Use of floated gillnet to reduce flatfish bycatch in a mixed-species gillnet fishery

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Abstract:

Bycatch of threatened flatfish species is a major concern in mixed-species bottom-set gillnet fisheries in the Yellow Sea, China. Therefore, we tested floated gillnets against standard bottom-set gillnets to reduce bycatch by exploiting difference in species-specific fish behavior. Our results demonstrated that the floated gillnet design can greatly improve species and size selectivity. Floated gillnets significantly reduced the catch efficiency of marbled flounder (*Pseudopleuronectes yokohamae*) and stone flounder (*Platichthys bicoloratus*) by 83% and 86%, respectively, compared to standard bottom-set gillnets. Additionally, catches of undersized target species, fat greenling (*Hexagrammos otakii*), black rockfish (*Sebastes schlegelii*), and Asian paddle crab (*Charybdis japonica*), were significantly reduced by 52%, 79%, and 78%, respectively. However, this reduced the catches of legal-sized fat greenling, black rockfish and Asian paddle crab by 21%-26%. The catch efficiency of target species black scraper (*Thamnaconus modestus*) was significantly improved. Furthermore, significant variations in species composition between floated and standard gillnets were observed. The findings of this study can provide a more sustainable management of the mixed-species gillnet fisheries.

Keywords: Threatened flatfish species; mixed-species gillnet fisheries; bycatch reduction; gillnet design; alternative gear; sustainable fisheries.

1. Introduction

Gillnets are an important and ubiquitous passive fishing gear used worldwide, contributing to approximately 10% of global fish landings (Suuronen et al., 2012; He et al., 2021). Gillnet fisheries are highly diversified, characterized by the diversity and seasonality of target species, and versatile gear type used to capture them (He, 2006). Gillnets are easy to use, relatively inexpensive fishing gear that often shows an optimal size selectivity of the species targeted (He, 2006). Nonetheless, they can have limited species selectivity and, therefore, are associated with bycatch issues in mixed-species fisheries, including the bycatch of endangered, threatened and protected species (Gray and Kennelly, 2018).

Depending on the gear design, gillnets can be used to fish near the seabed, in mid-water and at the surface. Bottom-set gillnets are set at the seabed and widely used for targeting bottom-dwelling finfish, crustaceans, and other organisms. In the Yellow Sea, China, bottom-set gillnets are used in a mixed-species fishery in the coastal waters capturing various fish and crustacean species during spring and autumn seasons. In this fishery, black scraper (*Thamnaconus modestus*) is one of the most important commercial fish species with high nutritional and economic value. Its annual landings are reported to be around 13×10^4 t from 2017 to 2021 (MARA, 2018-2022). Asian paddle crab (*Charybdis japonica*) also contributes the gillnet catches in this fishery, and the annual landings in the past five years have ranged between 2.2×10^4 t and 3.5×10^4 t (MARA, 2018-2022). Other commonly targeted species during these fishing seasons are fat greenling (*Hexagrammos otakii*) and black rockfish (*Sebastes schlegelii*), although no official quantitative data is currently available on their landings (Zhang et al., 2022).

In this fishery, two flatfish species, marbled flounder (*Pseudopleuronectes yokohamae*) and stone flounder (*Platichthys bicoloratus*), are common bycatch species. Their stocks have declined since the 1960s (Chen et al., 1992; Dou, 1995) due to excessive fishing effort, extensive use of fishing gear (i.e., bottom trawls) with poor selectivity and associated severe bycatch and discard issues of juvenile individuals (Zhang et al., 2020; Yu et al., 2023a) and their slow growth rate and late attainment of sexual maturity slows the recovery of their stocks (Kume et al., 2006; Lee et al., 2009; Yamamoto et al., 2018; Yu et al., 2023a). The stock size of marbled flounder and stone flounder are critically low throughout their distribution range, including Japan, Korea, and Russia (Jeong et al., 2017; Tohoku National Fisheries Research Institute, 2019; Shuntov and Volvenko, 2020). For instance, in Japan, their stocks have declined by over 50% since the 2000s (Tohoku National Fisheries Research Institute 2019). In 2021, marbled flounder and stone flounder have been assessed by International Union for Conservation of Nature (IUCN) and are listed as Near Threatened and Vulnerable (Tomiyama et al., 2021a, b).

For the purpose of the marine biodiversity conservation and aquatic resource restoration, the Chinese State Council has implemented the aquatic resources breeding protection regulations since 1979 and emphasized the key protection of threatened flounder species (Chinese State Council, 1979). These protection regulations limited the catches of flounder species and prohibited the capture of juvenile and spawning individuals to improve the sustainability of the fishery resources. Despite this, several decades later, their populations are still at a critically low level with continuing decline (Aonuma et al. 2019). To mitigate this issue, the fishery management agency responsible for the Yellow Sea has undertaken stock enhancement programs (i.e., restocking of juveniles) for marbled flounder and stone flounder to increase their recruitment and encouraged developing a more species selective fishing gear to protect their stocks and avoid bycatch of these species (Li et al., 2019).

In this mixed-species gillnet fishery, the Chinese Ministry of Agriculture (MOA) has implemented a minimum landing size (MLS) of 5 cm carapace length (*cl*) for Asian paddle crab since 2004 (Yu et al., 2021). In 2014, Shandong province issued a bycatch limit regulation specifying that undersized individuals of target species, including Asian paddle crab, fat greenling, and black rockfish, should not exceed 25% of the total catches (in number of individuals) summed over deployments (Shandong Provincial Oceanic and Fishery Department, 2014). Although no MLS has been formulated for fat greenling and black rockfish, their length at first sexual maturity (LFM) (fat greenling: LFM=20 cm, black rockfish: LFM=15 cm) is often used as the reference point in fishery management (Tang et al., 2019; Yu et al., 2023a). Subsequently, MOA established the MLS for black scraper (i.e., 16 cm total length) in 2018 and specified that the undersized individuals should not exceed 20% of the total catches of this species (in weight of individuals) since 2020. These management regulations have been incorporated into China's Fishery Law. The fisheries management authorities are responsible for supervising illegal fishing activities, determining the extent of violations, and imposing corresponding penalties. If the prescribed proportion of undersized individuals is exceeded, the catch and illegal income from sales are confiscated, and a fine of up to 50,000 yuan (equivalent to $7193) may be imposed. In serious cases, such as multiple illegal operations, the fishing gear may be confiscated, and the fishing license may be revoked (MOA, 2022).

Under the existing fishery management system, improving the species and size selectivity of gillnets is an important step for increasing sustainability in mixed-species gillnet fisheries. For improving the gillnet size selectivity, several gear modifications, including mesh size, hanging ratio, construction material, and twine thickness, can be used. This could improve gillnet selectivity for certain target species of a specific size (Dinçer and Bahar, 2008; Lucchetti et al., 2020). However, in a mixed-species fishery, improving gillnet selectivity solely by modifying some of the gillnet technical parameters is often not possible due to, for example, differences in fish morphologies and swimming abilities. Furthermore, the capture and selection process in gillnets does not only depend on gear parameters and fish morphological characteristics, but also on fish behavior. The previous behavioral observations in *situ* found that marbled flounder and stone flounder, like most other flatfish species (Gibson, 2005), tend to bury themselves in the sand-muddy bottoms or swim along the seabed feeding on benthic organisms, with limited vertical migration due to their flat body structure. In contrast, the target species exhibit better maneuverability, swimming capacity, and higher dispersal ability in the bottom and mid-water layers for foraging (Jing et al., 2005; Kim et al., 2013; Yu et al., 2022). Therefore, modifying the standard bottom-set gillnets by utilizing these behavioral differences may offer an efficient and innovative solution for reducing bycatch in a mixed-species gillnet fishery (i.e., Godøy et al., 2003).

