Effect of artificial lights on catch efficiency and capture patterns in Asian paddle crab (*Charybdis japonica*) gillnet fishery

Mengjie Yu[a], Bent Herrmann[b,c,d], Kristine Cerbule[b,c], Changdong Liu[a], Liyou Zhang[a], Yanli Tang[a, *]

[a] *Fisheries College, Ocean University of China, 266003 Qingdao, Shandong, China*

[b] *SINTEF Ocean, Fishing Gear Technology, Willemoesvej 2, 9850, Hirtshals, Denmark*

[c] *UiT The Arctic University of Norway, N-9037, Tromsø, Norway*

[d] *DTU Aqua, Technical University of Denmark, Hirtshals, Denmark*

[*] Corresponding author.

E-mail: tangyanli_lab@163.com (Yanli Tang)

Abstract

The gillnet fishery targeting Asian paddle crab (*Charybdis japonica*) is an important commercial fishery in the Yellow Sea of China. However, low catch rates represent a challenge, and solutions for improving the catch efficiency are crucial for economical sustainability in this fishery. Therefore, we tested whether the use of artificial fishing lights could improve gillnet catch performance. Specifically, we investigated the effect of using different colored light-emitting diodes (LED) on gillnet catch efficiency and capture patterns. The results showed that attaching white and blue LED lights to gillnets did not significantly affect the catch efficiency of *C. japonica*, compared to the conventional gillnets without LED lights attached. However, green LED lights significantly improved catch efficiency of legal-sized *C. japonica* by an average of 57%. Furthermore, a significant reduction (~35%) in the catch efficiency of undersized crabs was observed for gillnets equipped with red LEDs; however, without any significant effect on catches of legal-sized *C. japonica*. Moreover, significant differences were observed for the catch composition of species between gillnets with and without LED lights. The findings of this study can provide insight into potential improvements of the fishing strategies in the *C. japonica* gillnet fishery.

Keywords: Gillnet; LED lights; catch efficiency; capture patterns; *Charybdis japonica*

1. Introduction

Crab fisheries represent a significant part of commercial crustacean catches in China. In 2021, the crab capture production reached 647,122 t, accounting for 34.8% of the total marine crustacean catches in China (Fisheries Administration Bureau, MARA, PRC, 2022). The Asian paddle crab (*Charybdis japonica*) is one of the most ecologically and economically important crab species in China, being widely distributed in the coastal waters of the Bohai Sea, Yellow Sea, and East Sea (Zhang et al., 2016; Yu et al., 2023). The annual landings for *C. japonica* range between 2.2×10^4 t and 3.5×10^4 t from 2017 to 2021 (MARA, 2018-2022). Due to the high nutritional and economic value, *C. japonica* is providing considerable income for fishing industry and coastal communities engaged in crab fisheries (Wang et al., 2005). In commercial fisheries, *C. japonica* is mainly targeted using different passive fishing gear types, such as stow nets, traps, pots, and gillnets (Yu et al., 2021).

Bottom-set gillnets are commonly used fishing gear for harvesting *C. japonica*, due to its low cost and ease of operation (Suuronen et al., 2012; Li et al., 2017). This fishery typically is conducted along the coast at depths ranging from 5-30 m, making it feasible for small vessels to carry out daily operations. The regulations for this fishery include a set a minimum landing size (MLS) of 50 mm carapace length (*cl*) for *C. japonica* (Yu et al., 2021) and a bycatch limit regulation specifying that undersized crabs should not exceed 25% of the total crab catches (in number of individuals) summed over deployments (Shandong Provincial Oceanic and Fishery Department, 2014). Furthermore, a closed season known as the "Summer Moratorium of Marine Fishing" (SMMF) from May 1st to September 1st is set in this fishery to protect the spawning stocks (Shen and Heino, 2014).

The implementation of the SMMF has significantly shortened the fishing period. Furthermore, the catch rates of *C. japonica* can be low during the open season, particularly for legal-sized individuals, which has raised concerns among fishers. During low-yield seasons, fishers tend to increase the number of gillnets and frequency of trips or move their fishing sites to more resource-rich areas based on their personal experience to maximize catches. However, these traditional fishing strategies face challenges in achieving efficient fishery due to rising operating costs (e.g., fuel, nets, and labor) and high catch rates of undersized individuals. Therefore, the current exploitation patterns in the fishery can result in low income and thus a financial burden on coastal communities that heavily rely on fishing as their primary source of income, implying that the fishing effort is not proportional to the amount of crab caught in this gillnet fishery. Therefore, solutions for improving the catch efficiency in this fishery are sought to maintain the economic viability of coastal communities.

The use of artificial lights to improve the catch efficiency of target species has been tested in different fisheries worldwide (see review by Nguyen and Winger (2019a)). For crab fisheries, previous studies have tested the effect of using different colored light emitting diodes (LED) on the catch efficiency of several crab species. For instance, results of several studies reported that green and white LED lights can significantly increase the catch efficiency of snow crab (*Chionoecetes opilio*) in both the Barents Sea and Canadian snow crab fisheries (Nguyen et al., 2017, 2019; Nguyen and Winger, 2019b; Cerbule et al., 2021a). Naimullah et al. (2022) found that green LED lights can improve the catch per unit effort of orange mud crab (*Scylla olivacea*) trap fishery in Setiu Wetlands of Malaysia. Susanto et al. (2022) investigated the response and behavior of blue swimming crab (*Portunus pelagicus*) towards different LED colors in laboratory conditions, and the results suggested that crab exhibits a high preference for blue LED lights. However, no practical applications of artificial lights such as LED lights have been reported to improve the catch efficiency of *C. japonica* gillnet fisheries.

Liu et al. (2012) evaluated the effects of artificial lights on the feeding rhythms and growth of *C. japonica* in the laboratory and found that *C. japonica* exhibited significantly higher feeding activity when exposed to blue and green color lights than to other color lights, and juvenile crabs had significantly higher growth rate in green color light than that in other color lights and no light. These results suggest that *C. japonica* has different phototaxis towards different light colors. Thus, specific artificial lights might provide an effective stimulus for attracting and aggregating *C. japonica.* However, considering the potential behavioral differences between laboratory and field conditions, it is essential to systematically assess how artificial lights affect the catch efficiency of *C. japonica* to understand the applicability of this technical measure in fisheries.

Artificial lights have been extensively used to reduce bycatch of various aquatic animals in gillnet fisheries across different regions, including elasmobranchs, sea turtles, finfish, and Humboldt squid (Wang et al., 2010, 2013; Ortiz et al., 2016; Darquea et al., 2020; Gautama et al., 2022; Senko et al., 2022). These observations suggest that applying LED lights in *C. japonica* gillnet fishery may potentially affect the species composition in the gillnet catches when different LED light colors are being tested. During low-yield seasons, the *C. japonica* gillnet fishery often captures a large proportion of different bycatch species. Some of the bycatch species have a high economic value; therefore, the captured individuals are usually retained by fishers to increase the income from the fishery. However, other unwanted bycatch species without any commercial value are discarded by the fishers. The response behavior of the different species to the LED lights can be species-specific. Therefore, it is also important to evaluate the effects of LED lights on the capture patterns in *C. japonica* gillnet fishery.

In this study, we conducted the first scientific investigation assessing the applicability of LED lights in *C. japonica* gillnet fishery in the Yellow Sea, China. We tested and compared the catch performance of gillnets equipped with different colored LED lights (illuminated gillnets) with gillnets that did not have LED lights attached (conventional gillnets). This study aims to address the following research questions:

- Can the use of LED lights improve the catch efficiency in gillnet fishery targeting *C. japonica*?

- If there are differences in catch efficiency for *C. japonica* between the illuminated and conventional gillnets, are they length-dependent?
- Is there is an optimal color of LED lights for improving the catch efficiency of *C. japonica*?
- Is the species composition in the gillnet fishery affected by the use of LED lights?

2. Materials and methods

2.1 Sea trials

Sea trials were conducted onboard a commercial fishing vessel "Lurongyuyang 62705" (6.7 m LOA) in April 2021 in the coastal waters of the Yellow Sea, China (Fig. 1). The study area was located at traditional commercial fishing grounds for targeting *C. japonica*. The substrate type in this area is a mixture of mud, sand, and rock, and the water depth ranges from 5 to 20 m.

Five gillnet configurations were used for the trials: a conventional gillnet without LED attached (CG) as a baseline gear, and treatment gillnets, where each sheet was equipped with different color LED lights: blue (BG), green (GG), red (RG), and white (WG). All gillnets (baseline and treatment nets) were identical regarding their construction and dimensions. Specifically, each gillnet was made of 0.23 mm green nylon monofilament twine with 90 mm fully stretched mesh size. The dimensions of each gillnet sheet were 50 m (length) × 1.8 m (height). During the deployment, the hanging ratio (E) was 0.5 for all nets. The float was composed of plastic foam, and the sinker was made of 500 lead blocks, each weighing 20 g. For each treatment gillnet sheet, ten LEDs were attached to the float line at an interval of 4.9 m using nylon cable ties (Fig. 2). The LEDs were manufactured by Zhejiang Underwater Fishing Light Factory. The spectral distributions of LEDs measured by Laser Spectrometer (UPPtek) are shown in Figure S1. Peak wavelengths were 465 nm for blue lights,516 nm for green lights, 633 nm for red lights, and 456 nm for white lights. The specifications, parameters, and other related information (e.g., price and illumination time) of the LEDs can be found in Yu et al. (2022a). A total of 15 gillnet sheets were used, and all gillnets were divided into five fleets, each containing three replicates for each configuration (Fig. 2). Each fleet was deployed approximately 200 m apart.

