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Comparison of fishing efficiency between biodegradable gillnets and conventional nylon gillnets

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ABSTRACT

Gillnets made of a new biodegradable resin (polybutylene succinate co-adipate-co-terephthalate (PBSAT) were tested under commercial fishing conditions to compare their fishing performance with that of conventional nylon (PA) nets. The relative catch efficiency between the two gillnet types was evaluated over the entirewinter fishing season for cod (*Gadus morhua*) in northern Norway. The nylon gillnets caught 21% more fish (in numbers) than the biodegradable gillnets throughout the fishing season and generally showed better catch rates for most length classes, except for sizes between 82 and 90 cm. The difference in elasticity and breaking strength could explain the major difference in the size structure of fish caught by each type of gillnets, especially for larger fish. The number of times that the gillnets were deployed affected the relative catch efficiency of the gillnets with the biodegradable continuously loosing efficiency compared to the nylon. Although less catch efficient than nylon gillnets, biodegradable gillnets still show great potential for reduction of ghost fishing and plastic pollution at sea caused by this fishery.

1. Introduction

Gillnets are among the most widely used fishing gears in the world and are commonly used by the commercial and artisanal fleets in all the oceans, fresh water and estuaries areas (Brandt, 2005). The effect of lost gillnets on the ecosystem is not well understood, although investigations have shown that lost gillnets can fish for years after they have been lost, a problem known as ghost fishing (Macfaden et al., 2009). International recognition of this problem is demonstrated through the large number of international organizations and agreements that now focus on lost gillnets and numerous national initiatives that have being implemented around the world (Gilman et al., 2016).

Also, in Norway gillnets are among the most important fishing methods, especially for the coastal fleet, however transparent gillnets are not used at all by the Norwegian fishermen. Instead, coloured gillnets are favoured because fishermen believe that certain colours reduce the contrast between the net and its background and therefore increase the fishing efficiency of the gillnet; also, because coloured gillnets provide a better contrast with the aluminium and/or stainless-steel sorting boards and make the removal of fish from the nets easier. Gillnetting is mostly carried out by the coastal fleet, and in 2017, this fleet was integrated by 5 705 boats smaller than 28 m (length overall, LOA) and used approx. 2.3 million gillnets. Of them, 13 941 gillnets were reported lost at sea in 2017 (Norwegian Environment Agency, 2018) (according to the Norwegian legislation every lost net should be reported). Based on information provided by fishermen, the Norwegian Directorate of Fisheries carry out systematic annual retrieval operation of lost gillnets (and other fishing gears) from the most intensively fished areas along the coast (Humbolstad et al., 2003; Gilman et al., 2016). Despite more than 20 400 lost gillnets have been retrieved since 1983, the recovery rate is considered to be low. Of the 13 941 gillnets that were reported lost at sea in 2017 (Norwegian Environment Agency, 2018), only 815 nets were retrieved in 2017 (Norwegian Directorate of Fisheries, 2018). This low recovery rate is because the low rate of reporting of lost gears and the highly demanding retrieving operations, especially if they are carried out in deep waters (400–1000 m) with strong currents in the areas, and uncertainties associated with the accuracy of the lost gear's position (Norwegian Environment Agency, 2018). Therefore, and parallel to the gear retrieval program, research has also focused on assessing the possibility of using biodegradable

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plastic materials to manufacture gillnets.

In the last decade, a large number of studies have shown that uncoloured (transparent) gillnets made of poly butylene succinate (PBS) resin blended with poly butylene adipate-co-terephthalate (PBAT) resin can be naturally degraded in sea water by the action of bacteria and algae, and simultaneously these studies documented the fishing efficiency of the new nets by direct comparison with conventional nylon gillnets (Park et al., 2007a, 2007b; 2010; Park and Bae, 2008; Bae et al., 2012, 2013; An and Bae, 2013; Kim et al., 2013, 2016). In addition, Kim et al. (2016) reported that gillnets made of blended PBS and PBAT resin began to degrade within two years of being submerged in sea water and that by then those gillnets would have become weak enough to stop catching fish. However, gillnets made of blended PBS and PBTA resins have poor tinting strength and can cause problems such as decreased strength and elasticity due to coloration (Kim et al., 2017).

Gillnets made of biodegradable plastic materials, like PBS and PBAT, have been considered as potential mitigation measures to reduce ghost fishing and plastic pollution at sea caused by lost gears (Brown and Macfadyen, 2007; Large et al., 2009; Macfadyen et al., 2009; Gilman, 2015; Gilman et al., 2016). However, for an environmentally safe application of such biodegradable plastics at sea it is important to prove that the intermediate breakdown products, even those that are degradable, do not have any ecotoxicological effects on the ecosystem. Simultaneously, for biodegradable gillnets to be adopted by the industry, they should prove to be at least as efficient as conventional nylon gillnets and not compromise the profitability of the fishing operations. The present study addresses the second concern: fishing efficiency. This study was designed to assess the relative catch efficiency and changes of catch efficiency due to use (aging) of gillnets made of a new biodegradable resin (polybutylene succinate co-adipate-co-terephthalate (PBSAT)) throughout the entire winter fishing season for cod in northern Norway. The catch efficiency, catch rate, and effect of use and wear of the biodegradable PBSAT gillnets were directly compared to those of conventional nylon gillnets.

