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Fishing efficiency of biodegradable PBSAT gillnets and conventional nylon gillnets used in Norwegian cod (*Gadus morhua*) and saithe (*Pollachius virens*) fisheries

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Fishing trials were carried out to compare the relative fishing efficiency of gillnets made of a new biodegradable resin (polybutylene succinate co-adipate-co-terephthalate, PBSAT) with conventional (nylon) nets. The fishing trials covered two consecutive fishing seasons (2016 and 2017) for cod (*Gadus morhua*) and saithe (*Pollachius virens*) in northern Norway. Results generally showed better catch rates for the nylon gillnets. The biodegradable PBSAT gillnets caught 50.0% and 26.6% fewer cod, and 41.0% and 22.5% fewer saithe than the nylon gillnets in 2016 and 2017, respectively. Even though the relative catch efficiency of the biodegradable gillnets was slightly better in 2017 than in 2016, the difference with respect to the catch efficiency of nylon gillnets may be too large for biodegradable gillnets to be accepted by fishermen if they were available commercially. Tensile strength measurements of the nylon and biodegradable PBSAT gillnets carried out before and after the fishing trials showed that the both types of gillnets had significant reductions in tensile strength and elongation at break, especially in 2017. Although less catch efficient than nylon gillnets, biodegradable PBSAT gillnets show great potential for reducing ghost fishing and plastic pollution at sea, which are major problems in these fisheries.

Keywords: biodegradable gillnet, catch efficiency, cod, cod fishery, ghost fishing, gillnet fishery, PBSAT resin, saithe

Introduction

Fishing gears that continue fishing after they have been lost (or abandoned) is known as ghost fishing (Breen, 1990). Lost fishing gears, apart from being associated with the catch of target and none-target species, also causes a variety of harmful impacts to coral reefs and benthic fauna, contributes to marine pollution by introducing synthetic (none-biodegradable) plastic materials into the marine food web, causes economic losses from marine species mortalities and due to replacement of lost gears, and diverse costs related to retrieving operations (Al-Masroori *et al.*, 2004; Brown and Macfadyen, 2007; Large *et al.*, 2009; Macfadyen *et al.*, 2009; Gilman, 2015; Gilman *et al.*, 2016; Lusher *et al.*, 2017). From all these problems, marine pollution caused by none-degradable plastics has become one of the most serious problems worldwide (Lusher *et al.*, 2017; Chae and An, 2017). Recognition to all these problems is nowadays demonstrated through the large number of international organizations and agreements that currently focus on reducing the effect of abandoned, lost, or otherwise discarded fishing gear (ALDFG) and numerous national initiatives that have being implemented around the world to mitigate their impact on the marine ecosystem (Gilman *et al.*, 2016).

There is extensive literature presenting mitigating measures and methods to reduce the effects of ALDFG on the environment (Al-Masroori *et al.*, 2004; Matsuoka *et al.*, 2005; Brown and Macfadyen, 2007; Large *et al.*, 2009; Macfadyen *et al.*, 2009; