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Can operational tactics compensate for weaker tensile properties of biodegradable gillnets?

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Abstract :

This study aimed at discriminating between the effects of physical strain due to the interactive effect of gear operation and degradation, and degradation only, on the differences in breaking strength, strain and stiffness at break of PBSAT (biodegradable) and PA6 (nylon) gillnet materials, and to compare the effect of fish species and resulting capture mode on catch efficiency for a roundfish species, Atlantic cod (Gadus morhua), and a flatfish species, European plaice (Pleuronectes platessa) in the Danish coastal gillnet fishery. The PBSAT meshes were much weaker than PA6 already at the start of the experiment. There were 58% (CI: 38-79%) less cod and 32% (CI: 17-49%) less plaice after 4 months in the PBSAT gillnets. We did not observe significant differences between the interactive effect of gear operation and degradation, and degradation only, and in capture modes. We conclude that reduction in catch efficiency results from a combination of weaker mechanical properties worsened by degradation during e.g. transport and storage, and a species given shape and swimming ability.

Keywords : ALDFG, Biodegradable, Capture mode, Material stiffness, Set nets, Tensile strength, Wear and tear

1. Introduction

Gillnets are used throughout the world to target different fish species by capturing individuals swimming without noticing into the gear which is deployed at sea as a wall of netting (He 2006; He et al. 2021). Gillnets can be an environmentally friendly option due to lower fuel consumption, direct benthic impacts only during retrieval of the gear, and good size selectivity (Suuronen et al, 2012). However, the potential to persist in the marine environment for many years when gillnets are lost, abandoned, or otherwise discarded challenges the sustainability of the gillnet fishery due to potential prolonged unintended capture of marine animals (ghost fishing) and macro- and micro-plastic pollution (Suuronen et al. 2012; Brakstad et al. 2022). Gillnets are usually made of decay-resistant polyamide material (PA6, also known as nylon) or polyethylene terephthalate (PET) which has replaced traditional degradable materials like cotton or hemp due to its high elasticity and tensile strength (Matsushita et al. 2008; Brakstad et al. 2022). Biodegradable netting could fundamentally change the green profile of gillnet fisheries as it degrades faster than synthetic plastics by naturally occurring microorganisms if exposed to the marine environment for prolonged periods (Tokiwa et al. 2009; Kim et al. 2016; Brakstad et al. 2022). To be used commercially without compromising the profitability of the fishing operations, the biodegradable fishing gear must however show a comparable catch efficiency during fishing to that of the commercial material, driven by the mechanical properties of the netting. Biodegradable resins such as polybutylene succinate-co-adipate-co-terephthalate (PBSAT, Kim et al. 2017) are promising candidates for replacing synthetic plastics in gillnets, and new alternatives with improved tensile strength, stiffness and elasticity such as polybutylene adipate-co-butylene succinate-co-ethylene adipate-co-ethylene succinate (PBEAS) are constantly being developed (Seonghun et al. 2020; Yu et al. 2023; Park et al. 2023). Bioplastics are more sensitive to moisture content, which may challenge the extrusion process (Sikora and Majewski 2021) or require the development of custom heat-treatment of the knots when manufacturing a gillnet panel from monofilament twines (Park and Kim 2012; Park et al. 2015; Kim et al. 2020). As polymer experts are developing the next generation of custom biodegradable resins, few options are currently available as a commercial fishing product. Gear technology may help extend the lifespan of fishing gears made of commercially available biodegradable materials (PBSAT at the time of the study) by playing on operational tactics such as gear handling and choice of target species.

Numerous environmental factors, such as exposure to UV radiation and waves contribute to weathering and degradation of gillnets during the fishing operation (nets deployed at sea) and storage of the nets (onboard or between fishing seasons) in addition to biodegradation, resulting in changed surface characteristics and reduced catch efficiency (Dahm et al. 1989; Grimaldo et al. 2020a; Grimaldo et al. 2020b; Kim et al. 2016). The multi-scale approach (monofilament, knot, and net) developed in Le Gué et al. (2024) revealed that knots are not only the weakest point of the net but also where degradation is most rapid, as tightening of the knot during fishing operations increases the likelihood of cracks and their propagation (Le Gué et al., 2024). From a practical point of view, open marine environment make it difficult to control for degradation, but one might act on wear and tear by handling the gear differently when relevant. Physical strain was studied at the seabed (Brakstad et al. 2022), but little is known about the effect of use and wear (e.g., abrasion in the hauling machine, untangling the catch) on the physical degradation of the gillnets. The first aim of this study was to discriminate between the effects of physical strain due to the interactive effect of gear operation and degradation, and degradation only, on the differences in breaking strength, strain and stiffness at break of PBSAT and PA6 gillnet materials.

In addition to gear characteristics, catch efficiency depends on fish morphology, behaviour, and swimming ability. Some modes of capture, i.e., how the fish is caught and retained by the meshes, are more effective at catching fish at a given size than others (with a given mesh size) (Hickford and Schiel 1996; Methven and Schneider 1998; Hovgård et al. 1999; Grati et al. 2015; Hovgård and Lassen 2000; He 2006; Savina et al. 2022). A recent study showed reduced probability of capture by the gills in the PBSAT compared to the PA6 nets for cod (Atlantic cod, *Gadus morhua*) (Cerbule et al. 2022b). Indeed, it was suggested that stiffer and less elastic material such as the synthetic plastics PA6, may catch more fish by gilling, while the more flexible and elastic material such as the bio-resin PBSAT, may fish more by snagging (Grimaldo et al. 2020b). PBSAT has shown to be a viable alternative in Korean fisheries (Park et al. 2010; An et al. 2013; Kim et al. 2016; Seonghun et al. 2020), but experiments conducted in Norway and Greenland for the roundfish species cod and saithe (*Pollachius virens*) as well as the flatfish species Greenland halibut (*Reinhardtius hippoglossoides*) showed lower catch efficiency at commercial size compared to PA6 nets (Grimaldo et al. 2018a, 2018b, 2019, 2020a, 2020b; Cerbule et al. 2022b). We hypothesize that capture mode of smaller flatfish such as plaice (European plaice, *Pleuronectes platessa*) found in the Danish fisheries might be better at retaining catch in the biodegradable material than larger flatfish or roundfish. The second aim of this study was to compare the effect of fish species and resulting capture mode on catch efficiency of PBSAT and PA6 gillnet materials.

We collected data in the Danish coastal gillnet fishery, which is one of the most important commercial gillnet fisheries in Denmark targeting both a flatfish species, plaice, and a roundfish species, cod (Ulrich and Andersen 2004; Savina et al. 2017).

2. Material and methods

2.1. Gear design and deployment

Netting panels were custom-made by the same supplier S-EnPol (Korea, bought in 2020 when the company was still in activity) according to the commercial requirements for the Danish commercial coastal plaice and cod fishery using Double weaver's knots. The biodegradable nets were made of PBSAT (most suited commercially available biodegradable material at the time of the study), and the standard nets of PA6. Description of the materials including molecular weight and Young's modulus are given in Le Gué at al. (2024).

The nets were mounted by the gear manufacturer Hvalpsund Net (Mørenot, Denmark) for the Danish commercial coastal plaice and cod fishery. Each gillnet sheet had 75 mm half-mesh size (150 mm full mesh size), was made of 0.40 mm monofilament twine, 15.5 meshes deep, 4000 knots long and green in color. The netting panel was mounted with a floatline of 1000 g / 100 m buoyancy (no. 2 flex, Hvalpsund) with 4 mm hanging wire and a leadline of 7 kg / 100 m weight (no. 3 with lead, Hvalpsund) with a 4 mm hanging wire. The netting was mounted 5 meshes on 21.5 cm on the floatline and 5 meshes on 23.5 cm on the leadline. Consequently, each mounted gillnet sheet was about 55 m long and had a hanging ratio of 30%. Inner mesh size measurements were taken for 20 gillnet meshes for each PBSAT and PA6 gillnets in the dry state before the sea trials by inserting a steel ruler and using light hand force to stretch the mesh (Holst et al., 1998).

All nets were deployed for 20-25 hours from a commercial Danish gillnetter (vessel length 9.44 m and engine power 53 kW) on shallow sandy fishing grounds off the coast of Hirtshals (Skagerrak). A total of eight PBSAT and eight PA6 nets were deployed in an alternated order with about 1 m between individual panels to form two fleets (Figure 1). The nets were joined as one long fleet for the last four days of the trial to facilitate handling by the commercial fisher. Following each deployment, each fleet was hauled onboard using a net hauler (Netop, Denmark).

We designed our experiment to test differences between the two netting materials (PBSAT, PA6) at the beginning of (spring) and throughout (summer, autumn) the commercial fishing season. The initial trials were conducted over ten days in May-June 2021. The nets were used for three additional days in mid-July 2021 but very few cod catches made us postpone the trial, and nets were thus kept in the fisher's storage unit at the harbour (wooden crates in a small shed) following commercial practices. The final trials were conducted over ten days in September 2021.

2.2. Mesh breaking force, strain and stiffness

Since earlier results suggest that stiffness may better explain the difference in catch efficiency between biodegradable and synthetic gillnets than tensile strength (Grimaldo et al. 2020b), we determined and compared the tensile strength, strain and stiffness at break of PBSAT and PA6 meshes. Tensile strength is how much load the material can withstand without breaking when it is stretched. Strain helps determine the flexibility of the material, while stiffness refers to a material's ability to resist strain when subjected to an applied load.