2. Materials and methods

2.1. Biodegradable PBSAT resin

The new PBSAT resin is an aliphatic-aromatic co-polyester prepared using 1.4-butanediol as an aliphatic glycol (as base materials) and dicarboxylic acids such as succinic acid and adipic acid (which are aliphatic components) and dimethyl terephthalate (which is an aromatic component). The PBSAT resin includes multiple dicarboxylic acid residue components, unlike the polybutylene succinate (PBS) resin that includes one dicarboxylic acid residue or the polybutylene adipate-co-terephthalate (PBAT) resin that includes two dicarboxylic acid residues (Kim et al., 2017, patent EP3214133 A1). The new PBSAT resin has biodegradability properties, exhibits an excellent coloration effect, and does not cause problems such as a decrease in strength due to coloration, which occurs with PBS and PBAT resins. The biodegradable PBSAT resin composition includes a colorant at 0.005–0.015 parts by weight. To improve the properties of monofilament yarn formed from the coloured resin, additives such as anti-oxidants and UV stabilizers may be included at 0.2–0.5 parts by weight with respect to 100 parts by weight of the PBSAT resin (Kim et al., 2017).

2.2. Experimental gillnets

Features of green biodegradable PBSAT gillnets, herein called bio gillnets, were compared with those of conventional blue nylon gillnets, herein called nylon gillnets, during fishing trials. Each gillnet had 210 mm nominal mesh opening, was made of 0.7 mm monofilament, and was 30 meshes in height and 275 meshes long (approx. 55 m stretched length). To provide buoyancy, each gillnet was fixed to a 27.5-meter-long and 26 mm diameter SCANFLYT-800 float line with a buoyancy of 150 g m^{-1}. To provide weight, they were attached to 27.5-meter-long and 16 mm diameter DANLINE lead line with weight of 360 g m^{-1}. Consequently, an assembled gillnet was 27.5 m long and had a hanging ratio of 0.5. We used two sets of gillnets in the experiments. Each set consisted of 16 gillnets, with eight bio gillnets (B) and eight nylon gillnets (N). The gillnets were arranged in such a way that they provided the best information for paired comparison, nylon versus bio net, accounting for spatial and temporal variation in the availability of cod. With individual sets being the basic unit for the subsequently paired analysis (described in Section 2.4), it was important that within each gillnet set averaged over nets that the bio and nylon nets were approximately exposed to the same spatial variability in cod availability. This could in principle be achieved by alternating between the two types of nets after each net sheet as B-N-B-N-B-N-B-N-B-N-B-N-B-N-B-N. However, for easing of registration of fish on board in relation to the type of net in which it was caught, the alternation in net types were only applied after each second net sheet. Therefore, to make conditions as equal between net types a possible set 1 was arranged as N-BB-NN-BB-NN-BB-NN-BB-N and set 2 as B-NN-BB-NN-BB-NN-BB-NN-B. Each set was deployed at least 3.6 km (two nautical miles) from each other to guarantee sampling independence. Actual measurements of the mesh openings (four rows of 20 meshes each) were taken with a Vernier calliper without applying tension to the meshes and showed that the mean mesh openings of nylon gillnets and bio gillnets were 210.6 ± 1.1 mm and 204.3 ± 2.1 mm, respectively.

2.3. Fishing vessel, fishing grounds and catch

The experiment was designed to cover the entire winter season for migrating cod and was conducted on board the coastal gillnet boat "MS Karoline" (10.9 m LOA) between 24 January and 8 March 2017, except on 16 February when the research vessel "Johan Ruud" (30 m LOA) was used to operate the gillnets due to bad weather conditions. The fishing grounds chosen for the tests were located off the coast of Troms (Northern Norway) between 70°21′–70°22′N and 19°39′–19°42′E, which is a common fishing area for coastal vessels from Troms (Fig. 1). The fishing depth varied between 55 and 145 m, and sea temperature varied between 4 and 6 °C.

A total of 88 gillnet deployments were carried out during the experimental period. Scientists on board the "MS Karoline" sorted out the catch by type of gillnet and measured the total lengths (to the nearest cm) of all fish caught in 44 deployments. Data from two deployments were lost. One additional data set was collected on board the research vessel "Johan Rudd" on 16 February (deployment no. 24) using the same sets of experimental gillnets and in the same fishing ground as the "MS Karoline."