Following the commercial fishing pattern, gillnets were set at twilight and retrieved in the morning of the following day after approximately 12 h soak time. After each trial, catches were sorted and identified at a species level. All individuals of the bycatch species were counted and recorded, and all *C. japonica* were measured for *cl* (defined as the distance from the frontal notch to the posterior margin of the carapace) to the nearest mm using calipers.

2.2 Modelling the length-dependent catch efficiency between baseline and treatment gillnets

We estimated the length dependent catch efficiency between the non-illuminated baseline gillnets and each of the illuminated treatment gillnets separately following the procedure described below.

The catch data were analyzed 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_{cl}) summed over deployments:

$$CC_{cl} = \frac{\sum_{j=1}^{m}\{nt_{cl,j}\}}{\sum_{j=1}^{m}\{nt_{cl,j} + nb_{cl,j}\}} \tag{1}$$

where $nb_{cl,j}$ and $nt_{cl,j}$ are the numbers of crab that were measured in each length class *cl* for the conventional (baseline) and illuminated (treatment) gillnets with the specific LED light color (blue, green, red or white, respectively) in deployment *j*. *m* is the total number of deployments. The functional form of the catch comparison rate $CC(cl, \boldsymbol{v})$ was obtained using maximum likelihood estimation by minimizing the following expression (Herrmann et al., 2017):

$$-\sum_{cl}\left\{\sum_{j=1}^{m}\{nt_{cl,j} \times \ln\big(CC(cl,\boldsymbol{v})\big) + nb_{cl,j} \times \ln\big(1.0 - CC(cl,\boldsymbol{v})\big)\}\right\} \tag{2}$$

where $\boldsymbol{v}$ represents the parameters that describe the catch comparison curve defined by $CC(cl, \boldsymbol{v})$. The outer summation in expression (2) is the summation over length classes *cl* in the experimental data. When the catch efficiency of the baseline and treatment 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_{cl} was modelled by the function $CC(cl, \boldsymbol{v})$ using the following equation:

$$CC(cl, \boldsymbol{v}) = \frac{exp\big(f(cl, v_0, \dots, v_k)\big)}{1 + exp\big(f(cl, v_0, \dots, v_k)\big)} \tag{3}$$

where *f* is a polynomial of order *k* with coefficients v_0-v_k. The values of the parameters ***v*** describing $CC(cl, \boldsymbol{v})$ were estimated by minimizing equation (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 $CC(cl, \boldsymbol{v})$. 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 $CC(cl, \boldsymbol{v})$, we obtained the relative catch efficiency (also named catch ratio) $CR(cl, \boldsymbol{v})$ using the following equation:

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

$CR(cl, \boldsymbol{v})$ quantifies the relative catch efficiency between the illuminated treatment gillnet with a specific LED light color and the baseline gillnet. If the catch efficiency of both treatment and baseline gillnets is equal, then $CR(cl, \boldsymbol{v}) = 1.0$ (Cerbule et al., 2022a). $CR(cl, \boldsymbol{v}) = 1.5$ would mean that the treatment gillnet is catching 50% more of the crabs with length *cl* than the baseline gillnet. By contrast, $CR(cl, \boldsymbol{v}) = 0.5$ would mean that the treatment gillnet is only catching 50% of the crabs with length *cl* caught by the baseline gillnet (Brinkhof et al., 2022; Grimaldo et al., 2023).

We estimated confidence intervals (CIs) for $CC(cl,\boldsymbol{v})$ and $CR(cl,\boldsymbol{v})$ using a double bootstrapping method (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 treatment and baseline 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 crab 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 equations:

$$\begin{aligned} CR_{average-} &= 100 \times \frac{\sum_{cl<MLS}\sum_{j=1}^{m}\{nt_{cl,j}\}}{\sum_{cl<MLS}\sum_{j=1}^{m}\{nb_{cl,j}\}} \\ CR_{average+} &= 100 \times \frac{\sum_{cl\geq MLS}\sum_{j=1}^{m}\{nt_{cl,j}\}}{\sum_{cl\geq MLS}\sum_{j=1}^{m}\{nb_{cl,j}\}} \end{aligned} \qquad (5)$$

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

2.3 Estimation of the discard ratio

To investigate how well the size selectivity of the baseline and treatment gillnets matched the size structure of *C. japonica* population present in the fishing ground, two fishing usability indicators ($nDRatio_{baseline}$ and $nDRatio_{treatmenmt}$) were estimated directly from the experimental catch data using the following equations:

$$
\begin{aligned}
nDRatio_{baseline} &= 100 \times \frac{\sum_{cl<MLS}\sum_{j=1}^{m}\{nb_{cl,j}\}}{\sum_{cl}\sum_{j=1}^{m}\{nb_{cl,j}\}} \\
nDRatio_{treatment} &= 100 \times \frac{\sum_{cl<MLS}\sum_{j=1}^{m}\{nt_{cl,j}\}}{\sum_{cl}\sum_{j=1}^{m}\{nt_{cl,j}\}}
\end{aligned}
\tag{6}
$$

where the outer summations include the length classes that were below the MLS of *C. japonica* (in nominator) and over-all length classes (in denominator). *nDRatio* quantifies the fraction of undersized *C. japonica* in the catch. Ideally, *nDRatio* should be as low as possible. The value of *nDRatio* is affected by both the size selectivity of the gear and the size structure of the *C. japonica* in the fishing grounds. Therefore, it provided an estimate that is specific to the population fished and cannot be extrapolated to other scenarios (Cerbule et al., 2021a). Confidence intervals for these indicators were obtained by the double bootstrapping method described above.

2.4 Length frequency distributions

Length frequency distribution and cumulative length frequency distribution analyses were used to quantify the proportion of the total catch of *C. japonica* for each carapace length class *cl* and up to a given carapace length class *CL*, captured for each gillnet configuration *g*. The analysis was conducted using the following equation (Herrmann et al., 2020; Cerbule et al., 2021a):

$$
\begin{aligned}
Dn_{g,cl} &= \frac{\sum_{j=1}^{m} n_{g,cl,j}}{\sum_{j=1}^{m}\sum_{cl} n_{g,cl,j}} \\
CDn_{g,CL} &= \frac{\sum_{j=1}^{m}\sum_{cl=0}^{CL} n_{g,cl,j}}{\sum_{j=1}^{m}\sum_{cl} n_{g,cl,j}}
\end{aligned}
\tag{7}
$$

By incorporating the evaluation of Equation (7) in the double bootstrap described above, we obtained 95% CIs. Further, to compare the length distribution of *C. japonica* captured by the baseline and treatment gillnets, the differences in length frequency $\Delta Dn_{g,cl}$ and cumulative length frequency $\Delta CDn_{g,CL}$ between the baseline gillnet *A* and treatment gillnets *B* were estimated as follows:

$$\begin{gathered}\Delta Dn_{A,B,cl} = Dn_{B,cl} - Dn_{A,cl} \\ \Delta CDn_{A,B,CL} = CDn_{B,CL} - CDn_{A,CL}\end{gathered} \tag{8}$$

Efron 95% CIs for the $\Delta Dn_{A,B,cl}$ and $\Delta CDn_{A,B,CL}$ were obtained by the double bootstrapping method as described above.

2.5 Species dominance analysis

We examined the species dominance patterns determining species compositions captured in gillnets with different configurations (baseline and treatment). Specifically, we quantified the information about the catch composition of species abundances for baseline and all treatment gillnets separately by estimating the species dominance patterns as follows (Cerbule et al., 2022b; Herrmann et al., 2022):

$$d_{g,i} = \frac{\sum_{j=1}^{m} n_{g,i,j}}{\sum_{j=1}^{m} \sum_{i=1}^{K} n_{g,i,j}} \tag{9}$$

In Equation (9), $n_{g,i,j}$ is the number of individuals of the species *i* according to the predefined species index (species rank) counted in gillnet configuration *g* during 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. Furthermore, in this study we used separate ranking for legal-sized and undersized *C. japonica,* respectively. The catch dominance curves were estimated for each gillnet configuration *g* with the following equation (Warwick et al., 2008; Herrmann et al., 2022):

$$D_{g,I} = \frac{\sum_{j=1}^{m} \sum_{i=1}^{I} n_{g,i,j}}{\sum_{j=1}^{m} \sum_{i=1}^{K} n_{g,i,j}} \text{ with } 1 \leq I \leq K \quad (10)$$

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

Based on using Equations (9) and (10), 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 2.2-2.5 were conducted using the software SELNET (Herrmann et al., 2012, 2016, 2017, 2022), software version date 27 March 2023.

3. Results

3.1 Description of experiments and catches

Thirteen valid deployments were conducted during the sea trials. The water depth ranged from 9.7 to 14.9 m, and the gillnet soak time varied between 11.0 to 13.6 h (Table 1). A total of 2212 *C. japonica* were caught and length measured in all gillnets. The *cl* size ranged from 35 to 75 mm throughout the experiment. Furthermore, nine bycatch species were observed during the trials (Table 2).

3.2 Length-dependent catch efficiency

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

The length-dependent catch comparison and catch ratio curves for BG *vs*. CG and WG *vs*. CG showed no significant differences in catch efficiency as the 95% CIs included the baseline for equal catch efficiency for all sizes of *C. japonica* (Fig. 3). The length-integrated average values ($CR_{average-}$ and $CR_{average+}$) also reflected non-significant differences in average catch ratio for both undersized- and legal-sized crabs between BG and CG and WG and CG gillnets (Table 3).

For the comparison between GG and CG, the catch comparison and catch ratio curves showed that the GG had significantly higher catch efficiency than CG for *C. japonica* length classes between 4.5-7.5 cm (Fig. 3). When averaged over the length classes, the GG caught significantly more legal-sized *C. japonica* than CG ($CR_{average+}$ =157.28% (CI: 127.07%-187.50%)), while increase for undersized individuals was not significant (Table 3).