Besides the two threatened flatfish species, a variety of non-target species are also frequently captured by this gillnet fishery. Currently, no regulations exist regarding the capture of these bycatch species. Some of them are commercially valuable and thus retained by fishers for sale or consumption, while the unwanted bycatch species are often discarded. As gear modifications can potentially alter the catch composition, it is essential to evaluate the effects of specific gillnet configurations on catch performance of both target and bycatch species. This evaluation can have implications for developing new gear designs, conserving biodiversity, and establishing regulations for managing bycatch in this fishery.

The objective of this study was to develop a new gillnet design that could effectively reduce the bycatch of marbled flounder and stone flounder while maintaining the catch efficiency of legal-sized target species in mixed-species gillnet fisheries. Specifically, we tested and compared the catch performance of floated gillnets with standard bottom-set gillnets commonly used in the fishery to answer the following research questions:

- Can floated gillnets effectively reduce bycatch of marbled flounder and stone flounder?
- Do floated gillnets affect the catch efficiency of legal-sized target species?
- Does the species composition in the gillnet fishery change when using floated gillnets?

2. Materials and methods

2.1 Sea trials

Sea trials were conducted onboard the commercial fishing vessel "Lurongyuyang 65873" (12.0 m LOA, 100 hp) in September 2021 in the coastal waters of the Yellow Sea, China (Fig. 1). The study area is located at YanWei, which is one of the most important fishing grounds in the Yellow Sea, China. The substrate type is a mixture of mud, sand, and rock, and the water depth ranges from 5 to 20 m.

2.2 Gear modification and experimental design

Standard bottom-set gillnets were made of 0.20 mm green nylon monofilament with 70 mm fully stretched mesh size. The dimensions of each gillnet sheet were 50 m (length) × 2.2 m (height) with a hanging ratio (E) of 0.50. The mesh number in horizontal and vertical directions of each sheet were 1428 and 36, respectively. The float line was equipped with plastic floats, having a buoyancy of 80 g/m and sinker line with lead sinkers weighted 200g/m. These parameters were identical to the parameters of gillnets used in the commercial fishery, including material, twine thickness, dimensions, and float-sink ratio.

The floated gillnets were made by transforming the standard bottom-set gillnets through modification of the float line and sinker line configuration (Fig. 2). Specifically, eleven extra buoys were mounted to the float line at an interval of 5 m (each with a buoyancy of 1050 g). A solerope made of iron alloy (10 mm in diameter) was connected to the sinker line by 1.0 m nylon bridles (7 mm in diameter). The space between the bridles was 5 m. By such configurations, the solerope was in contact with the seabed, while the sinker line was 1 m suspending from the seabed, due to the additional floats (Fig. 2). The connected bridles can maintain gillnet stability.

A total of 30 gillnets sheets were used, where 15 sheets were standard gillnets and 15 floated gillnets. All gillnets were divided into 10 fleets, each containing three replicates for each configuration (i.e., standard gillnet and floated gillnet). Therefore, a total of 5 standard gillnet fleets and 5 floated gillnet fleets were deployed. The standard gillnet and floated gillnet fleets were deployed alternatively, with each standard gillnet fleet followed by a floated gillnet fleet (Fig. 2). Each fleet was deployed approximately 50 m apart. Two buoys and anchors each weighing 15 kg were connected to each end of the fleet.

Following the commercial fishing pattern, gillnets were set at twilight and retrieved the following day after approximately 24 h soak time. After each trial, catches were collected separately for each gillnet configuration and identified at a species level. All catches of flatfish and target species were sorted, subsampled (if needed), and frozen for length and weight measurement in the laboratory. Fish species were measured for total length, and crabs for *cl* to the nearest mm (using calipers). The weight of individuals was measured to the nearest 0.1 g. All individuals of the other bycatch species were counted and recorded.

2.3 Modelling the length-dependent catch efficiency between standard and floated gillnets

The catch data was analyzed for each species separately by modelling the length-dependent catch efficiency using the method outlined in Herrmann et al. (2017). This method models the experimental length-dependent catch comparison rate (CC_l) summed over deployments:

$$CC_l = \frac{\sum_{j=1}^{m}\left\{\frac{nt_{lj}}{qt_j}\right\}}{\sum_{j=1}^{m}\left\{\frac{nt_{lj}}{qt_j}+\frac{nc_{lj}}{qc_j}\right\}} \quad (1)$$

where nc_{lj} and nt_{lj} are the numbers of fish that were length measured in each length class l for the standard (control) and floated (treatment) gillnets in deployment j. One deployment covers the total catch per fishing day with the gillnet fleet. qc_j and qt_j are subsampling factors quantifying the fraction, based on weight, of the catch in the gillnets being length-measured in the respective deployment. m is the total number of deployments. The functional form of the catch comparison rate $CC(l, \boldsymbol{v})$ was obtained using maximum likelihood estimation by minimizing the following expression (Herrmann et al., 2017):

$$-\sum_{l}\left\{\sum_{j=1}^{m}\left\{\frac{nt_{lj}}{qt_j}\times\ln\bigl(CC(l,\boldsymbol{v})\bigr)+\frac{nc_{lj}}{qc_j}\times\ln\bigl(1.0-CC(l,\boldsymbol{v})\bigr)\right\}\right\} \quad (2)$$

where $\boldsymbol{v}$ is the parameters that describe the catch comparison curve defined by $CC(l,\boldsymbol{v})$. The outer summation in the expression (2) is the summation over length classes *l* in the experimental data. When the catch efficiency of the standard and floated gillnets is similar, the expected value for the summed catch comparison rate would be 0.5. Therefore, this value can be used to judge whether there is a difference in catch efficiency between the two gillnet configurations. The experimental CC_l was modelled by the function $CC(l,\boldsymbol{v})$ using the following equation:

$$CC(l,\boldsymbol{v})=\frac{exp\bigl(f(l,v_0,\dots,v_k)\bigr)}{1+exp\bigl(f(l,v_0,\dots,v_k)\bigr)} \quad (3)$$

where *f* is a polynomial of order *k* with coefficients v_0-v_k. The values of the parameters $\boldsymbol{v}$ describing $CC(l,\boldsymbol{v})$ were estimated by minimizing expression (2), which is equivalent to maximizing the likelihood of the observed catch data. We considered *f* of up to an order of 4 with parameters v_0, v_1, v_2, v_3, and v_4. Leaving out one or more of the parameters $v_0 \dots v_4$ resulted in 31 additional models also considered as candidates for the catch comparison $CC(l,\boldsymbol{v})$. Among these models, estimations of the catch comparison rate were made using multi-model inference to obtain a combined model (Burnham and Anderson, 2002; Herrmann et al., 2017; Grimaldo et al., 2018). The ability of the combined model to describe the experimental data was evaluated based on the *p*-value, which is calculated based on the model deviance and the degrees of freedom (Wileman et al., 1996; Herrmann et al., 2017). For the combined model to sufficiently describe the experimental data, the *p*-value should not be <0.05, except for cases in which the data are subject to overdispersion (Wileman et al., 1996). Based on the estimated catch comparison function $CC(l,\boldsymbol{v})$, we obtained the relative catch efficiency (also named catch ratio) $CR(l,\boldsymbol{v})$ using the following equation:

$$CR(l,\boldsymbol{v})=\frac{CC(l,\boldsymbol{v})}{1-CC(l,\boldsymbol{v})} \quad (4)$$

$CR(l,\boldsymbol{v})$ quantifies the relative catch efficiency between the floated gillnet and standard gillnet. If the catch efficiency of both gillnet configurations is equal, then

$CR(l, \boldsymbol{v})$ = 1.0 (Cerbule et al., 2022a). $CR(l, \boldsymbol{v})$ = 1.5 would mean that the floated gillnet is catching 50% more of the species with length *l* than the standard gillnet. In contrast, $CR(l, \boldsymbol{v})$ = 0.5 would mean that the floated gillnet is only catching 50% of the species with length *l* caught by the standard gillnet.

We estimated confidence intervals (CIs) for $CC(l, \boldsymbol{v})$ and $CR(l, \boldsymbol{v})$ using a double bootstrapping method described in Herrmann et al. (2017). This bootstrapping method accounts for between-deployment variability (the uncertainty in the estimation resulting from between-deployment variation of catch efficiency in the gillnets) and within-deployment variability (the uncertainty about the size structure of the catch for the individual deployments). However, contrary to this double bootstrapping method, in the current study the outer bootstrapping loop accounting for between-deployment variation was performed paired for the standard and floated gillnets, taking full advantage of the experimental design in which, the gillnet configurations were fished simultaneously on the same fishing ground.

By multi-model inference in each bootstrap iteration, the method also accounted for the uncertainty resulting from uncertainty in model selection. We performed 1000 bootstrap repetitions and calculated the Efron 95% CIs (Efron, 1982). To identify sizes of species with significant differences in catch efficiency, we checked for length classes in which the 95% CIs for the catch ratio curve did not include 1.0.

Length-integrated average values (in percentage) for the catch ratio ($CR_{average}$) were estimated directly from the experimental catch data by the following equation:

$$CR_{average} = 100 \times \frac{\sum_{l}\sum_{j=1}^{m}\left\{\frac{nt_{lj}}{qt_j}\right\}}{\sum_{l}\sum_{j=1}^{m}\left\{\frac{nc_{lj}}{qc_j}\right\}}$$

$$CR_{average-} = 100 \times \frac{\sum_{l<M}\sum_{j=1}^{m}\left\{\frac{nt_{lj}}{qt_j}\right\}}{\sum_{l<M}\sum_{j=1}^{m}\left\{\frac{nc_{lj}}{qc_j}\right\}} \qquad (5)$$

$$CR_{average+} = 100 \times \frac{\sum_{l\geq M}\sum_{j=1}^{m}\left\{\frac{nt_{lj}}{qt_j}\right\}}{\sum_{l\geq M}\sum_{j=1}^{m}\left\{\frac{nc_{lj}}{qc_j}\right\}}$$

where the outer summations include the length classes in the catch during the experimental fishing period for all length classes (for $CR_{average}$), and length classes below (for $CR_{average-}$) and above (for $CR_{average+}$) the MLS or LFM. M represents the specific MLS or LFM for each species accordingly. In contrast to the length-dependent evaluation of the catch ratio $CR(cl,\boldsymbol{v})$, $CR_{average}$, $CR_{average-}$, and $CR_{average+}$ are specific for the population structure encountered during the sea trials and cannot be extrapolated to other areas and seasons in which the size structure of each species may be different (Cerbule et al., 2021a,b).

2.4 Estimation of discard ratio

Two exploitation pattern indicators ($nDRatio_{Treatment}$ and $nDRatio_{Control}$) were estimated directly from the experimental data. Then, by incorporating the length-weight relationship, $w(l) = a \times l^b$, the weight-based indicators ($wDRatio_{Treatment}$ and $wDRatio_{Control}$) were obtained. These indicators can be estimated using the following equations:

$$
\begin{aligned}
nDRatio_{Treatment} &= 100 \times \frac{\sum_{l<M}\sum_{j=1}^{m}\left\{\frac{nt_{lj}}{qt_j}\right\}}{\sum_{l}\sum_{j=1}^{m}\left\{\frac{nt_{lj}}{qt_j}\right\}} \\
nDRatio_{Control} &= 100 \times \frac{\sum_{l<M}\sum_{j=1}^{m}\left\{\frac{nc_{lj}}{qc_j}\right\}}{\sum_{l}\sum_{j=1}^{m}\left\{\frac{nc_{lj}}{qc_j}\right\}} \\
wDRatio_{Treatment} &= 100 \times \frac{\sum_{l<M}\sum_{j=1}^{m}\left\{a \times l^b \times \frac{nt_{lj}}{qt_j}\right\}}{\sum_{l}\sum_{j=1}^{m}\left\{a \times l^b \times \frac{nt_{lj}}{qt_j}\right\}} \\
wDRatio_{Control} &= 100 \times \frac{\sum_{l<M}\sum_{j=1}^{m}\left\{a \times l^b \times \frac{nc_{lj}}{qc_j}\right\}}{\sum_{l}\sum_{j=1}^{m}\left\{a \times l^b \times \frac{nc_{lj}}{qc_j}\right\}}
\end{aligned}
\tag{6}
$$

where the outer summations include the length classes that were below M representing MLS or LFM of each target species accordingly (in nominator) and over-all length classes (in denominator). a and b are coefficients of the length–weight relationship for target species. The $nDRatio_{Treatment}$ and $nDRatio_{Control}$ quantify the fraction of undersized target species in the catch (in number) caught by the floated gillnet and standard gillnet, respectively, while $wDRatio_{Treatment}$ and $wDRatio_{Control}$ are in weight. Ideally, *nDRatio* and *wDRatio* should be as low as possible (i.e., close to 0). The values of these indicators are affected by both the size selectivity of the gillnets and the size structure of the target species population in the fishing grounds. Therefore, it provides an estimate that is specific for the targeted population and that cannot be extrapolated to other scenarios (Cerbule et al., 2021a). Confidence intervals for these indicators were obtained by the double bootstrapping method mentioned above.

2.5 Species dominance analysis

We examined the species dominance patterns determining species compositions captured in gillnets with the two different configurations (standard and floated gillnets). Specifically, we estimated the catch dominance, in terms of number of individuals, for standard and floated gillnets separately, as follows (Cerbule et al., 2022b; Herrmann et al., 2022; Yu et al., 2023b):

$$d_{g,i} = \frac{\sum_{j=1}^{m}\{q_{g,i,j} \times n_{g,i,j}\}}{\sum_{j=1}^{m}\sum_{i=1}^{K}\{q_{g,i,j} \times n_{g,i,j}\}} \quad (7)$$

In Equation (7), $n_{g,i,j}$ is the number of individuals of the species *i* according to the predefined species index (species rank) counted in the subsample in gillnet configuration *g* during deployment *j*. Specifically, following the procedure described in Petetta et al. (2023), a fixed rank was assigned to each single species caught in the sea trials, by including it into one of the following four categories: flatfish bycatch species, target species, wanted bycatch species, and unwanted bycatch species. $q_{g,i,j}$ is the fraction of species *i* in the catch being counted in gillnet configuration *g* in deployment *j*. *K* is the total number of species observed in the gillnet catches.

To quantify relative species abundance in a given sample, cumulative dominance curves are often used, including when comparing fishing gear catches (i.e., Cerbule et al., 2022b; Petetta et al., 2023). In this study, we used cumulative dominance curves based on number of individuals observed for each species captured by gillnets with different configurations showing the cumulative proportional abundances plotted against a fixed species rank. This approach, similar as used in other studies (i.e., Cerbule et al., 2022b) allows comparison of the steepness of the cumulative dominance curves to obtain an overview on how many species are dominant and the distribution of their relative dominance in the catches. The catch dominance curves were estimated for each gillnet configuration *g* using the following equation (Warwick et al., 2008; Herrmann et al., 2022):

$$D_{g,I} = \frac{\sum_{j=1}^{m}\sum_{i=1}^{I}\left\{q_{g,i,j} \times n_{g,i,j}\right\}}{\sum_{j=1}^{m}\sum_{i=1}^{K}\left\{q_{g,i,j} \times n_{g,i,j}\right\}} \quad \text{with} \;\; 1 \leq I \leq K \tag{8}$$

where *I* is the species index summed up to in the nominator.