Tensile properties of the gillnet samples were found by strength tests performed in accordance with ISO 1806:2002 on determination of mesh breaking load of netting in fishing nets (Figure 2), for which mesh breaking force and resulting stiffness of meshes is given in N. We used an electromechanical test machine from Instron equipped with a load cell of 1 kN capacity. Tensile testing was performed in wet conditions, with samples that had been wetted for 24-72 hours at room-tempered tap water. All fibres were kept in the climate room until right before testing at 23 °C and 65% relative humidity. The fibres were tested within 20 min after removing them from the climate room. New samples were also tested in dry conditions to consider the effect of water on tensile properties. Initial mesh length of gillnets was found as the mesh opening at pretension of 1 N. A displacement-controlled tensile load was applied with a rate of 120 mm/min for both PBSAT and PA6 (adjusted according to the mesh size) to have the same test settings for all samples. Tensile properties were measured and found based on at least 18 replicates. Only samples where the break happened at the knot were accepted according to the principle of the ISO standard. The standard also prescribes that failure must happen within 20 ± 3 s. However, this was not possible to achieve for the different net materials, when the rate was kept the same for all samples. Therefore, failures that happened within 20 ± 5 s were considered acceptable.

For each replicate, the tensile strength at break was determined as the peak of the load-elongation curve, and the corresponding elongation was taken as the elongation at break. Strain was calculated as the displacement / (2 x mesh opening) in %. The stiffness of the mesh was determined as the slope of the load-elongation curve from 0.2 to 0.6 x tensile strength at break. The mesh stiffness versus strain was determined by calculating the slope using a window of 10 N width at different strain levels. Results for each set of samples are given as the average of all tested replicates.

We tested differences between the two netting materials (PBSAT, PA6) at several timepoints throughout the commercial fishing season: at the beginning of the experiment, at the end of the first sea trial (spring) after 10 days of use and at the end of the second sea trial (autumn) after 4 months of use and storage. We used difference (delta) in mean results with 95% percentile confidence interval based on bootstrapping (1000 repetitions). There is a significant difference if delta does not contain 0.00 within the confidence interval (Efron 1982; Herrmann et al. 2018).

2.3. Wear and tear effect

For each netting material (PBSAT, PA6) and each timepoint (at the beginning, after 10 days and after 4 months), we applied the procedures described above for two sample types to investigate the effect from wear and tear due to fishing, i.e., tension in the netting including when hauling the net and potential damages at the bottom, or during sorting when disentangling the catch. The first samples consisted of several small pieces of netting (PBSAT and PA6, ~ 1 m^2) put in a meshed net bag on the headline of the gillnet fleets at the beginning of the experiment so that the netting was protected (“Bag”). The second samples consisted of small pieces of netting cut directly from the netting panels (PBSAT and PA6, ~ 1 m^2), i.e., the “fishing” netting.

2.4. Catch comparison and catch ratio

All plaice and cod were measured onboard for their total length to the closest cm below. To assess the relative catch performance of PBSAT against PA6 netting, length-dependent catch comparison and catch ratio analyses (Herrmann et al. 2017) were performed separately for plaice and cod. Count data for number of fish in the different length classes *l* of each species were used to estimate the sizedependent catch comparison rate *CC*(*l*) with 95% Efron percentile confidence intervals (Efron 1982). We considered all fleets from a fishing day to constitute one deployment. The experimental CC_l summed over all gillnet fleet deployments *h* during each season is expressed by:

$$CC_l = \frac{\sum_{j=1}^{h} nPBSAT_{jl}}{\sum_{j=1}^{h}\left\{nPBSAT_{jl} + nPA6_{jl}\right\}} \quad (1)$$

where $nPBSAT_{jl}$ and $nPA6_{jl}$ are the numbers of individuals of length class *l* caught by the PBSAT and PA6 nets, respectively, in deployment *j*.

To model the length-dependent catch comparison rate *CC*(*l*) averaged over hauls, we used maximum likelihood estimation by minimizing the following expression:

$$-\sum_{j=1}^{h}\sum_{l}\left\{nPBSAT_{jl} \times ln(CC(l,\boldsymbol{v})) + nPA6_{jl} \times ln(1.0 - CC(l,\boldsymbol{v}))\right\} \quad (2)$$

where $\boldsymbol{v}$ represents the parameters describing the catch comparison rate $CC(l, \boldsymbol{v})$. We adapted a flexible model for $CC(l, \boldsymbol{v})$ often applied in catch comparison studies (Krag et al. 2014):

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

where f is a polynomial of order *k* with coefficients v_0 to v_k so that $\boldsymbol{v} = (v_0,\ldots, v_k)$. To enable sufficient flexibility in the model, f was considered up to an order of four. Leaving out one or more of the parameters $v_0,\ldots,v_4$ provided 31 additional models that were considered as potential models to describe $CC(l, \boldsymbol{v})$. The selection of the final models was based on multimodel inference (Akaike 1971; Burnham and Anderson 2002; Herrmann et al. 2017). The ability of the combined model to describe the experimental data was based on the *p*-value, which is calculated based on the model deviance and degrees of freedom (Wileman et al. 1996; Herrmann et al. 2017). For the combined model to be a candidate model to describe the experimental data, the *p*-value should not be < 0.05 and the model deviance and the degrees of freedom should show values within the same order of magnitude (Wileman et al. 1996). We used a nested bootstrapping method (1000 bootstrap repetitions) to estimate the 95% confidence intervals for $CC(l, \boldsymbol{v})$ that accounts for uncertainty due to within- and between-deployment variation in the cath data (Lomeli et al. 2019).

To quantify the differences in catches between the PBSAT and PA6 nets, we estimated the catch ratio $CR(l,\boldsymbol{v})$ from the relationship with $CC(l,\boldsymbol{v})$ (Herrmann et al. 2017):

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

If the catch efficiency of both nets is equal, i.e., if there is no significant effect of the netting material on the catch efficiency, the $CR(l,\boldsymbol{v})$ would be 1.0. In contrast, $CR(l,\boldsymbol{v})$ = 1.25 and $CR(l,\boldsymbol{v})$ = 0.75 would mean that the PBSAT nets on average catch 25% more and 25% less individuals of length *l* than the PA6 nets, respectively.

Catch comparison results are commented with reference to a Minimum Conservation Reference Size (MCRS, threshold for commercial size) of 27 cm for plaice and 30 cm for cod in Skagerrak.

2.5. Capture mode probability

2.5.1. Capture mode categories

During the hauling of each individual gillnet sheet (PBSAT or PA6), all plaice and cod were registered for their mode of capture in one of ten categories, distinct for flatfish and roundfish (Figure 3), before handling the fish. Specifically, the netting section around each fish was carefully unfolded or stretched out to identify the capture mode as the fish was still held in the netting wall. This was performed to identify the initial capture mode and avoid additional entanglement caused by deck handling. In total, five observers participated in the two sea trials. All observers were trained for identifying the capture modes similarly, and there were always two observers onboard during the entire data collection.

The capture mode categories were adapted from previous work (Hovgård et al. 1999; Hovgård and Lassen 2000; Wileman et al. 2000; Holst et al. 2002; Savina et al. 2022) and adjusted after observations during a pilot experiment onboard prior to the trials. Specifically, due to the specific morphology of the flatfish, some capture modes had not been observed in previous studies mainly focusing on roundfish species. The primary mode of capture in each instance was defined by the position and tension of the twine. The tightest meshes indicated the primary mode capturing the fish in the netting, or, alternatively, the position of the net mark, i.e., a wound on the fish's body caused by mesh chafing (Yokota et al. 2001). A fish was assigned one or several modes of capture or classified as «Uncertain» if it was difficult to determine the primary mode of capture.

2.5.2. Assumed primary capture mode

In case multiple capture modes were observed for one individual, we assumed a primary capture mode according to the following principles (Savina et al. 2022). In general, we defined the primary mode based on the principle of likely sequence. It is expected that the fish will penetrate the meshes first with the head (swimming forward). If caught further down the body, then in a second time the fish can be snagged further up towards the head. Indeed, it is unlikely that a fish would be caught by the head after being caught by the mouth, or maxillary. Therefore, we assumed that the primary capture mode for the multiple modes, for example, when the fish is registered captured by "mouth", or "maxillary", and "head" would be "head". In line with this principle, we propose that a fish cannot be caught by the gill after being caught by the mouth, maxillary, or head, and similarly cannot be caught by the body after being caught by the mouth, or head, or gill. We always assumed that entanglement happened after the initial capture, and cases with entanglement were considered with the other capture mode as primary, e.g., maxillary or head, or gill. All other multiple occurrences, i.e., not possible to decide (mouth and maxillary) or more than three capture modes, were treated as "Uncertain" in a conservative approach (Savina et al. 2022).