For RG *vs*. CG, the catch ratio results showed a significant reduction in catch efficiency for undersized *C. japonica*, while no significant differences for the capture of legal-sized *C. japonica* (Fig. 3). The length-integrated average values also showed a similar pattern (Table 3). Specifically, the catches of undersized crabs were significantly reduced by 35.14% (CI: 2.33%-59.35%). The results showed an indication of decrease in catches of legal-sized crabs; however, it was not statistically significant (Table 3).

3.3 Discard ratio

There were no significant differences in discard ratio between the baseline and treatment gillnets (Table 3). For the baseline gillnet, the fraction of undersized *C. japonica* in the total crab catches was marginally higher than 25%; however, it was not significant (Table 3). For all treatment gillnets, the bycatch ratios of undersized *C. japonica* were slightly below 25%, varying from 21.99% to 24.88% (Table 3).

3.4 Length frequency distributions

The length frequency distribution curves showed that the catch of both treatment and baseline gillnets comprised a larger proportion of legal-sized *C. japonica* (Fig. 4). The four pairwise comparisons between treatment and baseline gillnets did not show significant differences in length frequency distributions for both undersized and legal-sized crabs (Fig. 4). The comparisons of the cumulative length frequency distributions also reflected a similar pattern (Fig. 5).

3.5 Species dominance

The species dominance values (Table 4), and species cumulative dominance patterns (Fig. 6) showed that *C. japonica* dominated the species composition captured in baseline and treatment gillnets. Specifically, the percentage of undersized and legal-sized *C. japonica* summed up over 58% in gillnets with different configurations (Table 4). Additionally, the percentage of wanted bycatches (i.e., species with a commercial value) in the total catch varied from 11% to 19% for gillnets with different configurations, while a larger percentage was observed for unwanted bycatches (i.e., species without a commercial value), ranging from 17% to 22% (Table 4).

No significant differences in catch composition were observed between GG and CG as well as WG and CG (Table 4; Fig. 6). The comparison between BG and CG showed that undersized *C. japonica* was less dominant in catches of BG (Fig. 6). When comparing the RG and CG, the difference in cumulative catch dominance curves showed that *C. japonica* was significantly less represented in the catch composition in RG than CG while the opposite was observed for bycatch species (Fig. 6). Specifically, *Hexagrammos otakii* and *Hexagrammos agrammus* only contributed by 5.86% (CI: 3.18%-8.89%) and 6.38% (CI: 3.80%-9.40%) to the total catches of CG, respectively, while accounting for 13.22% (CI: 8.41%-18.41%) and 14.67% (CI: 10.47%-19.54%) of total catches for RG.

4. Discussion

This study demonstrates that the effect of LED lights on the catch efficiency of *C. japonica* in this gillnet fishery differs depending on the light color used. Specifically, green LEDs can significantly enhance the catch efficiency of *C. japonica*. To our knowledge, this study is the first to assess the effects of artificial lights on catch efficiency in the crab gillnet fishery. Therefore, the findings of this study can offer a relevant insight into the suitability of using artificial lights to increase the catches in *C. japonica* gillnet fishery.

Our study found that the green LED light was effective in increasing the catchability of *C. japonica*, while the blue LED light did not have a significant impact compared to gillnets that did not have any LED light attached. This contrasts with the findings of Liu et al. (2012), who reported that *C. japonica* exhibited positive phototaxis to both blue and green lights during laboratory experiments. However, Nguyen et al. (2017) observed varying behavioral reactions of snow crab to LED lights of the same color in laboratory and in field conditions, thus highlighting the importance of field experiments in verifying the laboratory observations. The effects of artificial lights on fishing practices are better understood through field experiments. Furthermore, our study revealed that white light did not affect the catch efficiency of *C. japonica*, while red light had a negative impact on the capture efficiency due to retention of significantly less undersized *C. japonica*. These findings have implications for the use of LED lights in fishing practices.

The intrinsic mechanisms of the species-specific reaction of *C. japonica* to different colored LED lights remain unclear. It is widely accepted that the species-specific spectral sensitivity results from the long-term adaptation and evolution of each species in specific environments (Johnson et al., 2002; Kuliñski and Styczyñska-Jurewicz, 2002; Nguyen and Winger, 2019a). Earlier studies also suggested the response of marine organisms to artificial lights could be attributed to various mechanisms, including positive phototaxis, preference for optimal light intensity, investigatory reflex, feeding on prey that are attracted to the light, schooling behavior, disorientation, or simply out of curiosity (Arimoto, 2013; Nguyen and Winger, 2019a). Therefore, additional anatomical, electrophysiological, and behavioral studies in laboratory conditions and *in situ* would contribute to fill the current knowledge gap about these species-specific responses to lights.

The results showed that the effects of green and red LEDs on the catch efficiency of *C. japonica* were length-dependent. Specifically, the green-lighted gillnet showed an increasing catch efficiency with the increase of crab sizes, while the gillnet with red LEDs would reduce the catch efficiency of undersized crabs without any significant effect on the catches of legal-sized individuals. These results might be explained by several factors. First, the visual system of the crab varies across ontogeny, resulting in changes in spectral sensitivity and corresponding behavioral and physiological patterns, such as feeding strategy, spatial vision, navigation, and prey recognition (Cronin and Jinks, 2001; Marchesan et al., 2005; Nguyen and Winger, 2019a). Second, the size-dependent swimming ability can provide more opportunities for large individuals to approach the vicinity of illuminated gillnets compared to the undersized crabs. Additionally, *C. japonica* is known to exhibit strong territorial consciousness and aggressive behavior (Yu et al., 2021). The presence of larger individuals near illuminated nets may prevent smaller individuals approaching the gear. Future research using underwater video recordings would be beneficial for providing more insight into this explanation.

Although green LED lights could significantly improve the catch efficiency of legal-sized *C. japonica* and increase the profit for the fishers, the potential impacts on the whole species composition in the gillnet catches should be fully taken into consideration. Specifically, the application of artificial light may also increase the capture probability of non-target species and negatively affect the biodiversity in ecosystems. Our study showed that the application of green LED did not significantly affect the catch composition in *C. japonica* gillnet fishery, while red LED increase the risk of catching bycatch species (i.e., *H. otakii* and *H. agrammus*). By understanding the effects of light fishing techniques on both target and non-target species, fisheries managers can implement sustainable practices to minimize negative impacts and ensure the long-term viability of *C. japonica* gillnet fisheries.

In order to apply new fishing technologies in an existing capture fishery, the current management regulations and acceptance of the new technologies by the fishers should be considered. Our results showed that applying green LED light in gillnets would not contradict the bycatch ratio regulation as the proportion of undersized crabs was below 25%, which, furthermore, would improve the sustainability of this fishery. Additionally, green-illuminated gillnets achieved higher catch efficiency of legal-sized crabs compared to the conventional gillnet. This result could effectively alleviate the financial burden on coastal communities caused by the fishing moratorium. Moreover, ease of use and low cost are crucial factors in determining whether fishers will voluntarily adopt the light fishing technology (Senko et al., 2022; Yu et al., 2022a). In gillnet fishing, LEDs are convenient to install on the float lines and can remain illuminated for multiple trials without requiring battery replacement. The operational mode of illuminated gillnets is identical to that of conventional nets, making it easy for fishers to adopt this technology without additional training. Previous studies have found that while the use of LEDs can increase the catchability of target species in specific fisheries, the economic benefits remain unclear due to the high investment of LEDs required (Nguyen and Winger, 2018; Nguyen et al., 2019). However, the domestically manufactured LEDs used in this study are priced at only 8 yuan per light (equivalent to $1.16/light), making the investment small compared to the potential increase in income. These advantages make the adoption of the light fishing technique feasible for gillnet fisheries on a large scale.

The findings of this study can also serve as a reference for the application of LEDs in other fisheries targeting *C. japonica*, in addition to gillnet fishery. For example, crab pots/traps are also commonly used by fishers in small-scale fisheries in coastal China to capture *C. japonica* (Yu et al., 2021, 2022b). However, these fishing gears are characterized by low catch efficiency, making the use of green LED lights in pot/trap fisheries a promising alternative to increase the pot/trap catch efficiency. Apart from China, *C. japonica* is also widely distributed in other countries and regions, including Japan, Korea, Southeast Asia, and Oceania (Zhang et al., 2016; Yu et al., 2021). In Australia and New Zealand, *C. japonica* is deemed as an invasive species, competing with local crabs and causing severe ecological damage, and is feared as a carrier of viral diseases that may cause devastating damage to the aquaculture industry (Smith et al., 2003; Vazquez Archdale and Kuwahara, 2006). The results of our study may aid in the more effective eradication of *C. japonica* from invaded ecosystems.

Several studies have reported that the number, position, and intensity of LED lights affect the size selectivity and catch efficiency of fishing gear (Marchesan et al., 2005; Hannah et al., 2015). For instance, Lomeli et al. (2018) found that ten LED-configured trawls caught significantly more Pacific hake (*Merluccius productus*) than unilluminated trawls, while the five- and 20-LED configurations did not affect the mean

Pacific hake catches. Yamashita et al. (2012) reported that 24-36 MH lamps and 50 blue LED lamps appeared to have the optimal fishing effect for squid jigging. In this study, we added ten LED lights to the float line of gillnets as a preliminary measure. Future work should focus on the factors mentioned above and their interactions, which are essential for better understanding the performance of artificial lights in gillnet fisheries.