2.4. Modelling the size-dependent catch efficiency between gillnet types

We used the statistical analysis software SELNET (Sistiaga et al., 2010; Herrmann et al., 2012, 2016) to analyze the catch data and conduct length-dependent catch comparison and catch ratio analyses. Using the catch information (numbers and sizes of cod in each gillnet set deployment), we wanted to determine whether there was a significant difference in the catch efficiency averaged over deployments between the nylon gillnet and the bio gillnet. We also wanted to determine if a potential difference between the gillnet types could be related to the size of the cod. Specifically, to assess the relative length-dependent catch efficiency effect of changing from nylon gillnet to bio gillnet, we used the method described in Herrmann et al. (2017) and compared the catch data for the two net types. This method models the length-dependent catch comparison rate (CC_l) summed over gillnet set deployments (for the full deployment period):

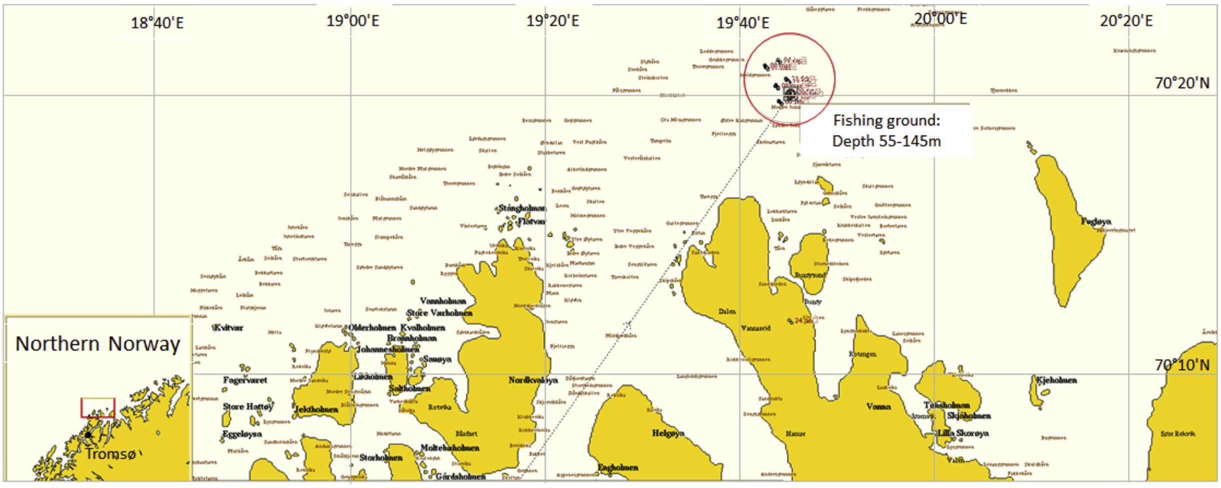

Fig. 1. The fishing grounds in Northern Norway: the red circle shows the position of each of the gillnet settings. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

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

where nc_{lj} and nt_{lj} are the numbers of cod caught in each length class l for the nylon gillnet (*control*) and the bio gillnet (*treatment*) in deployment j of a gillnet set (first or second set). m is the number of deployments carried out with one of the two sets. The functional form for the catch comparison rate $CC(l,v)$ (the experimental being expressed by Eq. (1)) was obtained using maximum likelihood estimation by minimizing the following expression:

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

where v represents the parameters describing the catch comparison curve defined by $CC(l,v)$. The outer summation in the equation is the summation over length classes l. When the catch efficiency of the bio gillnet and nylon gillnet is similar, the expected value for the summed catch comparison rate would be 0.5. Therefore, this baseline can be applied to judge whether or not there is a difference in catch efficiency between the two gillnet types. The experimental CC_l was modelled by the function $CC(l,v)$ using the following equation:

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

where f is a polynomial of order k with coefficients v_0 to v_k. The values of the parameters v describing $CC(l,v)$ were estimated by minimizing Eq. (2), which was 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 $v_0 \ldots v_4$ led to 31 additional models that were also considered as potential models for the catch comparison $CC(l,v)$. 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. The p-value, which was calculated based on the model deviance and the degrees of freedom, should not be < 0.05 for the combined model to describe the experimental data sufficiently well, except for cases for which the data are subject to overdispersion (Wileman et al., 1996; Herrmann et al., 2017). Based on the estimated catch comparison function $CC(l,v)$ we obtained the relative catch efficiency (also named catch ratio) $CR(l,v)$ between the two gillnet types using the following relationship:

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

The catch ratio is a value that represents the relationship between catch efficiency of the bio gillnet and that of the nylon gillnet. Thus, if the catch efficiency of both gillnets is equal, $CR(l,v)$ should always be 1.0. $CR(l,v) = 1.5$ would mean that the bio gillnet is catching 50% more cod with length l than the nylon gillnet. In contrast, $CR(l,v) = 0.8$ would mean that the bio gillnet is only catching 80% of the cod with length l that the nylon gillnet is catching.

The confidence limits for the catch comparison curve and catch ratio curve were estimated using a double bootstrapping method (Herrmann et al., 2017). This bootstrapping method accounts for between-set variability (the uncertainty in the estimation resulting from set deployment variation of catch efficiency in the gillnets and in the availability of cod) as well as within-set variability (uncertainty about the size structure of the catch for the individual deployments). However, contrary to the double bootstrapping method (Herrmann et al., 2017), the outer bootstrapping loop in the current study accounting for the between deployment variation was performed paired for the bio gillnet and nylon gillnet, taking full advantage of the experimental design with the bio gillnet and nylon gillnet being deployed simultaneously (see Fig. 1). By multi-model inference in each bootstrap iteration, the method also accounted for the uncertainty due to uncertainty in model selection. We performed 1000 bootstrap repetitions and calculated the Efron 95% (Efron, 1982) confidence limits. To identify sizes of cod with significant differences in catch efficiency, we checked for length classes in which the 95% confidence limits for the catch ratio curve did not contain 1.0.

