Comparison of physical properties and fishing performance between biodegradable PLA and conventional PA trammel nets in grey mullet (*Mugil cephalus*) and red-lip mullet (*Liza haematocheila*) fishery

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Abstract:

Marine plastic pollution and continuous capture of marine animals, so-called “ghost fishing”, by abandoned, lost, or otherwise discarded fishing gear (ALDFG) are global concerns. This study investigated whether biodegradable polylactic acid (PLA) monofilaments can be used to replace conventionally used non-biodegradable polyamide (PA) in trammel net fishery for limiting ALDFG associated effects. It evaluated the physical properties of PLA and PA monofilaments and compared fishing performance of PLA and PA trammel nets in a commercial mullet fishery in the Yellow Sea, China. Although PA monofilament exhibited superior physical properties, no significant differences in catch efficiency between PA and PLA trammel nets were observed. Fish of both species were mainly captured by pocketing which can further explain observed similar catch efficiency. These initial results suggest a potential for applying biodegradable materials in trammel net fisheries. Therefore, further long-term testing is encouraged to investigate whether this promising performance is persistent over long-term.

Keywords: Marine plastic pollution, Ghost fishing, ALDFG, Biodegradable materials, Trammel nets, Catch efficiency.

1. Introduction

Plastic is among the most common types of litter in the marine environment (Novikov et al., 2021), and fisheries represent one of the marine plastic pollution sources due to abandoned, lost, or otherwise discarded fishing gear (ALDFG). Fishing gear often is made of non-biodegradable plastic materials with high breaking strength and durability providing high catch efficiency. However, the same material properties also enable the gear to continue capturing marine animals for years in case of being lost at sea, a process called "ghost fishing" (Matsuoka et al., 2005). Ghost fishing caused by ALDFG can affect both target and non-target species, including those classified as endangered, threatened, and protected (Gilman et al., 2016). Ghost fishing mortalities resulting from ALDFG are recognized as a significant source of wastage and negatively affect the sustainability and economic effectiveness in the marine capture sector (Gilardi et al., 2010; Antonelis et al., 2011). Furthermore, even after ALDFG lose their ghost fishing capabilities over long time at sea, they do not disappear from the aquatic environment. Instead, the plastic material breaks down into smaller particles known as macro- and microplastics (Moore, 2008). These particles accumulate within marine food webs and can cause negative impacts on marine ecosystems and food security (Wang et al., 2019).

Passive fishing gear, such as gillnets, trammel nets, and pots or traps, exhibits the highest potential for ghost fishing, primarily because their capture process relies on fish swimming into the gear (Gilman et al., 2016). Therefore, this process can continue also after all control over the gear is lost (Hubert et al., 2012) as is the case in ALDFG. In recent decades, ALDFG originating from entanglement fishing gear such as gillnets and trammel nets has gained significant international attention, owing to the worldwide usage of this fishing gear type (He et al., 2021). The most common material type used in gillnets and trammel nets is monofilament polyamide (nylon; PA). This material is preferred due to the combination of the properties of this material that provide both optimal tensile strength and elasticity. These material properties are important for providing a high catch efficiency of the gear but can cause the above-described challenges if the gear is lost at sea (He, 2006). Furthermore, ALDFG in case of entanglement gear can have high ghost fishing efficiency at capturing different species, in some instances consisting of several cycles of ghost fishing before the netting material breaks down and loses its fishing abilities (Pawson, 2003). However, the extent of this problem can differ between different fisheries and fishing grounds.

China stands as the greatest contributor to global marine capture fisheries, with gillnet and trammel nets becoming a commonly used fishing gear in Chinese coastal fisheries. According to statistics from 2021, approximately 90,000 marine fishing vessels were engaged in gillnet and trammel net fisheries, constituting about 55% of the total number of fishing vessels and accounting for 23.2% of the total marine landings, equivalent to approximately 2.2 million tons (MARA, 2022). Among the various fisheries, the trammel net fishery targeting grey mullet (*Mugil cephalus*) and red-lip mullet (*Liza haematocheila*) stands as one of the most representative examples. Over the past decade, the annual total marine landings combined of grey mullet and red-lip mullet have fluctuated between 18.3×10^4 t and 28.6×10^4 t, providing a crucial source of income, sustenance, and nutrition for coastal communities encompassing millions of people (MARA, 2022). In the context of this fishery, the occurrence of gear loss or component detachment is a common phenomenon resulting from various factors, including collisions with numerous passing vessels and active fishing gear (i.e., trawls), adverse sea weather conditions, strong currents, and improper fishing practices (Chen, 2020). While no official reports or scientific studies have systematically quantified the fishing gear losses within Chinese fisheries, it is reported that the incidental loss rates of gillnets and trammel nets are notably high on a global scale (Richardson et al., 2019). According to local fishers, trammel net loss rates (percentage of lost nets per vessel per year) in this mullet fishery range between 3% and 8% (personal communication of first author). Considering the scale of Chinese trammel net fisheries, the number of fishing vessels, and the number of trammel net sheets used per vessel, ranging from 10-40, it can be inferred that the amount of ALDFG generated in this fishery is substantial (MARA, 2022).

Due to the growing concerns for marine environmental and ecological conservation, Chinese Ministry of Agriculture and sea-related trade associations, research institutes, universities, and enterprises nationwide have taken a joint initiative in 2023 to explore effective strategies to manage and control ALDFG (Chinese Ministry of Agriculture, 2023). Considerable efforts are also being made globally to alleviate environmental issues by ALDFG such as preventive methods by avoiding and minimizing the incidences of gear loss, and approaches for reducing the longevity of ALDFG (Gilman et al., 2016). Development and use of environmentally friendly biodegradable plastic materials in fishing gear has emerged as a promising strategy to reduce the marine plastic pollution and limit ghost fishing. Recent studies have investigated the applicability of different new biodegradable plastic materials, including polylactic acid (PLA) resin, polybutylene succinate (PBS) resin blended with polybutylene adipate-co-terephthalate (PBAT) resin, and polybutylene succinate co-adipate-co-terephthalate (PBSAT) resin, as potential replacements for conventional nylon material in several gillnet fisheries in South Korea, China, and Norway. A consistent finding among these studies was that nylon nets exhibited higher catch efficiency than biodegradable nets, with the difference being significant in most cases (Bae et al., 2012, 2013; Grimaldo et al., 2018ab, 2019, 2020ab; Shu et al., 2021; Cerbule et al., 2022) and slightly higher in a few instances (Park et al., 2007a; An et al., 2013; Kim et al., 2016, 2020). The results showing reduced catch efficiency of fishing gear made of biodegradable plastic materials have raised concerns regarding potential acceptance of biodegradable materials by the commercial fishing industry due to reduced profitability.

The observed reduction in catch efficiency of nets made of these tested biodegradable plastic materials can be attributed to their inferior physical properties compared to convention nylon nets. The physical properties of netting, such as tensile strength, elasticity, and flexibility/stiffness, are determined by the twine material and monofilament thickness. Previous studies conducted physical property tests and reported that nylon monofilament exhibited 3–77% higher tensile strength and 3–72% higher elongation at break than biodegradable plastic (PLA, PBS, PBS and PBAT blend, and PBSAT) monofilament of the same thickness (Park et al., 2007b; An et al., 2013; Kim et al., 2016, 2020; Grimaldo et al., 2018ab, 2019; Shu et al., 2021). Additionally, several studies demonstrated that nylon nets also possessed significantly greater flexibility compared to biodegradable plastic nets (Kim et al., 2016, 2020). In a comprehensive assessment of the effects of physical properties on the relative catch efficiency between biodegradable PBSAT and nylon gillnets, Grimaldo et al. (2020a) found that tensile strength could not account for the decreased catch efficiency of cod (*Gadus morhua*) and saithe (*Pollachius virens*) in biodegradable nets. Instead, other material properties such as elasticity and stiffness of the materials might be the main parameters affecting the catch efficiency of the gear. Therefore, when testing new biodegradable materials for applications in fishing gear, it is crucial to gain a clear understanding of which specific physical properties are more relevant to the catch efficiency in the specific fisheries.

Cerbule et al. (2022) proposed that understanding the species-specific capture mechanisms in gillnets can offer valuable insights into how use of different materials can influence catch efficiency, thus providing essential guidance for enhancing the physical properties of biodegradable gillnets. Trammel nets and gillnets employ distinct capture mechanisms due to the differences in their net structures (He, 2006). Trammel nets and gillnets both can capture fish through snagging, gilling, wedging, and entangling. However, trammel nets have a unique capture mechanism, pocketing, which can be defined as that fish swimming into the net collides with the small-meshed inner panel and push it through the large-meshed outer panel, creating a pocket where the fish becomes retained (He, 2006). A new method has been developed and implemented to estimate the length-dependent capture mode probability of target species in gillnet fisheries (Cerbule et al., 2022; Savina et al., 2022; Brinkhof et al., 2023). However, the capture modes in trammel net fisheries have not yet been scientifically quantified. Applying such an approach in trammel net fisheries could yield quantitative information on how gear characteristics, such as twine materials and monofilament thickness can affect the capture patterns of specific species and gear efficiency.

In this study, we evaluated and compared the physical properties of PLA and PA monofilaments. Subsequently, we investigated the applicability of biodegradable PLA monofilaments in trammel net fishery targeting grey mullet and red-lip mullet in the

Yellow Sea, China. Specifically, we investigated whether there were significant differences in initial catch efficiency and capture modes between nets made of the biodegradable PLA and conventionally used nylon material of different monofilament diameter and determined if any potential relationship existed between relative catch efficiency, capture modes, and the physical properties of biodegradable PLA and conventional PA trammel nets.

2. Materials and methods

2.1 Monofilament materials

Biodegradable PLA and conventional PA monofilaments with three different diameters (i.e., 0.20 mm, 0.25 mm, and 0.45 mm) used in this study were manufactured through the melt spinning process at the New Fishing Materials laboratory of East China Sea Fisheries Research Institute, Chinese Academy of Fishery Sciences.

2.2 Physical property testing

Tensile strength, elongation at break, and flexibility of biodegradable PLA and conventional PA monofilaments were tested in dry and wet conditions. The dry condition represents that the monofilaments were dried at 60 ℃ in a vacuum oven for 12 hours. The wet condition represents the samples immersed in distilled water for 24 hours.

The tensile strength and elongation at break were measured for 20 replicates for each case using a universal testing machine (Instron 4466; USA) (Shu et al., 2021). For the tensile strength tests, the clamping distance was 750 mm and tensile speed was 400 mm/min.

Flexibility representing the ability of materials to resist deformation of the monofilaments was tested following the Brandt method (Andres and Garrother, 1964; Kim et al., 2016). The test samples were prepared by evenly wrapping the monofilaments around a cylinder (diameter of 4 cm) 20 times to form a coil, followed by using adhesive to fix coil shape, and then removing coil from the cylinder (Kim et al., 2016). Flexibility was measured by the force required to compress the samples to a diameter of 2.5 cm using the testing device (Instron 68SC-2, USA), at the compression speed of 50mm/min. The flexibility was measured for 10 replicates for each case. The larger the force required, the lower the flexibility of the monofilaments. These tests were conducted under a constant laboratory environment (temperature: 25 ℃; relative humidity: 65%).

Unpaired t-test were used to examine whether there were significant differences in physical properties between PLA and PA monofilaments in dry and wet conditions.