In conclusion, our results demonstrate that artificial lights have great potential to be applied in the *C. japonica* gillnet fishery. By comparing the catch performance of gillnets mounted with different colored LED lights, green LED light was recommended as the optimal one because it significantly improved the catch efficiency of legal-sized crabs, and meanwhile did not affect the catch composition in this fishery. To facilitate the application of LED lights in *C. japonica* gillnet fishery and similar fisheries, more field experiments are further needed.

Funding

This study was supported by the Project of Marine and Fishery Technology Innovation of Shandong (No. 2017HYCX007).

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.

Acknowledgements

We thank the Xixiakou Fisheries Group Company for assistance and express our gratitude to Captain Cai for his advice and help during the experiments. We express our gratitude to the editor and reviewers for their valuable comments, which improved our manuscript greatly.

Reference

Arimoto, T., 2013. Fish behaviour and visual physiology in capture process of light fishing. Symposium on impacts of fishing on the environment: ICES-FAO Working Group on Fishing Technology and Fish Behaviour. May 6–10, Bangkok, Thailand.

Brinkhof, J., Grimaldo, E., Herrmann, B., Pettersen, H., 2022. The effect of grid size on catch efficiency and by-catch in the demersal trawl fishery for Norway pout (*Trisopterus esmarkii*). Ocean Coast. Manag. 229, 106333. https://doi.org/10.1016/j.ocecoaman.2022.106333.

Burnham, K.P., Anderson, D.R., 2002. Model Selection and Multi model Inference: A Practical Information-Theoretic Approach, 2nd ed. Springer, New York. ISBN 978- 0.387-22456-5.

Cerbule, K., Herrmann, B., Grimaldo, E., Grimsmo, L., Vollstad, J., 2021a. The effect of white and green LED-lights on the catch efficiency of the Barents Sea snow crab (*Chionoecetes opilio*) pot fishery. PLOS ONE 16, e0258272. https://doi.org/10.1371/journal.pone.0258272.

Cerbule, K., Jacques, N., Pettersen, H., Ingólfsson, Ó.A., Herrmann, B., Grimaldo, E., Larsen, R.B., Brinkhof, J., Sistiaga, M., Lilleng, D., Brčić, J., 2021b. Bycatch reduction in the deep-water shrimp (*Pandalus borealis*) trawl fishery with a large mesh top panel. J. Nat. Conserv. 61, 126001. https://doi.org/10.1016/j.jnc.2021.126001.

Cerbule, K., Herrmann, B., Grimaldo, E., Larsen, R.B., Savina, E., Vollstad, J., 2022a. Comparison of the efficiency and modes of capture of biodegradable versus nylon gillnets in the Northeast Atlantic cod (*Gadus morhua*) fishery. Mar. Pollut. Bull. 178, 113618. https://doi.org/10.1016/j.marpolbul.2022.113618.

Cerbule, K., Savina, E., Herrmann, B., Larsen, R.B., Paul Feekings, J., Ahm Krag, L., Pellegrinelli, A., 2022b. Quantification of catch composition in fisheries: A methodology and its application to compare biodegradable and nylon gillnets. J. Nat. Conserv. 70, 126298. https://doi.org/10.1016/j.jnc.2022.126298.

Cronin, T.W., Jinks, R.N., 2001. Ontogeny of vision in marine crustaceans. Am. Zool. 41, 1098–1107. https://doi.org/10.1093/icb/41.5.1098.

Darquea, J.J., Ortiz-Alvarez, C., Córdova-Zavaleta, F., Medina, R., Bielli, A., Alfaro-Shigueto, J., Mangel, J.C., 2020. Trialing net illumination as a bycatch mitigation measure for sea turtles in a small-scale gillnet fishery in Ecuador. Lat. Am. J. Aquat. Res. 48, 446–455. https://doi.org/10.3856/vol48-issue3-fulltext-2428.

Efron, B., 1982. The jackknife, the bootstrap and other resampling plans. In: SIAM Monograph No. 38; CBSM-NSF Regional Conference Series in Applied Mathematics, Philadelphia, ISBN 978-0-89871-179-0.

Fisheries Administration Bureau, MARA, PRC, 2022. China fishery statistics yearbooks. China Agriculture Press, Beijing, China.

Gautama, D.A., Susanto, H., Riyanto, M., Wahju, R.I., Osmond, M., Wang, J., 2022. Reducing sea turtle bycatch with net illumination in an Indonesian small-scale coastal gillnet fishery. Front. Mar. Sci. 9:1036158. https://doi.org/10.3389/fmars.2022.1036158.

Grimaldo, E., Herrmann, B., Vollstad, J., Su, B., Moe, F., Larsen, R.B., Tatone, I., 2018. Fishing efficiency of biodegradabale PBSAT gillnets and conventional nylon gillnets used in Norwegian cod (*Gadus morhua*) and saithe (*Pollachius virens*) fishieries. ICES J. Mar. Sci. 75, 2245–2256.

http://dx.doi.org/10.1093/icesjms/fsy108.

Grimaldo, E., Brinkhof, J., Herrmann, B., Cerbule, K., Grimsmo, L., Pettersen, H., 2023. Improved bycatch reduction in the mixed demersal trawl fishery for Norway pout (*Trisopterus esmarkii*). Estuar. Coast. Shelf Sci. 281, 108189. https://doi.org/10.1016/j.ecss.2022.108189.

Hannah, R.W., Lomeli, M.J.M., Jones, S.A., 2015. Tests of artificial light for bycatch reduction in an ocean shrimp (*Pandalus jordani*) trawl: Strong but opposite effects at the footrope and near the bycatch reduction device. Fish. Res. 170, 60–67. https://doi.org/10.1016/j.fishres.2015.05.010.

Herrmann, B., Sistiaga, M., Nielsen, K.N., Larsen, R.B., 2012. Understanding the size selectivity of redfish (*Sebastes* spp.) in North Atlantic trawl codends. J. Northwest Atl. Fish. Sci. 44, 1–13. https://doi.org/10.2960/J.v44.m680.

Herrmann, B., Krag, L.A., Feekings, J., Noack, T., 2016. Understanding and predicting size selection in diamond-mesh cod ends for Danish seining: a study based on sea trials and computer simulations. Mar. Coast. Fish. 8, 277–291. https://doi.org/10.1080/19425120.2016.1161682.

Herrmann, B., Sistiaga, M., Rindahl, L., Tatone, I., 2017. Estimation of the effect of gear design changes on catch efficiency: Methodology and a case study for a Spanish longline fishery targeting hake (*Merluccius merluccius*). Fish. Res. 185, 153–160. https://doi.org/10.1016/j.fishres.2016.09.013.

Herrmann, B., Sistiaga, M., Larsen, R.B., Brinkhof, J., Gjøsund, S.H., Jacques, N., Santos, J., 2020. Catch pattern and size selectivity for a gear designed to prevent fish injuries during the capture process in a North-East Atlantic demersal trawl fishery. Reg. Stud. Mar. Sci. 40, 101525. https://doi.org/10.1016/j.rsma.2020.101525.

Herrmann, B., Cerbule, K., Brčić, J., Grimaldo, E., Geoffroy, M., Daase, M., Berge, J., 2022. Accounting for Uncertainties in Biodiversity Estimations: A New Methodology and Its Application to the Mesopelagic Sound Scattering Layer of the High Arctic. Front. Ecol. Evol. 10, 775759. https://doi.org/10.3389/fevo.2022.775759.

Johnson, M. L., Gaten, E., Shelton, M. J., 2002. Spectral sensitivities of five marine decapod crustaceans and a review of spectral sensitivity variation in relation to habitat. J. Mar. Biol. Ass. U.K. 82, 835–842. https://doi.org/10.1017/S0025315402006203.

Kuliñski, W., Styczyñska-Jurewicz, E., 2002. Light spectrum preference in the European eel Anguilla Anguilla (L.). Arch. Pol. Fish. 10, 167–175. https://doi.org/10.9774/GLEAF.978-1-909493-38-4_2.

Li, X., Xu, C., Sun, Z., Tang, Y., 2017. Fishing gear and method in the Yellow Sea and Bohai Sea. Ocean press, Beijing, China.

Liu, H., Jiang, Y., Luan, P., Wang, S., Chi, J., Liu, X., Zhao, J., 2012. Effects of color light on feeding and growth in Asian swimming crab *Charybdis japonica*. J. Dalian. Ocean. Univ. 27, 529–533.

Lomeli, M.J.M., Groth, S.D., Blume, M.T.O., Herrmann, B., Wakefield, W.W., 2018. Effects on the bycatch of eulachon and juvenile groundfish by altering the level of artificial illumination along an ocean shrimp trawl fishing line. ICES J. Mar. Sci. 75, 2224–2234. https://doi.org/10.1093/icesjms/fsy105.

MARA, 2018-2022. China Fishery Yearbook 2018-2022. China Agriculture Press, Beijing, China.

Marchesan, M., Spoto, M., Verginella, L., Ferrero, E.A., 2005. Behavioural effects of artificial light on fish species of commercial interest. Fish. Res. 73, 171–185. https://doi.org/10.1016/j.fishres.2004.12.009.

Naimullah, M., Lan, K.-W., Ikhwanuddin, M., Amin-Safwan, A., Lee, W.-Y., 2022. Unbaited Light-Emitting Diode Traps Performance for Catching Orange Mud Crabs. J. Mar. Sci. Technol. 30. https://doi.org/10.51400/2709-6998.2565.

Nguyen, K.Q., Humborstad, O.-B., Løkkeborg, S., Winger, P.D., Bayse, S.M., 2019. Effect of light-emitting diodes (LEDs) on snow crab catch rates in the Barents Sea pot fishery. ICES J. Mar. Sci. 76, 1893–1901. https://doi.org/10.1093/icesjms/fsz062.

Nguyen, K.Q., Winger, P.D., 2018. Location, orientation, and economic performance of low-powered LED lights inside snow crab traps in eastern Canada (Hirtshals, Denmark: International Council for the Exploration of the Sea-Food and Agriculture Organization of the United Nations Working Group on Fishing Technology and Fish Behaviour (WGFTFB).

Nguyen, K.Q., Winger, P.D., 2019a. Artificial Light in Commercial Industrialized Fishing Applications: A Review. Rev. Fish. Sci. Aquac. 27, 106–126. https://doi.org/10.1080/23308249.2018.1496065.

Nguyen, K.Q., Winger, P.D., 2019b. A trap with light-emitting diode (LED) lights: Evaluating the effect of location and orientation of lights on the catch rate of snow crab (*Chionoecetes opilio*). Aquac. Fish. 4, 255–260. https://doi.org/10.1016/j.aaf.2019.03.005.

Nguyen, K.Q., Winger, P.D., Morris, C., Grant, S.M., 2017. Artificial lights improve the catchability of snow crab (*Chionoecetes opilio*) traps. Aquac. Fish. 2, 124–133. https://doi.org/10.1016/j.aaf.2017.05.001.

Ortiz, N., Mangel, J., Wang, J., Alfaro-Shigueto, J., Pingo, S., Jimenez, A., Suarez, T., Swimmer, Y., Carvalho, F., Godley, B., 2016. Reducing green turtle bycatch in small-scale fisheries using illuminated gillnets: the cost of saving a sea turtle. Mar. Ecol. Prog. Ser. 545, 251–259. https://doi.org/10.3354/meps11610.

Petetta, A., Herrmann, B., Li Veli, D., Virgili, M., De Marco, R., Lucchetti, A., 2023. Every animal matters! Evaluating the selectivity of a Mediterranean bottom trawl fishery from a species community perspective. PLOS ONE 18, e0283362. https://doi.org/10.1371/journal.pone.0283362.

Senko, J.F., Peckham, S.H., Aguilar-Ramirez, D., Wang, J.H., 2022. Net illumination reduces fisheries bycatch, maintains catch value, and increases operational efficiency. Curr. Biol. 32, 911-918.e2. https://doi.org/10.1016/j.cub.2021.12.050.

Shandong Provincial Oceanic and Fishery Department, 2014. Shandong Province marine fishing gear special rectification action Implementation Plan. Available at: http://hyj.shandong.gov.cn/.

Shen, G., Heino, M., 2014. An overview of marine fisheries management in China. Mar. Policy 44, 265–272. https://doi.org/10.1016/j.marpol.2013.09.012.

Smith, P.J., Webber, W.R., McVeagh, S.M., Inglis, G.J., Gust, N., 2003. DNA and morphological identification of an invasive swimming crab, *Charybdis japonica*, in New Zealand waters. N. Z. J. Mar. Freshw. Res. 37, 753–762. https://doi.org/10.1080/00288330.2003.9517205.

Susanto, A., Suuronen, P., Gorgin, S., Irnawati, R., Riyanto, M., Wahyudin, Nurdin, H.S., Hamzah, A., Supadminingsih, F.N., Syafrie, H., 2022. Behavioral response and retinal adaptation of Blue swimming crab (*Portunus pelagicus*) exposed to LED lights – Led light as a potential artificial attractant in trap fishing. Fish. Res. 250, 106274. https://doi.org/10.1016/j.fishres.2022.106274.

Suuronen, P., Chopin, F., Glass, C., Løkkeborg, S., Matsushita, Y., Queirolo, D., Rihan, D., 2012. Low impact and fuel efficient fishing—Looking beyond the horizon. Fish. Res. 119–120, 135–146. https://doi.org/10.1016/j.fishres.2011.12.009.

Vazquez Archdale M., Añasco, C.P., Hiromori, S., 2006. Comparative fishing trials for invasive swimming crabs *Charybdis japonica* and *Portunus pelagicus* using collapsible pots. Fish. Res. 82, 50–55. https://doi.org/10.1016/j.fishres.2006.08.009.

Wang, J., Fisler, S., Swimmer, Y., 2010. Developing visual deterrents to reduce sea turtle bycatch in gill net fisheries. Mar. Ecol. Prog. Ser. 408, 241–250. https://doi.org/10.3354/meps08577.

Wang, J., Barkan, J., Fisler, S., Godinez-Reyes, C., Swimmer, Y., 2013. Developing ultraviolet illumination of gillnets as a method to reduce sea turtle bycatch. Biol. Lett. 9, 20130383. https://doi.org/10.1098/rsbl.2013.0383.

Wang, C., Chen, J., Ye, X., Wang, W., 2005. Analysis of Nutrients Composition of *Charybdis japonica*. Acta. Nutri. Sini, 27, 81–83.

Warwick, R.M., Clarke, K.R., Somerfield, P.J., 2008. k-Dominance Curve. In: Jørgensen, S.E., Fath, B.D. (Eds.), Encyclopedia of Ecology. Academic Press, Oxford, pp. 2055–2057.

Wileman, D., Ferro, R.S.T., Fonteyne, R., Millar, R.B., 1996. Manual of methods of measuring the selectivity of towed fishing gear. ICES Coop. Res. Rep. 215.

Yamashita, Y., Matsushita, Y., Azuno, T., 2012. Catch performance of coastal squid jigging boats using LED panels in combination with metal halide lamps. Fish. Res.

113, 182–189. https://doi.org/10.1016/j.fishres.2011.10.011.

Yu, M., Zhang, L., Liu, C., Tang, Y., 2021. Improving size selectivity of round pot for *Charybdis japonica* by configuring escape vents in the Yellow Sea, China. PeerJ 9, e12282. https://doi.org/10.7717/peerj.12282.

Yu, M., Liu, C., Zhang, L., Tang, Y., 2022a. Application of light-emitting diodes (LEDs) fishing lights to improve catch rates of small-scale trammel net fishery in the Yellow Sea, China. Front. Mar. Sci. 9, 1036979. https://doi.org/10.3389/fmars.2022.1036979.

Yu, M., Liu, C., Tang, Y., Zhang, L., Zhao, W., 2022b. Effects of escape vents on the size selection of whelk (*Rapana venosa*) and Asian paddle crab (*Charybdis japonica*) in the small-scale pot fishery of the Yellow Sea, China. Hydrobiologia 849, 3101–3115. https://doi.org/10.1007/s10750-022-04899-5.

Yu, M., Liu, C., Sun, L., Zhang, L., Tang, Y., 2023. A new concept for bycatch reduction in small-scale accordion-shaped trap fisheries of the Yellow Sea, China. Fish. Res. 263, 106685. https://doi.org/10.1016/j.fishres.2023.106685.

Zhang, P., Li, C., Li, W., Zhang, X., 2016. Effect of an escape vent in accordion-shaped traps on the catch and size of Asian paddle crabs *Charybdis japonica* in an artificial reef area. Chin. J. Oceanol. Limnol. 34, 1238–1246. https://doi.org/10.1007/s00343-016-5114-1.

Tables

Table 1 Summary details of the catch data of *C. japonica* in the sea trials using conventional gillnets without LED light (CG) and treatment gillnets with blue (BG), green (GG), red (RG) and white (WG) LED lights.

Trip ID	**Date**	**Soak time (h)**	**Depth (m)**	**Catch number**				
				CG	**BG**	**GG**	**RG**	**WG**
1	12/04/2021	12.3	11.7	34	35	52	25	36
2	13/04/2021	11.5	12.5	14	23	42	20	32
3	14/04/2021	12.5	10.5	26	23	44	17	35
4	15/04/2021	13.0	13.5	39	25	40	16	27
5	16/04/2021	11.5	12.2	29	32	55	21	27
6	17/04/2021	12.2	13.6	34	32	51	21	30
7	18/04/2021	12.3	12.9	38	35	35	23	30
8	19/04/2021	11.0	11.7	29	33	36	26	35
9	20/04/2021	13.0	14.3	33	39	42	24	22
10	21/04/2021	11.3	14.9	30	27	36	24	32
11	22/04/2021	13.6	14.4	39	40	58	25	37
12	23/04/2021	12.0	13.0	33	28	50	37	39
13	24/04/2021	12.2	9.7	35	54	68	44	59
Total				413	426	609	323	441

Table 2 List of bycatch species and number of individuals captured for the gillnets with different configurations during the experiments. Species names marked with * denote species of wanted catch.

		Number of individuals				
Species name	**Common name**	**CG**	**BG**	**GG**	**RG**	**WG**
Sebastes schlegelii (Hilgendorf, 1880) *	Black rockfish	28	66	81	28	74
Hexagrammos otakii (Jordan & Starks, 1895) *	Fat greenling	34	55	47	73	49
Mesocentrotus nudus (A. Agassiz, 1864) *	Sea urchin	2	1	2	6	1
Sebastes hubbsi (Matsubara, 1937)	Armored rockfish	51	57	83	25	59
Hexagrammos agrammus (Temminck & Schlegel, 1843)	Spotty belly greenling	37	60	72	81	43
Pseudopleuronectes yokohamae (Günther, 1877)	Marbled flounder	2	4	2	1	2
Patiria pectinifera (Muller & Troschel, 1842)	Starfish	4	1	6	5	3
Platichthys bicoloratus (Basilewsky, 1855)	Stone flounder	4	6	2	4	5
Hemicentrotus pulcherrimus (A. Agassiz, 1864)	Sea urchin	5	5	0	6	3

Table 3 Catch ratio (*CR*) results (in %) and fit statistics of four illuminated gillnet treatments for *C. japonica* using the conventional gillnet as baseline. Values in parentheses represent 95% confidence intervals. DOF denotes degrees of freedom.