Based on using Equations (7) and (8), Efron 95% CIs were estimated for the dominance curves following the bootstrap procedure described in Herrmann et al. (2022). This procedure enables estimation of the uncertainty around the dominance curves induced by limited sample sizes for individual deployments as well as for between deployment variation in species dominance values.

2.6 Software

All the data analysis procedures described in sections 2.3-2.5 were conducted using the software SELNET (Herrmann et al., 2012, 2016, 2017, 2022), software version date 27 March 2023.

3. Results

Twelve valid deployments were conducted during the sea trials corresponding to twelve fishing days with all fleets. The gillnet soak time ranged from 20.2 to 26.0 h, and the water depth ranged from 7.5 to 17.1 m (Table 1). Sufficient data were collected for marbled flounder, stone flounder, black scraper, fat greenling, black rockfish, and Asian paddle crab to be included in the catch comparison analysis. The subsampling factors and the number of fish measured in the floated and standard gillnets are presented in Table 1. Furthermore, eleven other bycatch species were observed and counted during the experimental period (Table 2).

3.1 Length-dependent catch efficiency

For all catch comparisons between floated and standard gillnets, the estimated *p*-value was above 0.05, demonstrating that the model described the experimental data sufficiently well (Tables 3 and 4).

For the flatfish bycatch species, the length-dependent catch comparison and catch ratio curves showed that the floated gillnets significantly reduced the catch efficiency of marbled flounder and stone flounder throughout the length classes compared to standard gillnets (Fig. 3). The length-integrated average values ($CR_{average}$) also reflected significant differences in average catch ratio for these two species between floated and standard gillnets (Marbled flounder: $CR_{average}$=17.06% (CI: 13.05%-20.97%), Stone flounder: $CR_{average}$=14.25% (CI: 11.38%-17.68%); Table 3).

For the target species, the catch comparison and catch ratio curves showed that the floated gillnets had significantly higher catch efficiency than standard gillnets for black scraper length classes between 13.5-24.5 cm (Fig. 4). When averaged over all length classes, the floated gillnets caught significantly more undersized and legal-sized black scraper than standard gillnets ($CR_{average-}$ =127.16% (CI: 102.17%-153.49%), $CR_{average+}$=163.17% (CI: 136.22%-196.11%); Table 4). For the other three target species, the catch ratio results showed that the floated gillnets significantly reduced the catch efficiency for fat greenling, black rockfish, and Asian paddle crab at length classes between 12.5-21.5 cm, 10.5-19.5 cm, and 3.5-5.5 cm, respectively, while no significant differences in catch efficiency for other length classes (Fig. 4). The length-integrated average values showed that the catches of undersized fat greenling, black rockfish, and Asian paddle crab were significantly reduced by 51.57% (CI: 37.81%-62.01%), 78.98% (CI: 67.76%-87.82%), and 78.12% (CI: 66.79%-87.07%), respectively, while the catches of legal-sized individuals were reduced by 20.63%-25.88% (Table 4).

3.2 Discard ratio

There were significant differences in discard ratio for the target species between the floated and standard gillnets (Table 4). The *nDRatio* showed that the floated gillnets significantly reduced the discard ratio of fat greenling, black rockfish, and Asian paddle crab by 11.26%-26.24% compared to standard gillnets, as the CIs did not overlap (Table 4). The results also showed an indication of decrease in discard ratio of black scraper; however, it was not statistically significant (Table 4). The *wDRatio* also reflected a similar pattern. Specifically, the fraction of undersized black scraper and fat greenling in the total catches (in weight) was decreased from 25.33% (CI: 22.17%-28.64%) and 32.35% (CI: 27.78%-37.25%) to 20.70% (CI: 17.70%-24.08%) and 25.20% (CI: 21.80%-28.63%), respectively, while the discard ratio of black rockfish and Asian paddle crab was significantly reduced to 3.14% (CI: 2.04%-4.34%) and 8.25% (CI: 5.37%-11.07%), respectively.

3.3 Species dominance

The species dominance values (Table 5), and species cumulative dominance patterns (Fig. 5) showed significant differences in species composition between the floated and standard gillnets. Marbled flounder, stone flounder, black scraper, fat greenling, black rockfish, and Asian paddle crab dominated the species composition of the standard gillnets. Specifically, the percentage of these species summed up to 76% in the standard gillnets (Table 5). By contrast, marbled flounder and stone flounder were significantly less presented in the catch composition in the floated gillnets, only contributed by 3.74% (CI: 2.81%-4.79%) and 3.92% (CI: 3.07%-4.94%) to the total catches (Table 5). Black scraper was the most dominant species captured in the floated gillnets, accounting for 33.52% (CI: 30.75%-36.24%) of the total catches, followed by black rockfish, fat greenling, and Asian paddle crab, with percentage ranging from 8.62% to 17.63% (Table 5). By comparison, the target species were more dominant in catches of floated gillnets than standard gillnets (76.05% *vs*. 50.31%). Additionally, the percentage of wanted bycatches (i.e., bycatch species with a commercial value) in the total catch was 9.04% and 7.44% for the floated and standard gillnets, respectively, while unwanted bycatches (i.e., bycatch species without a commercial value) contributed by 7.26% and 16.07% (Table 5).

4. Discussion

Achieving effective species and size selectivity for different species is a major challenge in mixed-species gillnet fisheries worldwide (Ramírez-Amaro and Galván-Magaña, 2019). In this study, we designed floated gillnets by exploiting the behavioral difference between the target and bycatch species and successfully reduced the catch efficiency for unwanted flatfish bycatch and undersized target species in mixed-species gillnet fishery in the Yellow Sea, China. The findings of this study highlighted the importance of considering fish behavior when designing gear modifications for improving gillnet selectivity. Further, it demonstrated that floated gillnets could serve as a simple and effective technical measure to improve fisheries sustainability in Chinese gillnet fisheries.

Compared to other stationary fishing gears (e.g., traps and pots), gillnets have diverse fishing mechanisms including gilling, wedging, snagging, and entangling (He, 2006; Cerbule et al., 2022a; Savina et al., 2022). After gear retrieval, manual disentangling is necessary for catches caught in gillnets. In commercial fisheries, fishers usually remove target species carefully from the nets to maintain optimal catch quality to obtain high market prices. By contrast, flatfish and other bycatches are often recklessly extruded or disentangled by fishers due to the extra work for handling these species onboard. Such treatment could cause lethal or sublethal damage to bycatch species, significantly increasing their discard mortality (Lundin et al., 2015; Yu et al., 2022). Pre-catch mortality is also a significant threat to many endangered, threatened and protected species in gillnet fisheries (FAO, 2019). Swimming crabs and other carnivorous aquatic animals often feed on flatfish bycatch before gillnets are retrieved, which is one of the sources of fishing mortality for flatfish bycatches (personal observation of first author). The use of floated gillnets significantly reduced the catch efficiency of marbled flounder and stone flounder by minimizing the contact with the gillnets, thus making this gear configuration favorable for the protection of these threatened species.