Finally, a length-integrated average value for the catch ratio was estimated directly from the experimental catch data using the following equation:

$$CR_{average} = \frac{\sum_l \sum_{j=1}^{m} \{nt_{lj}\}}{\sum_l \sum_{j=1}^{m} \{nc_{lj}\}} \quad (5)$$

where the outer summation covers the length classes in the catch during the experimental fishing period.

2.5. Modelling the effect of number of times deployed on the length-integrated catch ratio

To investigate the effect of the number of times the gillnets were the deployed on the length-integrated catch ratio, the Eq. (5) was calculated for individual deployment sets such without the summation over gillnet sets. This led to a dataset consisting of pair values for number of times the gillnets were deployed and corresponding values for $CR_{average}$. Based on this dataset, we tested if the value for $CR_{average}$ changed linearly with number of deployment times (DNO) using the following equation:

$$CR_{average}(DNO) = \alpha \times DNO + \beta_l \quad (6)$$

The last part of the analysis using model (6) was conducted using the linear model function (lm) in statistical package R (version 2.15.2; www.r-project.org).

2.6. Tensile strength tests

Tensile strength tests were carried out on samples of the bio and nylon gillnets used in before and after fishing experiments using a H10KT universal tensile testing machine (Tinius Olsen TMC, PA, USA). Samples of gillnets measuring approx. 20 × 20 meshes were cut from the centre of the new and used gillnets. The tests were performed in wet conditions (at least 40 replicates for each case) according to ISO, 1086. Tensile strength, defined as the stress needed to break the sample, is given in kg, and elongation at break, defined as the length of the sample after it had stretched right when it breaks (L) is given relative to the initial mesh size in percentage.

2.7. Assessment of gillnet damage

The tensile strength tests showed that most of the meshes broke in the knots. We therefore assessed the degree of damage in the knots as an indication of the degree of damage of the gillnets. Two additional samples from each type of gillnets, each measuring 20 × 20 meshes, were visually inspected using a 20× magnifying glass. All knots from each gillnet sample were individually assessed; in total, 840 knots for each type of gillnet. The degree of damage was divided into four categories: 1) No damage, if the knot has a smooth and glossy surface; 2) slightly damaged, knots with roughened surface and/or with tightened knots; 3) badly damaged; knots with visible scratches and/or is peel off; 4) broken knot. The results are given as percentages of the total amount of knots from the sample. Some samples from each type of material were observed with a scanning electron microscope (SEM) to assess the changes in the surface.

3. Results

A total of 5103 cod were caught in the 43 gillnets deployments that were included in the analysis, with 2243 and 2850 cod caught by the bio gillnets and nylon gillnets respectively. Daily catches that varied between 73 and 498 cod. The mean effective fishing time (SD) (the time the gillnets remained at the sea bed) was 21 h 14 min (4 h 54 min). The mean (SD) fishing depth was 95.7 m (10.8 m). Table 1 shows catch data including set number, date, fishing time, number of fish caught, and minimum and maximum length of fish caught.

The catch was length-dependent for both types of gillnet, including fish from 70 to 120 cm, but with most of the fish being in the range of 85 to 110 cm (Fig. 2). The catch comparison rate was also highly length dependent, with smallest and biggest fish having a lower value for the bio gillnets, meaning that the nylon gillnet caught significantly more fish in those length classes (Fig. 2). The modelled catch comparison curve follows the main trend of the experimental points, which is supported by the fit statistics presented in Table 2. The estimated catch ratio curve clearly shows a significant difference between the bio gillnets and nylon gillnets for fish of certain length cases. The catch ratio curve of the bio gillnets was significantly lower than that of the nylon gillnets for almost all cod sizes except for those between 82 and 90 cm. In those length classes, the bio gillnets caught significantly more fish than the nylon gillnets (Fig. 2).

The length-integrated average value for the catch ratio of the bio gillnets with respect to the nylon gillnets (including all deployments) was 79.05%, meaning that the bio gillnets caught significantly 20.95% fewer fish than the nylon gillnets, as expressed by the narrow confidence limits (70.75–86.83) (Table 2). Individual analysis of the length-classes of 100, 105, 110, 115 and 120 cm revealed significant differences in the catch ratio for fish larger than 100 cm. In the length-classes of 100 and 110 cm, for instance, the bio gillnets caught 67.98% (CI = 59.88–75.79) and 46.32% (CI = 34.52–59.84) of what the nylon gillnets caught, respectively (Table 2).