2.3 Sea trials and experimental design

Sea trials were conducted onboard a coastal fishing vessel "Lurongyuyang 65873" (12.0 m LOA, 100 hp) under commercial conditions in May-June 2023. The fishing ground was located at the coast of the Yellow Sea, China, between 37°24′–37°26′ N and 122°33′–122°37′ E, which is a traditional fishing area for commercial trammel net fisheries targeting grey mullet and red-lip mullet. The fishing depths varied between 5 and 45 m.

The commercially used trammel nets in this fishery usually consist of an inner panel with 0.20 mm or 0.25 mm and outer panels with 0.45 mm monofilament diameters. Therefore, in this study, experimental fishing nets were produced using PLA and PA monofilaments with the same design parameters. In constructing the PLA trammel nets, both the inner and outer panels were made entirely of PLA monofilaments.

The fishing performance of 10 PLA and 10 PA trammel nets were tested during the sea trials. The dimensions of each trammel net sheet were 50 m in length and 1.2 m in height. The inner and outer panels were made of double knotted monofilament with hanging ratios of 0.50 and 0.60, respectively. According to the commercial fishing practice, the trammel nets were set (anchored) to capture fish at surface (Fig. 1). The mesh sizes of the inner panel and outer panels were 85 mm and 300 mm (fully stretched mesh size), respectively. The float line was 23 mm in diameter and equipped with polyvinyl chloride floats, with a buoyancy of 380 g/m. The sinker line was 35 mm in diameter and equipped with lead sinkers weighted 250 g/m. The experimental trammel nets were divided into two fleets (Fig. 1):

Fleet 1: 10 trammel net sheets with 0.20 mm monofilament diameter for inner panel and 0.45 mm for outer panel, consisting of 5 trammel nets made of biodegradable PLA monofilament (B) and 5 nets of conventional PA monofilament (N), arranged in following order: B-N-B-N-B-N-B-N-B-N.

Fleet 2: 10 trammel net sheets with 0.25 mm monofilament diameter for inner panel and 0.45 mm for outer panel, consisting of 5 trammel nets made of biodegradable PLA monofilament (B) and 5 nets of conventional PA monofilament (N), arranged in following order: B-N-B-N-B-N-B-N-B-N.

Within each fleet, the distance between individual trammel net sheet was 0.5 m. Two fleets were deployed approximately 200 m apart. Two buoys and anchors each weighing 20 kg were connected to each end of the fleet. Following the commercial fishing pattern, trammel nets were set at twilight and retrieved in the following day after approximately 12 h soak time. During the gear retrieval, capture mode of each individual grey mullet and red-lip mullet was observed for each trammel net type separately. We classified the following five different modes of capture: snagging, gilling, wedging, entangling, and pocketing (He, 2006). One or several capture modes were recorded for each individual. In cases of multiple capture modes observed for an individual fish, we applied the principle of likely sequence to define the primary capture mode (Savina et al., 2022; Cerbule et al., 2022). For example, a fish captured by snagging and gilling would be recorded as gilling. Additionally, considering the unique capture mode (i.e., pocketing) of trammel nets, if a fish caught by both snagging and pocketing, pocketing would be defined as the primary capture mode. Finally, the corresponding total length of each grey mullet and red-lip mullet was measured to the closest cm below.

2.4 Modelling the length-dependent catch efficiency between trammel net types

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 length-dependent (l) catch comparison rate ($CC(l)$) and catch ratio ($CR(l)$) summed over trammel net deployments during the entire experimental period.

However, contrary to Herrmann et al. (2017) and following Cerbule et al. (2022), the analysis was performed paired for the PLA and PA trammel nets, taking full advantage of the experimental design in which the trammel net configurations were fished simultaneously on the same fishing ground. Specifically, using the catch information (numbers and lengths of fish in each trammel net fleet deployment), we can determine whether there was a significant difference in the catch efficiency averaged over deployments between PLA and PA trammel nets with the same monofilament diameter. Same method was applied to assess relative length-dependent catch efficiency between PLA or PA trammel nets with different monofilament diameters. We also evaluated if any potential differences in catch efficiency between trammel net types could be related to the total length of fish of each species. Finally, the length-integrated average values for the catch ratio ($CR_{average}$) were estimated directly from the experimental catch data. Uncertainties were estimated by bootstrapping. Details about the estimation of $CC(l)$, $CR(l)$, and $CR_{average}$ can be found in the supplementary material S1.

2.5 Modelling the length-dependent capture mode probability

Conditioned capture, the length-dependent capture probability $CPq(l)$ by a specific capture mode q (snagging, gilling, wedging, entangling, or pocketing) was estimated using the method outlined in Savina et al. (2022). Specifically, we used the catch numbers of fish by each of the capture modes and the corresponding total length in each of the trammel net types separately. The analysis was conducted separately for each species, type of net, and independently for each capture mode. Finally, the length-integrated average values for the capture mode probability ($CPq_{average}$) were estimated directly from the experimental catch data. Uncertainties were estimated by bootstrapping. Details about the estimation of $CPq(l)$, and $CPq_{average}$ can be found in the supplementary material S2.

2.6 Software

All the data analysis procedures described in sections 2.4-2.5 were conducted using the software SELNET (Herrmann et al., 2012, 2016). Unpaired t-test (section 2.2) was conducted in statistical software R (version 4.1.2) (R Core Team, 2021). The graphics were produced using the package ggplot2 (Wickham, 2016) in software R.

3. Results

3.1 Physical properties of monofilaments

The tensile strength and elongation curves for monofilaments of PLA and PA materials are shown in Fig. 2 and the physical properties of each monofilament are presented in Table 1 and Table 2. Generally, irrespective of dry and wet conditions, the tensile strength of knotless PA monofilament was significantly higher than that of knotless PLA monofilament with the same diameter (t-test, p-value <0.05). There were no significant differences in elongation at break between knotless PA and PLA monofilaments of 0.20 mm or 0.25 mm under both dry and wet conditions (t-test, p-value >0.05). For 0.45 mm monofilament, the elongation of knotless PA monofilament was significantly (t-test, p-value $=7.9\times10^{-8}$) 35.9% and (t-test, p-value $=1.0\times10^{-5}$) 19.0% higher than that of knotless PLA monofilament in dry and wet conditions, respectively.

Similarly, the breaking strength of knotted PA monofilament was significantly higher than that of knotted PLA monofilament with the same diameter under both dry and wet conditions (t-test, p-value <0.05). Significant differences were observed for elongation at break between knotted PA and PLA monofilaments of the same diameter under dry and wet conditions (t-test, p-value <0.05), except for comparison between 0.20 mm PA and PLA monofilaments in dry condition (t-test, p-value $=0.56$).

The results of flexibility test for each monofilament are shown in Table 3. The flexibility of PA monofilaments was significantly higher than that of PLA monofilaments of the same diameter under both dry and wet conditions (t-test, p-value <0.05). The p-values of the unpaired t-test can be found in the supplementary material S3.

3.2 Catch efficiency of PLA *versus* PA trammel nets

A total of 34 valid fleet deployments was conducted during the fishing trials over one month. In total, 2076 grey mullet and 1579 red-lip mullet were caught and included in the catch comparison analysis, with 992 and 1084 grey mullet and 766 and 813 red-lip mullet captured in the PLA and PA trammel nets, respectively. For all catch comparisons between PLA and PA trammel nets, the estimated *p*-value was above 0.05, demonstrating that the model described the experimental data sufficiently well (Table 4).

The length-dependent catch comparison and catch ratio curves showed no significant differences in catch efficiency between PLA and PA trammel nets with the same monofilament diameter (0.20 mm or 0.25 mm) for both grey mullet and red-lip mullet as the 95% CIs included the baseline of equal catch efficiency for all length classes (Fig. 3; Fig. 4). The length-integrated average values ($CR_{average}$) also reflected a similar pattern. A slight reduction in the catches was estimated for biodegradable trammel nets; however, it was not statistically significant (Table 4).

3.3 Effect of monofilament thickness on catch efficiency

The catch comparison results for grey mullet and red-lip mullet between the PLA and between the PA trammel nets with different monofilament diameter were presented in Figs. 5-6 and Table 5. The fit statistics of the four pairwise catch comparisons showed that the modelled catch comparison curves fitted the experimental data well (p-value>0.05; see supplementary material S1 for explanation).

For either PLA or PA trammel nets, increasing monofilament thickness from 0.20 mm to 0.25 mm did not have significant effect on the catch efficiency for both fish species throughout the length classes (Figs. 5-6). The length-integrated average values also reflected non-significant differences in average catch ratio for all cases (Table 5).

3.4 Length-dependent capture mode probability by trammel net types

The capture modes of all captured grey mullet and red-lip mullet were recorded separately for the four types of trammel nets, resulting in a total of 2076 and 1579 capture mode records for grey mullet and red-lip mullet distributed over the five capture modes (Fig.7; Table 6). The fit statistics showed that the modelled capture mode probability curves described the experimental data well except for three cases in which the *p*-value was below 0.05 (Table 7, Table 8; see supplementary material S2 for explanation). However, in these cases, the capture mode probability curves represented the trends in experimental data well (Fig. 8). Therefore, the low *p*-value was assumed to be due to overdispersion in the data (Wileman et al., 1996).

For all types of trammel nets, the capture modes observed for both fish species showed a similar length-dependent capture pattern (Figs. 8-9). Wedging was the capture mode with highest capture probability for individuals at smaller length classes. The wedging capture probability gradually decreased with the increase of fish length, and then gilling became the most dominant capture mode. The gilling capture probability curves was presented as bell-shaped and reached its maximum probability for grey mullet with approximately 40 cm long and red-lip mullet with approximately 42 cm long. Then, pocketing became the predominant capture mode for a wide range of length classes and accounted for the majority of capture probability for grey mullet at length classes between 43 and 61 cm and red-lip mullet at length classes between 46 and 60 cm. Additionally, snagging was only detected for grey mullet and red-lip mullet at length classes between 40-43 cm and 43-46 cm, respectively. No clear length-dependent pattern was observed for entangling, which was more likely to occur in larger length classes.

For grey mullet, the main capture mode probability was accounted by pocketing in all types of trammel nets. Specifically, the length-integrated average values for the capture mode probability ($CPq_{average}$) showed that the pocketing capture probability was higher than 75% for the four types of trammel nets (Table 7). Wedging and gilling were the secondary modes for the capture of grey mullet and showed a similar contribution, with each constituting approximately 8%-10% of the total individuals caught (Table 7). Snagging and entangling shared a minor proportion in the total catches, below 3% and 5%, respectively (Table 7).

The pattern in length-integrated capture mode probability of red-lip mullet was similar to that of grey mullet. When averaged over length classes, the pocketing capture probability was higher than 66% and 60% for the PLA and PA nets, respectively (Table 8). Wedging and gilling accounted for approximately 25% of the total catches, and no significant differences were found between gilling and wedging capture probability (Table 8). Only a minor proportion of red-lip mullet was captured by snagging and entangling, not exceeding 4% and 8%, respectively (Table 8).

For both fish species, there were no significant differences in length-integrated average values of each capture mode probability between two materials and monofilament thicknesses (Table 7, Table 8).

4. Discussion

This study represents the first systematic investigation into the feasibility of replacing conventional nylon material with a biodegradable plastic material in commercial trammel net fisheries to reduce ALDFG caused marine plastic pollution and ghost fishing. This research encompassed both laboratory-based physical property tests and in-situ fishing trials to evaluate the applicability of biodegradable PLA material in trammel nets. The results showed that the PLA trammel nets exhibited similar initial catch efficiency and capture modes as PA nets, despite the physical properties test demonstrated that PA monofilament exhibited superior physical properties compared to PLA monofilament. Additionally, there were no significant differences in catch efficiency between the same material monofilaments of two different thickness tested in this study.