		BG vs. CG	GG vs. CG	RG vs. CG	WG vs. CG
cl (mm)	35	96.41 (54.93-125.20)	123.34 (62.96-184.55)	68.74 (34.61-95.19)	95.83 (47.30-140.00)
	40	97.87 (64.30-123.80)	128.69 (85.49-175.94)	70.62 (46.01-95.17)	98.10 (58.11-139.16)
	45	99.58 (73.62-122.40)	134.48 (105.47-171.07)	72.81 (53.69-95.87)	100.72 (68.20-137.73)
	50	101.57 (80.73-122.28)	140.69 (116.43-172.23)	75.34 (58.22-97.80)	103.72 (77.84-134.59)
	55	103.88 (86.50-123.76)	147.31 (123.24-181.76)	78.21 (62.88-101.18)	107.15 (87.31-132.23)
	60	106.53 (89.91-129.24)	154.31 (126.64-192.66)	81.45 (65.63-105.14)	110.05 (92.44-136.99)
	65	109.59 (91.72-136.24)	161.67 (128.89-208.28)	85.09 (66.27-114.83)	115.46 (92.61-154.99)
	70	113.09 (90.15-152.30)	169.32 (120.74-236.28)	89.17 (61.26-132.20)	120.47 (86.71-184.97)
	75	117.09 (85.60-182.66)	177.16 (106.47-272.29)	93.70 (53.83-168.22)	126.14 (77.27-232.14)
	$CR_{average-}$	95.50 (69.01-140.24)	120.72 (83.33-181.61)	64.86 (40.65-97.67)	87.39 (51.56-150.68)
	$CR_{average+}$	105.96 (87.83-126.48)	157.28 (127.07-187.50)	83.11 (65.99-101.77)	113.91 (93.31-137.31)
	$nDRatio_{treatmenmt}$	24.88 (20.28-30.59)	22.00 (18.17-25.65)	22.29 (15.88-29.78)	21.99 (17.00-26.52)
	$nDRatio_{baseline}$	26.88 (20.62-32.79)			
	p-value	0.6175	0.2142	0.6059	0.4911
	Deviance	2.65	5.81	2.72	3.41
	DOF	4	4	4	4

Table 4 Species dominance values (in %) for the gillnets with different configurations (95% confidence intervals in brackets). Values in parentheses represent 95% confidence intervals.

Species	**CG**	**BG**	**GG**	**RG**	**WG**
Legal-sized *Charybdis japonica*	52.07 (46.60-57.87)	46.99 (41.35-51.56)	52.49 (47.96-57.00)	45.47 (39.51-51.13)	50.44 (45.55-54.78)
Undersized *Charybdis japonica*	19.14 (14.38-23.97)	15.56 (12.24-19.30)	14.92 (11.86-18.58)	13.04 (8.96-18.10)	14.52 (10.63-18.64)
Sebastes schlegelii	4.83 (2.60-7.54)	9.69 (6.58-13.45)	8.95 (6.16-11.95)	5.07 (2.40-7.92)	10.85 (7.72-14.12)
Hexagrammos otakii	5.86 (3.18-8.89)	8.08 (5.34-10.93)	5.19 (3.00-7.42)	13.22 (8.41-18.41)	7.18 (4.51-9.91)
Mesocentrotus nudus	0.34 (0.00-1.10)	0.15 (0.00-0.66)	0.22 (0.00-0.71)	1.09 (0.16-2.48)	0.15 (0.00-0.62)
Sebastes hubbsi	8.79 (5.25-13.41)	8.37 (5.21-11.36)	9.17 (6.50-12.38)	4.53 (1.79-7.38)	8.65 (5.69-11.96)
Hexagrammos agrammus	6.38 (3.80-9.41)	8.81 (5.86-12.41)	7.96 (5.50-10.90)	14.67 (10.47-19.54)	6.30 (3.70-9.76)
Pseudopleuronectes yokohamae	0.34 (0.00-1.23)	0.59 (0.00-1.66)	0.22 (0.00-0.75)	0.18 (0.00-0.86)	0.29 (0.00-0.93)
Patiria pectinifera	0.69 (0.00-1.81)	0.15 (0.00-0.68)	0.66 (0.00-1.54)	0.91 (0.00-2.13)	0.44 (0.00-1.36)
Platichthys bicoloratus	0.69 (0.00-1.88)	0.88 (0.00-2.33)	0.22 (0.00-0.74)	0.72 (0.00-1.81)	0.73 (0.00-1.86)
Hemicentrotus pulcherrimus	0.86 (0.00-2.12)	0.73 (0.00-1.82)	0.00 (0.00-0.00)	1.09 (0.00-2.42)	0.44 (0.00-1.48)

Figures

Figure 1 Map of study area in the Yellow Sea of China where the gillnets were deployed.

Figure 2 Experimental setup showing **a:** the deployment of gillnet fleets without LED lights attached (baseline) and treatment gillnets with blue, green, red and white LEDs (ten LED lights attached on each treatment gillnet sheet). **b**: the dimensions of one of the five gillnet fleets. **c**: an example of the LED lights used in these experiments (manufactured by Zhejiang Underwater Fishing Light Factory). E= hanging ratio.

Figure 3 Catch comparison rates and catch ratios of the illuminated gillnets for Asian paddle crab (*Charybdis japonica*). Left column: the modelled catch comparison rates (black line) with 95% confidence intervals (black stippled curves). The gray solid and dashed lines represent summed population for the illuminated and conventional gillnets, respectively. Circles represent the experimental rates. Right column: the estimated catch ratios (black line) with 95% confidence intervals (black stippled curves). Vertical solid lines represent the minimum landing size (MLS) of Asian paddle crab. Horizontal stippled lines represent the baseline at which the two gillnet configurations have equal catch efficiency. CG, conventional gillnet; BG, blue-lighted gillnet; GG, green-lighted gillnet; RG, red-lighted gillnet; WG, white-lighted gillnet.

Figure 4 Length frequency distributions between the illuminated and conventional gillnets. Left column: length frequency distribution curves (solid lines) with 95% confidence intervals (dotted lines) representing the estimated length frequency for the illuminated (black) and conventional gillnets (gray). Right column: length frequency distribution curves (solid lines) with 95% confidence intervals (dotted lines) represent the differences in length frequency between illuminated and conventional gillnets. Vertical solid lines represent the minimum landing size of Asian paddle crab (*Charybdis japonica*). Horizontal dashed lines are baseline for no difference in length frequency distribution between the two gillnet configurations.

Figure 5 Cumulative length frequency distributions between the illuminated and conventional gillnets. Left column: cumulative length frequency distribution curves (solid lines) with 95% confidence intervals (dotted lines) for the illuminated (black) and conventional gillnets (gray). Right column: cumulative length frequency distribution curves (solid lines) with 95% confidence intervals (dotted lines) representing the differences between illuminated and conventional gillnets. Vertical solid lines represent the minimum landing size of Asian paddle crab (*Charybdis japonica*). Horizontal dashed lines indicate no difference in cumulative length frequency between the two gillnet configurations.

Figure 6 Cumulative species dominance curves for gillnets with different configurations. Left column: cumulative dominance curves (solid lines) with 95% confidence intervals (dotted lines) for the species caught by the illuminated gillnets (black) and the conventional gillnet (gray). Right column: pairwise difference (delta) for cumulative dominance curves (solid lines) with 95% confidence intervals (dotted lines) representing the differences in the cumulative species dominance between illuminated and conventional gillnets. Horizontal dashed lines are baseline for no significant difference in cumulative species dominance between the two gillnet configurations. The x-axis shows the species ID: 1 Legal-sized *C. japonica*, 2 Undersized *C. japonica*, 3 *S. schlegelii*, 4 *H. otakii*, 5 *M. nudus*, 6 *S. hubbsi*, 7 *H. agrammus*, 8 *P. yokohamae*, 9 *P. pectinifera*, 10 *P. bicoloratus*, 11 *H. pulcherrimus*.

Figure 1

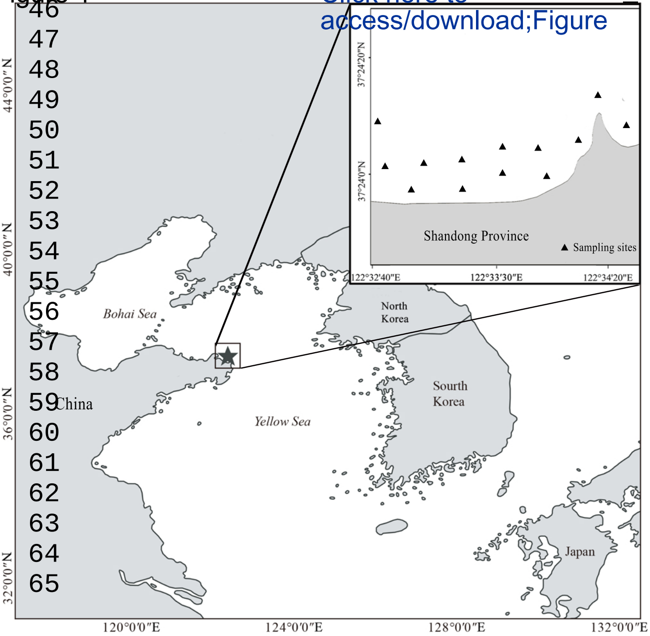

37°24'20"N
37°24'0"N
Shandong Province
▲ Sampling sites
122°32'40"E
122°33'30"E
122°34'20"E
44°0'0"N
40°0'0"N
36°0'0"N
32°0'0"N
Bohai Sea
North Korea
Sourth Korea
China
Yellow Sea
Japan
120°0'0"E
124°0'0"E
128°0'0"E
132°0'0"E