The effect of number of times that the gillnets were deployed (parameter α) on the length-integrated catch ratio showed a significant (p-value < 0.03, R^2 value = 0.1948) decrease in relative catch efficiency for the bio gillnet compared to the nylon gillnet Fig. 3), meaning that the accumulated number of deployments did affect the relative catch efficiency between the gillnets.

The average breaking strength of the new nylon gillnets was 22.6 kg (CI = 21.1–24.2 kg), while that of bio gillnets was 18.8 kg (CI = 17.8–19.8 kg), representing a significant difference (t-test, $p = 2.2 \times 10^{-15}$) of 16.9% in favour of the nylon gillnets. The average elongation at break of nylon gillnets was 40.0% (CI = 37.7–42.3%), while that of bio gillnets was 37.3% (CI = 36.4–38.2%), meaning that the bio gillnets was significantly (t-test, $p = 5.0 \times 10^{-7}$) 6.8% less elastic than the nylon gillnets (Table 3).

The difference in the average tensile strength between new and used gillnets was significant for the bio gillnets (t-test, $p = 1.5 \times 10^{-3}$), but not for the nylon gillnets (t-test, $p = 3.5 \times 10^{-7}$). The elongation at break of used bio gillnets (17.2%, CI = 14.6–19.8%) was significantly (t-test, $p = 6.9 \times 10^{-7}$) reduced by 10% with respect to the new bio gillnets (18.8% CI = 17.8–19.8%) (Table 3) Used bio gillnets were significantly (t-test, $p = 1.6 \times 10^{-6}$) 10.4% weaker and (t-test, $p = 1.3 \times 10^{-11}$) 17.3% less elastic than used nylon gillnets.

Both types of gillnets were considerably more damaged after the fishing experiments, showing several more knots with visible surface damage than new gillnets. Bio gillnets had 66% and 19% of slightly and badly damaged knots; while nylon gillnets showed 74.5% and 16% respectively. In addition, the bio gillnets had 8.6% of broken knots while the nylon gillnets only 3.3% (Table 4). SEM images revealed physical damages that apparently were caused by use and wear throughout the fishing season (i.e., abrasion in the hauling machine, friction due to contact with hard surfaces when the gillnets were operated on deck), which turned the smooth and glossy surface of the materials (when new) into very rough surfaces after the fishing trials.

4. Discussion

The model used to analyse the length-dependent catch efficiency of the gillnets provided a good description of the catch data set. Considering that the gillnets were used in 88 deployments over a period of approximately two months, the use of a linear model was useful to specifically investigate the effect of number of gillnet deployments on the length-averaged catch ratio and showed a significant decrease in catch efficiency for the bio gillnet compared to the traditional nylon gillnet. Laboratory material testing and assessment of gillnets damage helped explaining the differences in catch efficiency between the two types of gillnet and the loss of catch efficiency due to use and wear.

On average, the bio gillnets caught 21% fewer fish (in numbers) than the nylon gillnets throughout the fishing season. The results generally showed better catch rates for the nylon gillnets than for the bio gillnets for most of the length classes; however, catch rates for the bio gillnets for cod between 82 and 90 cm were significantly better than those of the nylon gillnets. The differences in mesh size can account for some of the difference in the size distributions of fish caught by each type of gillnets. However, the difference in elasticity and tensile strength could explain the major difference in catch efficiency observed between the two types of gillnets, especially for larger fish. The two type of gillnet used in our experiments had different colours (blue for nylon and green for bio nets) which could potentially affect their

Table 1
Catch data.