In recent years, the use of various biodegradable plastic materials in commercial fisheries has gained attention, with each material having specific properties and related advantages. For instance, upon comparing our physical property test results with those reported by Kim et al. (2020), we found that the 0.20 mm PLA monofilament exhibited significantly higher knotless and knotted breaking strength than the 90w% PBS and 10w% PBAT blend monofilament of a similar thickness. Additionally, the 0.25 mm PLA monofilament showed higher knotted breaking strength and lower knotless breaking strength and flexibility compared to the PBSAT monofilament of a similar diameter. Results of some studies suggest that the biodegradable PLA material is not breaking down optimally when exposed to marine environment (Deroiné, 2014; Bagheri et al., 2017; Huang et al., 2020; Le Gué et al, 2023). However, results of another study testing the monofilament PLA material in the seawater conditions shows that it starts to reduce the tensile strength after 6 month exposure (Min et al., 2017). This time further corresponds to fishing season in trammel net fishery. Thus, these results suggest that the PLA material would have a potential for showing an optimal fishing performance while used in commercial fishery which is a crucial aspect for implementing biodegradable materials for commercial applications. Therefore, the selection of biodegradable materials for fishing gear may need to be tailored to the specific fishery, as the intricate relationship between material properties, capture modes, and catch efficiency can be fishery specific.

Gillnets and trammel nets can exhibit distinct capture modes for different target species due to variations in species morphology, swimming ability and behavior. Therefore, unveiling the underlying capture modes of gillnets and trammel nets for specific target species is crucial in assessing the impact of biodegradable materials on catch efficiency. For instance, several studies have reported that gilling and wedging are the dominant capture modes for gillnets targeting cod (Cerbule et al., 2022; Savina et al., 2022; Brinkhof et al., 2023). In particular, Cerbule et al. (2022) found that the number of cod caught by gilling and wedging in PA gillnets was notably higher than in biodegradable PBSAT gillnets. Consequently, they concluded that the observed reduced catch efficiency of biodegradable nets could be attributed to alterations in specific capture modes, which might be influenced by differences in material properties. Furthermore, Grimaldo et al. (2020a) suggested that a stiffer and less elastic material may be more effective in catching fish through gilling, whereas a more flexible and elastic material is better suited for snagging fish.

Our results revealed that pocketing was the main capture mode for trammel nets capturing grey mullet and red-lip mullet, contributing to more than 75% and 60% of the total catches, respectively. We also found that changes in monofilament materials from PA to PLA and their associated physical properties did not have significant effect on the probability of pocketing capture mode. We speculated that pocketing may be less influenced by material properties, including strength, elasticity, and flexibility than other capture modes. Consequently, this could explain why the catch efficiency of PLA and PA nets for both species remained similar. Furthermore, the occurrence of pocketing may be more closely related to the fish size and swimming behavior.

The results of this study also showed that snagging and entangling constituted a minor proportion of the total catches of grey mullet and red-lip mullet in PLA and PA trammel nets. Furthermore, in this trammel net fisheries, snagging was only observed for a limited range of mullet length classes, which contrasted with earlier studies of capture modes in gillnets that reported cod being captured by snagging across a wide range of fish lengths (Cerbule et al., 2022; Savina et al., 2022; Brinkhof et al., 2023). This can be attributed to different factors such as the differences in fishing gear construction between gillnets and trammel nets, and possibly, the discrepancy in morphological characteristics and swimming behaviors across species. For instance, cod has a wide mouth gape and occasionally swim forward with its mouth open (Lobyrev and Hoffman, 2018). This behavior results in the fish coming into contact with the threads of nettings using its mouth first, enabling various snagging scenarios, including getting stuck by the mouth, maxillary, and head. In contrast, grey mullet and red-lip mullet have smaller mouth opening and typically swim forward with their mouths closed (laboratory observations of first author). As a result, mullet was only observed being snagged by their head sections (Fig. 7a). Additionally, grey mullet and red-lip mullet lack protruding anatomical structures in their heads, making it easier for them to escape when captured by snagging and not enmeshed tightly. Furthermore, gilling and wedging also contributed only a small proportion to the capture of these two species. This is caused by the matching degree between fish body size and design parameters of the trammel nets, primarily the mesh size of inner panel.

The capture mode probability of both fish species was observed to be highly length-dependent. For instance, smaller sized individuals are more frequently caught by gilling and wedging, and larger individuals are more easily caught by pocketing. This process is determined by the size distributions of target species and technical parameters of trammel nets used, primarily mesh size and hanging ratio. Therefore, the length-integrated average values of catch ratio and capture mode probability are specific for the population structure encountered during the sea trials, which cannot be extrapolated to other areas and seasons in which the size structure of each species may be different (Cerbule et al., 2022). Additionally, changes in the mesh size and hanging ratio can also affect the catch performance of PLA and PA nets in specific fishery.

Monofilament thickness is an important variable affecting the capture patterns and catch efficiency of gillnets and trammel nets (He, 2006; Grati et al., 2015). However, in this study, we found that increasing the monofilament diameter from 0.20 mm to 0.25 mm did not have significant effects on catch efficiency and capture modes of both PLA and PA trammel nets. One possible reason is that the difference in monofilament diameter between 0.20 mm and 0.25 mm may not be large enough to elicit notable differences in catch efficiency and capture modes. Furthermore, it is likely that pocketing, being the dominant capture mode, is less influenced by monofilament thickness compared to other capture modes such as gilling and snagging, which have been previously shown to be more susceptible to variations in monofilament thickness (Grati et al., 2015). These results suggested that using biodegradable trammel nets made of thicker twine might be a favorable option due to the higher breaking strength, enhanced durability, and prolonged lifespan without compromising catch efficiency. However, it is noteworthy that this would need longer time for degradation if lost at sea. Except for the inner panel, monofilament thickness is also of significance for outer panels of trammel nets since fish are captured by pocketing in the netting of both, inner and outer panels.

The fishing season for grey mullet and red-lip mullet usually lasts for three months a year, and the service life of conventional PA nets commonly used in this fishery ranges between six and nine months, i.e., from two to three consecutive fishing seasons. Our study demonstrated no significant differences in catch performance between the PLA and PA nets during initial tests with using trammel nets of new PLA and PA materials. Additionally, Min et al. (2017) found that the mechanical properties of PLA monofilament remained constant in the seawater for up to 6 months, indicating that biodegradable PLA trammel nets could potentially display optimal catch efficiency over a consecutive fishing period. However, besides degradation rate in seawater, the repeated use and wear of fishing gear in practice can also contribute to a decrease in material properties and potentially accelerate the degradation of biodegradable materials (Grimaldo et al., 2020b). As the physical performance of biodegradable materials diminishes to a certain threshold, there is a possibility of reduced fishing efficiency. Therefore, it is necessary to assess the effects of long-term usage on the catch efficiency of biodegradable PLA nets over longer fishing periods. Such long-term studies are imperative for gaining a comprehensive understanding of the material's durability and effectiveness over time. However, conducting and reporting preliminary results, as demonstrated in this study, play a crucial role in assessing the viability of biodegradable PLA materials for potential commercial development. Specifically, it contributes at identifying biodegradable materials that show promising initial results for further long-term experiments. Thereby, this approach prevents the allocation of resources to unsuccessful research and development efforts in more comprehensive studies (Cerbule et al., 2023). Nevertheless, it is essential to acknowledge that these initial promising results of this study must be complemented by subsequent investigations evaluating the long-term performance of the materials under extended periods of use.

From a commercial fishery perspective, apart from catch performance, cost-effectiveness represents a significant determinant of whether the fishing industry and artisanal fishers are willing to adopt biodegradable fishing gear. Currently, the development of biodegradable fishing gear is still undergoing initial trials in China, and the production cost of PLA nets is much higher than that of PA nets. Nonetheless, with more attention being paid to marine environmental conservation in recent years, the government can provide incentives to the production and supply of biodegradable fishing gears and the purchase of nets by fishers by granting subsidies. Furthermore, the production costs of the new biodegradable materials can be reduced if the production is scaled up for commercial applications.

To ensure the environmentally safe utilization of biodegradable plastic materials at sea, it is essential to understand whether intermediate breakdown products, including degradable components, can impose toxicity on marine ecosystem. However, the available information regarding the decomposition process of degradable plastics and the impacts of intermediate products on genotypic and phenotypic traits of marine organisms, as well as their enrichment effects in the food chain and food web is limited. Therefore, additional tests showing that the new biodegradable materials do not have any negative ecotoxicological effects on the marine environment are further crucial before the material is used in large scale.

Biodegradable fishing gear has emerged as a potential measure to address the pressing issues of marine pollution and ghost fishing caused by ALDFG. While acknowledging that this solution may not be flawless, further development of biodegradable plastic materials can contribute at safeguarding marine ecosystems and reducing the detrimental impacts of ghost fishing, thereby fostering the sustainable utilization of ocean resources.

5. Conclusion

By testing and comparing the physical properties and fishing performance of PLA and PA trammel nets, main conclusions can be drawn as below:

1) PLA trammel nets exhibited similar catch efficiency as PA nets during the initial trials, despite the PA monofilament exhibited superior physical properties compared to PLA monofilament.

2) Increasing the diameter from 0.20 to 0.25 mm for both PLA and PA monofilaments did not significantly affect the catch efficiency for both species.

3) Pocketing is the main capture mode for both species which may explain the observed similar catch efficiency.

4) Biodegradable materials may have great potential for application in trammel net fisheries, but further long-term testing is required.

CRediT authorship contribution statement

Mengjie Yu: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing - original draft, Writing - review and editing. **Yanli Tang**: Conceptualization, Funding acquisition, Project administration, Supervision, Writing - original draft. **Minghua Min**: Conceptualization, Methodology,

Funding acquisition, Project administration, Supervision, Writing - original draft. **Bent Herrmann**: Formal analysis, Methodology, Software, Supervision, Validation, Writing - original draft, Writing - review and editing. **Kristine Cerbule**: Formal analysis, Methodology, Validation, Visualization, Writing - original draft. **Changdong Liu**: Conceptualization, Data curation, Supervision. **Yilin Dou**: Investigation. **Liyou Zhang**: Investigation.

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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Table 1 Tensile strength and elongation at break of knotless monofilaments of nylon (PA) and biodegradable (PLA) materials in dry and wet conditions. SD: standard deviance.

Materials	Diameter (mm)	Linear density (dtex)		Tensile strength (N) (±SD)		Elongation (%) (±SD)	
		Dry	Wet	Dry	Wet	Dry	Wet
PA	0.20	378	392	21.65 ± 0.43	20.40 ± 0.54	21.21 ± 0.92	22.54 ± 0.65
	0.25	561	586	30.78 ± 0.62	29.70 ± 0.62	21.12 ± 1.89	25.67 ± 1.57
	0.45	1846	1918	82.19 ± 3.76	76.60 ± 3.40	18.04 ± 1.26	19.38 ± 0.98
PLA	0.20	462	484	16.19 ± 0.41	16.91 ± 0.27	21.93 ± 0.66	22.67 ± 0.85
	0.25	695	699	19.16 ± 0.98	19.06 ± 0.65	22.03 ± 1.28	25.01 ± 1.02
	0.45	1998	2025	46.78 ± 1.69	49.05 ± 4.14	13.27 ± 1.42	16.29 ± 1.13

Table 2 Tensile strength and elongation at break of knotted monofilaments of nylon (PA) and biodegradable (PLA) materials in dry and wet conditions. SD: standard deviance.