In order to facilitate the uptake of such new gear design in capture fisheries, it is necessary to provide stakeholders with quantitative information on how specific gear modifications would impact the exploitation pattern in fishing practice. Our results showed that floated gillnets significantly reduced the catch efficiency of marbled flounder and stone flounder by 83% and 86%, respectively, compared to standard gillnets. Additionally, the discard ratio (in weight) of black scraper decreased from 25.33% to 20.70%, and the fractions of undersized black rockfish and Asian paddle crab (in number) dropped significantly below 25%, which aligns with current management regulations. From the perspective of both, the policy makers and fishers, these promising results showed that adopting floated gillnets would effectively support existing management regulations in this mixed-species fisheries and reduce the risk of illegal fishing and related penalties. However, no single measure can achieve the "perfect selectivity" for all species in a mixed-species fisheries (Sala et al., 2008; Brčić et al., 2018). It is noted that although the discard ratio (in number) of fat greenling was significantly decreased by approximately 11%, it was still above the bycatch limits (i.e., 25%). Furthermore, the adoption of bycatch reduction devices or bycatch reduction technologies often results in decreased catch efficiency of legal-sized target species, and great losses of target catches may hinder their commercial applicability. Our results showed that floated gillnets would result in losses of legal-sized fat greenling, black rockfish, and Asian paddle crab ranging from 21%-26%. Despite this, the catches of legal-sized black scraper were significantly increased by 63%. Considering the higher market prices of black scraper (approx. 95 yuan/kg) than that of the other three target species (average price of approx. 70 yuan/kg), this could compensate for the losses in commercial profits.

In addition to the need for economical sustainability in fishing practices, fishers' voluntary adoption of new gear designs is influenced by ease of use and low cost. The floated gillnets are easy to design as they require only a few floats at the float lines and a chain to the sinker line. Therefore, this design would not add to the workload during the fishing process (personal communication with fishers). Additionally, such gear modification requires low additional investments compared to the standard gillnet. Last but not least, reduced bycatch can save the time and workforce demanded onboard during the fishing process (Rudershausen et al., 2016). Overall, floated gillnets have significant potential for application in mixed species gillnet fisheries.

The catchability of different target species is supposed to be influenced by various factors such as their spatial distribution, feeding strategies, and circadian rhythm. For instance, fat greenling, black rockfish, and Asian paddle crab are bottom-dwelling species (Yu et al., 2023a), while black scraper is found in the middle and lower water layers and exhibits diel vertical migration (Kim et al., 2013). The use of floated gillnets may improve the efficiency of catching black scraper due to its distribution pattern, which contrasts with other target species. Moreover, our results showed that catch efficiency varied with the size of the target species. These species typically exhibit ontogenetic diet shifts, with their dietary breadth index increasing significantly as length class increases (Kim et al., 2013; Xu et al., 2018). Hence, larger individuals have bigger active sphere, and greater mobility can provide more opportunities for them to approach the floated gillnets, resulting in length-dependent catch efficiency.

In mixed-species fisheries, changes in fishing strategies or gear modifications can often shift the catch composition, including the bycatch proportion (Kalayci and Yecilsisek, 2014; Soe et al., 2022; Yu et al., 2024). Although floated gillnets significantly reduce the catch efficiency of marbled flounder and stone flounder, it may result in the capture of other bycatch species. Therefore, it is crucial to consider the potential impacts of floated gillnets on the whole species composition of the gillnet catches. Our study reveals that the floated gillnet significantly reduced the dominance of bycatch species, indicating that it can effectively reduce the risk of catching unintended species increasing sustainability in this fishery. Additionally, the higher abundance of pelagic species (i.e., spotted anchovy (*Konosirus punctatus*)) and lower abundance of the other benthic bycatch organisms were observed for the floated gillnet when comparing with the standard gillnet, which is again related to the different depths in which the two gears effectively fished. This has been observed also in other studies testing the "guarding net" in trammel nets (Metin et al., 2009; Sartor et al., 2018). They reported that rising of trammel net above the lead line by using "guarding net" could significantly reduce the bycatch of demersal species. Furthermore, our results showed that some benthic invertebrates (e.g., starfish (*Patiria pectinifera*) and sea urchin (*Mesocentrotus nudus* and *Hemicentrotus pulcherrimus*)) are still captured by the floated gillnet, which might be related to the influence of water current on the behavior of these species and gillnets. Future studies could employ underwater recordings to quantify fish behavior and net condition in detail, which could benefit further optimization of gillnet design.

The findings of this study are relevant not only for this gillnet fishery but can also be applicable to other fisheries along the Pacific Northwest coast that face similar challenges in conserving marbled flounder and stone flounder (Yu et al., 2023a). While species distribution, catch composition, and fishing gear may vary across different regions, the gear modification techniques employed in this study could be used as a model for reducing flatfish bycatch in various gillnet fisheries. Additionally, our study reveals that differences in fish behavior could also offer means to reduce bycatch of other species in gillnet fisheries.

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CRediT authorship contribution statement

Mengjie Yu: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing - original draft, Writing - review & editing. **Bent Herrmann:** Formal analysis, Methodology, Software, Supervision, Validation, Writing - original draft; Writing - review & editing. **Kristine Cerbule:** Formal analysis, Methodology, Validation, Visualization, Writing - original draft, Writing - review & editing. **Changdong Liu:** Conceptualization, Data curation, Supervision. **Liyou Zhang:** Investigation. **Yanli Tang:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Tables

Table 1 Overview of 12 deployments showing date, soak time, depth, number of measured individuals (two flatfish bycatch species and four target species), and subsampling factor (in parentheses) for the floated gillnet (FG) and standard gillnet (SG).

Trip ID	Date	Soak time (h)	Depth (m)	Marbled flounder		Stone flounder		Black scraper		Fat greenling		Black rockfish		Asian paddle crab	
				FG	SG	FG	SG	FG	SG	FG	SG	FG	SG	FG	SG
1	12/09/2021	24.3	11.9	16(1.00)	51(0.50)	14(1.00)	39(0.33)	47(0.33)	47(0.50)	35(0.50)	35(0.33)	21(0.33)	29(0.25)	36(1.00)	38(0.50)
2	13/09/2021	25.5	8.3	9(1.00)	33(0.50)	12(1.00)	46(0.50)	43(0.33)	40(0.50)	25(0.50)	37(0.33)	33(0.50)	37(0.33)	28(1.00)	31(0.50)
3	14/09/2021	22.0	10.5	10(1.00)	30(0.50)	10(1.00)	32(0.33)	40(0.33)	29(0.33)	29(0.50)	28(0.20)	41(0.50)	28(0.25)	28(1.00)	39(0.50)
4	15/09/2021	23.5	7.7	15(1.00)	40(0.50)	15(1.00)	32(0.33)	28(0.20)	26(0.33)	50(1.00)	34(0.33)	32(0.50)	29(0.25)	37(1.00)	29(0.50)
5	16/09/2021	26.0	10.2	16(1.00)	44(0.50)	18(1.00)	37(0.33)	44(0.33)	44(0.50)	30(0.50)	32(0.33)	28(0.33)	24(0.20)	30(1.00)	31(0.50)
6	17/09/2021	21.2	15.6	11(1.00)	45(0.50)	11(1.00)	34(0.33)	29(0.20)	46(0.50)	39(0.50)	37(0.33)	35(0.50)	31(0.25)	28(1.00)	32(0.50)
7	18/09/2021	20.2	11.9	7(1.00)	53(0.50)	10(1.00)	33(0.33)	45(0.33)	45(0.33)	35(0.50)	37(0.33)	24(0.33)	27(0.25)	37(1.00)	32(0.50)
8	19/09/2021	21.8	10.3	16(1.00)	36(0.50)	20(1.00)	39(0.33)	40(0.33)	34(0.33)	52(1.00)	50(0.50)	24(0.33)	26(0.25)	37(1.00)	22(0.50)
9	20/09/2021	22.3	14.5	16(1.00)	43(0.50)	18(1.00)	38(0.33)	45(0.33)	44(0.50)	41(0.50)	35(0.33)	29(0.33)	25(0.20)	36(1.00)	31(0.50)
10	21/09/2021	20.5	17.1	20(1.00)	50(0.50)	18(1.00)	42(0.33)	50(0.33)	39(0.33)	44(0.50)	24(0.20)	28(0.33)	27(0.20)	35(1.00)	26(0.50)
11	22/09/2021	24.0	14.0	13(1.00)	42(0.50)	13(1.00)	25(0.20)	52(0.33)	35(0.33)	34(0.50)	37(0.33)	34(0.50)	41(0.33)	39(1.00)	34(0.50)
12	23/09/2021	22.6	7.5	38(1.00)	54(0.33)	37(1.00)	34(0.20)	53(0.33)	57(0.50)	29(0.33)	25(0.20)	13(0.20)	34(0.20)	30(0.50)	36(0.33)

Table 2 List of bycatch species and number of individuals captured for the floated gillnets (FG) and standard gillnets (BG) during the experiments.