Figure 2

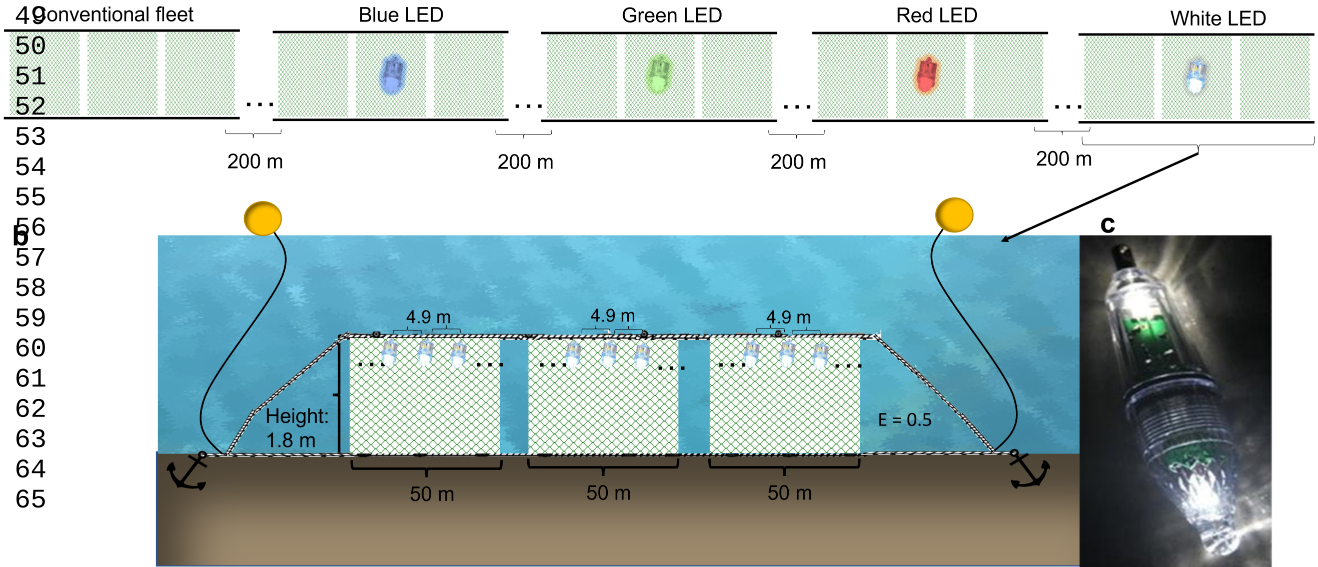

Conventional fleet
Blue LED
Green LED
Red LED
White LED
200 m
200 m
200 m
200 m
b
4.9 m
4.9 m
4.9 m
Height:
1.8 m
E = 0.5
50 m
50 m
50 m
c

Figure 3

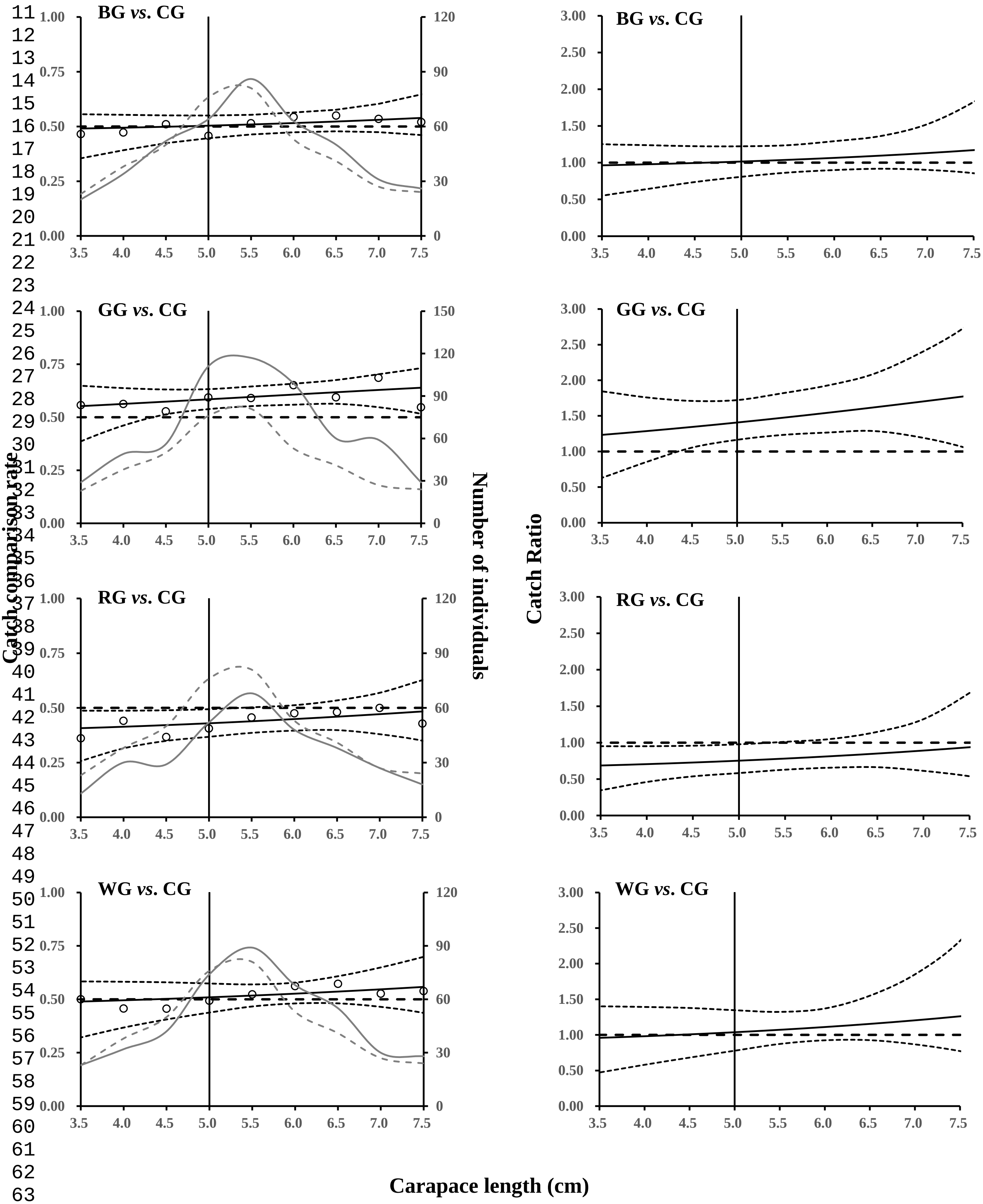

BG vs. CG
GG vs. CG
RG vs. CG
WG vs. CG
BG vs. CG
GG vs. CG
RG vs. CG
WG vs. CG
Catch comparison rate
Number of individuals
Catch Ratio
Carapace length (cm)
0.00
0.25
0.50
0.75
1.00
0
30
60
90
120
150
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5

Figure 4

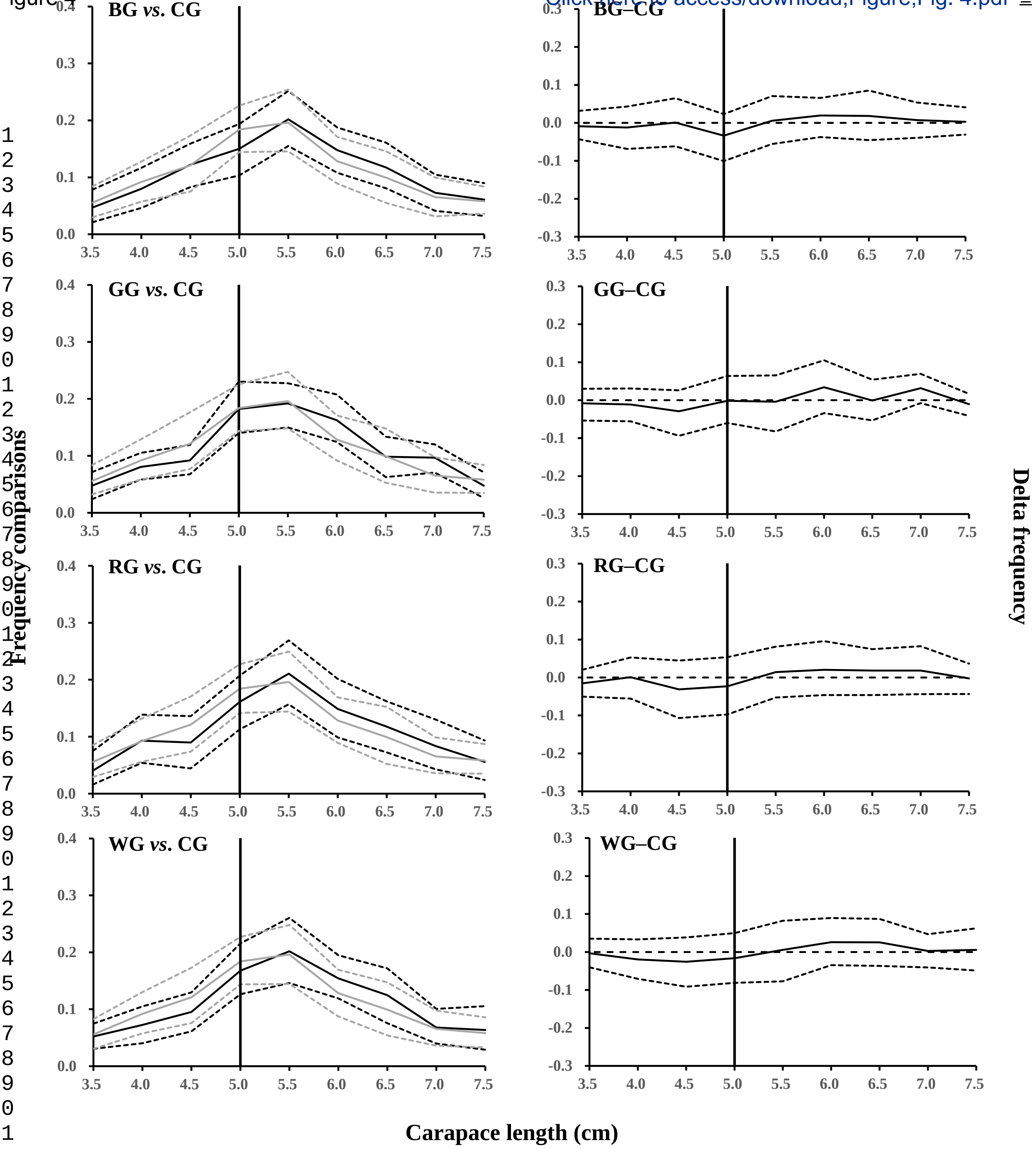

BG *vs.* CG
BG–CG
GG *vs.* CG
GG–CG
RG *vs.* CG
RG–CG
WG *vs.* CG
WG–CG
Frequency comparisons
Delta frequency
Carapace length (cm)
0.0
0.1
0.2
0.3
0.4
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5

