, 2004), for this purpose. OSMOSE simulates the whole lifecycle of multiple interacting marine species and has been widely used in various marine ecosystems around the world to evaluate the impacts of fishing and climate change (Travers-Trolet *et al.*, 2014; Fu *et al.*, 2017, 2020; Guo *et al.*, 2020).

In this study, we chose one of the most exploited shallow seas in China, the Yellow Sea, as a study case, where overexploitation has led to large changes in the fish community structure, diversity, and the food webs (Jin and Tang, 1996; Shen and Heino, 2014; Szuwalski *et al.*, 2020). OSMOSE was parameterized and calibrated for the Yellow Sea ecosystem and hereinafter referred to as the OSMOSE-YS model. We used the OSMOSE-YS model to simulate the dynamics of multiple commercial species (pelagic, demersal, and invertebrate species) in the Yellow Sea to investigate whether the ecosystem is exploited in a balanced way under different fishing pressure scenarios, and to explore how the advantages of BH can be realized for different species. At the end, we discussed, from the viewpoint of EBFM, how fisheries management can control or adjust fishing pressure on the basis of the existing fishing patterns in order to minimize fishing impacts on ecosystem structure while maintaining sustainable yield from the ecosystems.

Materials and methods

Study area and OSMOSE model

The Yellow Sea is a semi-closed marginal sea located in the Northwest Pacific Ocean, covering a total area of about 400000 km^2 with an average water depth of 44 m (Yang *et al.*, 2003; Zhang *et al.*, 2016). The Yellow Sea is adjacent to the Bohai Sea in the north and the East China Sea in the south (Figure 1), comprised of various species associated with different niches (Xu and Jin, 2005).

The Yellow Sea benefits 10% of the world's population for marine resources, economic opportunities, and ecological services (Wang *et al.*, 2016). It also provides important spawning and feeding grounds for many commercially important fish species (Jin and Tang, 1996). However, since the 1980s, overexploitation has led to large changes in the fish community structure and diversity, and the functioning of food webs (Jin and Tang, 1996; Shen and Heino, 2014). In particular, fishing has selectively removed larger individuals or higher trophic levels species resulting in the reduction of fish size and biomass of vulnerable species (Xu and Jin, 2005). In this study, we specifically focused on 13 commercially and ecologically important species, including 5 pelagic (Japanese anchovy (JA), *Engraulis japonicus*; Chub mackerel (CM), *Scomber japonicus*; Japanese Spanish mackerel

(JSM), *Scomberomorus niphonius*; Silver pomfret (SP), *Pampus argenteus*; and South American pilchard (SAP), *Sardinops sagax*), 5 demersal (Largehead hairtail (LH), *Trichiurus japonicus*; Small yellow croaker (SYC), *Larimichthys polyactis*; Pacific cod (PC), *Gadus macrocephalus*; Yellow striped flounder (YSF), *Pseudopleuronectes herzensteini*; and Pacific sandlance (PS), *Ammodytes personatus*), and 3 invertebrate species (Southern rough shrimp (SRS), *Trachysalambria curvirostris*; Japanese flying squid (JFS), *Todarodes pacificus*; and Swimming crab (SC), *Portunus trituberculatus*) that contribute to a major part of the total biomass (Supplementary Table S1).

The OSMOSE-YS model simulates the life cycle of the 13 focus species, from the egg stage to the terminal age, at a time step of 3 months. At the first time-step after the production of eggs, the total number of eggs of each population is split into 120 super individuals (referred to as "schools"), which share the same body length, age, food requirement, and spatial coordinates at a given time step and are distributed spatially according to input distribution maps from geo-referenced data of research surveys. At each time step, OSMOSE-YS simulates biological and ecological processes, including growth, predation, starvation, fishing, reproduction, and spatial movement. The biological parameters inputted into the model were obtained from previous studies (Supplementary Table S1). The average growth of the schools follows the von Bertalanffy growth model, and individual growth variability is determined by consumption rate and prey availability (Shin and Cury, 2004). Reproduction occurs for schools achieving sexual maturity at the end of each time step, producing eggs proportional to the spawning stock biomass, sex ratio, and relative annual fecundity (Fu *et al*., 2013; Travers-Trolet *et al*., 2014). Predation is assumed to be opportunistic and size-based, depending on their spatiotemporal co-occurrence and the minimum and maximum predator/prey size ratios, which are derived from observed diets and species' mean sizes (Fu *et al*., 2013).

In addition to the 13 focus species, two plankton (phytoplankton and zooplankton) groups were also included as food sources; their biomasses and distributions were derived from a calibrated biogeochemical model (i.e. FVCOM-NEMURO; Yu *et al*., 2020). The two plankton groups and 13 focus species are linked through trophic interactions to represent the Yellow Sea food web. However, we did not consider the predation impact of the focus species on the plankton groups, meaning the trophic interactions between the high trophic level focus species and the plankton groups is one-way forcing instead of two-way doubling (Travers-Trolet *et al*., 2014).

The OSMOSE-YS was calibrated using an evolutionary algorithm (EA), which has been developed for the calibration of complex stochastic models (Duboz *et al*., 2010; Oliveros-Ramos and Shin, 2016). The unknown parameters for each modelled species were estimated by fitting the simulated species biomass and yield to observed data using maximum likelihood objective functions (Oliveros-Ramos *et al*., 2017). The unknown parameters estimated in the OSMOSE-YS model for each species include larval mortality rates of focus species, availability coefficients of plankton accessibility to the modelled species, fishing mortality for exploited species, and a catchability index (Supplementary Table S2). The catchability index was used to account for the availability of exploited species to fishing gears by scaling the OSMOSE-YS model outputs. Observed yield for the period 1970–2014 in the Yellow Sea was obtained from the Sea Around Us project (Pauly and Zeller, 2016), and the observed biomass data were estimated by the optimized catch-only method (OCOM; Zhou *et al*., 2018; Supplementary Table S3). The calibration process used the "calibraR" (https://cran.r-project.org/web/packages/calibrar) R packages (Oliveros-Ramos and Shin, 2016; Oliveros- Ramos *et al*., 2017).

BH

BH can be expressed either in terms of production (P) or productivity (P/B) using the following equations (Eqs. 1 and 2):

$$\textbf{Balance to production (BH1)}: F(x) = c_1 \cdot P(x) = c_1 \cdot g(x) \cdot B(x) \tag{1}$$

$$\textbf{Balance to productivity (BH2)}: F(x) = c_2 \cdot \frac{P(x)}{B(x)} = c_2 \cdot g(x) \tag{2}$$

For both equations, F(x) is the fishing mortality for species x, and P(x) is the species-specific production calculated from the biomass (B), and growth (g) of species x. In BH1, c_1 is a constant of proportionality, while c_2 in BH2 is a constant between 0 and 1 for all ecological groups, and they both determine the intensity of fishery exploitation. BH1 is similar to a "state-dependent" or "sliding" harvest control rule for target species because of its dependence on biomass (Berger *et al*., 2012). Moreover, BH can take place at either the species level (*sBH*) or species- and size-level (*ssBH*) (Zhou *et al*., 2019). The *sBH* balances fishing mortality across the widest possible range of species within an ecosystem, while the *ssBH* balances fishing mortality across the ranges of species and sizes within species.

There are practical difficulties in implementing BH because it requires knowledge for species-specific production and it presents technical limitations in the application of moderate fishing mortality rates proportional to species- and size-level productivity (Kolding *et al*., 2016a; Zhou *et al*., 2019). These practical difficulties hinder the implementation of BH, particularly for large-scale industrial fisheries (Zhou *et al*., 2019). Therefore, in this study, we did not implement BH in the OSMOSE-YS model, rather, we carried out various fishing scenarios using historical fishing pressure as a benchmark and determined if these fishing scenarios attributed to BH.

Simulation scenarios

The OSMOSE-YS model was initialized at the biomass levels of the year 1970 for the 13 focus species and calibrated for the period from 1970 to 2014. The species-specific fishing mortality from the calibrated model for this period was regarded as a historical baseline scenario, "S_{base}." Then, we simulated two types of fishing scenarios "$S_{decrease}$" and "$S_{increase}$" (i.e. decreasing or increasing fishing mortality from "S_{base}") to investigate whether or how BH would be achieved under different fishing pressures (Table 1). Each type of fishing scenarios decreased or increased the fishing mortality rate from 10 to 90% of the baseline scenario (with a step of 10%) in the last 10 years of the simulation (2005–2014) in order to identify fishing mortality rates that would constitute BH. In addition, to investigate how varying fishing pressure on different functional groups may have impacted the YS ecosystem and how BH can achieve its benefits, we examined the simulation scenarios separately by functional groups. The four types of fishing scenarios include (Table 1):

Table 1. List of all simulation scenarios.

Scenarios		Species												
		JA	CM	JSM	SP	SAP	LH	SYC	PC	YSF	PS	SRS	JFS	SC
S_{base}														
$S_{decrease}$	S_{all}	○	○	○	○	○	○	○	○	○	○	○	○	○
	S_{pel}	○	○	○	○	○								
	S_{dem}						○	○	○	○	○			
	S_{inv}											○	○	○
$S_{increase}$	S_{all}	○	○	○	○	○	○	○	○	○	○	○	○	○
	S_{pel}	○	○	○	○	○								
	S_{dem}						○	○	○	○	○			
	S_{inv}											○	○	○

Note: The common names of the species represented by the abbreviations are shown in Supplementary Table S1; ○ represents that this species is subjected to changes (decreasing or increasing) in fishing mortality rate. $S_{decrease}$: decreasing fishing mortality rate from the baseline level by 10, 20, …, up to 90%; $S_{increase}$: increasing fishing mortality rate from the baseline level by 10, 20, …, up to 90%; S_{all}: fishing for all; S_{pel}: fishing for pelagic species; S_{dem}: fishing for demersal species; and S_{inv}: fishing for invertebrate.

(1) S_{all}: $S_{decrease\ for\ all}$ or $S_{increase\ for\ all}$ where all the focus species were subjected to decreasing or increasing fishing mortality rate by 10, 20, …, up to 90%.
(2) S_{pel}: $S_{decrease\ for\ pelagic\ species}$ & $S_{increase\ for\ pelagic\ species}$ where pelagic species were subjected to decreasing or increasing fishing mortality rate by 10, 20, …, up to 90% while other functional groups (demersal species and invertebrate species) were harvested at historical levels.
(3) S_{dem}: $S_{decrease\ for\ demersal\ species}$ & $S_{increase\ for\ demersal\ species}$ where demersal species were subjected to decreasing or increasing fishing mortality rate by 10, 20, …, up to 90% while other functional groups were harvested at historical levels.
(4) S_{inv}: $S_{decrease\ for\ invertebrate}$ & $S_{increase\ for\ invertebrate}$ where invertebrate species were subjected to decreasing or increasing fishing mortality rate by 10, 20, …, up to 90% while fish groups (pelagic species and demersal species) were harvested at historical levels.

In total, 36 scenarios of decreasing fishing pressure and 36 scenarios of increasing fishing pressure were considered; these 72 scenarios are detailed in Table 1. Statistical analyses were conducted by one-way ANOVA at both the species and functional group levels. Through these simulation scenarios, we aimed to provide suggestions for fishery management that would be easier to operate than directly implementing the BH strategy, given the current technological and practical limitations of operating different fishing selectivity and fishing pressure at different species- and size-levels.

Assessing fishing scenarios against BH

Using the time series of productivity and biomass of the focus species derived from the OSMOSE-YS model outputs, we assessed all the 72 fishing scenarios against all BH forms (i.e. *sBH1*, *sBH2*, *ssBH1*, and *ssBH2*). We used linear fitting models that were executed with the package "stats" in R (R Core Team, 2022) to determine whether the fishing mortality rate implemented in OSMOSE-YS was proportional to production or productivity. The fitting linear models are expressed as:

$$sBH1 : F_i \sim Production_i - 1 \tag{3}$$

$$sBH2 : F_i \sim Productivity_i - 1 \tag{4}$$

$$ssBH1 : F_i^s \sim Production_i^s - 1 \tag{5}$$

$$ssBH2 : F_i^s \sim Productivity_i^s - 1 \tag{6}$$

where F_i, $Production_i$, and $Productivity_i$ are fishing mortality rate, production and productivity for species *i*; F_i^s, $Production_i^s$, and $Productivity_i^s$ are fishing mortality rate, production and productivity for species *i* and size *s*. The "-1" in the models means omitting the intercept. At the species level (*sBH*), *F* was the fishing mortality rate for each species during the simulation, while at the species- and size-level (*ssBH*), *F* was the fishing mortality rate at the size of each species from the model outputs. The multiple R^2 of the model was used to detect whether BH (*sBH* or *ssBH*) occurred, and BH was considered to occur when R^2 reached 0.5. For *sBH2* and *ssBH2*, the estimated coefficient c_2 for all ecological groups should be between 0 and 1 for the fishing scenario to be considered BH2. Once the BH state was assessed, we evaluated the occurrences of BH under different scenarios and identified balanced fishing strategies in the Yellow Sea ecosystem. We further compared the biomass and yield of focus species among the different scenarios to determine the differences between balanced and unbalanced fishing strategies under four types of scenarios.

Result

Assessing the occurrences of BH

Under the historical fishing mortality baseline scenario, *sBH1* did not occur ($R^2 = 0.40$), while *sBH2* did ($R^2 = 0.62$) (Figure 2a, Supplementary Figure S1). The R^2 was below 0.5 under all fishing mortality rates for the four types of fishing scenarios (i.e. S_{all}, S_{pel}, S_{dem}, and S_{inv}) and no *sBH1* occurred (Supplementary Figure S1). In the scenario of S_{all}, *sBH2* occurred at all levels of fishing mortality rates ($R^2 > 0.5$ and c_2 between 0 and 1) and the harvest got closer to a balanced one (higher R^2) as fishing mortality rates got further decreased from the baseline. This trend was in contrast to the scenario of S_{pel}, where R^2 increased with increasing fishing mortality rate and *sBH2* did not occur when fishing mortality rate dropped below 40% of the baseline. The scenarios of S_{dem} and S_{inv} followed a similar trend where R^2 was highest when fishing mortality rate decreased by 20% from the baseline, and *sBH2* did not occur when fishing mortality rate was either too high or too low. The occurrences of *ssBH* varied by species, and the fitting results for the four types of fishing scenarios showed that R^2 values for *ssBH2* were higher than those for *ssBH1* (Figure 2b, Sup-

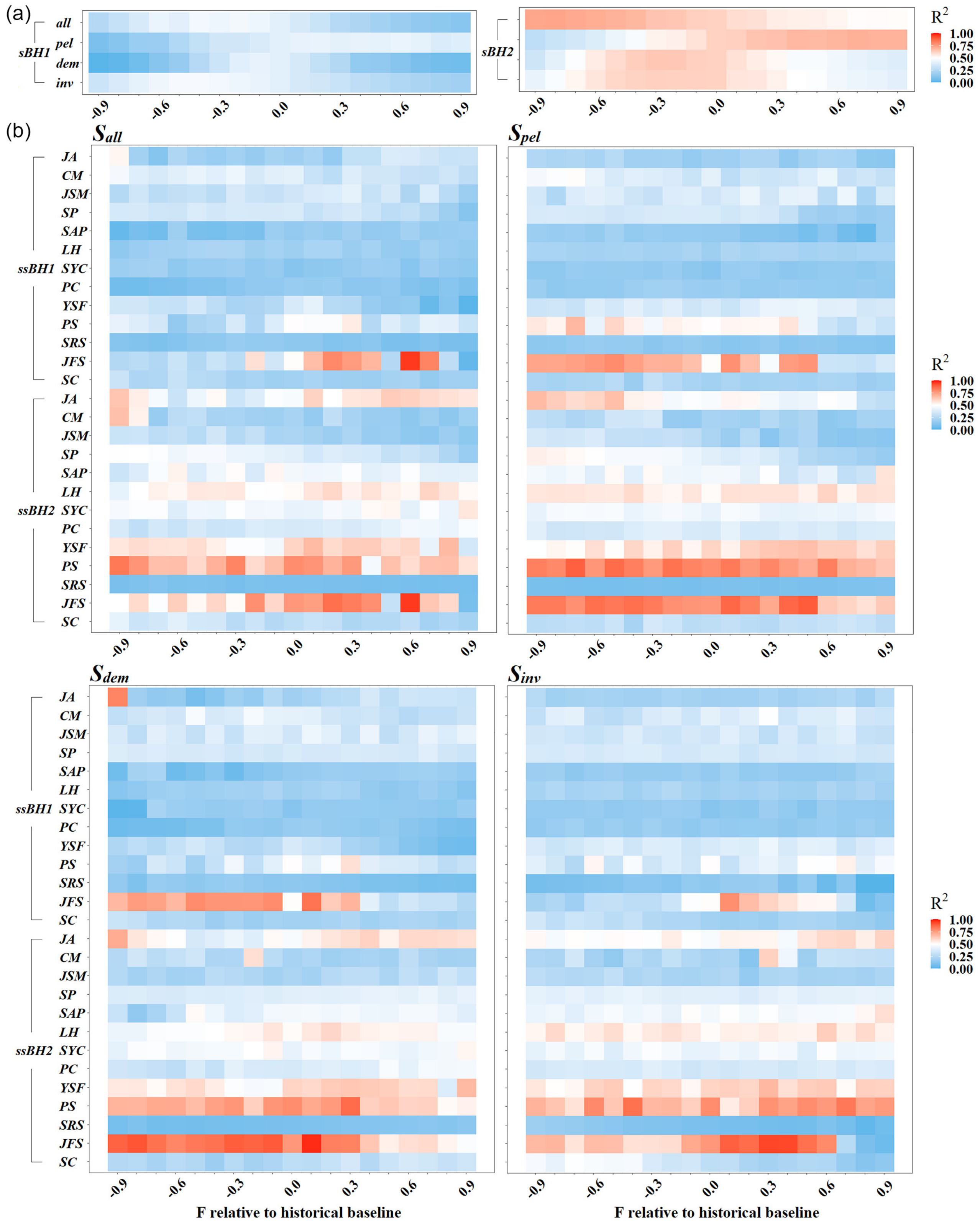

Figure 2. (a) R^2 of fitting linear models for *sBH1* and *sBH2* in four types of scenarios (S_{all}: fishing for all species; S_{pel}: fishing for pelagic species; S_{dem}: fishing for demersal species; and S_{inv}: fishing for invertebrate), and (b) R^2 of fitting linear models for *ssBH1* and *ssBH2* on all modelled species in four types of scenarios. The R^2 values of fitting linear models are shown in Supplementary Figures S1–S5.

plementary Figures S2–5). As an example, the assessment of a fishing scenario against *ssBH2* in the case of $S_{decrease\ 90\%}$ for S_{all} was performed by linear regression of size-level fishing mortality rates versus productivity time series to determine whether they were proportional, indicating whether BH at the size level was achieved for specific species (Supplementary Figure S6). In this case, BH at the size level (*ssBH2*) occurred for JA, CM, SP, YSF, and PS (Supplementary Figures S6A, B, D, I, and J).

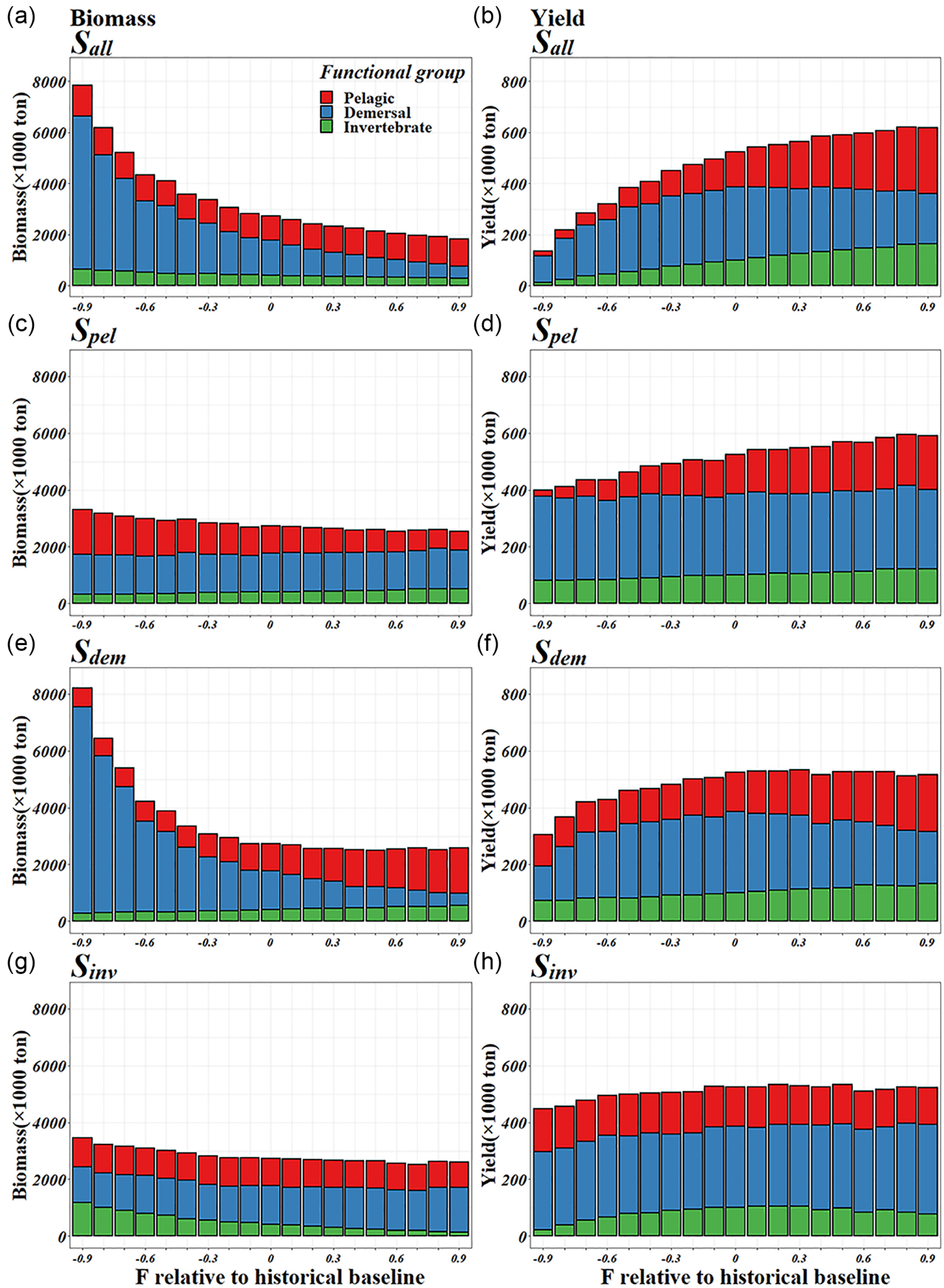

Figure 3. Changes of biomass and yield of functional groups under four types of fishing scenarios (S_{all}: fishing for all species; S_{pel}: fishing for pelagic species; S_{dem}: fishing for demersal species; and S_{inv}: fishing for invertebrate).

Relative changes in biomass and yield

Total biomass decreased with increasing fishing mortality rate from 90% reduction to 90% increase from the historical baseline in the S_{all} scenario (Figure 3a). In the S_{dem} scenario, total biomass decreased even more drastically when fishing mortality rate increased from 90% reduction to the historical baseline, and the reduction in biomass mainly occurred for demersal species (Figure 3e). When fishing mortality rate increased from the historical baseline, total biomass became stabilized (Figure 3e). In the scenarios of S_{pel} and S_{inv}, total biomass was rather stable with fewer fluctuations despite the large changes of fishing mortality rate from 90% reduction to 90% increase from the historical baseline (Figure 3c and g).

Total yield generally increased with fishing mortality rate particularly in the S_{all} scenario (Figure 3b). The yield for pelagic species increased with the fishing mortality rate in all the cases (Figure 3b, d, and f) except for S_{inv} (Figure 3h). However, the demersal yield showed bell shapes in the scenarios of S_{all} and S_{dem} (Figure 3b and f), while it remained stable in S_{pel} (Figure 3d) but showed a slight increase in S_{inv} (Figure 3h). The yield for invertebrate species showed a clear increasing trend with an increasing fishing mortality rate in the S_{all} scenario (Figure 3b) but a bell shape in the S_{inv} scenario (Figure 3h). In the other two scenarios (S_{pel} and S_{dev}), the invertebrate yield increased under increasing fishing mortality was rather minor (Figure 3d and f).

In the S_{all} scenario, relative changes in biomass showed the highest magnitude of fluctuations when fishing mortality rate increased from 90% reduction to the historical baseline (Figure 4a), which was followed by S_{dem} (Figure 4c). And in the S_{all} scenario, biomass for all species decreased as the fishing mortality rate increased from 90% reduction to the historical baseline, except for two small pelagic species, JA and SAP (Figure 4a). In all other scenarios (S_{pel}, S_{dem}, and S_{inv}), an increasing fishing mortality rate resulted in downward biomass trends for their respective functional groups, while causing fluctuations for other functional groups (Figure 4b, c, and d). Similarly, increasing fishing mortality rate on specific functional groups resulted in increasing biomass trends for the other functional groups. For instance, in the scenario of S_{pel}, the biomass of demersal species and invertebrates, such as LH, PC, SRS, JFS, and SC increased with increasing fishing mortality rates (Figure 4b).

Consistent with the relative biomass changes, the fluctuations in the relative yield in the scenarios of S_{all} and S_{dem} were greater than that in S_{pel} and S_{inv} (Supplementary Figure S7A and C). Increasing fishing mortality generally increased the yield of most pelagic species and invertebrates (JA, CM, SP, SAP, PS, SRS, and SC), while the opposite trend was observed for demersal species, such as LH, SYC, PC, and YSF in S_{all} (Supplementary Figure S7A). Increasing fishing mortality for pelagic species could increase yields for all pelagic species in S_{pel} (Supplementary Figure S7B). However, further increasing the fishing mortality rate from the historical baseline for demersal species resulted in a lower yield in S_{dem}, leading to an upward trend in the yields of other functional groups, such as JA, CM, SAP, and all invertebrate species (Supplementary Figure S7C).

Relationship between BH and biomass/yield

Figure 5 showed the cases for the four types of fishing scenarios where *sBH2* occurred. For the scenario of S_{all}, all fishing mortality cases resulted in sBH2 (Figure 5a). For the scenario of S_{pel}, *sBH2* occurred under higher fishing mortality rates with higher yields (Figure 5b). By contrast, for the scenarios of S_{dem} and S_{inv}, *sBH2* occurred under intermediate fishing mortality rates with intermediate yield (Figure 5c and d).

Species-specific biomass under all fishing mortality rates in the four types of fishing scenarios showed that the occurrences of *ssBH1* mainly concentrated in species PS and JFS (Figure 6a, c, e, and g). And *ssBH1* had a significant effect on the biomass in S_{inv} (Table 2). However, *ssBH1* did not occur for demersal species LH with the highest biomass under the fishing mortality rates of $S_{decrease\ 90\%}$ and $S_{decrease\ 80\%}$ for S_{dem}, $S_{decrease\ 90\%}$ for S_{all}. Neither did ssBH1 occur for species SRS with the lowest biomass under the fishing mortality rates of $S_{increase\ 90\%}$ and $S_{increase\ 60\%}$ for S_{inv}nor for species PC under the fishing mortality rate of $S_{increase\ 90\%}$ for S_{dem}. The p-value of the one-way variance analysis (ANOVA) showed that *ssBH1* had a significant effect on biomass for JA and JFS (Table 2).

In the scenario of S_{pel}, *ssBH2* occurred mainly under decreased fishing mortality rates with higher biomass (Figure 6b). Similarly, for the scenarios of S_{dem} and S_{inv}, *ssBH2* occurred mainly under decreased fishing mortality rates for demersal and invertebrate species, respectively (Figure 6f and h). In addition, under these two scenarios, *ssBH2* also occurred in other functional groups when fishing mortality increased. The results of the ANOVA for biomass in all four types of fishing scenarios showed significant effects of *ssBH2* on the biomass of targeted functional groups (Table 2). On the other hand, the occurrence of *ssBH2* in species JA, CM, SP, YSF, PS, and JFS had significant effects on the biomass (Table 2).

The yield variation of different species showed that *ssBH1* occurred only in the scenarios for PS and JFS, and few scenarios for JA and CM (Supplementary Figures S8A, C, E, and G). At the functional group level, the ANOVA results showed significant effects of *ssBH1* on yield variation in the four types of fishing scenarios (Table 2). Also, at the species level, the ANOVA results indicated that ssBH1 had a significant effect on the yield of JA and CM (Table 2). In $S_{pel}$and S_{inv}, *ssBH2* occurred mainly under decreased fishing mortality rates for the respective functional groups (Supplementary Figures S8D and H). For JA and LH, *ssBH2* occurred under fishing mortality rates, which resulted in a higher yield. By contrast, for species YSF, PS, and JFS, *ssBH2* occurred under the fishing mortality rates associated with lower yield (Supplementary Figures S8B, D, F, and H). At the targeted functional group level, the ANOVA results for yield showed no significant effect of *ssBH2* on yield under all four types of fishing scenarios (Table 2). On the species level however, there were significant effects of *ssBH2* on yield for CM, SP, YSF, PS, and JFS (Table 2).

Discussion

Using the individual-based ecosystem simulation model OSMOSE-YS, we were able to investigate how BH at the species- and size-level might occur and how fish species biomass and yield might change in a BH state to further achieve the advantages of this strategy in the ecosystem. Through four types of fishing scenarios, that is, fishing for all, pelagic, demersal, and invertebrate species, where fishing mortality rates varied within the range of 90% decrease to 90% increase from the historical baseline with a 10% increment, we investigated how the focus species and the YS ecosystem responded to the different levels of fishing pressure. Specifically, we studied changes in biomass and yield under four types of fishing scenarios and assessed the occurrences of BH state.

BH strategy for highly exploited multispecies fisheries

The concept of BH, which is in contrast to common practice, especially in fisheries of developed countries, has been

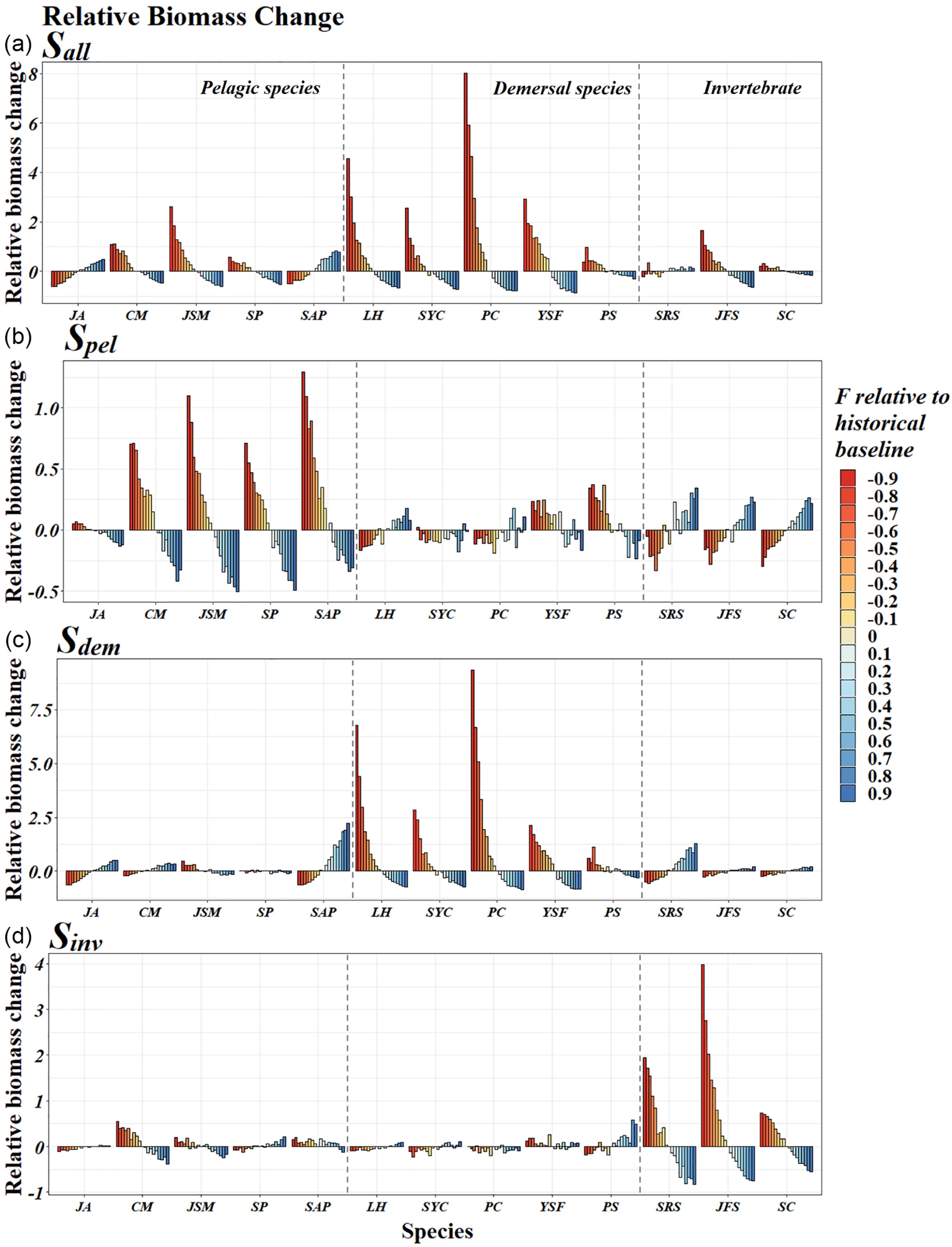

Figure 4. Biomass change relative to the baseline scenario (where fishing mortality rates were set to their historical levels) for each modelled species under four types of scenarios (S_{all}: fishing for all species; S_{pel}: fishing for pelagic species; S_{dem}: fishing for demersal species; and S_{inv}: fishing for invertebrate). The fill colour from red to blue represents the fishing mortality rate from low to high.

examined by various modelling techniques (Law *et al.*, 2016; Heath *et al.*, 2017; Zhou and Smith, 2017; Plank, 2018; Zhou *et al.*, 2019). In this study, we examined BH in large-scale and highly exploited multispecies fisheries in China based on both production and productivity that were produced by the OSMOSE model.

There are some empirical evidences to show BH in small-scale fisheries in developing countries (Kolding and van

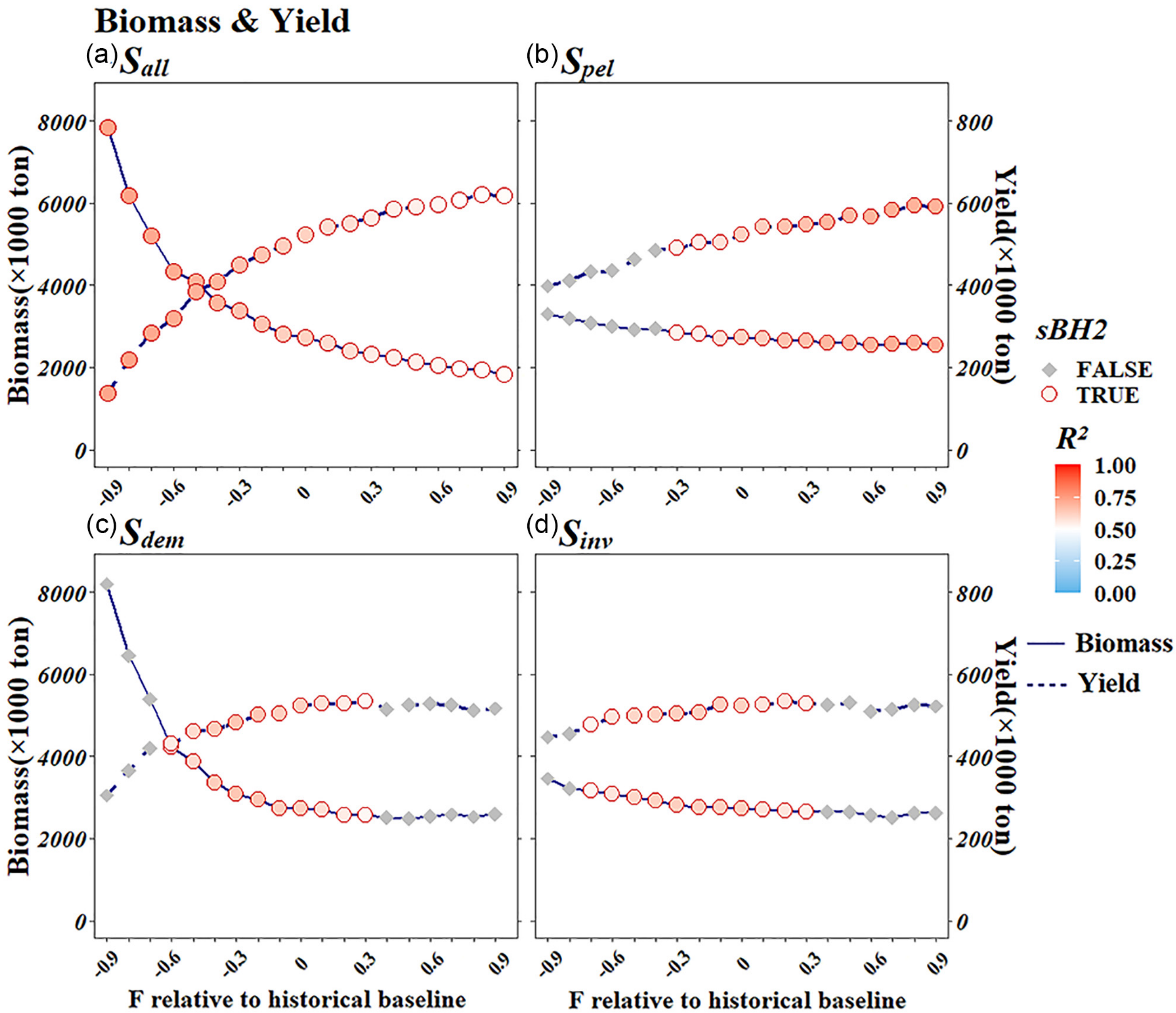

Figure 5. Change of total biomass and yield for four types of scenarios (S_{all}: fishing for all species; S_{pel}: fishing for pelagic species; S_{dem}: fishing for demersal species; and S_{inv}: fishing for invertebrate). The point indicates that *sBH2* occurs, while the grey quadrilateral indicates that *sBH2* does not occur. The fill colour from blue to red represents the R^2 of fitting linear models for *sBH2* increasing from 0 to 1.

Zwieten, 2014; Zhou *et al.*, 2019; Pelage *et al.*, 2021). For instance, the weakly enforced inland fisheries in Africa, where fishing was primarily for yield rather than profit, demonstrated an emergent fishing pattern that seemed to follow the BH concept (Kolding and van Zwieten, 2014; Peter and van Zwieten, 2018). In addition, the fishing pattern of northeast Brazil's tropical small-scale fisheries was typically in line with BH, being proportional to the production at species- and size-levels (Pelage *et al.*, 2021).

Although empirical evidences show that BH in small-scale subsistence fisheries of developing countries has resulted in high yield and food supplies with low impacts on ecosystem structure, it is still uncertain whether these experiences can be transported intact to large-scale commercial fisheries in developed countries (Burgess *et al.*, 2016; Howell *et al.*, 2016; Kolding *et al.*, 2016a; Zhou *et al.*, 2019; Nilsen *et al.*, 2020). Large-scale commercial fisheries in developed countries tend to be more selectively concentrating on certain species and sizes preferred in the market, while small-scale fisheries in developing countries employ a wider range of different fishing gears and face more generalist markets, making the fisheries resemble BH at a greater degree (Kolding *et al.*, 2014; Zhou *et al.*, 2019; Burgess and Plank, 2020).

China's fisheries management provides the world's most outstanding empirical case for discussing the trade-off between total ecosystem production and ecosystem structure conservation (Szuwalski *et al.*, 2020). Fisheries in the China Seas have been intensive, indiscriminate, relatively non-selective, and no discard with a wide range of species and sizes being available in the market (Szuwalski *et al.*, 2017). Available biological and fisheries data from the China Seas as well as empirical studies indicated trophic cascades with catches consisting of mostly one-year-old fish, community structure shifting towards species of lower value, larger predatory fish being severely reduced, and the life history characteristics of these predatory fish species having been significantly changed, resulting in reduced mean size and truncated age composition (Tang *et al.*, 2016; Szuwalski *et al.*, 2017).

From the standpoint of BH strategy, such indiscriminate fishing is disapproved as it is contrary to the goal of BH to

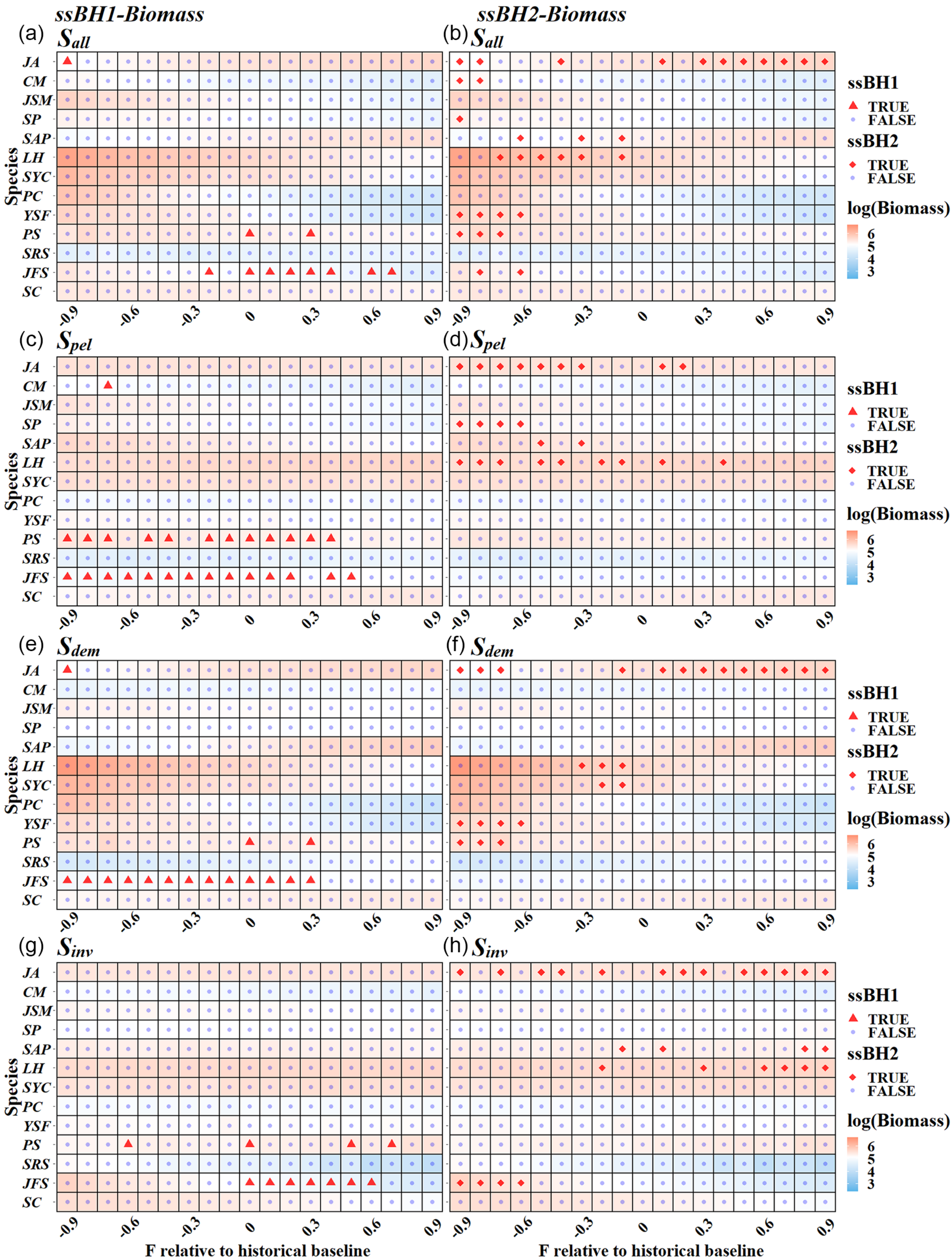

Figure 6. Change of biomass (in log scale) of each modelled species for four types of scenarios (S_{all}: fishing for all species; S_{pel}: fishing for pelagic species; S_{dem}: fishing for demersal species; and S_{inv}: fishing for invertebrate). The fill colour from blue to red represents the log biomass from low to high. The red triangle indicates that *ssBH1* occurs and the red diamond indicates that *ssBH2* occurs, while the blue dot indicates that *ssBH1* or *ssBH2* does not occur.

protect large marine taxa, and therefore it should be avoided in either the BH debate or the quest to support BH implementation (Pauly *et al.*, 2016; Zhou *et al.*, 2019). A series of policies to control fishing intensity had been implemented in China, including gear restrictions, the "Double-Control" system (controlling the number and engine power of fishing vessels), and summer fishing moratoriums (Shen and Heino, 2014; Szuwalski *et al.*, 2017). Although these measures can

Table 2. The ANOVA *p*-values of the F-statistic of biomass and yield changes.

Response		Biomass		Yield	
Variable		ssBH1	ssBH2	ssBH1	ssBH2
Fishing target	All	0.117	$4.77 \times 10^{-5***}$	0.0816.	0.266
	Pelagic	0.108	$8.06 \times 10^{-10***}$	0.0224*	0.229
	Demersal	0.111	0.0523.	0.00446**	0.725
	Invertebrate	0.0435*	$1.82 \times 10^{-11***}$	0.0676.	0.168
Species	JA	0.00111**	0.00355**	0.0331*	0.488
	CM	0.130	$3.38 \times 10^{-5***}$	0.681.	0.000405***
	JSM	–	–	–	–
	SP	–	$2.58 \times 10^{-11***}$	–	$2.27 \times 10^{-12***}$
	SAP	–	0.378	–	0.108
	LH	–	0.773	–	0.165
	SYC	–	0.743	–	0.398
	PC	–	–	–	–
	YSF	–	$2.68 \times 10^{-15***}$	–	$2.68 \times 10^{-5***}$
	PS	0.949	$2.85 \times 10^{-9***}$	0.125	$9.66 \times 10^{-11***}$
	SRS	–	–	–	–
	JFS	0.000126***	$2.39 \times 10^{-14***}$	0.180	0.000334***
	SC	–	–	–	–

Note: signifiant codes: 0 "***" 0.001 "**" 0.01 "*" 0.05 "." 0.1 ' ' 1. The models are: anova[lm(Biomass~ssBH1)], anova[lm(Biomass~ssBH2)], anova[lm(Yield~ssBH1)], and anova[lm(Yield~ssBH2)]. *ssBH1* and *ssBH2* are binary variables (1 for *ssBH* occurrence, 0 for *ssBH* non-occurrence).

improve sustainability in principle, their enforcement is not strong enough, and fishing activities are not restricted in a way that allows recovery (Shen and Heino, 2014). In this study, the results of biomass and yield changes under different fishing mortality support previous studies, especially pointing out that a continuous increase in fishing pressure would lead to a biomass decline for demersal species but a stable yield mainly from small pelagic fish (Figure 3; Shen and Heino, 2014).

Large-scale reformation of fisheries management has been planned in China, and quota-based domestic fisheries management for single species, illustrated by pilot projects on total allowable catch (TAC) management, has been discussed as a potential direction, and launched in coastal provinces in 2017–2018 to gain experience in yield control (Ministry of Agriculture and Rural Affairs of the PRC, 2017; Kritzer *et al.*, 2022). In addition, since 2018, China has implemented minimum allowable catch standards and juvenile fish proportion management regulations for 15 economically important fish species, including largehead hairtail, in order to protect juvenile fish resources (Ministry of Agriculture and Rural Affairs of the PRC, 2018). Previous research on China's fisheries strategy also suggested that the implementation of such single-species quota-based management in the currently lightly managed and highly exploited multispecies fisheries (which accounted for a large proportion of global catches) may result in global catch decreasing (Szuwalski *et al.*, 2017). It may therefore be necessary for China to develop new management approaches in the context of reformation, rather than relying directly on the examples of other large seafood-producing countries, and also to consider the impact of management changes on the entire ecosystem in an integrated manner, rather than focusing only on single species (Szuwalski *et al.*, 2017; 2020). At the same time, the discussion of BH, a potentially valuable strategy for EBFM, can serve as a useful strategic inspiration (Zhou *et al.*, 2019; Burgess and Plank, 2020) and a viable direction of fisheries management reformation.

Consequently, this study aimed to analyse the occurrence of BH and its effects by simulating four types of fishing scenarios that adjusted fishing mortality rates for all the modelled species as well as for three different functional groups, respectively, while keeping the fishing pattern consistent to the historical baseline. The approach of this study differed to some extent from previous modelling studies of BH that pre-determined BH fishing patterns, which we also concur since they allowed a more intuitive observation of the effects of BH on the ecosystem (Law *et al.*, 2012, 2016; Jacobsen *et al.*, 2014; Plank, 2018; Nilsen *et al.*, 2020; Rehren and Gascuel, 2020). However, the previous approach of pre-setting BH scenarios, that is setting fishing mortality rate for different species proportional to its respective productivity, may be difficult to achieve in actual fisheries management and operations because it can be challenging to obtain the required biological information of production and productivity for every species particularly in the environment of high fishery technology (Zhou *et al.*, 2019). This implementation difficulty remains one of the main points of the BH debate (Froese *et al.*, 2016; Rehren and Gascuel, 2020). By exploring a whole range of fishing mortality rates (either increasing or decreasing by 10 to 90% relative to the historical baseline) under different scenarios of fishing for different functional groups, we were able to identify fishing strategies that would constitute BH, producing high yield for specific species while ensuring their biomass sustainability. In the process of guiding fishery exploitation, the good fishing strategies identified in our study can then be used as a basis for easily adjusting fishing pressure to achieve the advantages of BH, and more specifically, can provide recommendations for fishing pressure for fisheries targeting different functional groups to achieve high yield of target species while conserving other species or functional groups. Moreover, the proportional adjustment of fishing mortality rates ensured that the fishing pattern was consistent with the existing one, avoiding a complete change in fishing pressure after the overall implementation of BH, which would make the results more instructive for the fishery management in a specific region.

Applying BH

In previous studies, BH was initially defined as fishing mortality proportional to production (i.e. BH1), while subsequent studies have proposed BH2 with fishing mortality proportional to productivity or the P/B ratio as one of the suggested alternatives (Jacobsen *et al*., 2014; Zhou *et al*., 2019; Nilsen *et al*., 2020). The differences between the two definitions have been discussed in detail at a conference in Scotland, and the key difference between these two is that fishing mortality in BH1 is sensitive to biomass and converges to zero as biomass decreases, whereas fishing mortality in BH2 is not directly related to biomass and is density-independent (Heath *et al*., 2017). Therefore, BH1 enables explicit conservation of species richness because its fishing mortality decreases with population depletion. However, BH1 is more difficult to implement than BH2 because it requires information on stock biomass (Heath *et al*., 2017). Previous studies have theoretically explored the consequences of applying these two forms using size-based and multispecies interaction models (Law *et al*., 2016; Heath *et al*., 2017; Zhou and Smith, 2017; Plank, 2018; Zhou *et al*., 2019). Our results based on the OSMOSE model contribute to the current debate between the two definitions of BH (Heath *et al*., 2017; Zhou *et al*., 2019). Consistent with previous findings, we concluded that BH2 was easier to achieve than BH1; therefore, the occurrence of the BH2 was more extensively assessed in our study. However, the on-going discussion on definitions suggests that further research and other modelling techniques are still needed to explore and understand different alternative approaches (Zhou *et al*., 2019).