			Number of individuals	
Category	Species name	Common name	FG	SG
Wanted bycatch species	*Konosirus punctatus*	Spotted anchovy	332	14
	Sebastiscus marmoratus	Marbled rockfish	90	330
	Mesocentrotus nudus	Sea urchin	8	171
	Chirolophis japonicus	eelpout	12	86
	Zoarces elongatus	eelpout	10	102
	Paralichthys olivaceus	Bastard halibut	11	68
Unwanted bycatch species	*Hexagrammos agrammus*	Spotty belly greenling	146	467
	Sebastes hubbsi	Armored rockfish	125	397
	Hemicentrotus pulcherrimus	Sea urchin	28	238
	Patiria pectinifera	Starfish	39	213
	Scyra quadridens	Kelp crab	14	134

Table 3 Fit statistics and catch ratio (*CR*) results (in %) of floated gillnets for marbled flounder (*Pseudopleuronectes yokohamae*) and stone flounder (*Platichthys bicoloratus*). Values in parentheses represent 95% CIs. DOF denotes degrees of freedom.

	Marbled flounder	Stone flounder
p-value	0.4010	0.9841
Deviance	17.81	6.33
DOF	17	16
$CR_{average}$	17.06 (13.05-20.97)	14.25 (11.38-17.68)

Table 4 Fit statistics and catch ratio (*CR*) results (in %) of floated gillnets for four target species. Values in parentheses represent 95% CIs. DOF denotes degrees of freedom.

	Black scraper	Fat greenling	Black rockfish	Asian paddle crab
p-value	0.9889	0.9972	0.9988	0.1998
Deviance	2.62	2.29	2.70	5.99
DOF	10	11	13	4
$CR_{average-}$	127.16 (102.17-153.49)	48.43 (37.99-62.19)	21.02 (12.18-32.24)	21.88 (12.93-33.21)
$CR_{average+}$	163.17 (136.22-196.11)	76.11 (60.96-95.70)	74.12 (61.40-89.38)	79.37 (65.38-96.27)
$nDRatio_{Treatment}$	38.59 (33.92-43.43)	45.51 (40.97-49.62)	9.34 (6.18-12.64)	17.87 (12.07-23.43)
$nDRatio_{Control}$	44.64 (40.74-48.47)	56.76 (51.64-61.78)	26.64 (23.85-29.10)	44.11 (37.74-50.91)
$wDRatio_{Treatment}$	20.70 (17.70-24.08)	25.20 (21.80-28.63)	3.14 (2.04-4.34)	8.25 (5.37-11.07)
$wDRatio_{Control}$	25.33 (22.17-28.64)	32.35 (27.78-37.25)	9.56 (8.24-10.93)	22.80 (18.23-27.72)

Table 5 Species dominance values (in %) for the floated gillnet (FG) and standard gillnet (SG) in terms of number of individuals. Values in parentheses represent 95% CIs.

Category	Species rank	Species name	Common name	FG	SG
Flatfish bycatch species	S1	*Pseudopleuronectes yokohamae*	Marbled flounder	3.74 (2.81-4.79)	11.62 (10.17-13.28)
	S2	*Platichthys bicoloratus*	Stone flounder	3.92 (3.07-4.94)	14.56 (13.13-15.96)
Target species	S3	*Thamnaconus modestus*	Black scraper	33.52 (30.75-36.24)	12.07 (10.94-13.33)
	S4	*Hexagrammos otakii*	Fat greenling	16.28 (14.59-18.19)	14.25 (12.76-15.92)
	S5	*Sebastes schlegelii*	Black rockfish	17.63 (15.17-19.99)	15.53 (13.97-17.08)
	S6	*Charybdis japonica*	Asian paddle crab	8.62 (7.59-9.74)	8.46 (7.32-9.56)
Wanted bycatch species	S7	*Konosirus punctatus*	Spotted anchovy	6.64 (5.72-7.61)	0.15 (0.04-0.29)
	S8	*Sebastiscus marmoratus*	Marbled rockfish	1.80 (1.20-2.48)	3.49 (2.77-4.20)
	S9	*Mesocentrotus nudus*	Sea urchin	0.16 (0.04-0.32)	1.81 (1.28-2.41)
	S10	*Chirolophis japonicus*	eelpout	0.24 (0.06-0.43)	0.91 (0.53-1.31)
	S11	*Zoarces elongatus*	eelpout	0.20 (0.06-0.39)	1.08 (0.74-1.44)
	S12	*Paralichthys olivaceus*	Bastard halibut	0.22 (0.06-0.42)	0.72 (0.39-1.07)
Unwanted bycatch species	S13	*Hexagrammos agrammus*	Spotty belly greenling	2.92 (2.20-3.70)	4.95 (4.18-5.72)
	S14	*Sebastes hubbsi*	Armored rockfish	2.50 (1.86-3.23)	4.20 (3.65-4.80)
	S15	*Hemicentrotus pulcherrimus*	Sea urchin	0.56 (0.31-0.86)	2.52 (2.10-2.98)
	S16	*Patiria pectinifera*	Starfish	0.78 (0.47-1.10)	2.26 (1.76-2.71)

	S17	*Scyra quadridens*	Kelp crab	0.28 (0.10-0.49)	1.42 (1.03-1.82)

Figures

Figure 1 Map of study area in the Yellow Sea of China where the experimental trials were conducted (indicated by crosses).

Figure 2 Experimental setup showing **a**: the deployment of floated and standard gillnets fleets. **b**: schematic diagram (not in scale) of the floated gillnet configuration.

Figure 3 Catch comparison rates and catch ratios of the floated gillnets for marbled flounder (*Pseudopleuronectes yokohamae*) and stone flounder (*Platichthys bicoloratus*). Upper panel: the modelled catch comparison rates (black line) with 95% CIs (gray area). The gray solid and dashed lines represent the summed population for the floated and standard gillnets, respectively. Circles represent the experimental rates. Lower panel: the estimated catch ratios (black line) with 95% CIs (gray area). Horizontal stippled lines represent the baseline at which the two gillnet configurations have equal catch efficiency.

Figure 4 Catch comparison rates and catch ratios of the floated gillnets for black scraper (*Thamnaconus modestus*), fat greenling (*Hexagrammos otakii*), black rockfish (*Sebastes schlegelii*) and Asian paddle crab (*Charybdis japonica*). Upper panel: the modelled catch comparison rates (black line) with 95% CIs (gray area). The gray solid and dashed lines represent the summed population for the floated and standard gillnets, respectively. Circles represent the experimental rates. Lower panel: the estimated catch ratios (black line) with 95% CIs (gray area). Vertical solid lines represent the minimum landing size (MLS) or length at first sexual maturity (LFM) for each target species. Horizontal stippled lines represent the baseline at which the two gillnet configurations have equal catch efficiency.