Figure 5

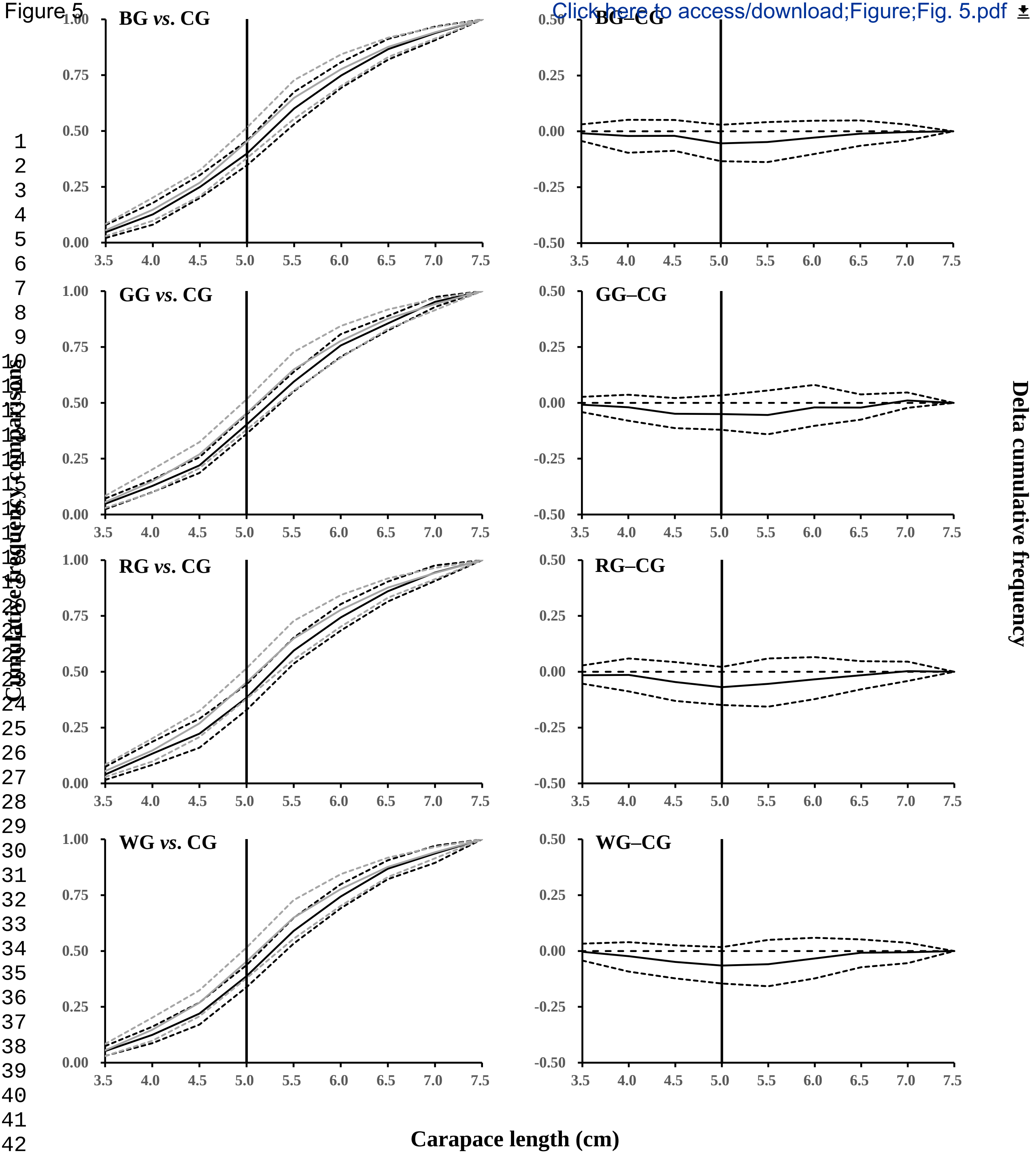
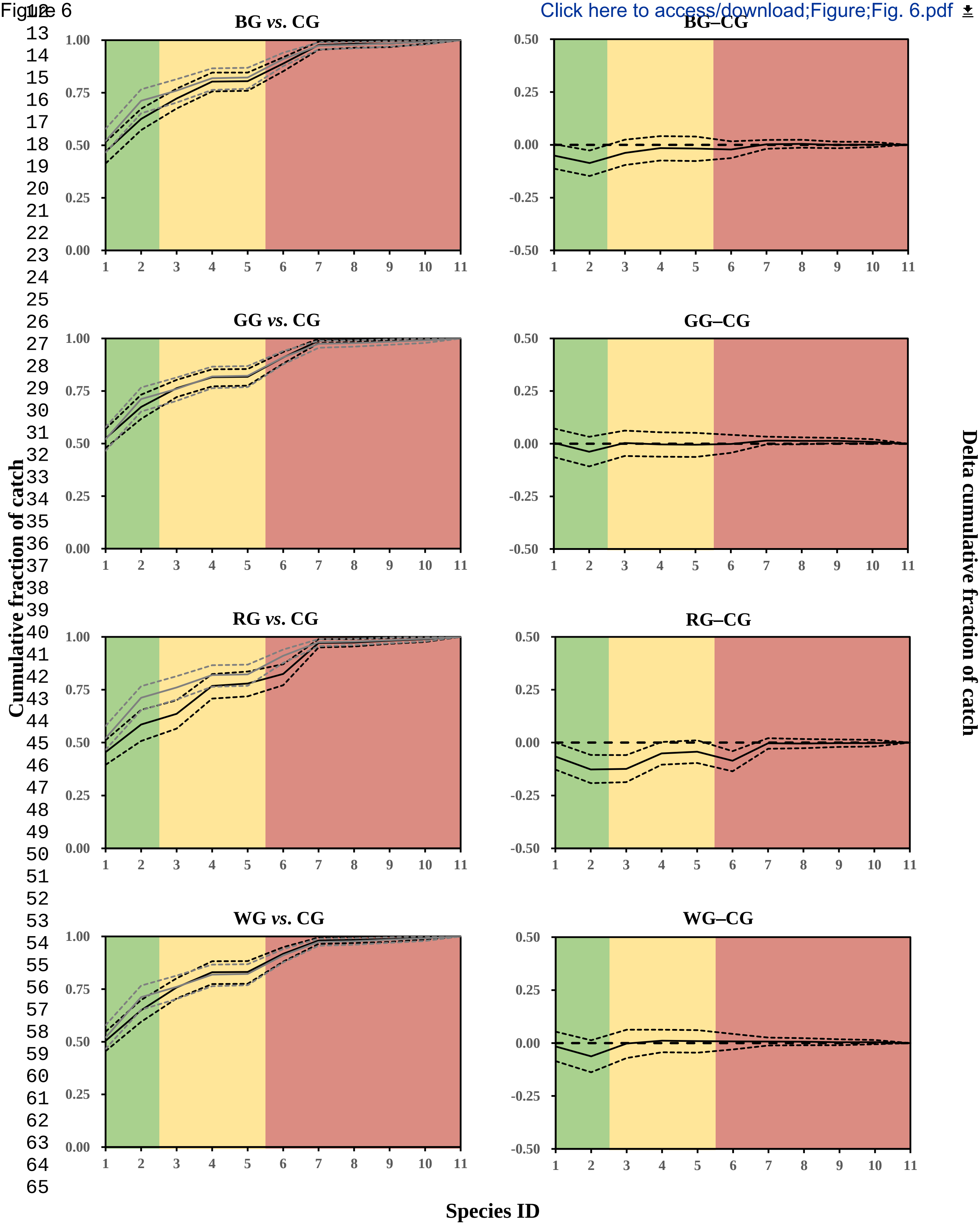

BG *vs.* CG
BG–CG
GG *vs.* CG
GG–CG
RG *vs.* CG
RG–CG
WG *vs.* CG
WG–CG
0.00
0.25
0.50
0.75
1.00
-0.50
-0.25
0.00
0.25
0.50
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
Cumulative frequency comparisons
Delta cumulative frequency
Carapace length (cm)

Figure 6


BG *vs.* CG
BG–CG
GG *vs.* CG
GG–CG
RG *vs.* CG
RG–CG
WG *vs.* CG
WG–CG
1.00
0.75
0.50
0.25
0.00
0.50
0.25
0.00
-0.25
-0.50
1
2
3
4
5
6
7
8
9
10
11
Cumulative fraction of catch
Delta cumulative fraction of catch
Species ID

Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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.

Fig. S1