Set no.	Setting date	Fishing time (hh:mm)	Fishing depth (m) (min. - max.)	Accumulated number of deployments	Number of cod in bio gillnets	Number of cod in nylon (PA) gillnets	Minimum fish length (cm)	Maximum fish length (cm)
1	24.01.2018	9h 20m	90–125	1	81	80	70	120
2	24.01.2018	10 h 10m	85–125	1	48	57	73	119
1	01.02.2018	6h 00m	55–110	9	94	104	70	120
2	01.02.2018	5h 30m	80–130	9	42	57	70	112
1	02.02.2018	24 h 00m	55–110	10	36	26	70	120
2	02.02.2018	24 h 00m	75–130	10	61	48	70	120
1	03.02.2018	22 h 00m	55–110	11	93	91	70	117
2	03.02.2018	22 h 30m	75–110	11	135	142	70	120
1	04.02.2018	22 h 25m	55–110	12	87	116	70	112
2	04.02.2018	22 h 10m	75–130	12	85	103	70	120
1	06.02.2018	20 h 50m	55–110	14	41	63	70	116
2	06.02.2018	20 h 50m	75–130	14	69	89	70	116
1	07.02.2018	22 h 45m	55–110	15	49	80	70	114
2	07.02.2018	22 h 45m	75–130	15	75	85	73	115
1	08.02.2018	22 h 40m	55–110	16	6	12	70	113
2	08.02.2018	22. 35m	75–130	16	36	44	70	120
1	09.02.2018	23 h 05m	55–110	17	1	4	70	118
2	09.02.2018	23 h 35m	75–130	17	31	37	72	117
1	16.02.2018	24 h 00m	55–130	24	148	207	72	119
1	20.02.2018	19 h 05m	75–130	28	8	7	76	120
2	20.02.2018	19 h 15m	55–110	28	74	115	81	120
1	21.02.2018	26 h 25m	75–130	29	28	24	70	110
2	21.02.2018	27 h 05m	55–110	29	144	155	77	120
1	22.02.2018	21 h 10m	75–130	30	124	150	83	120
2	22.02.2018	21 h 00m	100–145	30	105	119	73	120
1	23.02.2018	21 h 35m	55–110	31	23	32	71	119
2	23.02.2018	19 h 05m	100–145	31	66	77	70	120
1	01.03.2018	21 h 05m	55–110	37	19	43	83	110
2	01.03.2018	21 h 35m	76–130	37	18	27	86	119
1	02.03.2018	21 h 50m	66–120	38	14	25	80	120
2	02.03.2018	22 h 50m	76–130	38	7	32	80	120
1	03.03.2018	23 h 20m	66–120	39	39	83	76	120
2	03.03.2018	24 h 25m	76–132	39	124	132	72	116
1	04.03.2018	23 h 00m	66–122	40	4	7	89	110
2	04.03.2018	23 h 00m	74–130	40	7	13	93	116
1	05.03.2018	23 h 20m	60–120	41	11	18	88	109
2	05.03.2018	23 h 00m	74–130	41	13	21	89	118
1	06.03.2018	23 h 15m	60–120	42	25	36	79	118
2	06.03.2018	23 h 20m	75–130	42	27	50	80	120
1	07.03.2018	23 h 05m	65–120	43	59	84	76	119
2	07.03.2018	23 h 05m	75–130	43	27	31	76	118
1	08.03.2018	23h05m	65–120	44	37	77	77	120
2	08.03.2018	23 h 00m	76–130	44	32	47	77	118

relative fishing efficiency (Balik and Cubuk, 2001). However, compared to what was reported by Balik and Cubuk (2001) gillnetting in shallow (< 6 m) Mediterranean lake waters the depths in our experiments were much larger (55–145 m) and also was carried out during the end of the darkest period in northern Norway (natural phenomenon known as polar night). During this period of the year, the Sun's path goes completely under the horizon, even when it is at its highest (about midday). Therefore, we expect that none of the gillnets would be visible for the cod during the capture process leading us to assume that difference in gillnet colour is not responsible for the difference in catch efficiency observed. Other differences in catch efficiency may be related to different modes of catching fish (snagging—caught by the mouth or teeth or other part of the head region; gilling—caught with the mesh behind the gill cover (no twine in the mouth); wedging—caught by the largest part of the body (no twine in the mouth); entangling—caught by the spine, fins, or other parts of the body as a result of struggling) (Grati et al., 2015), these were not assessed in this experiment.

The lower catch efficiency observed in the bio gillnets respect to the nylon nets, especially for larger fish could be explained by the difference in braking strength and elasticity. Material testing of the new gillnets revealed that the bio gillnets were indeed considerable weaker (16.9%) and less elastic (6.8%) than nylon gillnets. Large cod (> 100 cm) may have managed to break the meshes of bio gillnets and avoid getting caught. Our results are in agreement with those reported by Grimaldo et al. (2018a,2018b) while assessing the catch characteristic of gillnets for cod, saithe *Pollachius virens* and Greenland halibut *Reinhardtius hippoglossoides*, Bae et al. (2013) for flounder *Cleisthenes pinetorum*, and those by Kim et al. (2016) for yellow croaker *Larimichthys polyactis*. The scientists found that the fishing efficiency of nylon gillnets were 1.1–1.4 times higher than those of the biodegradable nets and concluded that the flexibility of a bio gillnets was proved to be positively correlated to the fishing capacity, thus higher flexibility, the higher fishing capacity.

The effect of number of times deployed on the average catch ratio was significant at 95% confidence, meaning that the catch efficiency of the bio gillnets (relative to the nylon gillnets) was negatively correlated with number of gillnet deployments. Use and wear of the gillnets throughout the fishing season made the bio gillnet loss on average 9% of their original tensile strength, although variability was high. Visual inspection of the monofilaments and knots of the bio gillnets showed splintering and weakening, thus they stretched less and broke more easily. Tensile strength measurements of used PBSAT gillnets showed some meshes breaking at 11.7 kg load, whereas the weakest nylon (PA) mesh broke at 16.1 kg load. Although the nylon gillnet monofilaments also showed an 11% reduction of tensile strength, the gillnets were still strong enough to retain cod of large length classes. Curiously, elasticity