Figure 5 Cumulative species dominance curves for the floated and standard gillnets. Cumulative dominance curves (solid lines) with 95% CIs (dotted lines) for the species caught by the floated gillnets (black) and the standard gillnet (gray). The x-axis shows the species ID: 1 *P. yokohamae*, 2 *P. bicoloratus*, 3 *T. modestus*, 4 *H. otakii*, 5 *S. schlegelii*, 6 *C. japonica*, 7 *K. punctatus*, 8 *S. marmoratus*, 9 *M. nudus*, 10 *C. japonicus*, 11 *Z. elongatus*, 12 *P. olivaceus*, 13 *H. agrammus*, 14 *S. hubbsi*, 15 *H. pulcherrimus*, 16 *P. pectinifera*, 17 *S. quadridens.* The blue, green, yellow, and red areas represent the flatfish bycatch species, target species, wanted bycatch species, and unwanted bycatch species, respectively.

Figure 1

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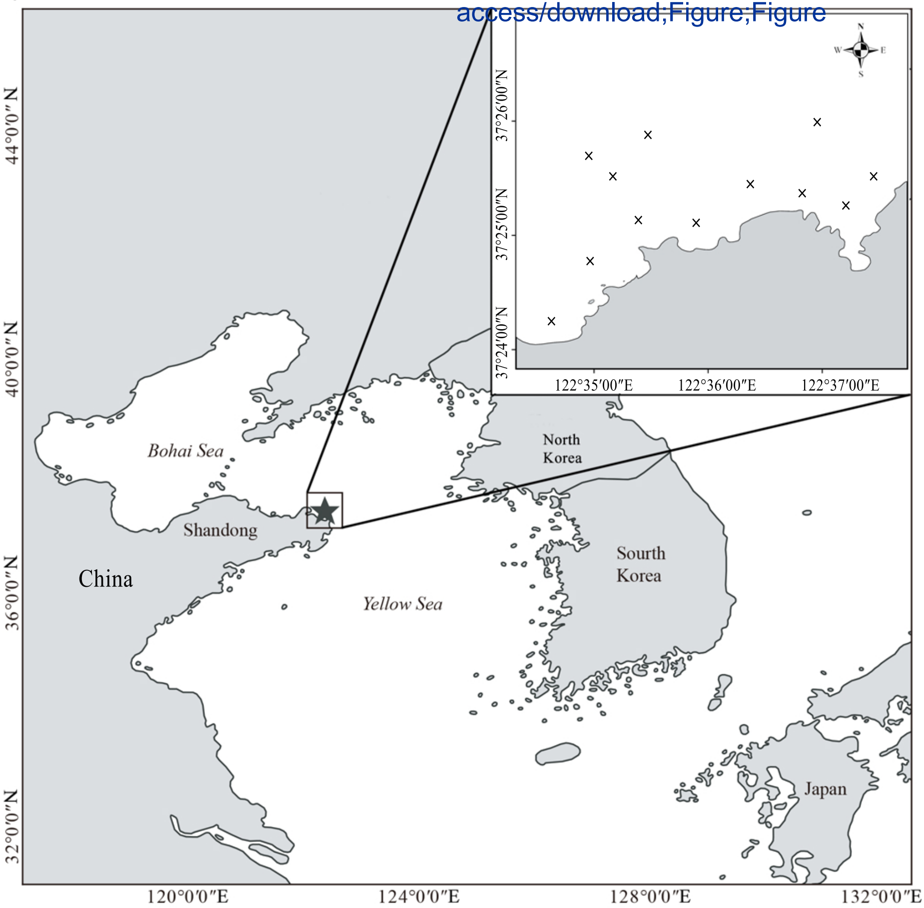

Figure 2

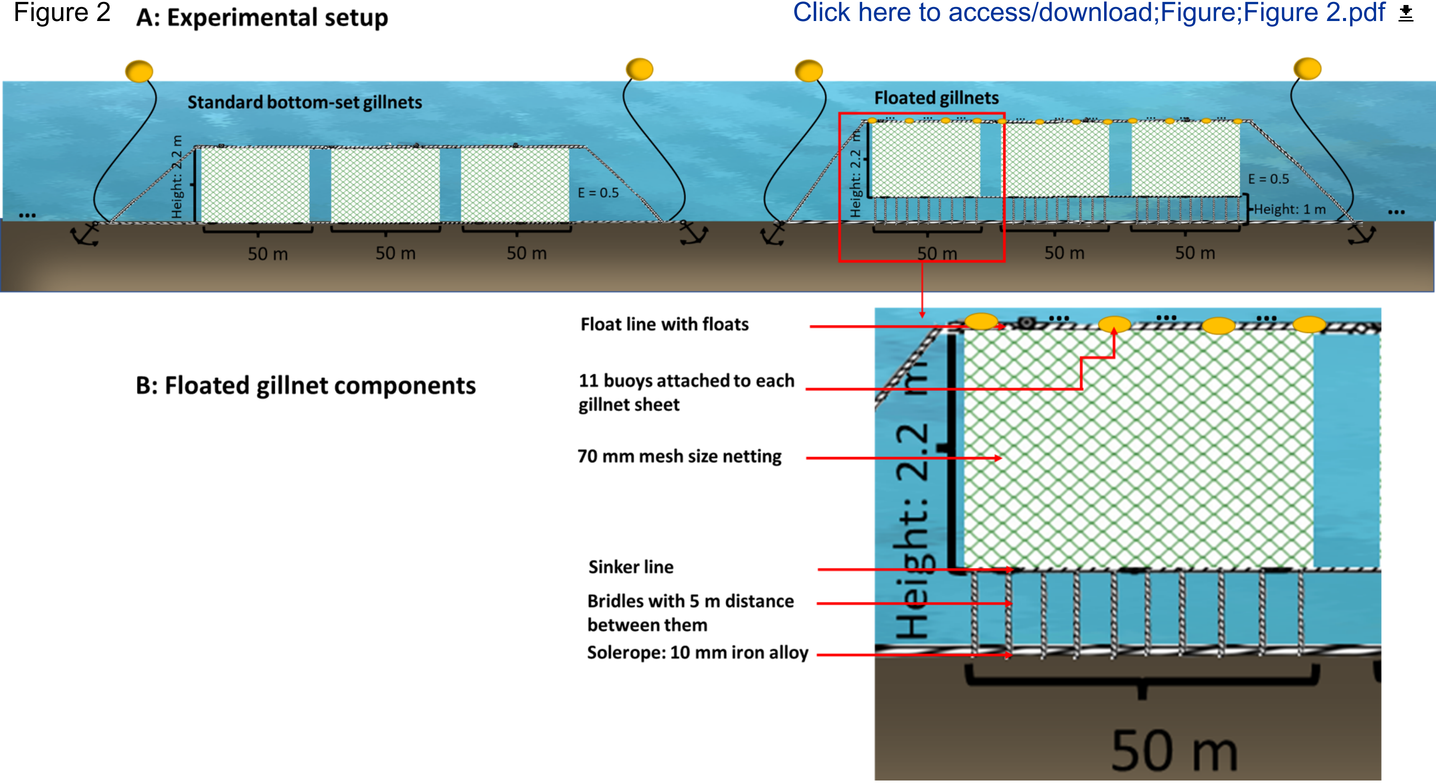
A: Experimental setup
Standard bottom-set gillnets
Height: 2.2 m
E = 0.5
50 m
50 m
50 m
Floated gillnets
Height: 2.2 m
E = 0.5
Height: 1 m
50 m
50 m
50 m
B: Floated gillnet components
Float line with floats
11 buoys attached to each gillnet sheet
70 mm mesh size netting
Sinker line
Bridles with 5 m distance between them
Solerope: 10 mm iron alloy
Height: 2.2 m
50 m

Figure 3

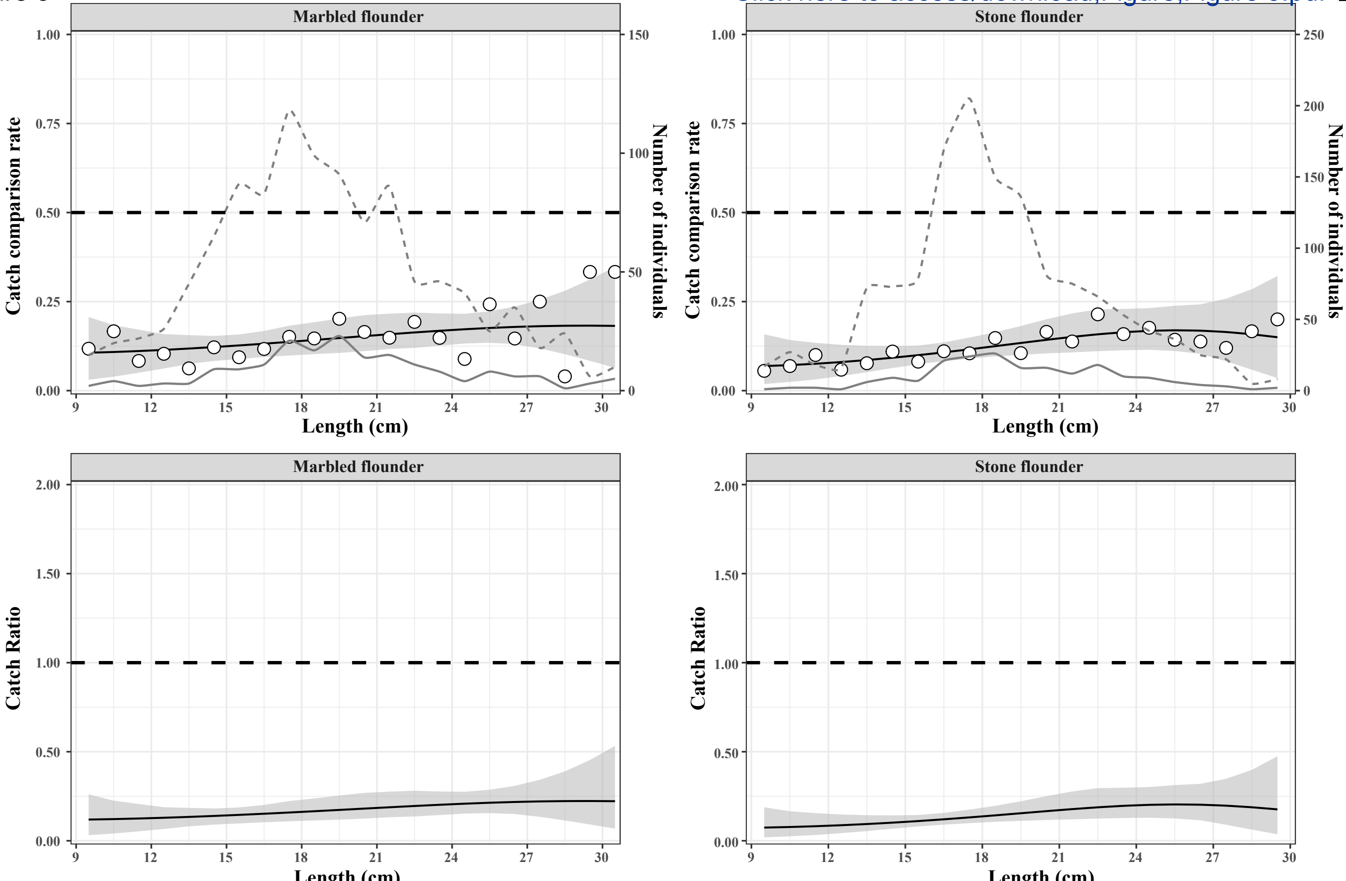
Marbled flounder
Stone flounder
Catch comparison rate
Number of individuals
Length (cm)
Marbled flounder
Stone flounder
Catch Ratio
Length (cm)

Figure 4

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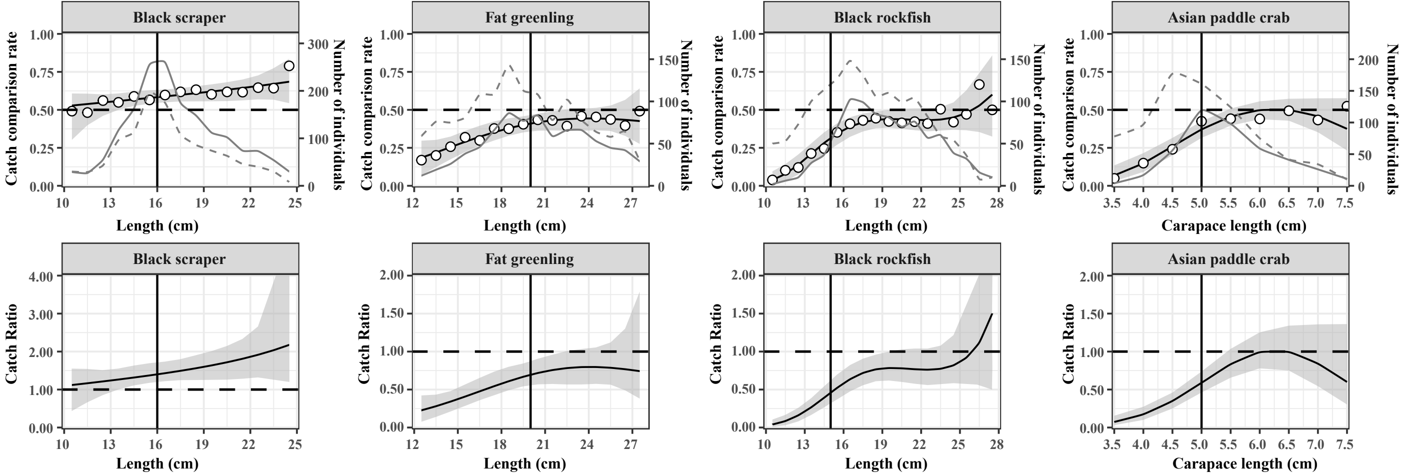
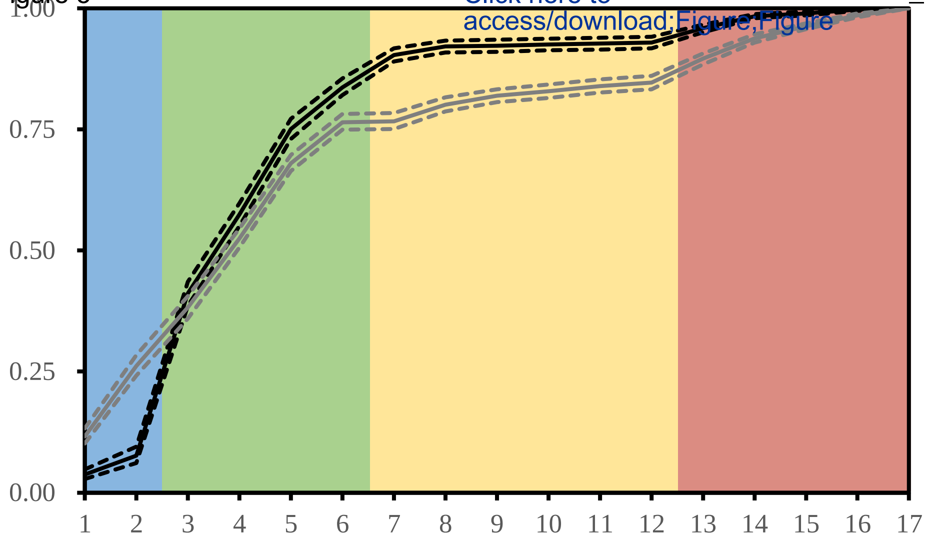


Figure 5



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