2.5.3. Modelling the length-dependent and length-integrated capture mode probability

We used the numbers and length measurements of fish in gillnets in each of the modes to determine, conditioned capture, the length-dependent probability for fish being caught with each of the capture modes and for each net type (Savina et al. 2022). The total number of modes was limited to seven due to software restrictions. For plaice, for which data was collected for ten different modes, "Mouth" and "Tip" were considered as one mode (i.e., "Mouth, Tip"), and we did not include "Pelvic fin" (mode with lowest number of individuals) and "Uncertain". Conditioned capture, the expected probability for capturing a fish of total length *l* in capture mode *q* will be:

$$CPq_l = \frac{\sum_{j=1}^{h} n_{qlj}}{\sum_{j=1}^{h} \sum_{i=1}^{Q} n_{ilj}} \quad (5)$$

where n_{qlj} is the number *n* of fish caught per length class *l* with capture mode *q* in deployment *j,* where all fleets from a fishing day constitute a deployment. *h* is the total number of deployments. *Q* is the number of capture modes *i* considered. The functional description of the capture mode probability $CPq(l, \boldsymbol{v})$, experimentally expressed by Equation (5), was obtained using maximum likelihood estimation by minimizing Expression (6):

$$-\sum_{j=1}^{h} \sum_{l} \left\{ n_{qlj} \times ln[CPq(l,\boldsymbol{v})] + \left(-n_{qlj} + \sum_{i=1}^{Q} n_{ilj} \right) \times ln[1.0 - CPq(l,\boldsymbol{v})] \right\} \quad (6)$$

where $\boldsymbol{v}$ represents the parameters describing the capture mode probability curve defined by *CPq*(*l*, $\boldsymbol{v}$) that spans the value range [0.0;1.0]. *CPq*(*l*, $\boldsymbol{v}$) is modelled as (Krag et al. 2014; Herrmann et al. 2017; Savina et al. 2022):

$$CPq(l,\boldsymbol{v}) = \frac{exp[f(l,v_0,\ldots,v_k)]}{1+exp[f(l,v_0,\ldots,v_k)]} \qquad (7)$$

In Equation (7), *f* is a polynomial of order *k* with coefficients v_0-v_k, such that $\boldsymbol{v} = (v_0,\ldots,v_k)$. The values of the parameters $\boldsymbol{v}$ describing *CPq*(*l*, $\boldsymbol{v}$) are estimated by minimizing the Expression (6). We considered *f* of up to an order of 4. Leaving out one or more of the parameters $v_{0,}\ldots,v_4$, at a time resulted in 31 additional candidate models for the capture mode probability function $CPq(l,\boldsymbol{v})$. Among these models, the mode probability was estimated using the multi-model inference to obtain a combined model (Burnham and Anderson 2002; Herrmann et al. 2017).

We used a bootstrapping method (1000 bootstrap repetitions) to estimate the 95% percentile confidence intervals to account for uncertainty due to within- and between-deployment variation in the mode of capture (Savina et al. 2022).

Length-integrated average value for the capture mode probability ($CPq_{average}$) was estimated directly from the experimental catch data using the following equation:

$$CPq_{average} = \frac{\sum_l \sum_{j=1}^{h} n_{qlj}}{\sum_l \sum_{j=1}^{h} \sum_{i=1}^{Q} n_{ilj}} \qquad (8)$$

where the outer summations include the size classes in the catch during the experimental fishing period. In contrast to the length-dependent evaluation of the capture mode probability curve $CPq(l,\boldsymbol{v})$, $CPq_{average}$ are specific for the population structure encountered during the experimental trials and cannot be extrapolated to other scenarios in which the size structure of the fish species may be different (Savina et al. 2022).

2.5.4. Modelling differences in capture mode probabilities

As resampling was random and independent between the two bootstrap populations of results for CPq_{PBSAT} and CPq_{PA6}, it is valid to generate the bootstrap population of results for the difference in capture mode probabilities between the PBSAT and PA6 nets (“Delta”) and Efron percentile 95% confidence bands (Efron 1982) using the two independently generated bootstrap files (Herrmann et al. 2018; Cerbule et al. 2022a). If the value 0.0 was not within the obtained confidence bands, then the capture mode probability for PBSAT and PA6 differed significantly.

2.6. Software

We used the statistical software SELNET (Herrmann et al. 2012) to analyse the catch comparison and capture mode data. We used the packages dplyr (Wickham et al. 2020) for data formatting and ggplot2 (Wickham 2016) for graphical output in R statistical software (R Core Team 2021).

3. Results

3.1. Gear design and deployment

Measurements of the mesh openings showed that the mean mesh size was 148.0 ± 1.44 mm for the PBSAT and 148.8 ± 0.36 mm for the PA6 gillnets (mean ± standard deviation).

We caught a total of 1652 plaice and 905 cod (spring and autumn trials), out of which 1 plaice and 5 cod were not included in further analysis due to missing length information (Table 1).

3.2. Mesh breaking force: initial characterisation, and wear and tear effect

We only accounted for break at the knot to follow the ISO standard (Table 2), but, contrary to PA6, there were many (invalid) occurences where the PBSAT broke at other points of the netting.

Dry and wet samples showed similar loads, strains and stiffness at break for both PBSAT and PA6 (Table 2, Figure 4). Further results only considered the wet state, representative of the behavior of the mesh in use after deployment at sea.

Figure 4 (left) shows typical load-strain curves obtained from the mechanical testing of dry and wet meshes made from PBSAT and PA6, with the peak of each curve being the failure. A small jump towards the end of the elongation curve (Figure 4) indicated that the monofilament slips in the knot, causing a local loss of load, before the knot starts to tight again, resulting in a load increase. Such local loss of load leads to an overestimation of the mesh strain and is more visible on the working curves for PA6 meshes as they are more slippery, leading to an increase of the mesh strain up to 1.5% (Figure 4). Figure 4 (right) also shows an inflection in the mesh stiffness with increasing mesh strain for PBSAT meshes, whereas PA6 meshes have a more linear increase in the stiffness. PBSAT meshes are stiffer than PA6 meshes for small strains, but their stiffness decreases with increasing load, while stiffness of PA6 meshes increases.

Already at the start of the experiment (unused netting), load, strain and stiffness at break were significantly lower for the PBSAT compared to the PA6 meshes (Table 2, Figure 4). Further comparisons were thus only run between fishing and bag samples for each material and season independently. The difference due to the interactive effect of gear operation and degradation, and degradation only, was only significant for PA6 (Table 2). After 10 days, the fishing PA6 meshes were significantly stiffer than those protected in the bag. On the contrary, after 4 months, the load, strain and stiffness at break of the PA6 meshes protected from wear and tear (i.e., “Bag”) were all significantly higher than those fishing.

3.3. Catch comparison and catch ratio

Due to low cod abundance during the second set of trials, catch comparison results for cod in used nets need to be taken with precaution since they are based on a very limited number of observations leading to uncertainty in the estimated catch ratio curve. Uncertainties are however reflected in the confidence bands around the catch ratio curves that are provided along with the results. The ability of the catch comparison curve to describe the experimental data was demonstrated by a p-value >0.05 together with residual deviances and degrees of freedom within the same order of magnitude (Table 3). For both plaice in spring and cod in autumn, the p-value was lower than 0.05 (Table 3), but the modelled curves followed the main trend in the data (Figure 5) and the low p-value was considered to be due to overdispersion in the experimental data.

Contrary to plaice, there was a significant difference between PBSAT and PA6 for capturing cod already after 10 days (spring) for fish between 33 and 42 cm, i.e., above MCRS (Table 3, Figure 5). At its lowest at 37 cm, the catch ratio for cod showed that the PBSAT nets caught 21% (CI: 3-42%) less individuals than the PA6 nets.

There was a significant difference between PBSAT and PA6 for both plaice and cod in the autumn (Table 3, Figure 5). After 4 months, the PBSAT nets caught down to 80% (CI: 70-91%) less plaice and 58% (CI: 38-79%) less cod than the PA6 nets, all above MCRS.

3.4. Length-dependent and length-integrated capture mode probability

Due to the low abundance of cod during the fishing trials in September 2021, few observations did not allow estimations of capture mode probability. The capture modes were observed for a total of 1639 plaice and 892 cod (missing capture mode for 12 plaice and 8 cod, Table 1), out of which 23 plaice were classified as “Uncertain” or “Pelvic fin” and thus not included in further analysis.

We could observe a single mode of capture for 66% of the plaice, mainly captured by the anal spine to the body, and 96% of the cod, mainly captured by the mouth. For 1% of the plaice and 0.3% of the cod, we were able to assume a primary mode based on the principle of likely sequence. Less than 1% of the capture modes for both species were left uncertain.

The ability of the capture mode probability curves to describe the experimental data was verified by the fit statistics (Table 3). In both the PBSAT and PA6 nets, the main capture mode for plaice was by the anal fin to body, with more than 65% of observations at all seasons (Table 3). There was a minor contribution of capture by the body and fish being entangled, with about 10-15% of the fish caught (Table 3). Cod was mostly caught by the mouth, with about 95-96% of the fish in both the PBSAT and PA6 nets (Table 3).

We compared differences in capture mode probability between PBSAT and PA6 when the catch efficiency was significantly different, i.e., for plaice after 4 months in the autumn and for cod after 10 days in the spring. There was no significant difference in capture mode probability between PBSAT and PA6 neither for plaice, nor for cod (Table 3).

4. Discussion

In this study, we aimed to discriminate between the effects of physical strain due to the interactive effect of gear operation and degradation, and degradation only, on the differences in breaking strength, strain and stiffness at break of PBSAT and PA6 gillnet materials, and to compare the effect of fish species and resulting capture mode on catch efficiency of PBSAT and PA6 gillnet materials.