Materials	Diameter (mm)	Tensile strength (N) (±SD)		Elongation (%) (±SD)	
		Dry	Wet	Dry	Wet
PA	0.20	19.11 ± 2.00	17.55 ± 2.05	15.56 ± 2.32	18.28 ± 2.43
	0.25	22.90 ± 2.18	20.31 ± 1.02	14.25 ± 2.99	14.50 ± 1.54
	0.45	54.76 ± 2.38	51.98 ± 4.31	12.57 ± 3.51	14.37 ± 3.03
PLA	0.20	11.87 ± 1.06	11.91 ± 0.47	16.31 ± 1.87	14.17 ± 1.06
	0.25	15.89 ± 1.75	16.24 ± 1.83	18.17 ± 2.03	18.70 ± 1.29
	0.45	38.76 ± 2.98	44.76 ± 4.01	10.36 ± 0.50	12.25 ± 1.03

Table 3 Flexibility of nylon (PA) and biodegradable (PLA) monofilaments in dry and wet conditions. SD: standard deviance.

Materials	Diameter (mm)	Flexibility (N) (±SD)	
		Dry	Wet
PA	0.20	0.035 ± 0.002	0.019 ± 0.002
	0.25	0.058 ± 0.004	0.042 ± 0.010
	0.45	0.581 ± 0.029	0.381 ± 0.035
PLA	0.20	0.173 ± 0.006	0.163 ± 0.005
	0.25	0.342 ± 0.010	0.358 ± 0.008
	0.45	2.785 ± 0.114	2.879 ± 0.062

Table 4 Fit statistics, catch ratio (*CR*) results (in %), and number of fish caught in nylon (PA) and biodegradable (PLA) trammel nets. Results for catch comparisons between PLA and PA trammel nets with 0.20 mm monofilament (left column) and 0.25 mm monofilament (right column). Values in parentheses represent 95% confidence intervals. DOF denotes degrees of freedom.

		0.20 mm monofilament	0.25 mm monofilament
Grey mullet	*p*-value	0.6585	0.4546
	Deviance	18.79	22.09
	DOF	22	22
	$CR_{average}$	89.95 (74.57-109.89)	93.11 (80.91-107.29)
	Number in PLA nets	492	500
	Number in PA nets	547	537
Red-lip mullet	*p*-value	0.9464	0.9993
	Deviance	10.99	5.63
	DOF	20	20
	$CR_{average}$	93.41 (77.86-113.90)	95.10 (76.83-115.89)
	Number in PLA nets	397	369
	Number in PA nets	425	388

Table 5 Fit statistics, catch ratio (*CR*) results (in %), and number of fish caught in nylon (PA) and biodegradable (PLA) trammel nets. Results for comparisons between PLA trammel nets (left column) and between PA trammel nets (right column) with 0.25 mm and 0.20 mm monofilaments. Values in parentheses represent 95% confidence intervals. DOF denotes degrees of freedom.

		PLA trammel nets	PA trammel nets
Grey mullet	*p*-value	0.7894	0.8161
	Deviance	16.52	16.00
	DOF	22	22
	$CR_{average}$	101.63 (87.33-119.61)	98.17 (83.28-115.08)
	Number in nets with 0.25 mm monofilament	500	537
	Number in nets with 0.20 mm monofilament	492	547
Red-lip mullet	*p*-value	0.9090	0.6732
	Deviance	12.20	16.69
	DOF	20	20
	$CR_{average}$	92.95 (76.09-114.81)	91.29 (76.28-109.51)
	Number in nets with 0.25 mm monofilament	369	388
	Number in nets with 0.20 mm monofilament	397	425

Table 6 Number of fish observed for each capture mode in nylon (PA) and biodegradable (PLA) trammel nets of the two monofilament diameters.

	Materials	Monofilament diameter (mm)	Capture modes					
			Snagging	Gilling	Wedging	Pocketing	Entangling	Total
Grey mullet	PLA	0.20	12	38	48	383	11	492
	PA	0.20	9	46	58	411	23	547
	PLA	0.25	9	41	43	392	15	500
	PA	0.25	6	44	59	407	21	537
Red-lip mullet	PLA	0.20	12	66	47	264	8	397
	PA	0.20	16	63	58	258	30	425
	PLA	0.25	6	53	35	266	9	369
	PA	0.25	12	54	43	251	28	388

Table 7 Fit statistics and length-integrated average values ($CPq_{average}$) of the length-dependent capture mode probability for grey mullet (*Mugil cephalus*) in nylon (PA) and biodegradable (PLA) trammel nets. Values in parentheses represent 95% confidence intervals. DOF denotes degrees of freedom.

Materials	Monofilament diameter (mm)		Capture modes				
			Snagging	Gilling	Wedging	Pocketing	Entangling
PLA	0.20	*p*-value	>0.9999	0.9994	>0.9999	0.0930	0.2221
		Deviance	2.75	6.48	3.36	31.15	26.72
		DOF	22	22	22	22	22
		$CPq_{average}$	2.44 (1.15-4.04)	7.72 (5.45-9.69)	9.76 (5.70-13.32)	77.85 (72.87-82.16)	2.24 (1.02-3.51)
PA	0.20	*p*-value	>0.9999	0.9962	>0.9999	0.0165	0.0653
		Deviance	1.91	8.33	4.05	38.41	32.76
		DOF	22	22	22	22	22
		$CPq_{average}$	1.65 (0.74-2.69)	8.41 (6.24-10.65)	10.60 (8.33-12.95)	75.14 (70.02-79.82)	4.20 (1.88-6.88)
PLA	0.25	*p*-value	>0.9999	0.2189	>0.9999	0.0017	0.1419
		Deviance	2.76	26.80	5.50	46.47	29.10
		DOF	22	22	22	22	22
		$CPq_{average}$	1.80 (0.63-3.11)	8.20 (6.00-10.53)	8.60 (6.79-10.39)	78.40 (74.60-82.19)	3.00 (1.39-4.97)
PA	0.25	*p*-value	>0.9999	0.4840	0.9981	<0.0001	0.3349
		Deviance	2.16	21.60	7.58	58.23	24.24
		DOF	22	22	22	22	22

$CPq_{average}$	1.12 (0.36-2.18)	8.19 (6.09-10.86)	10.99 (8.17-13.83)	75.42 (71.16-79.93)	4.28 (2.01-7.29)

Table 8 Fit statistics and length-integrated average values ($CPq_{average}$) of the length-dependent capture mode probability for red-lip mullet (*Liza haematocheila*) in nylon (PA) and biodegradable (PLA) trammel nets. Values in parentheses represent 95% confidence intervals. DOF denotes degrees of freedom.

Materials	Monofilament diameter (mm)		Capture modes				
			Snagging	Gilling	Wedging	Pocketing	Entangling
PLA	0.20	*p*-value	>0.9999	0.9176	>0.9999	0.0575	0.5045
		Deviance	2.76	11.96	4.36	30.83	19.27
		DOF	20	20	20	20	20
		$CPq_{average}$	3.02 (1.55-4.46)	16.62 (12.83-20.38)	11.84 (8.46-15.90)	66.50 (60.28-72.37)	2.02 (0.00-5.09)
PA	0.20	*p*-value	>0.9999	0.9998	0.9998	0.3582	0.6390
		Deviance	0.62	4.85	4.89	21.68	17.21
		DOF	20	20	20	20	20
		$CPq_{average}$	3.76 (2.32-5.42)	14.82 (11.33-18.46)	13.65 (10.29-17.34)	60.71 (55.81-65.18)	7.06 (4.02-9.91)
PLA	0.25	*p*-value	>0.9999	>0.9999	>0.9999	0.8337	>0.9999
		Deviance	1.12	3.42	1.83	13.94	1.45
		DOF	20	20	20	20	20
		$CPq_{average}$	1.63 (0.27-3.55)	14.36 (10.91-17.94)	9.48 (7.01-11.71)	72.09 (68.70-75.79)	2.44 (0.57-4.80)
PA	0.25	*p*-value	>0.9999	0.9997	>0.9999	0.5737	0.9243
		Deviance	0.35	5.12	1.92	18.21	11.75
		DOF	20	20	20	20	20

$CPq_{average}$	3.09 (1.29-4.95)	13.92 (10.05-18.45)	11.08 (7.36-15.30)	64.69 (57.40-72.95)	7.22 (3.71-10.69)

Figures

Figure 1 Experimental trammel net setup used during the sea trials. Fleet 1 contained biodegradable (PLA) and nylon (PA) trammel nets with 0.20 mm monofilament diameter. Fleet 2 contained biodegradable (PLA) and nylon (PA) trammel nets with 0.25 mm monofilament diameter. Fleets were deployed in the same pattern as surface-set nets according to the commercial fishing practice.

Figure 2 Tensile strength and elongation curves of knotless and knotted nylon (PA) and biodegradable (PLA) monofilaments under dry and wet conditions.

Figure 3 Catch comparison and catch ratio analysis between biodegradable (PLA) and nylon (PA) trammel nets with 0.20 mm monofilaments (left column) and between biodegradable and nylon trammel nets with 0.25 mm monofilaments (right column) for grey mullet (*Mugil cephalus*). Upper panel: the modelled catch comparison rate (black line) with 95% confidence intervals (gray area). The gray solid and dashed lines represent the summed population for the PLA and PA trammel nets, respectively. Circles represent the experimental rates. Lower panel: the estimated catch ratio (black line) with 95% confidence intervals (gray area). Horizontal stippled lines represent the baseline at which the two trammel net types have equal catch efficiency.

Figure 4 Catch comparison and catch ratio analysis between biodegradable (PLA) and nylon (PA) trammel nets with 0.20 mm monofilaments (left column) and between biodegradable and nylon trammel nets with 0.25 mm monofilaments (right column) for red-lip mullet (*Liza haematocheila*). Upper panel: the modelled catch comparison rates (black line) with 95% confidence intervals (gray area). The gray solid and dashed lines represent the summed population for the PLA and PA trammel nets, respectively. Circles represent the experimental rates. Lower panel: the estimated catch ratios (black line) with 95% confidence intervals (gray area). Horizontal stippled lines represent the baseline at which the two trammel net types have equal catch efficiency.

Figure 5 Catch comparison and catch ratio analysis between biodegradable (PLA) trammel nets with 0.25 mm and 0.20 mm monofilaments (left column) and between nylon (PA) trammel nets with 0.25 mm and 0.20 mm monofilaments (right column) for grey mullet (*Mugil cephalus*). Upper panel: the modelled catch comparison rates (black line) with 95% confidence intervals (gray area). The gray solid and dashed lines represent the summed population for the trammel nets with 0.25 mm and 0.20 mm monofilaments, respectively. Circles represent the experimental rates. Lower panel: the estimated catch ratios (black line) with 95% confidence intervals (gray area). Horizontal stippled lines represent the baseline at which the two trammel net types have equal catch efficiency.

Figure 6 Catch comparison and catch ratio analysis between biodegradable (PLA) trammel nets with 0.25 mm and 0.20 mm monofilaments (left column) and between nylon (PA) trammel nets with 0.25 mm and 0.20 mm monofilaments (right column) for red-lip mullet (*Liza haematocheila*). Upper panel: the modelled catch comparison rates (black line) with 95% confidence intervals (gray area). The gray solid and dashed lines represent the summed population for the trammel nets with 0.25 mm and 0.20 mm monofilaments, respectively. Circles represent the experimental rates. Lower panel: the estimated catch ratios (black line) with 95% confidence intervals (gray area). Horizontal stippled lines represent the baseline at which the two trammel net types have equal catch efficiency.

Figure 7 Capture modes observed during the fishing trials: (a) snagging; (b) gilling; (c) wedging; (d) entangling; (e) and (f) pocketing.

Figure 8 Length-dependent capture mode probability of four types of trammel nets for grey mullet (*Mugil cephalus*) (from left to right: biodegradable (PLA) nets with 0.20 mm monofilaments, nylon (PA) nets with 0.20 mm monofilaments, biodegradable nets with 0.25 mm monofilaments, and nylon nets with 0.25 mm monofilaments). The black line represents the modelled capture mode probability as bias-corrected mean with 95% confidence intervals (gray area) fitted to the experimental rate (circles). The gray solid and dashed lines represent the summed population for the specific trammel net type and total catch for each capture mode.

Figure 9 Length-dependent capture mode probability of four types of trammel nets for red-lip mullet (*Liza haematocheila*) (from left to right: biodegradable (PLA) nets with 0.20 mm monofilaments, nylon (PA) nets with 0.20 mm monofilaments, biodegradable nets with 0.25 mm monofilaments, and nylon nets with 0.25 mm monofilaments). The black line represents the modelled capture mode probability as bias-corrected mean with 95% confidence intervals (gray area) fitted to the experimental rate (circles). The gray solid and dashed lines represent the summed population for the specific trammel net type and share of total catch for each capture mode.

Figure 1

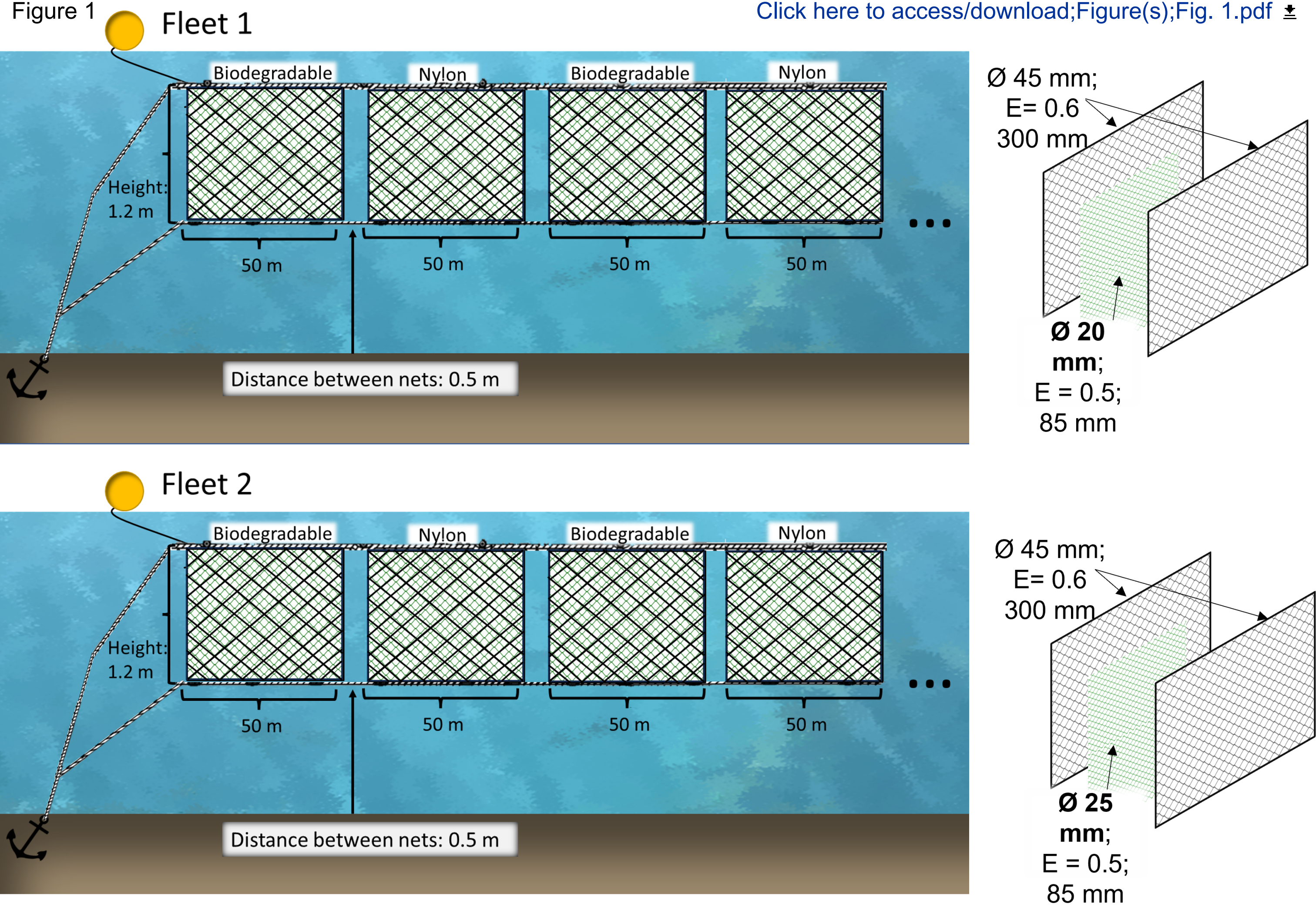
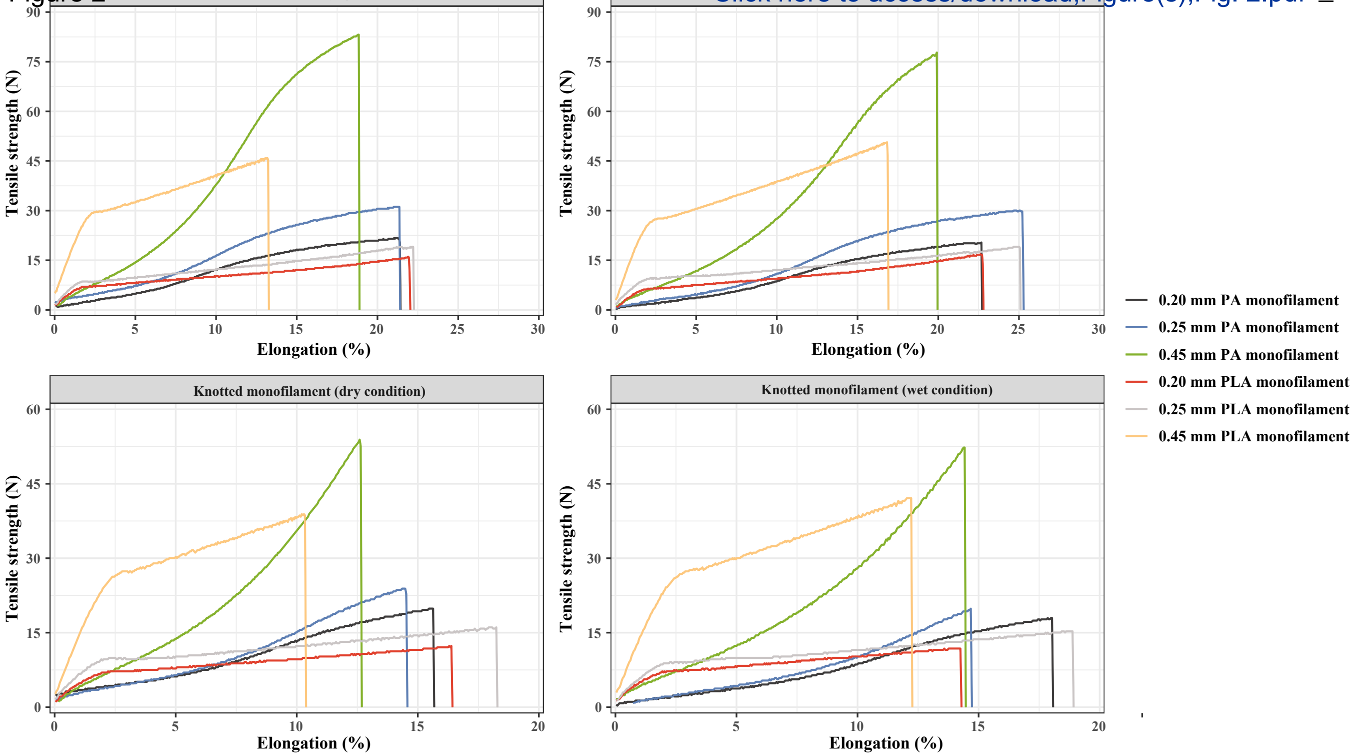

Fleet 1
Biodegradable
Nylon
Biodegradable
Nylon
Height: 1.2 m
50 m
50 m
50 m
50 m
Distance between nets: 0.5 m
Ø 45 mm; E= 0.6 300 mm
Ø 20 mm; E = 0.5; 85 mm
Fleet 2
Biodegradable
Nylon
Biodegradable
Nylon
Height: 1.2 m
50 m
50 m
50 m
50 m
Distance between nets: 0.5 m
Ø 45 mm; E= 0.6 300 mm
Ø 25 mm; E = 0.5; 85 mm

Figure 2



Knotless monofilament (dry condition)
Knotless monofilament (wet condition)
Knotted monofilament (dry condition)
Knotted monofilament (wet condition)
Tensile strength (N)
Elongation (%)
0.20 mm PA monofilament
0.25 mm PA monofilament
0.45 mm PA monofilament
0.20 mm PLA monofilament
0.25 mm PLA monofilament
0.45 mm PLA monofilament