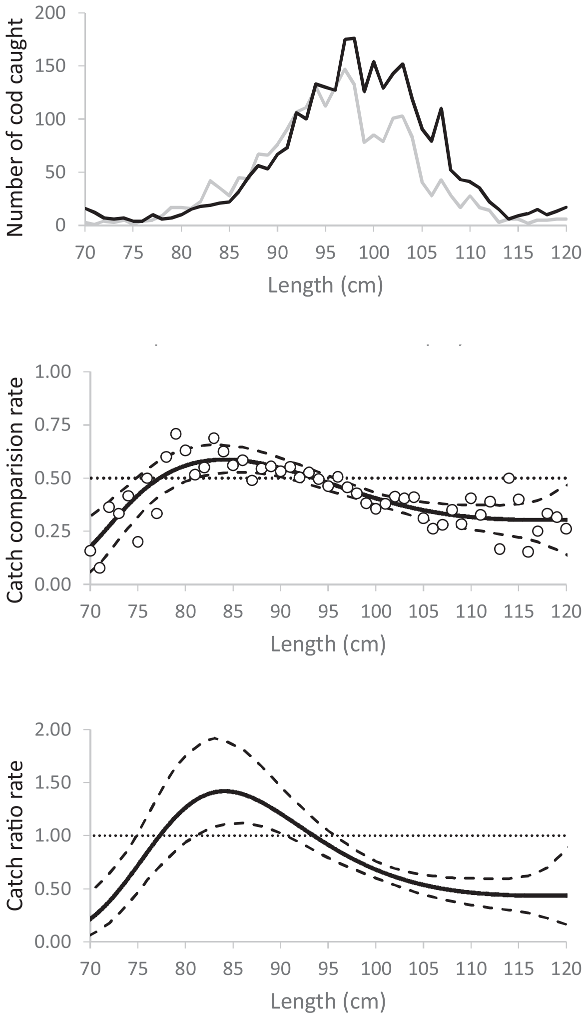

Fig. 2. Top: size distribution of fish caught with each type of gillnet (black curve for nylon (PA) gillnet and grey curve for bio gillnet). Centre: Catch comparison rate based on all deployments, with circle marks representing the experimental rate and the curve representing the modelled catch comparison rate. Dotted line at 0.5 represent the baseline where both types of gillnets fish equally. Stippled curves represent 95% confidence limits for the estimated catch comparison curve. Bottom: Estimated catch ratio curve based on all deployments. Dotted line at 1.0 represent the baseline where both types of gillnets fish equally. Stippled curves represent 95% confidence limits for the estimated catch ratio curve. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Table 2
Catch rate results and fit statistics obtained for the bio gillnet vs. nylon (PA) gillnet based on all deployments. Values in parentheses represent 95% confidence limits. DOF denotes degrees of freedom.

Length (cm)	Catch ratio (%)
70	21.42 (6.25–46.92)
75	71.96 (46.28–101.92)
80	126.27 (93.59–174.99)
85	141.18 (111.40–185.52)
90	120.71 (102.29–146.30)
95	91.25 (79.14–104.54)
100	67.98 (59.88–75.79)
105	53.61 (44.37–63.04)
110	46.32 (34.52–59.84)
115	43.68 (28.45–607.04)
120	43.51 (16.31–86.60)
Average	79.05 (70.75–86.83)
p-value	0.5447
Deviance	44.28
DOF	46

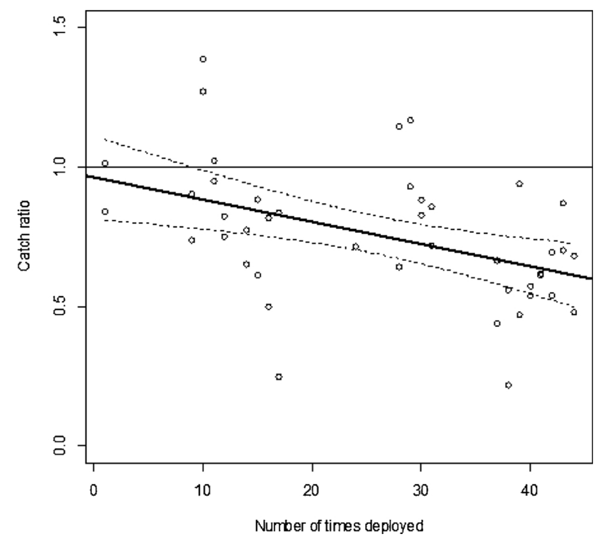

Fig. 3. Fit of linear model testing of the effect of number of times deployed on average catch ratio. At 1.0, both biodegradable gillnets and nylon (PA) gillnets fish equally. Circle marks represent the experimental length-integrated catch ratio (average catch ratio) for individual deployments. The thick line represents the modelled effect of number of times deployed on the average catch ratio. The two stipple curves represent 95% confidence bands for the linear model.

of the used nylon gillnets was unchanged over time, which likely contributed to these nets not reducing their catch efficiency. Furthermore, biological degradation, which was not assessed in this study, may be confounded with the effect of use and wear of the bio gillnets and probably also contributed to the weakening of the material.

The reduction in elasticity that was measured in the bio gillnets by the end of the fishing experiments was most likely due to roughening and splintering of the surface due to use and wear of the bio gillnet monofilaments. However, the loss of elasticity is probably also an indication of changes in the physical properties of the PBSAT material due to biodegradation. Kim et al. (2016) reported that uncoloured biodegradable PBS-PBAT gillnets slowly degraded in cold sea water ($< 5\,^{\circ}C$). The temperature of the sea water where the fishing experiments were carried out in the current study oscillated between 4 and 6 °C, suggesting that biological degradation was perhaps also a cause of tensile strength and elasticity reduction of the PBSAT nets.