We should first highlight some methodological limitations to our study, which we believe are key factors to be accounted for when further testing for new bio-resins in comparison to e.g. ISO guidelines initially drafted for synthetic plastics. The slipping in the knot lead to an overestimation of the length during the test. Since the stiffness is the ratio between load and elongation, our test underestimates the stiffness of the mesh. We also noticed that, unlike PA6 meshes, the PBSAT meshes could easily break at other points of the netting than the knot, which implies that some parts of the PBSAT meshes were at least 50% (i.e., 2 monofilaments for one knot) less resistant. In line with previous studies, we demonstrated that PBSAT was weaker and elongated more at break than PA6 of similar twine diameter (i.e., 0.55 mm, since twine diameter affects breaking strength) (Bae et al. 2013; Kim et al. 2016; Grimaldo et al. 2020a, 2018b). Our results apply only for meshes with knots and thus it is not possible to compare with previous studies testing the monofilament only (Seonghun et al. 2020; Brakstad et al. 2022). It is also important to note that our experiment used the most suited commercially available biodegradable material at the time of the study, i.e., PBSAT, but it is not necessarily the most successful resin for gillnets (see e.g. further development of PBEAS) and unused nets (such as those used in the spring) do not mean “degradation-free”, which can happen already during transport and storage. Indeed, the breaking strength of PBSAT netting of comparible diameter was lower in our study (65 N at the start of the experiment) than in previous studies, for which the average breaking strength for new PBSAT meshes were between 109 N (11.1 kg) and 130 N (13.3 kg), decreasing down to 93 N (9.5 kg) at most after 92 deployments (Grimaldo et al. 2018a, 2020b). We can however compare the PBSAT behavior against its standard baseline (PA6 in this case) to try and understand the operational drivers of observed differences in catch efficiency.

The PBSAT mesh was much weaker compared to the PA6 already at the beginning of our experiment. We did not find any effect of the interactive effect of gear operation and degradation, compared to degradation only, on breaking strength, strain and stiffness at break for PBSAT meshes. However, we observed that PBSAT meshes were stiffer than PA6 meshes for small strains, which make them harder to open compared to PA6 meshes and could make it more difficult for the fish to be caught, resulting in lower catch efficiency. When handling the catch, we also observed that the difference in visible damage (large holes) between the PBSAT and PA6 netting got bigger as the nets got older. Such large holes in the netting may then directly affect catch efficiency, in line with observations at the three scales of interest for commercial application (twine, mesh with knots and netting panel in Le Gué et al., 2024) that demonstrated a clear weakness at the knot.

Lower catch efficiency over time in PBSAT gillnets is in line with the results of earlier studies in the Norwegian cod fishery (Grimaldo et al. 2018b, 2020a; Cerbule et al. 2022b), with a 57.50% (CI: 37.93-79.49%) reduction in catch efficiency for cod between PBSAT and PA6 gillnets after 4 months observed in our study compared to e.g. 50.0% (CI: 31.4–73.3%) and 73.4% (51.9–102.7%) after 3 months (Grimaldo et al. 2018b). As a reference point, changes on a Ø55 mm PBSAT surfaces (i.e., axial cracks) in a natural seawater-sediment microcosm became apparent after 24 months of incubation (Brakstad et al. 2022). Reduction in catch efficiency does not match biodegradation rates observed in controlled systems, and thus has to also result from a combination of weaker mechanical properties worsened by degradation during e.g. transport and storage. It is important to note that, though our experiment started with unused nets, it was not possible to fully manage many uncontrolled conditions before our experiment even started that can affect degradation of the two materials, i.e., several production sites in Asia, transport from Korea to Denmark, storage before mounting at the net maker, and eventually storage at the research institute before sea trials.

To the best of our knowledge, this study was the first assessing length-dependent capture modes in gillnets for flatfish species. Modes of capture depend on the specific gillnet design and its parameters such as hanging ratio, mesh size or material type (Hansen 1974; Hamley 1975; Hovgård 1996; Samaranayaka et al. 1997; Hovgård et al.,1999; Wileman et al. 2000; Yokota et al. 2001; Holst et al. 2002; He, 2006; Grati et al. 2015; Cerbule et al. 2022b). In this study, we observed the performance of PBSAT and PA6 gillnets, keeping other gear design parameters similar. The estimation of capture mode probability provided valuable information to explain the observed differences in catch efficiency when previously assessing the performance of biodegradable gillnets for cod (Cerbule et al. 2022b), but we did not find any significant differences between the PBSAT and PA6 nets in our study, neither for plaice, nor for cod. The main capture mode for plaice was by the anal fin to body. The main capture mode for cod was by mouth, as fish are too small to be caught in other capture modes with respect to the fish size, morphology and mesh geometry (fish up to 55 cm total length; Savina et al. 2022). Loss of cod already after 10 days, compared to plaice for which losses were only significant after 4 months, might then only be related to differences in the two species' shape and swimming ability in relation to the higher likelihood of PBSAT to break compared to PA6. Differences in species traits might however not be valid for all species, as use of PBSAT did not affect overall species composition in the same coastal Danish fishery for plaice and cod (Cerbule et al. 2022a).

Currently, the use of gillnets made of biodegradable material in the commercial and recreational fisheries is optional. Higher production costs, lower catch efficiency and lower lifespan are serious limits to the commercial use of PBSAT gillnets (Standal et al. 2020). Our trials were run over the course of a few months while, in this fishery, the gillnets are normally used for longer periods, i.e., up to 1 year if fished constantly, but they are often used during a season of 3-5 months over several years. The bio-resins would thus need to provide comparable catch efficiency to the standard material (PA6 in our case) not only during the first deployments, but also over a few months for several years. Because gillnetters often target several species, one should also consider optimal tensile properties for both flat and roundfish species. Systematic mechanical studies of biodegradable candidates are needed to provide an optimal catch and degradation profile that would be accepted by the industry. Considering the cost of sea trials, mechanical properties should be properly assesssed before testing at sea. We can only stress the need to propose guidelines suited to testing of alternative new materials. Future work should also look into the main drivers of the degradation process of these materials.

Data availability

Upon request to corresponding author.

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Contributors' statement

E.S.: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization (including figure 1, 3 and 5), Writing – original draft

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Competing interests

The authors declare there are no competing interests.

References

Akaike H. 1971. Information theory and an extension of the maximum likelihood principle. 2nd International Symposium on Information Theory. Abstracts of Papers 276.

An H.-C., Kim S.-H., Lim J.-H., Bae J.-H. 2013. Catching efficiency of the biodegradable gill net for Pacific herring (*Clupea pallasii*). J. Kor. Soc. Fish. Tech 49: 341–351. https://doi.org/10.3796/KSFT.2013.49.4.341

Ando M., Nishiyabu A., Tsukamasa Y., Makinodan Y. 1999. Post-mortem softening of fish muscle during chilled storage as affected by bleeding. J. Food Sci. 64: 423–428. https://doi.org/10.1111/j.1365-2621.1999.tb15056.x

Bae B.-S., Lim J.-H., Park S.-W., Kim S.-H., Cho S.-K. 2013. Catch characteristics of the gillnets for flounder by the physical property of net filament in the East Sea. J. Kor. Soc. Fish. Tech. 49: 95–105.

Brakstad O.G., Sørensen L., Hakvåg S., Føre H.M., Su B., Aas M., Ribicic D., Grimaldo E. 2022. The fate of conventional and potentially degradable gillnets in a seawater-sediment system. Mar. Pollut. Bull. 180: 113759. https://doi.org/10.1016/J.MARPOLBUL.2022.113759

Burnham K., Anderson D. 2002. Model selection and multimodel inference: A practical Information-Theoretic Approach. New York, Springer. https://doi.org/10.1007/978-0-387-22456-5_7

Cerbule K., Savina E., Herrmann B., Larsen R.B., Feekings J.P., Krag L.A., Pellegrinelli A. 2022a. 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

Cerbule K., Herrmann B., Grimaldo E., Larsen R.B., Savina E., Vollstad J. 2022b. 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

Dahm E., Suuronen P., Lehtonen E. 1989. Weathering experiments with netting material for stationary fishing gear. ICES Fish Capture Committee Paper C.M. 1989/B:34.

Efron B. 1982. The Jackknife, the Bootstrap and Other Resampling Plans. CBMS-NSF Regional Conference Series in Applied Mathematics, Monograph 38. SIAM, Philadelphia. http://dx.doi.org/10.1137/1.9781611970319.

Grati F., Bolognini L., Domenichetti F., Fabi G., Polidori P., Santelli A., Scarcella G., Spagnolo A. 2015. The effect of monofilament thickness on the catches of gillnets for common sole in the Mediterranean small-scale fishery. Fish. Res. 164: 170–177. https://doi.org/10.1016/j.fishres.2014.11.014

Grimaldo E., Herrmann B., Vollstad J., Su B., Moe Føre H., Larsen R.B., Tatone I., Pol M. 2018a. Fishing efficiency of biodegradable PBSAT gillnets and conventional nylon gillnets used in Norwegian cod (*Gadus morhua*) and saithe (*Pollachius virens*) fisheries. ICES J. Mar. Sci. 75: 2245–2256. https://doi.org/10.1093/icesjms/fsy108

Grimaldo E., Herrmann B., Tveit G.M., Vollstad J., Schei M. 2018b. Effect of using biodegradable gillnets on the catch efficiency of Greenland halibut. Mar. Coast. Fish. 10: 619–629. https://doi.org/10.1002/mcf2.10058

Grimaldo E., Herrmann B., Su B., Føre H.M., Vollstad J., Olsen L., Larsen R.B., Tatone I., 2019. Comparison of fishing efficiency between biodegradable gillnets and conventional nylon gillnets. Fish. Res. 213: 67–74. https://doi.org/10.1016/j.fishres.2019.01.003

Grimaldo E., Herrmann B., Jacques N., Kubowicz S., Cerbule K., Su B., Larsen R., Vollstad J. 2020a. The effect of long-term use on the catch efficiency of biodegradable gillnets. Mar. Pollut. Bull. 161: 111823. https://doi.org/10.1016/J.MARPOLBUL.2020.111823

Grimaldo E., Jacques N., Vollstad J., Su B. 2020b. Effect of mechanical properties of monofilament twines on the catch efficiency of biodegradable gillnets. PLoS One 15: e0234224. https://doi.org/10.1371/journal.pone.0234224

Hamley J. 1975. Review of gillnet selectivity. J. Fish. Res. Board Can. 32: 1943–1969.

Hansen R.G. 1974. Effect of different filament diameters on the selective action of monofilament gillnets. Trans. Am. Fish. Soc. 103: 386–387.

He P. 2006. Gillnets: Gear design, fishing performance and conservation challenges. Mar. Technol. Soc. J. 40: 12–19. https://doi.org/10.4031/002533206787353187

He P., Chopin F., Suuronen P., Ferro R.S.T., Lansley J. 2021. Classification and illustrated definition of fishing gears. FAO Fisheries and Aquaculture Technical Paper No. 672. Rome, FAO. 110p. https://doi.org/10.4060/cb4966en.

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., 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., Krag L.A., Krafft B.A. 2018. Size selection of Antarctic krill (*Euphausia superba*) in a commercial codend and trawl body. Fish. Res. 207: 49–54. https://doi.org/10.1016/J.FISHRES.2018.05.028

Hickford M.J.H., Schiel D.R. 1996. Gillnetting in southern New Zealand: Duration effects of sets and entanglement modes of fish. Fish. Bull. 94: 669–677.

Holst R., Wileman D., Madsen N. 2002. The effect of twine thickness on the size selectivity and fishing power of Baltic cod gillnets. Fish. Res. 56: 303–312. https://doi.org/10.1016/S0165-7836(01)00328-9

Holst R., Madsen N., Moth-Poulsen T., Fonseca P., Campos A. 1998. Manual for gillnet selectivity. European Commission. 43p.

Hovgård H. 1996. A two-step approach to estimating selectivity and fishing power of research gill nets used in Greenland waters. Can. J. Fish. Aquat. Sci. 53: 1007–1013. https://doi.org/10.1139/f96-022

Hovgård H., Lassen H., Madsen N., Poulsen T.M., Wileman D.A. 1999. Gillnet selectivity for North Sea Atlantic cod (*Gadus morhua*): Model ambiguity and data quality are related. Can. J. Fish. Aquat. Sci. 56: 1307–1316. https://doi.org/10.1139/f99-070

Hovgård H., Lassen H. 2000. Manual on estimation of selectivity for gillnet and longline gears in abundance surveys. FAO Fisheries Technical Paper. 84p.

Kim S., Kim P., Lim J., An H., Suuronen P. 2016. Use of biodegradable driftnets to prevent ghost fishing: physical properties and fishing performance for yellow croaker. Anim. Conserv. 19: 309–319. https://doi.org/10.1111/acv.12256

Kim M.K., Yun K.C., Kang G.D., Ahn J.S., Kang S.M., Kim Y.J., Yang M.H., Byun K.S. 2017. Biodegradable resin composition and fishing net produced from same. Patent Application Pub. No. US 2017 / 0215756A1 1, 2015–2018.

Kim P., Kim S., Jeong S., Lee K., Oh W. 2020. Physical properties of biodegradable fishing net in accordance with heat-treatment conditions for reducing ghost fishing. Turk. J. Fish. Aquat. Sci. 20: 127–135. https://doi.org/10.4194/1303-2712-v20_2_05

Krag L.A., Herrmann B., Karlsen J.D. 2014. Inferring fish escape behaviour in trawls based on catch comparison data: Model development and evaluation based on data from Skagerrak, Denmark. PLoS One 9: 0088819. https://doi.org/10.1371/journal.pone.0088819

Le Gué L., Davies P., Arhant M., Vincent B., Tanguy E. 2023. Mitigating plastic pollution at sea: Natural seawater degradation of a sustainable PBS/PBAT marine rope. Mar. Pollut. Bull. 193: 115216.

Le Gué L., Savina E., Arhant M., Davies P., Gayet N., Vincent, B. 2024. Degradation mechanisms in PBSAT nets immersed in seawater. Polym. Degrad. Stab. 225: 110788.

Lomeli M.J.M., Wakefield W.W., Herrmann B. 2019. Evaluating off-bottom sweeps of a U.S. West Coast groundfish bottom trawl: Effects on catch efficiency and seafloor interactions. Fish. Res. 213: 204–211. https://doi.org/10.1016/j.fishres.2019.01.016

Matsushita Y., Machida S., Kanehiro H., Nakamura F., Honda N. 2008. Analysis of mesh breaking loads in cotton gill nets: Possible solution to ghost fishing. Fish. Sci 74: 230–235. https://doi.org/10.1111/J.1444-2906.2008.01517.X/METRICS

Methven D.A., Schneider D.C. 1998. Gear-independent patterns of variation in catch of juvenile Atlantic cod (*Gadus morhua*) in coastal habitats. Can. J. Fish. Aquat. Sci. 55: 1430–1442. https://doi.org/10.1139/F98-025

Park S., Kim S.-H., Choi H.-S., Cho H.-H. 2010. Preparation and physical properties of biodegradable polybutylene succinate/polybutylene adipate-co-terephthalate blend monofilament by melt spinning. J. Kor. Soc. Fish. Tech 46: 257–264. https://doi.org/10.3796/KSFT.2010.46.3.257

Park, S.-W., Kim, S.-H. 2012. Effects of heat setting temperature conditions on the mechanical properties of Polybutylene succinate (PBS) monofilament yarn after net-making. Bulletin of the Korean Society of Fisheries Technology, 48(1), 20–28. https://doi.org/10.3796/KSFT.2012.48.1.020

Park S., Kim S., Lim J., Choi H. 2015. Development of the submerged heat treatment machine for PBSAT(polybutylene succinate adipate–co–terephthalate) monofilament nets and its efficiency. Journal of the Korean Society of Fisheries Technology, 51(1), 94–101. https://doi.org/10.3796/KSFT.2015.51.1.094

Park S., Bae B., Cha B. jin, Kim Y. J., Kwak H. W. 2023. Development of poly(butylene adipate-co-butylene succinate-co-ethylene adipate-co-ethylene succinate) (PBEAS) net twine as biodegradable fishing gear. Marine Pollution Bulletin, 194, 115295. https://doi.org/10.1016/j.marpolbul.2023.115295

R Core Team 2021. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Available: https://www.R-project.org.

Samaranayaka A., Engås A., Jørgensen T. 1997. Effects of hanging ratio and fishing depth on the catch rates of drifting tuna gillnets in Sri Lankan waters. Fish. Res. 29: 1–12. https://doi.org/10.1016/S0165-7836(96)00524-3

Savina E., Krag L.A., Frandsen R.P., Madsen N. 2017. Effect of fisher's soak tactic on catch pattern in the Danish gillnet plaice fishery. Fish. Res. 196: 56–65. https://doi.org/10.1016/J.FISHRES.2017.08.009

Savina E., Herrmann B., Frandsen R.P., Krag L.A. 2022. A new method for estimating length-dependent capture modes in gillnets: a case study in the Danish cod (*Gadus morhua*) fishery. ICES J. Mar. Sci. 79: 373–381. https://doi.org/10.1093/icesjms/fsab267

Seonghun K., Pyungkwan K., Seongjae J., Kyounghoon L. 2020. Assessment of the physical characteristics and fishing performance of gillnets using biodegradable resin (PBS/PBAT and PBSAT) to reduce ghost fishing. Aquat. Conserv. 30: 10. https://doi.org/10.1002/aqc.3354

Sikora J.W., Majewski Ł. 2021. Modern Biodegradable Plastics-Processing and Properties Part II. Materials 14(10): 2523. https://doi.org/10.3390/ma14102523.

Standal D., Grimaldo E., Larsen R.B., 2020. Governance implications for the implementation of biodegradable gillnets in Norway. Mar. Policy, 122: 104238. https://doi.org/10.1016/j.marpol.2020.104238.

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

Tokiwa Y., Calabia B.P., Ugwu C.U., Aiba S. 2009. Biodegradability of plastics. Int. J. Mol. Sci. 10: 3722–3742. https://doi.org/10.3390/ijms10093722

Ulrich C., Andersen B.S. 2004. Dynamics of fisheries, and the flexibility of vessel activity in Denmark between 1989 and 2001. ICES J. Mar. Sci. 61: 308–322. https://doi.org/10.1016/j.icesjms.2004.02.006

Wickham H. 2016. Ggplot2: elegant graphics for data analysis. New York, Springer-Verlag.

Wickham H., François R., Henry L., Müller K. 2021. dplyr: a grammar of data manipulation. R package version 1.0.7. https://cran.r-project.org/package=dplyr.

Wileman D.A., Ferro R.S.T., Fonteyne R., Millar R.B. 1996. Manual of methods of measuring the selectivity of towed fishing gears. ICES Cooperative Research Reports (CRR). 126p. https://doi.org/10.17895/ices.pub.4628

Wileman D.A., Tschernij V., Madsen N., Holst R. 2000. Size selectivity and relative fishing power of Baltic cod gillnets. Havsfiskelaboratoriet. Meddelande, 329: 110–148.

Yokota K., Fujimori Y., Shiode D., Tokai T. 2001. Effect of thin twine on gillnet size-selectivity analyzed with the direct estimation method. Fish. Sci. 67: 851–856. https://doi.org/10.1046/j.1444-2906.2001.00332.x

Yu M., Tang Y., Min M., Herrmann B., Cerbule K., Liu C., Dou Y., Zhang L. 2023. 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. Mar. Pollut. Bull. 195: 115545. https://doi.org/10.1016/j.marpolbul.2023.115545

Table 1. Total number of plaice and cod caught in the PBSAT and PA6 gillnets (n) with mean (min-max) length (L) in cm for each fishing day ("Date", considered as a deployment). Data not included in further analysis due to the low number of fish is shaded in grey. The last four rows present the total number of individuals caught, measured (catch comparison), assessed and analysed for capture mode by species and netting material.

Date	Plaice				Cod			
	PBSAT		PA6		PBSAT		PA6	
	n	L (cm)	n	L (cm)	n	L (cm)	n	L (cm)
2021-05-22	21	34 (27-49)	13	33 (29-39)	43	38 (25-75)	36	39 (25-69)
2021-05-23	6	32 (29-34)	6	32 (29-36)	25	36 (27-46)	54	37 (25-51)
2021-05-24	6	33 (29-38)	14	31 (25-35)	31	38 (22-44)	55	38 (26-56)
2021-05-25	27	32 (24-40)	35	33 (27-41)	72	39 (25-64)	92	38 (26-67)
2021-05-26	32	32 (27-45)	40	33 (25-44)	93	38 (24-56)	100	38 (25-48)
2021-05-27	12	31 (25-38)	8	32 (26-35)	44	38 (27-56)	39	38 (26-66)
2021-05-28	11	33 (25-37)	14	33 (28-42)	34	37 (26-57)	48	36 (26-46)
2021-05-31	37	31 (25-36)	31	31 (24-36)	18	32 (24-43)	19	33 (26-46)
2021-06-01	38	33 (26-48)	23	31 (25-40)	16	36 (28-43)	27	37 (27-48)
2021-06-02	29	32 (22-48)	40	32 (25-42)	22	36 (26-50)	32	36 (26-48)
2021-07-10	6	34 (26-40)	11	34 (24-46)	5	36 (29-49)	4	33 (28-45)
2021-07-12	10	34 (29-37)	26	32 (21-43)	2	45 (42-48)	9	35 (30-52)
2021-07-14	12	28 (22-35)	9	31 (26-35)	3	36 (31-42)	7	38 (28-52)
2021-09-10	156	29 (21-42)	201	30 (23-40)	0	-	0	-
2021-09-11	42	29 (22-38)	51	29 (21-39)	0	-	0	-
2021-09-15	23	32 (28-37)	30	33 (24-39)	0	-	0	-
2021-09-19	8	29 (21-32)	11	33 (29-39)	0	-	0	-
2021-09-20	11	29 (23-37)	11	34 (22-40)	0	-	0	-
2021-09-21	11	33 (28-49)	17	28 (25-31)	0	-	0	-
2021-09-27	11	27 (21-35)	7	29 (24-37)	12	38 (23-58)	18	38 (27-69)
2021-09-28	43	32 (26-44)	47	33 (25-44)	2	31 (30-31)	3	42 (25-59)
2021-09-29	195	32 (24-44)	233	33 (24-48)	2	30 (29-31)	5	37 (25-61)
2021-09-30	37	32 (25-43)	63	34 (25-46)	7	31 (29-36)	14	37 (28-50)
Caught	756	-	896	-	401	-	504	-
Measured	756	31 (21-49)	895	32 (21-48)	398	37 (22-75)	502	37 (25-69)
Assessed for mode	747	31 (21-49)	892	32 (21-48)	393	38 (22-75)	499	37 (25-67)
Analysed for mode	735	31 (21-49)	881	32 (21-48)	393	38 (22-75)	499	37 (25-67)

Table 2. Total number of samples measured (n), load at break, time, displacement at break ("Disp."), strain and stiffness at break are given as mean (standard deviation) for PBSAT and PA6 at the start of the experiment for dry and wet samples, and after 10 days and 4 months for samples cut directly from the netting panels ("Fishing") or put in a meshed net bag on the headline of the gillnet fleets so that the netting is protected from wear and tear ("Bag"). Strain was calculated as the displacement / (2 x mesh opening) with mean mesh size of 148.0 mm for PBSAT and 148.8 mm for PA6. The difference ("Delta") in load, strain and mesh stiffness at break is given at the beginning of the experiment for wet samples between PBSAT and PA6, and after 10 days and 4 months (wet samples) for PBSAT and PA6 samples between "Fishing" and "Bag" as mean (95% percentile confidence intervals). There is a significant difference if delta does not contain 0.00 within the confidence interval, highlighted in bold.

Netting sample		n	Load (N)	Time (s)	Disp. (mm)	Strain (%)	Stiffness (N)
INITIAL CHARACTERISATION							
Dry	PBSAT	20	61.2 (4.1)	19.9 (0.8)	45.6 (2.5)	15.4 (0.9)	194.3 (7.6)
	PA6	20	77.9 (7.5)	17.7 (1.3)	32.6 (2.7)	26.2 (2.5)	298.8 (17.2)
Wet	PBSAT	20	64.5 (4.3)	20.7 (0.9)	47.2 (2.9)	16.0 (1.0)	189.6 (7.2)
	PA6	20	78.8 (6.1)	17.4 (1.1)	33.1 (2.3)	23.6 (7.0)	312.5 (16.0)
	Delta	-	**-14.2 (-17.3; -10.9)**	-	-	**4.3 (3.5; 5.1)**	**-122.9 (-130.5; -115.8)**
AFTER 10 FISHING DAYS							
PBSAT	Fishing	20	61.7 (8.2)	19.3 (1.8)	44.3 (3.8)	15.0 (1.3)	205.1 (10.7)
	Bag	18	59.5 (7.8)	19.5 (1.9)	44.9 (4.5)	15.2 (1.5)	198.1 (16.3)
	Delta	-	2.3 (-2.8; 6.7)	-	-	-0.2 (-1.7; 1.2)	7.0 (-0.9; 16.3)
PA6	Fishing	22	79.5 (9.7)	15.2 (1.5)	39.0 (2.9)	13.1 (1.0)	406.3 (34.4)
	Bag	22	78.0 (7.1)	15.7 (1.1)	39.5 (2.4)	13.3 (0.8)	366.2 (16.6)
	Delta	-	1.5 (-3.4; 6.4)	-	-	-0.8 (-1.8; 0.2)	**40.1 (24.4; 56.4)**
AFTER 4 FISHING MONTHS							
PBSAT	Fishing	22	56.2 (14.5)	17.9 (4.4)	42.7 (8.8)	14.4 (3.0)	207.2 (19.4)
	Bag	22	49.7 (7.7)	17.2 (2.2)	39.7 (4.9)	13.4 (1.6)	212.4 (14.6)
	Delta	-	6.5 (-0.04; 12.5)	-	-	1.0 (-1.6; 3.4)	-5.2 (-14.4; 4.1)
PA6	Fishing	22	70.5 (16.4)	14.4 (2.7)	37.0 (5.3)	12.4 (1.8)	342.9 (37.9)
	Bag	26	78.0 (6.1)	15.6 (1.0)	39.2 (2.4)	13.2 (0.8)	367.3 (14.6)
	Delta	-	**-7.5 (-14.8; -0.7)**	-	-	**-1.6 (-3.2; -0.1)**	**-24.0 (-39.6; -7.4)**

Table 3. Fit statistics given as p-value, deviance and degrees of freedom (DOF), and results of the catch comparison between PBSAT and PA6 (“Catch ratio”) and capture mode analysis for plaice and cod in spring and autumn. The catch ratio is given in % as bias-corrected mean (Efron percentile bootstrap 95% confidence limits), for all length classes (“Total”) as well as individuals below and above the Minimum Conservation Reference Size (MCRS), i.e., undersized individuals (“<MCRS”) and commercial sizes (“>MCRS”) with MCRS of 27 cm for plaice and 30 cm for cod. There is a significant difference if the catch ratio does not contain 100.0 within the confidence interval, highlighted in bold. The difference (“Delta”) in capture mode probability for each mode is given between PBSAT and PA6 for plaice in autumn and cod in spring (season for which each species is caught in significantly lower number in the PBSAT compared to the PA6 nets). There is a significant difference if delta does not contain 0.00 within the confidence interval (no cases observed).

	Season	Material	p-value	Deviance	DOF	Total	<MCRS	>MCRS
Plaice								
Catch ratio	Spring	-	0.0035	39.78	19	101.5 (75.2; 212.5)	118.2 (31.6; 450.0)	100.5 (73.9; 137.9)
	Autumn	-	0.1297	30.72	23	**80.0 (69.9; 90.7)**	121.7 (71.9; 193.3)	**76.96 (65.5; 89.8)**
Mouth, tip	Spring	PBSAT	0.92	8.9	16	1.9 (0.0; 4.5)	0.0 (0.0; 0.0)	2.0 (0.0; 4.9)
		PA6	0.61	12.0	14	1.4 (0.0; 4.0)	0.0 (0.0; 0.0)	1.5 (0.0; 4.2)
	Autumn	PBSAT	0.95	10.6	20	0.6 (0.0; 1.5)	0.0 (0.0; 0.0)	0.6 (0.0; 1.7)
		PA6	0.99	5.3	22	0.8 (0.0; 2.7)	0.0 (0.0; 0.0)	0.8 (0.0; 2.9)
	Delta	PBSAT-PA6	-	-	-	-0.2 (-2.2; 1.1)	0.0 (0.0; 0.0)	-0.2 (-2.4; 1.2)
Head	Spring	PBSAT	1.00	0.0	16	0.0 (0.0; 0.0)	0.0 (0.0; 0.0)	0.0 (0.0; 0.0)
		PA6	0.41	14.5	14	3.2 (0.6; 6.6)	0.0 (0.0; 0.0)	3.4 (0.6; 7.0)
	Autumn	PBSAT	0.24	24.2	20	4.2 (0.4; 13.5)	5.6 (0.0; 30.4)	4.1 (0.5; 12.0)
		PA6	0.88	14.8	22	2.3 (0.0; 4.9)	0.0 (0.0; 0.0)	2.4 (0.0; 5.1)
	Delta	PBSAT-PA6	-	-	-	2.0 (-2.9; 11.8)	5.6 (0.0; 30.4)	1.6 (-3.2; 10.6)
Gill	Spring	PBSAT	0.63	13.6	16	3.8 (0.9; 7.9)	0.0 (0.0; 0.0)	4.0 (1.0; 8.5)
		PA6	0.94	6.9	14	2.8 (0.8; 5.2)	0.0 (0.0; 0.0)	2.9 (0.9; 5.6)
	Autumn	PBSAT	0.29	22.9	20	2.9 (1.1; 5.4)	0.0 (0.0; 0.0)	3.2 (1.3; 6.2)
		PA6	0.56	20.4	22	1.7 (0.3; 3.0)	2.2 (0.0; 7.1)	1.6 (0.3; 2.8)
	Delta	PBSAT-PA6	-	-	-	1.2 (-0.8; 4.1)	-2.2 (-7.1; 0.0)	1.6 (-0.6; 4.8)
Anal fin to head	Spring	PBSAT	0.65	13.3	16	3. 8 (1.1; 7.3)	0.0 (0.0; 0.0)	4.0 (1.2; 7.8)
		PA6	0.73	10.4	14	1.8 (0.0; 4.8)	0.0 (0.0; 0.0)	2.0 (0.0; 5.1)
	Autumn	PBSAT	0.63	17.3	20	1.0 (0.0; 2.2)	1.9 (0.0; 10.0)	0.9 (0.0; 2.3)
		PA6	0.62	19.4	22	2.4 (0.0; 9.5)	0.0 (0.0; 0.0)	2.6 (0.0; 10.2)
	Delta	PBSAT-PA6	-	-	-	-1.5 (-8.8; 1.3)	1.9 (0.0; 10.0)	-1.7 (-9.5; 1.2)
Anal fin to body	Spring	PBSAT	0.62	13.7	16	74.6 (65.5; 84.8)	100.0 (100.0; 100.0)	73.0 (63.3; 83.7)
		PA6	0.21	18.0	14	72.9 (4.3; 79.3)	92.3 (64.3; 100.0)	71.7 (62.4; 78.5)
	Autumn	PBSAT	0.01	37.9	20	65.1 (55.2; 76.6)	81.5 (61.3; 91.1)	63.2 (53.4; 75.7)
		PA6	0.79	16.5	22	65.0 (51.8; 80.5)	84.8 (74.0; 96.4)	63.5 (50.0; 80.1)
	Delta	PBSAT-PA6	-	-	-	0.1 (-18.7; 18.9)	-3.3 (-27.5; 11.2)	-0.4 (-19.6; 19.1)
Body	Spring	PBSAT	0.81	11.1	16	5.2 (1.5; 9.7)	0.0 (0.0; 0.0)	5.5 (1.5; 10.5)
		PA6	0.54	12.9	14	9.2 (4.0; 15.2)	0.0 (0.0; 0.0)	9.8 (4.3; 15.8)
	Autumn	PBSAT	0.77	15.1	20	11.3 (2.1; 20.2)	3.7 (0.0; 9.3)	12.2 (1.7; 21.4)
		PA6	0.01	38.99	22	13.3 (2.8; 22.7)	2.2 (0.0; 11.1)	14.1 (2.9; 23.7)
	Delta	PBSAT-PA6	-	-	-	-1.9 (-16.2; 12.3)	1.5 (-8.0; 8.2)	-1.9 (-17.3; 13.2)
Entangled	Spring	PBSAT	0.65	13.3	16	10.8 (2.1; 20.7)	0.0 (0.0; 0.0)	11.5 (2.4; 22.0)
		PA6	0.00	32.4	14	8.7 (2.6; 15.7)	7.7 (0.0; 40-0)	8.8 (2.1; 16.4)
	Autumn	PBSAT	0.02	35.4	20	15.0 (9.0; 20.6)	7.4 (0.0; 16.1)	15.8 (9.4; 22.5)
		PA6	0.01	39.1	22	14.6 (6.6; 19.0)	10.9 (0.0; 20.0)	14.9 (6.5; 19.5)
	Delta	PBSAT-PA6	-	-	-	0.3 (-7.7; 9.7)	-3.5 (-15.1; 9.9)	0.9 (-7.3; 10.8)
Cod								
Catch ratio	Spring	-	0.3980	38.58	37	**79.3 (62.8; 95.3)**	76.1 (52.3; 113.8)	**80.0 (62.3; 95.6)**
	Autumn	-	0.0111	38.54	21	**57.5 (37.9; 79.5)**	55.6 (14.3; 128.6)	**58.1 (36.4; 81.5)**
Mouth	Spring	PBSAT	0.41	33.1	32	95.2 (92.5; 97.4)	98.5 (95.1; 100.0)	94.5 (90.1; 97.1)
		PA6	0.68	24.0	28	96.4 (93.5; 98.6)	100.0 (100.0; 100.0)	95.6 (92.0; 98.3)
	Delta	PBSAT-PA6	-	-	-	-1.2 (-4.7; 2.7)	-1.5 (-4.9; 0.0)	-1.1 (-5.4; 3.8)
Tip	Spring	PBSAT	1.00	2.0	32	0.3 (0.0; 0.9)	0.0 (0.0; 0.0)	0.3 (0.0; 1.1)
		PA6	0.99	13.3	28	1.0 (0.2; 2.2)	0.0 (0.0; 0.0)	1.2 (0.2; 2.6)
	Delta	PBSAT-PA6	-	-	-	-0.7 (-2.0; 0.3)	0.0 (0.0; 0.0)	-0.9 (-2.3; 0.4)

Head	Spring	PBSAT	0.94	20.7	32	1.5 (0.0; 3.6)	1.5 (0.0; 4.8)	1.5 (0.0; 3.5)
		PA6	0.96	16.1	28	0.8 (0.2; 1.8)	0.0 (0.0; 0.0)	1.0 (0.2; 2.3)
	Delta	PBSAT-PA6	-	-	-	0.7 (-1.3; 2.9)	1.5 (0.0; 4.8)	0.6 (-1.6; 2.7)
Gill	Spring	PBSAT	1.00	2.8	32	0.3 (0.0; 1.3)	0.0 (0.0; 0.0)	0.3 (0.0; 1.5)
		PA6	0.99	13.3	28	0.0 (0.0; 0.0)	0.0 (0.0; 0.0)	0.0 (0.0; 0.0)
	Delta	PBSAT-PA6	-	-	-	0.3 (0.0; 1.3)	0.0 (0.0; 0.0)	0.3 (0.0; 1.5)
Body	Spring	PBSAT	1.00	9.8	32	1.0 (0.0; 2.5)	0.0 (0.0; 0.0)	1.2 (0.0; 3.0)
		PA6	0.98	15.2	28	0.8 (0.0; 1.8)	0.0 (0.0; 0.0)	1.0 (0.0; 2.2)
	Delta	PBSAT-PA6	-	-	-	0.2 (-1.3; 1.8)	0.0 (0.0; 0.0)	0.2 (-1.6; 2.2)
Entangled	Spring	PBSAT	0.83	24.4	32	1.8 (0.0; 4.9)	0.0 (0.0; 0.0)	2.1 (0.0; 6.1)
		PA6	1.00	1.7	28	0.2 (0.0; 0.9)	0.0 (0.0; 0.0)	0.2 (0.0; 1.1)
	Delta	PBSAT-PA6	-	-	-	1.6 (-0.2; 4.8)	0.0 (0.0; 0.0)	1.9 (-0.3; 6.0)
Uncertain	Spring	PBSAT	1.00	0.0	32	0.0 (0.0; 0.0)	0.0 (0.0; 0.0)	0.0 (0.0; 0.0)
		PA6	1.00	11.3	28	0.8 (0.0; 2.3)	0.0 (0.0; 0.0)	1.0 (0.0; 2.7)
	Delta	PBSAT-PA6	-	-	-	-0.8 (-2.3; 0.0)	0.0 (0.0; 0.0)	-1.0 (-2.7; 0.0)

Figure 1. Gear rigging and sampling. A total of eight PA6 (nylon) and eight PBSAT (biodegradable) nets were deployed in an alternated order with about 1 m between individual panels to form two fleets. Samples of both PBSAT and PA6 were put in a meshed net bag on the headline of the gillnet fleets so that the netting is protected from wear and tear (“Bag”) and analysed after 10 days and 4 months, together with samples cut directly from the netting panels (“Fishing”).

Figure 2. Diagram representing how each mesh, made of two monofilaments, was cut from the netting panel and tested for mesh breaking force, strain and stiffness following the ISO 1806 guidelines.

Figure 3. Categories of the capture modes for flatfish (plaice) and roundfish (cod).

Figure 4. Load (N, left) and stiffness (N, right) as a function of mesh strain (%) obtained from the mechanical testing of meshes made from PBSAT, dry in light blue and wet in dark blue, and PA6, dry in orange and wet in red, at the start of the experiment.

Figure 5. Catch comparison rate, catch ratio and number of individuals for plaice and cod in spring and autumn. The upper panels present the modelled catch comparison rate (black line) with 95 % confidence interval (grey shade). The stippled line at 0.5 represents the point at which PBSAT and PA6 have an equal catch rate, with rates >0.5 indicating higher catches in the PBSAT than in the PA6, and rates <.5 indicating lower catches. Circles represent the experimental rates with size proportional to the number of individuals. The lower panels present the estimated catch ratio curve (black curve) with 95 % confidence interval (grey shade). The stippled line at 1.0 represents the point at which both netting materials have an equal catch ratio.