Figure 3

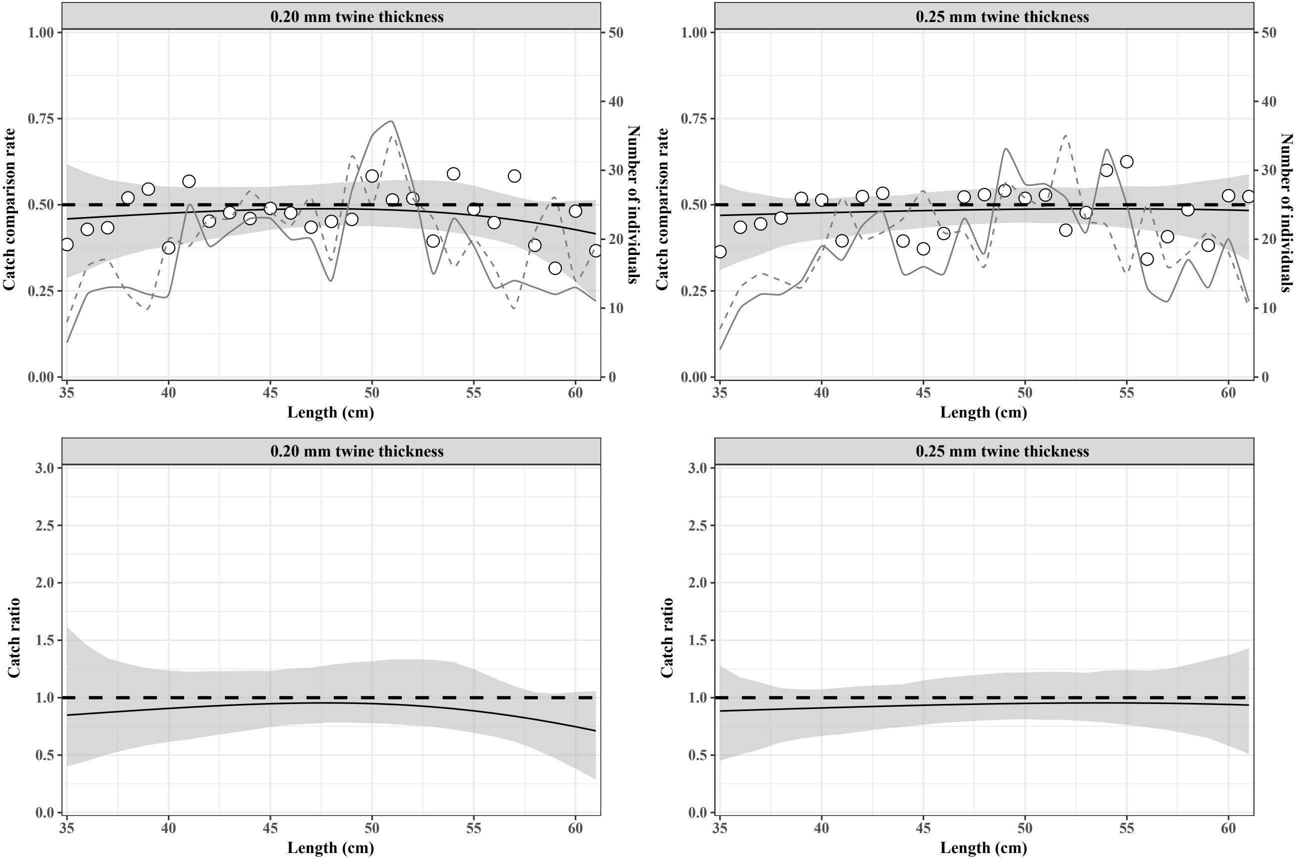

0.20 mm twine thickness
0.25 mm twine thickness
Catch comparison rate
Number of individuals
Length (cm)
Catch ratio
1.00
0.75
0.50
0.25
0.00
50
40
30
20
10
0
3.0
2.5
2.0
1.5
1.0
0.5
0.0
35
40
45
50
55
60

Figure 4

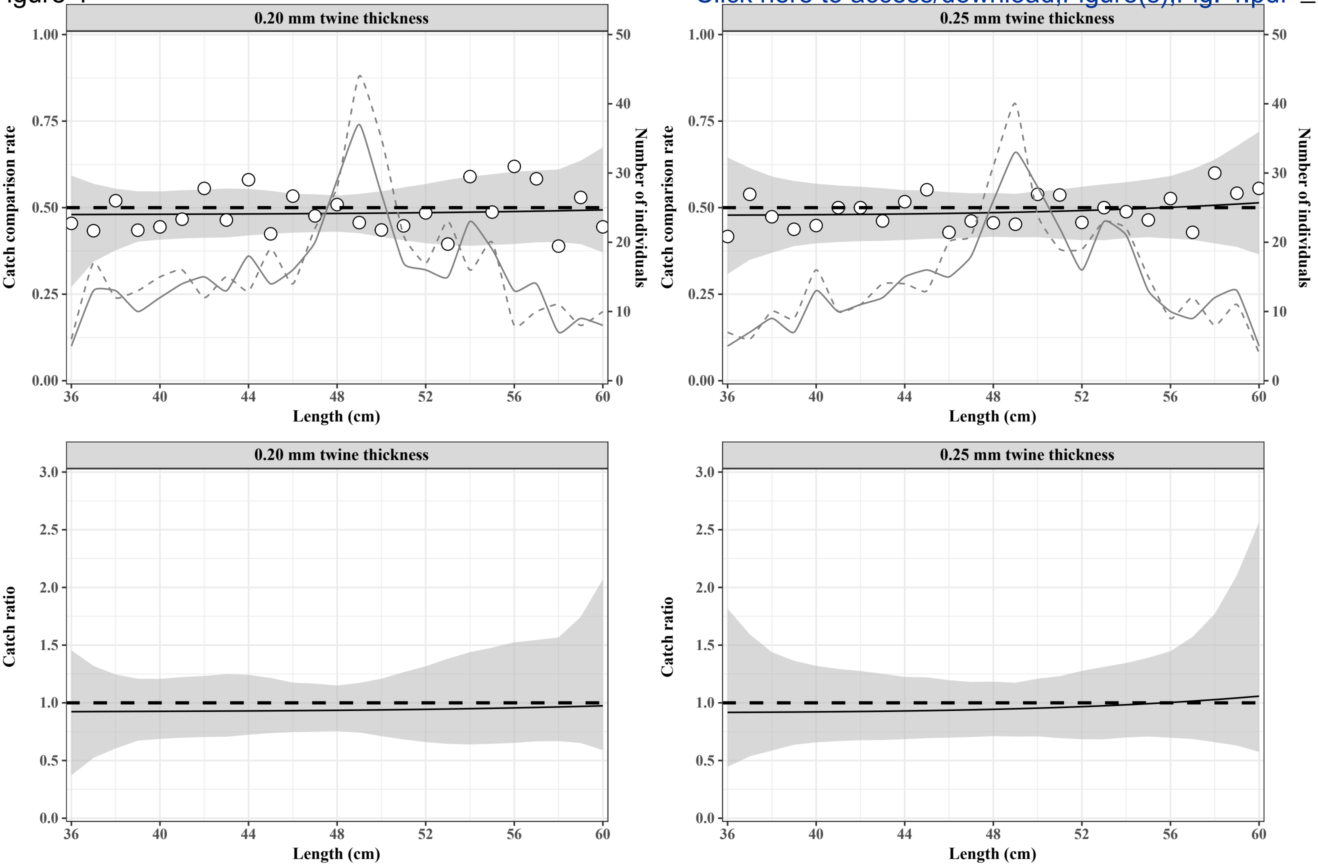

0.20 mm twine thickness
0.25 mm twine thickness
Catch comparison rate
Number of individuals
Length (cm)
0.20 mm twine thickness
0.25 mm twine thickness
Catch ratio
Length (cm)

Figure 5

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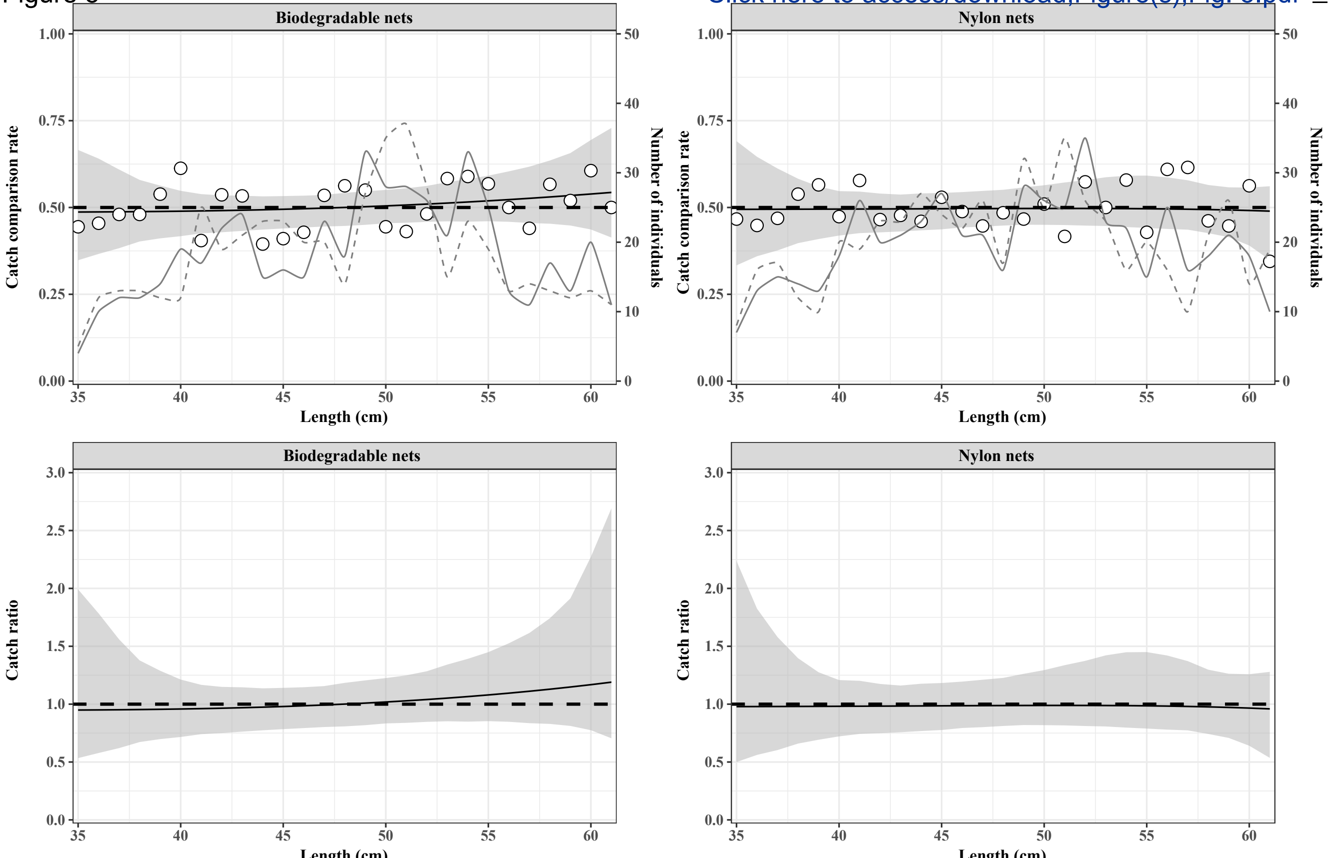

Figure 6

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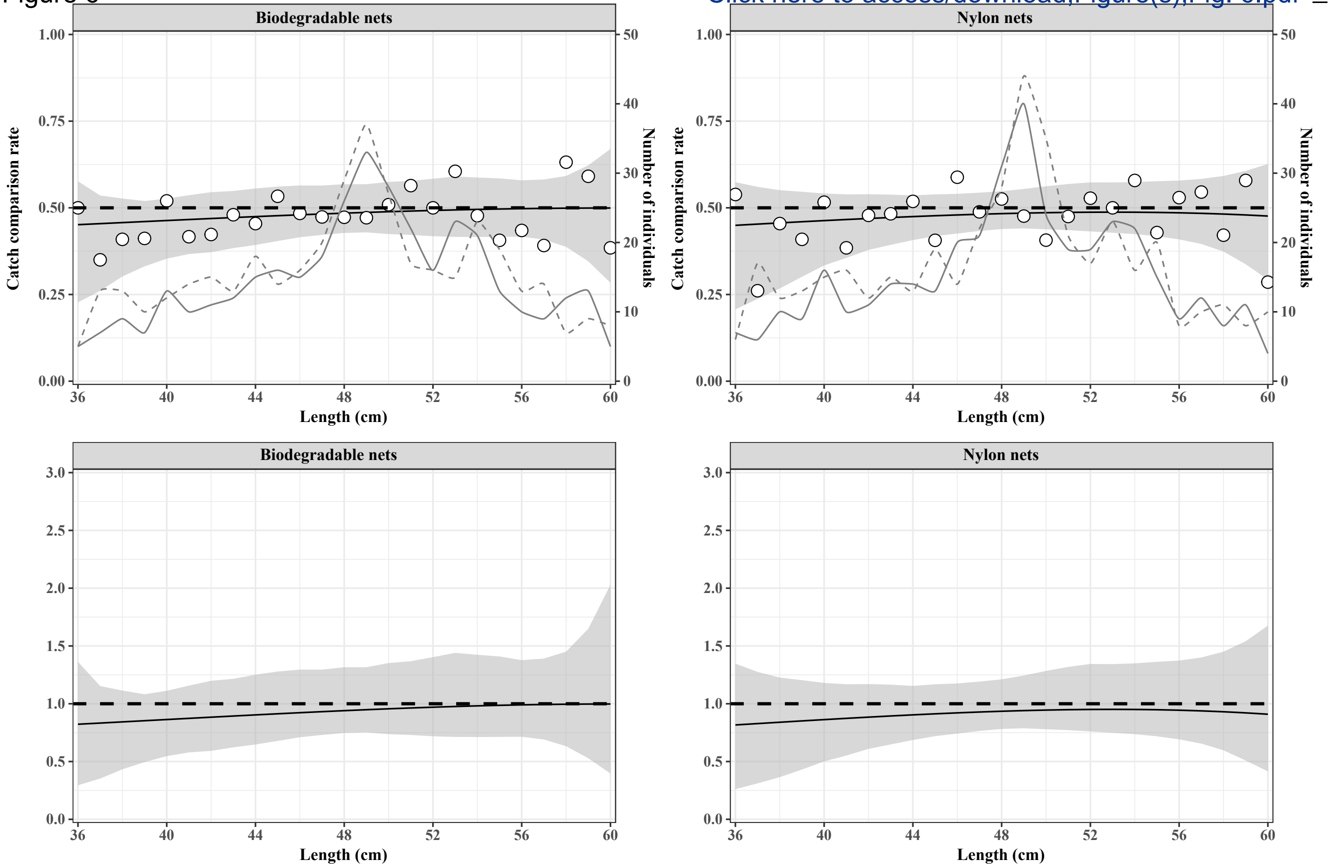


Figure 7

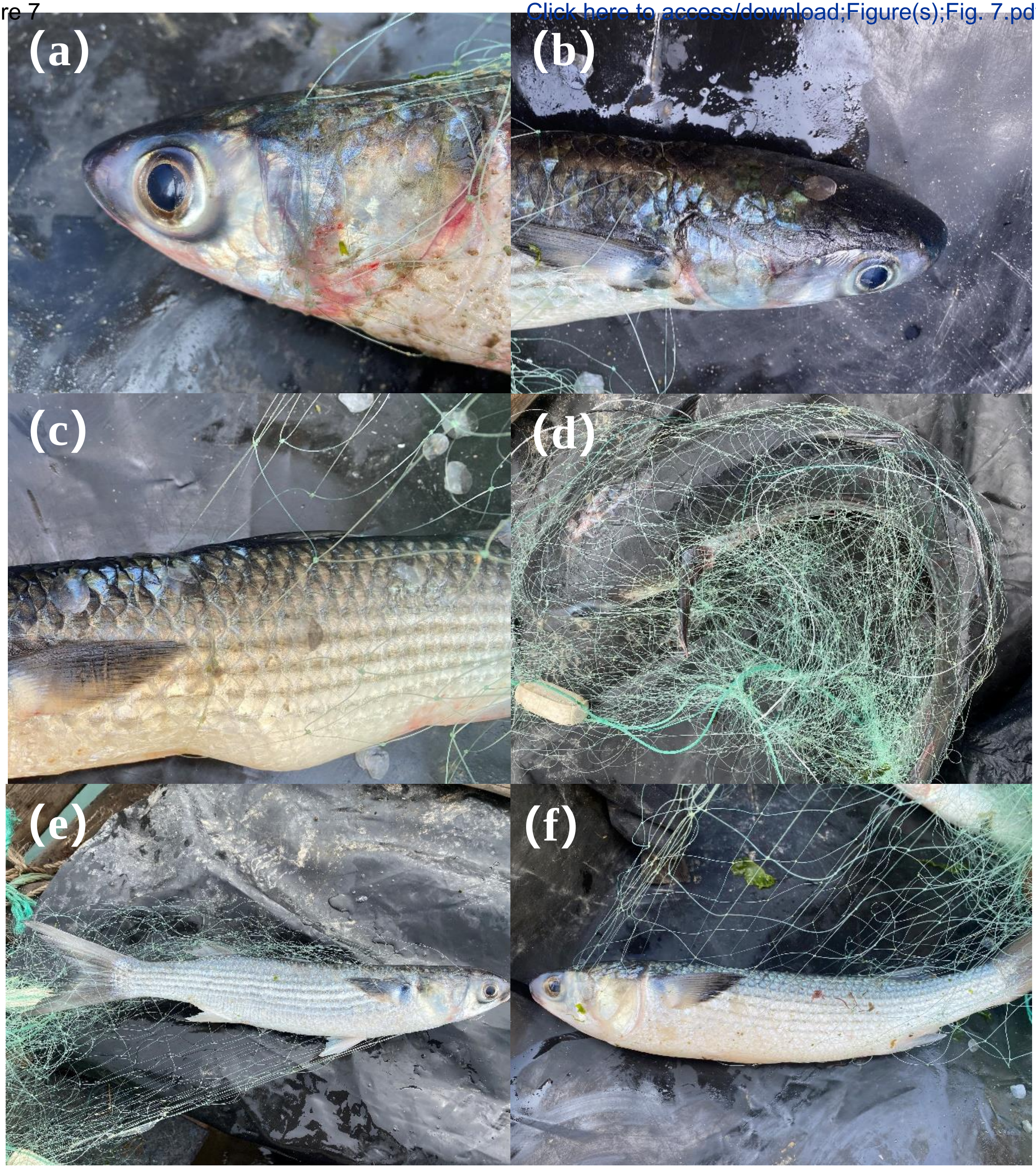


Figure 8

Click here to access/download;Figure(s);Fig. 8.pdf

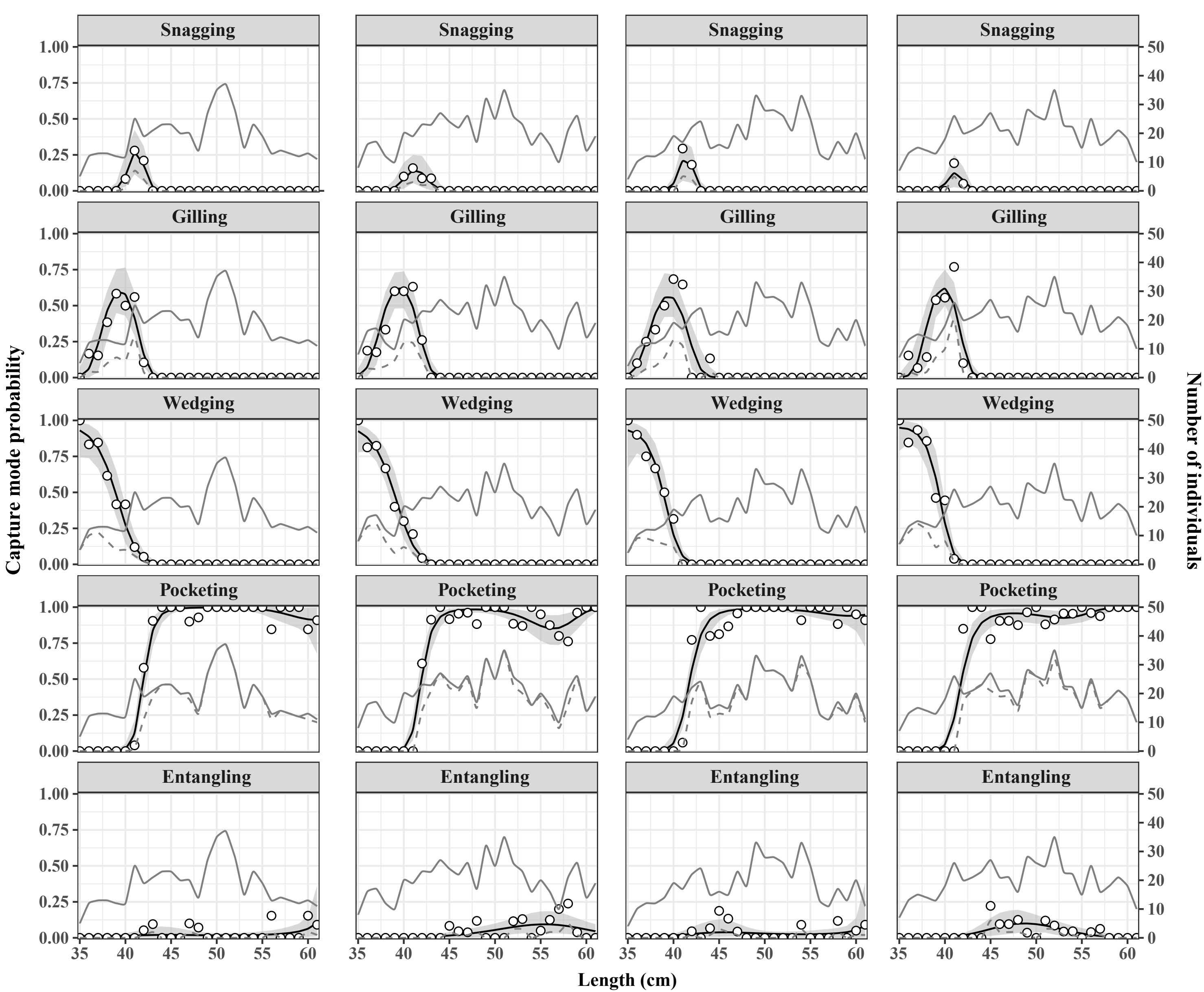
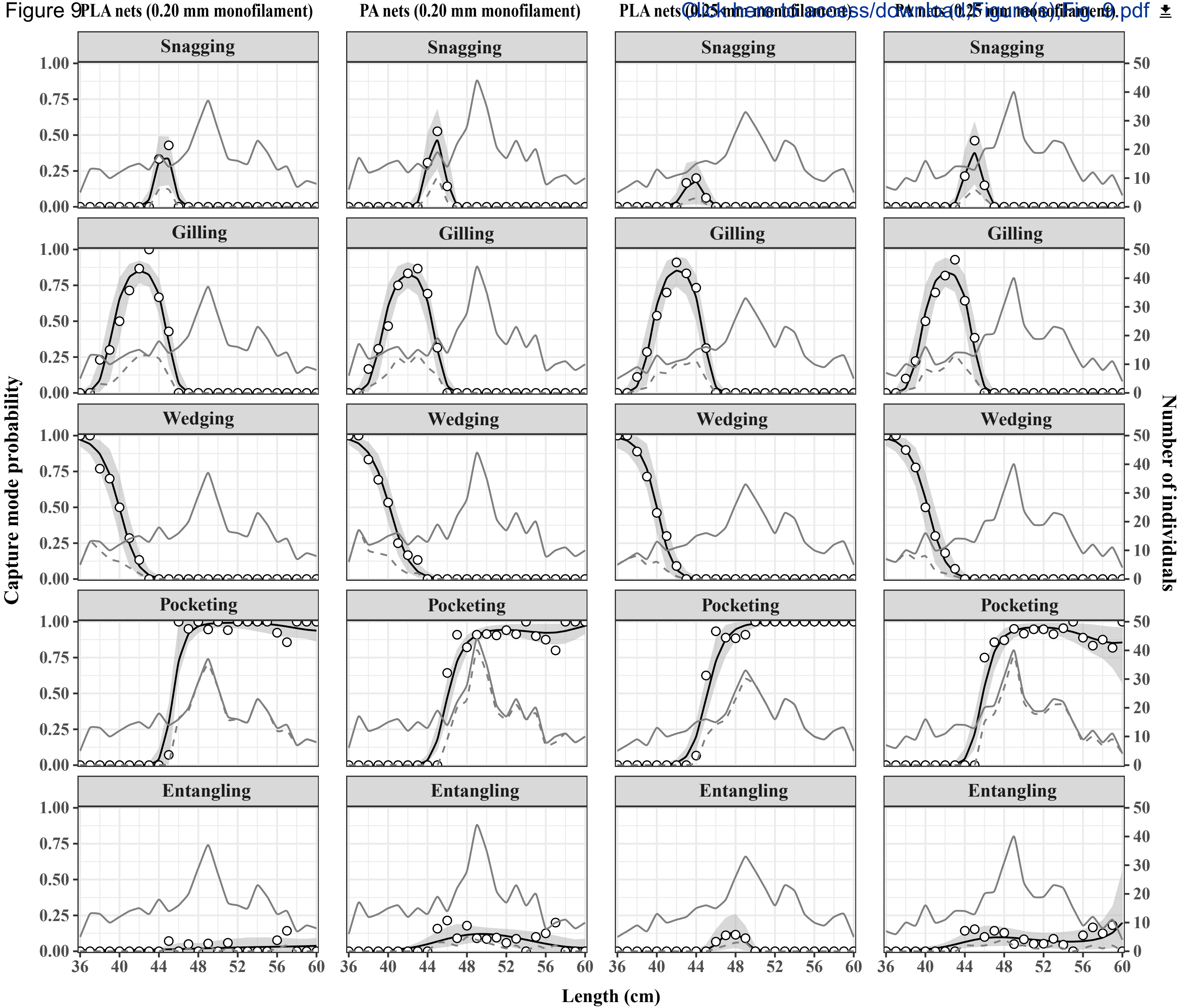