In this study, both BH1 and BH2 occurred at different levels, that is, *sBH* and *ssBH*, and exerted significantly different effects on biomass and yield. While *sBH1* did not occur at the species level, *sBH2* occurred in multiple scenarios and showed different trends in occurrences under the four types of fishing scenarios (Figure 2a), suggesting that *sBH1* was more difficult to occur than *sBH2* at the species level, a result that was also consistent with previous studies (Zhou *et al*., 2019). Specifically, Zhou *et al*., (2019) pointed out that *sBH1* was more difficult to implement in practical management because of the need for up-to-date species biomass information. At the species- and size-level, *ssBH1* was concentrated in some species, while *ssBH2* occurred more widely in different species and varied across fishing targets (Figures 2b and 6). ANOVA results on the relationship between the occurrence of *ssBH* and biomass/yield showed that *ssBH2* was significant for biomass in all fishing scenarios but *ssBH1* was significant only in S_{inv} (Table 2). By contrast, *ssBH1* had significant effects on yield in all target scenarios, while *ssBH2* had no significant effects on yield (Table 2). At the species level, *ssBH2* also had significant effects on biomass and yield for more species compared with *ssBH1*. Because of the more frequent occurrences of BH2 as well as the fact that biomass information for many nontargeted and unassessed species in the China Seas is not available, we focused on the two levels of BH2 (*sBH2* and *ssBH2*) in the following discussion. However, it is worth noting that BH1 could be more applicable and easily explored as a potential fishing strategy for exploited multispecies fisheries when biomass information is available (Costello *et al*., 2016; Cao *et al*., 2017).

BH on species and sizes in china

Compared to *sBH*, *ssBH* requires more research and coordination in management because of the need to clarify how the productivity of each species varies with its size (Zhou *et al*., 2019). Our results indicated that management measures to adjust fishing pressure for different target functional groups could achieve BH, ensuring a good trade-off between ecological objective and high yield, for example, *sBH* occurred under increased fishing pressure, where high yield could be achieved without collapsing total biomass in S_{pel} (Figure 5b). With the occurrence of *ssBH*, we could differentiate species that achieved size-level BH. Reducing the fishing mortality rate from the historical baseline allowed most of the corresponding functional groups to achieve BH with higher biomass but decreased yield (Figure 6 and Supplementary Figure S8). Other interesting phenomenon was that increasing fishing mortality rate in S_{dem} resulted in the occurrence of *ssBH*2 in JA (pelagic species), and increasing fishing mortality rate in S_{inv} resulted in the occurrence of *ssBH*2 in JA, SAP, and LH (Figures 6f and h and Supplementary Figures S8f and h). All these species maintained high biomass despite increased fishing mortality rates, illustrating that fishing for species of specific functional groups may allow other species or functional groups to achieve a BH status that not only protected their resources but also achieved the goal of high yield (Figures 6f and h and Supplementary Figures S8f and h). This finding can also serve as a reference for the current implementation of fishing vessel classification management and fishing gear standardization management in this region to protect endangered aquatic resources (Ministry of Agriculture and Rural Affairs of the PRC, 2017).

Currently, the high catches in China seas were recognized to be the consequences of removing larger predatory fish and enhancing the production of smaller fish as a result (Szuwalski *et al*., 2017). The multispecies management strategies were considered to be effective as long as biological factors, such as late maturity or slow growth, or economic factors, such as market demand, did not present excessive risks of overfishing for certain species, while species-specific fishing may need to be controlled when the risk was too high (Kritzer *et al*., 2022). Therefore, our findings support research to advance multispecies management in China, that is, a multispecies BH strategy at both species- and size-levels will facilitate the trade-off and achievement of high production and resource conservation goals, since the productivity we considered is species- and size-dependent (Zhou *et al*., 2019; Kritzer *et al*., 2022). Specifically, our results can provide recommendations for adjusting fishing pressure for fisheries targeting different functional groups to achieve high yield of target species and resource conservation of other species or functional groups. We further suggest that for multispecies fisheries in developing countries with similar fisheries status, the implementation of BH would be more oriented towards adjusting fishing mortality for specific functional groups to allow other species throughout the ecosystem to be harvested in a balanced manner.

As the first investigation on BH for highly exploited multispecies fisheries in developing countries using the OSMOSE model, all results should be considered tentative findings only. One potential weakness of this study is that the definition of the occurrence of BH was based on simple and basic criteria. Specifically, we performed simple BH estimation on model results for different scenarios rather than validating them using more complex and accurate models. We did this primarily because the results of the study were derived from model simulation without actual observations or sampling data. We were concerned that fitting the simulated results using more complex models, though improving the accuracy of the fitted estimation to some extent, may further emphasize the overly idealistic characteristic of the simulation process rather than highlighting the advantages of model studies that can easily simulate multiple scenarios. In future work, we do intent to further consider using a more flexible and accurate model. Nevertheless, our findings have provided perspectives on the application of BH as an initiation strategy in highly exploited multispecies fisheries and the sustainable exploitation of resources in such fisheries, which opens up the scope for this potentially valuable strategy to be implemented towards ecosystem approaches to fisheries (Garcia *et al.*, 2016; Zhou *et al.*, 2019).

Conclusion

By employing the individual-based multispecies ecosystem modelling OSMOSE, we were able to investigate the potential occurrences and advantages of BH in the highly exploited multispecies fisheries of the Yellow Sea ecosystem. Model results indicated that occurrences of *sBH* and *ssBH* varied with fishing pressure and fishing target, and that *ssBH* for most functional groups and species was significantly associated with biomass and yield. Simulation results under high fishing mortality rates for all species showed biomass decline of demersal species and a yield being dominated by small pelagic fish. Decreasing fishing mortality for specific functional groups enabled the species of these functional groups to achieve higher biomass in a BH state, while increasing fishing pressure on a specific functional group species may allow species of other functional groups to achieve a BH state that not only achieved high yield but also ensured resource protection. Our findings suggest that it is possible to achieve the goals of BH as an ecological tool by adjusting fishing pressure for some specific functional groups in highly exploited multispecies fisheries.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

Conflict of interest

The authors state that there are no conflicts of interest to declare.

Funding

This work was supported by the National Natural Science Foundation of China [grant number: 32073027, 41861134037]. Y-J.S. and N.B. were supported by the Biodiversa and Belmont Forum project SOMBEE (BiodivScen ERA-Net COFUND programme, ANR contract n°ANR-18-EBI4-0003-01).

Author contributions

R.S., P.S., and Y.T. conceptualized and designed the goals, simulations and interpretation of this study. R.S. and P.S. conducted the model building and structure. C.F., G.L., and Z.L. contributed to the data analysis. Y-J.S. and N.B. contributed to the model testing. R.S., P.S., and C.F. wrote and edited the manuscript, while all other authors have reviewed and revised it. All authors have given final approval of this manuscript.

Data availability

The data underlying this article will be shared on reasonable request to the corresponding author.

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Handling Editor: Ken Andersen