Figure 1.

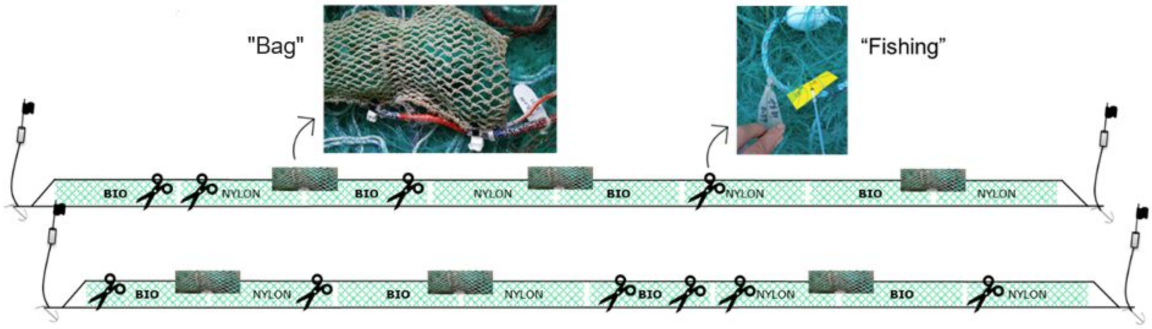


Figure 2.

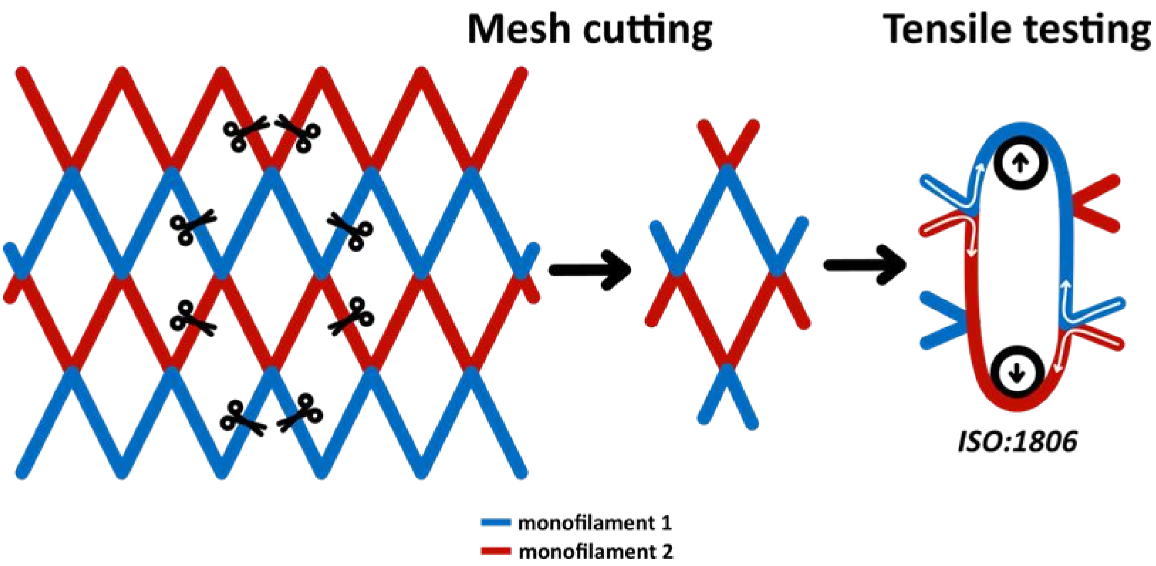
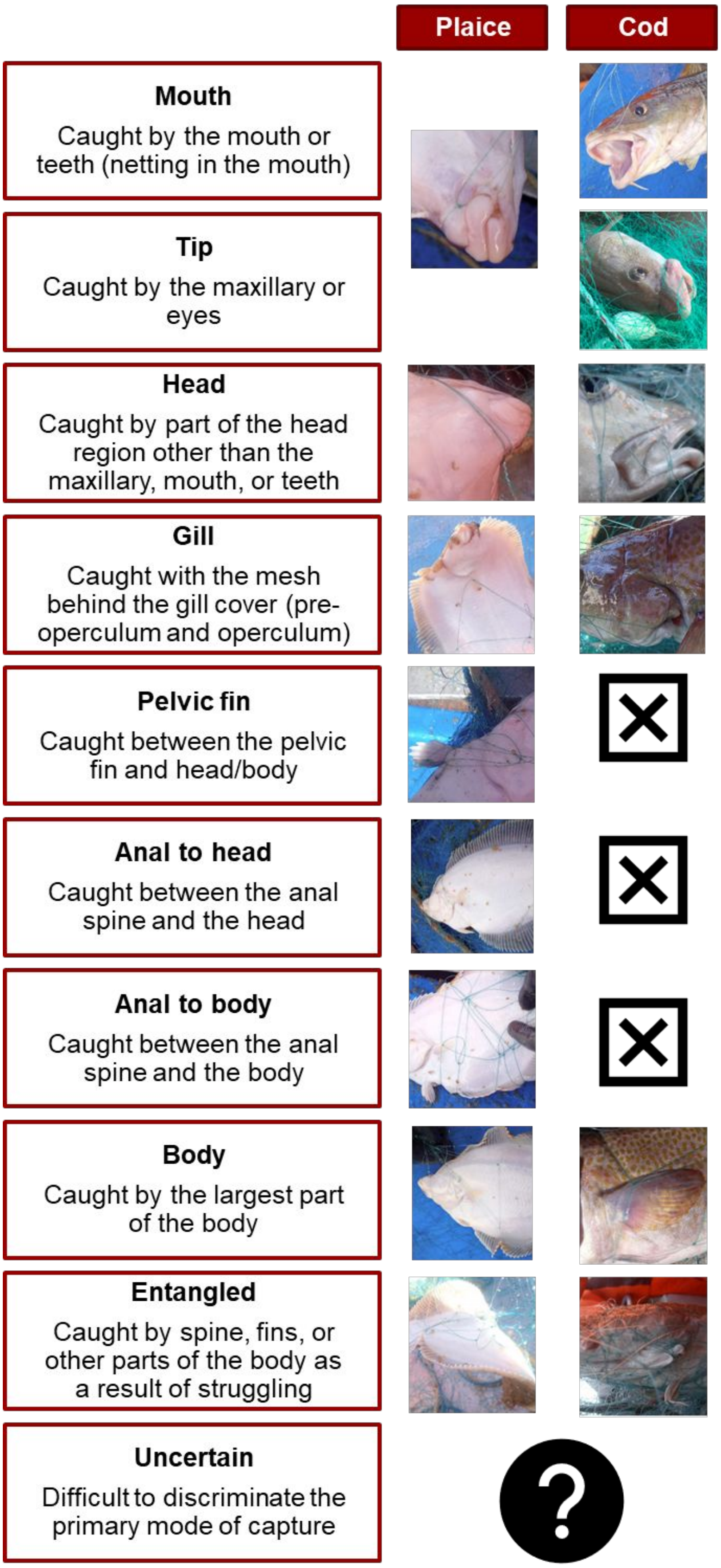


Figure 3.


Plaice
Cod
Mouth
Caught by the mouth or teeth (netting in the mouth)
Tip
Caught by the maxillary or eyes
Head
Caught by part of the head region other than the maxillary, mouth, or teeth
Gill
Caught with the mesh behind the gill cover (pre-operculum and operculum)
Pelvic fin
Caught between the pelvic fin and head/body
Anal to head
Caught between the anal spine and the head
Anal to body
Caught between the anal spine and the body
Body
Caught by the largest part of the body
Entangled
Caught by spine, fins, or other parts of the body as a result of struggling
Uncertain
Difficult to discriminate the primary mode of capture
?

 Canadian Journal of Fisheries and Aquatic Sciences (Author's Accepted Manuscript)

Figure 4.

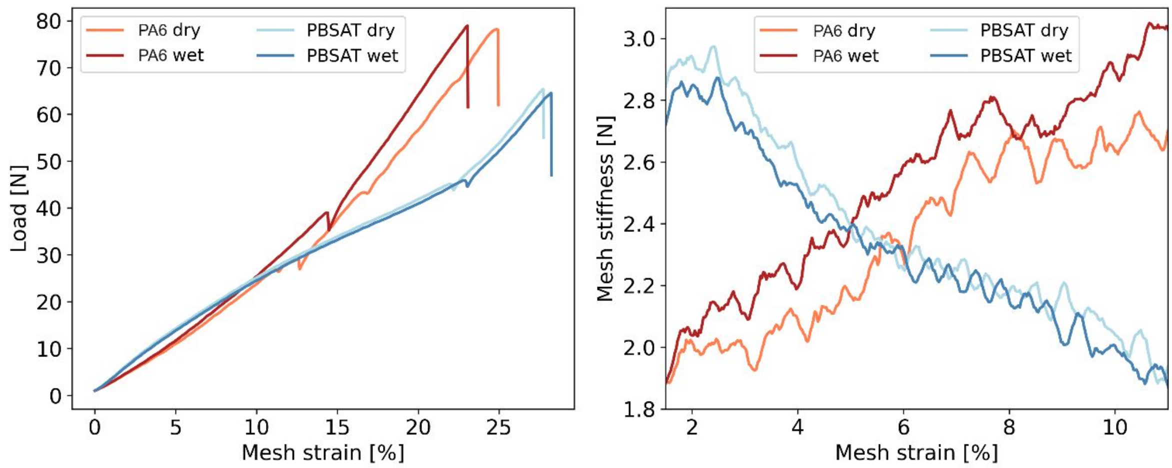


Figure 5.