Figure 9 Click here to access/download;Figure(s);Fig. 9.pdf



Supplementary material S1: Details on modelling the length-dependent catch efficiency between trammel net types

A. Length-dependent catch efficiency between biodegradable (PLA) and nylon (PA) trammel nets with same monofilament thickness

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:

$$CC_l = \frac{\sum_{j=1}^{m}\{nt_{lj}\}}{\sum_{j=1}^{m}\{nt_{lj} + nc_{lj}\}} \qquad (S1.1)$$

where nc_{lj} and nt_{lj} are the numbers of fish that were length measured in each length class *l* for the PA and PLA trammel net in deployment *j* of a trammel net fleet (Fleet 1 or 2, respectively). *m* is the total number of deployments carried out with each fleet. 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):

$$-\sum_{l}\sum_{j=1}^{m}\{nt_{lj} \times \ln(CC(l,\boldsymbol{v})) + nc_{lj} \times \ln(1.0 - CC(l,\boldsymbol{v}))\} \qquad (S1.2)$$

where ***v*** is the parameters that describe the catch comparison curve defined by $CC(l, \boldsymbol{v})$. The outer summation in the Expression (S1.2) is the summation over length classes *l* in the experimental data. When the catch efficiency of the PLA and PA trammel nets 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 PLA and PA nets. The experimental CC_l was modelled by the function $CC(l, \boldsymbol{v})$ using the following equation:

$$CC(l,\boldsymbol{v}) = \frac{exp(f(l, v_0, \ldots, v_k))}{1 + exp(f(l, v_0, \ldots, v_k))} \qquad (S1.3)$$

where *f* is a polynomial of order *k* with coefficients v_0-v_k. The values of the parameters ***v*** describing $CC(l, \boldsymbol{v})$ were estimated by minimizing expression (S1.2), 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). 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:

$$CR(l, \boldsymbol{v}) = \frac{CC(l, \boldsymbol{v})}{1 - CC(l, \boldsymbol{v})} \qquad (S1.4)$$

$CR(l, \boldsymbol{v})$ quantifies the relative catch efficiency between the PLA and PA trammel nets. If the catch efficiency of both trammel nets is equal, then $CR(l, \boldsymbol{v})$ = 1.0. $CR(l, \boldsymbol{v})$ = 1.5 would mean that the PLA trammel nets is catching 50% more of the fish with length *l* than the PA nets. In contrast, $CR(l, \boldsymbol{v})$ = 0.5 would mean that the PLA trammel nets is only catching 50% of the fish with length *l* caught by the PA nets.

We estimated confidence intervals (CIs) for $CC(l, \boldsymbol{v})$ and $CR(l, \boldsymbol{v})$ 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 trammel nets) 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 PLA and PA trammel nets, taking full advantage of the experimental design of deploying the PLA and PA trammel nets 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 fish 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:

$$CR_{average} = 100 \times \frac{\sum_l \sum_{j=1}^{m} \{nt_{lj}\}}{\sum_l \sum_{j=1}^{m} \{nc_{lj}\}} \qquad (S1.5)$$

where the outer summations include the length classes in the catches during the experimental fishing trials.

B. Length-dependent catch efficiency between PLA or PA trammel nets with different monofilament thickness

We estimated the length-dependent catch efficiency between PLA or PA trammel nets with different monofilament thickness using the same method and procedure as described above. Specifically, for Eq. (S1.1), nc_{lj} and nt_{lj} are the numbers of fish that were length measured in each length class *l* for the PA or PLA trammel nets with respectively 0.20 mm and 0.25 mm thickness in deployment *j*. *m* is the total number of deployments carried out with two fleets.

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Supplementary material S2: Details on modelling the length-dependent capture mode probability

Conditioned capture, the length-dependent capture probability by a specific capture mode was estimated using the method outlined in Savina et al. (2022). Specifically, we used the catch numbers of fish by each of the capture modes and the corresponding total length in each of the trammel net types separately. All trammel nets of the same material (PLA or PA) from each fleet deployment in each fishing day were considered as a base unit for the analysis. The analysis was conducted separately for each species and independently for each capture mode.

Conditioned capture, the expected probability for the capture mode q for fish of length l can be expressed as:

$$CPq_l = \frac{\sum_{j=1}^{h} n_{qlj}}{\sum_{j=1}^{h}\sum_{i=1}^{Q} n_{ilj}} \qquad (S2.1)$$

where n_{qlj} is the number n of fish caught by capture mode q belong to the length class l in deployment j. Q equals the total number of capture modes, and h is the total number of deployments. The functional form of the capture mode probability $CPq(l, \boldsymbol{v})$ was obtained using the maximum likelihood estimation by minimizing the following expression:

$$-\sum_{j=1}^{h}\sum_{l}\left\{n_{qlj} \times \ln[CPq(l, \boldsymbol{v})] + \left[-n_{qlj} + \sum_{i=1}^{Q} n_{ilj}\right] \times ln[1.0 - CPq(l, \boldsymbol{v})]\right\} (S2.2)$$

where $\boldsymbol{v}$ represents the parameters that describe the capture mode probability curve defined by $CPq(l, \boldsymbol{v})$. Equation (S2.1) and Expression (S2.2) together have a similar form to those commonly used for modelling the length-dependent catch comparison rate between two fishing gears (Krag et al., 2014). Thus, we applied the same technique to model $CPq(l, \boldsymbol{v})$ as is often used in catch comparison studies based on binominal count data (Herrmann et al., 2017) by using:

$$CPq(l, \boldsymbol{v}) = \frac{exp[f(l, v_0, \ldots, v_k)]}{1 + exp[f(l, v_0, \ldots, v_k)]} \qquad (S2.3)$$

where f is a polynomial of order k with coefficients v_0-v_k. The values of the parameters $\boldsymbol{v}$ describing $CPq(l, \boldsymbol{v})$ were estimated by minimizing Expression (S2.2). We considered f of up to an order of 4 with parameters v_0, v_1, v_2, v_3, and v_4. Excluding one or more of the parameters $v_0 \ldots v_4$ resulted in 31 additional models also considered as candidates for the capture mode probability $CPq(l, \boldsymbol{v})$. Among these models, estimations of capture mode probability were made using multi-model inference to obtain a combined model (Burnham and Anderson, 2002; Herrmann et al., 2017). 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 in cases in which the data are subject to overdispersion (Wileman et al., 1996). A double bootstrap method (1000 bootstrap repetitions) was used to estimate the Efron percentile 95% confidence intervals (CIs) (Efron, 1982) for the length-dependent capture mode probability curves by incorporating both within- and between-deployments variations (Herrmann et al., 2012, 2016; Savina et al., 2022).

Further, the length-integrated average value for the capture mode probability ($CPq_{average}$) was estimated directly from the experimental data as follows (Cerbule et al., 2022; Savina et al., 2022; Brinkhof et al., 2023):

$$CPq_{average} = \frac{\sum_l \sum_{j=1}^{h} n_{qlj}}{\sum_l \sum_{j=1}^{h} \sum_{i=1}^{Q} n_{ilj}} \qquad (S2.4)$$

where the outer summations include the length classes *l* in the catch during the fishing trials. Contrary to the evaluation of length-dependent capture mode probability $CPq(l, \boldsymbol{v})$, $CPq_{average}$ is specific to the size structure of the fish population present in the fishing grounds. Therefore, it provides an estimate that is specific for the targeted population and that cannot be extrapolated to other areas and seasons (Cerbule et al., 2022; Savina et al., 2022). The Efron percentile 95% CIs for $CPq(l, \boldsymbol{v})$ were estimated using the double bootstrap method as described above.

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Supplementary material S3

Table S3 P-values of the unpaired t-test for the comparisons of physical properties between PLA and PA monofilaments in dry and wet conditions.

Diameter (mm)	Knotless monofilament				Knotted monofilament				Flexibility	
	Tensile strength		Elongation		Tensile strength		Elongation			
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
0.20	8.96×10^{-32}	4.88×10^{-20}	0.28	0.44	9.91×10^{-17}	6.17×10^{-11}	0.56	2.66×10^{-10}	3.53×10^{-20}	6.84×10^{-21}
0.25	6.94×10^{-38}	8.47×10^{-36}	0.08	0.61	2.23×10^{-12}	1.61×10^{-8}	1.15×10^{-4}	2.02×10^{-9}	1.49×10^{-18}	1.68×10^{-25}
0.45	1.49×10^{-31}	8.68×10^{-25}	7.90×10^{-8}	1.00×10^{-5}	1.92×10^{-22}	9.92×10^{-8}	1.00×10^{-3}	4.00×10^{-4}	1.07×10^{-18}	2.98×10^{-23}

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 and editing. **Yanli Tang**: Conceptualization, Funding acquisition, Project administration, Supervision, Writing - original draft. **Minghua Min**: Conceptualization, Methodology, Funding acquisition, Project administration, Supervision, Writing - original draft. **Bent Herrmann**: Formal analysis, Methodology, Software, Supervision, Validation, Writing - original draft, Writing - review and editing. **Kristine Cerbule**: Formal analysis, Methodology, Validation, Visualization, Writing - original draft. **Changdong Liu**: Conceptualization, Data curation, Supervision. **Yilin Dou**: Investigation. **Liyou Zhang**: Investigation.