If lost, the biodegradable PBSAT and nylon gillnets will no longer be affected by use and wear (i.e., abrasion in the hauling machine, friction due to contact with hard surfaces when gillnets are operated on deck). In the case of bio gillnets, bacteria, algae, and fungi will take over and further degrade the material. Because the biodegradable materials are degraded into carbon dioxide, methane, and water, they do not have any additional impact on marine ecosystems (Kim et al., 2014a, b). In the case of nylon gillnets, weakening of the material nearly stops when the gear is lost, and degradation then occurs very slowly. It is well documented how nylon gillnets are highly resistant to degradation and how they eventually lose their capability for ghost fishing depending on conditions of the seafloor (Carr et al., 1990; Humborstad et al., 2003; Pawson, 2003; Santos et al., 2003; Tschernij and Larsson, 2003; Nakashima and Matsuoka, 2004; Pham et al., 2014). Furthermore, nylon gillnets do not entirely disappear; they just degrade into smaller plastic particles that may continue to disturb various processes in the marine ecosystem (Moore, 2008). According to Kim et al. (2016), biodegradable PBS-PBAT gillnets would stop catching fish after two years of being immersed in seawater. However, this conclusion is based on a

Table 3
Tensile strength (kg), elongation at break (%), with 95% confidence intervals (in brackets), for new and used gillnets.

	Tensile strength (kg)		Elongation at break (%)	
	New	Used	New	Used
Nylon netting	22.6 (21.1–24.2)	20.2 (18.4–21.9)	40.0 (37.7–42.3)	40.6 (37.6–43.6)
Biodegradable netting	18.8 (17.8–19.8)	17.2 (14.6–19.8)	37.3 (36.4–38.2)	32.6 (28.4–36.9)

Table 4
Assessment of gillnet damage after the fishing experiments. Values are given in percentage.

	No damage	Slightly damaged	Badly damaged	Broken
Bio gillnet	6.4	66.0	18.8	8.6
Nylon gillnet	6.0	74.5	16.2	3.3

degradation experiment with monofilament samples immersed in sea water, thus the samples were not affected by use and wear. The question of "how fast a biodegradable gillnet loses its ghost fishing capacity" depends greatly on when it is lost (new or old gillnet) and how much it has been used (use and wear).

The lifespan of the gillnets, in this case defined as the time the gillnets can be used for fishing, highly depends on their durability and the degree of damage that they suffer when fishing. In the Norwegian gillnet fishery for winter cod, a conventional nylon gillnet is mostly used for one season, and one season normally lasts between two and four months depending on the boat, the quota and the availability and catchability of fish. When the fishing season is over, fishermen normally change the sheets of nets for new ones. This is done because the cost of repairing the nets is by far larger than the costs of buying relative unexpensive nylon gillnets. In these circumstances the use of short lifespan bio gillnets could easily be an alternative to conventional nylon gillnets without representing a big investment for the fishermen and as long as the profitability of the fishing operations is not compromised. However, the results from the fishing trials did show that the bio gillnets caught 21% less fish than nylon gillnets. Based on the total length–gutted weight relationship for northeast Atlantic cod $W = 0.013 \times L^{2.86}$ (Walsh and Hiscock, 2005), the weight of the fish caught with the two experimental gillnets sets was approximately 29,291 kg, and according to the price in January-March 2016 ($2.75/kg) the catch had a value of approx. $80,552. The fact that the bio gillnets caught only 79% of what the nylon gillnets did was equivalent to approximately 3321 kg less of cod, which represented a loss of $9134. The "MS Karoline" used eight sets of gillnets in the 2016 fishing season (two of which were the experimental gillnet sets). If all gillnets used in this period had been bio gillnets, the 21% reduction in catch would have represented approximately $36,536 less income for the crew of the "MS Karoline".

The results of this study suggest that the difference in of the catch efficiency between the two types of gillnets may be explained by the initial differences in breaking strength and elasticity, and that this difference got bigger as the gillnets were more used. The changes in the physical properties of the material are not only due to use and wear when fishing but also, to a certain extent, to biological degradation. The new biodegradable PBSAT gillnets show potential to become a feasible alternative to conventional nylon gillnets, especially in short-seasoned fisheries such as those for cod, saithe and Greenland halibut, and they might contribute to reducing the duration of ghost fishing when lost. However, a 21% reduction of the catch can considerably affect the cost effectiveness of the fishing operation and the acceptance of biodegradable gillnets by fishermen. Nonetheless, the material is not yet fully developed, and there are challenges and knowledge gaps (i.e. beads, products of degradation, ecotoxicity) that should be addressed before drawing conclusions about the overall benefits of these new materials in gillnet fisheries. Ultimately, it is up to regulatory institutions to decide whether to introduce biodegradable gillnets in the deep-water gillnet fishery in Norway in order to reduce ghost fishing or to let fishermen continue using the most effective nylon gillnets with well-known consequences if they are lost.

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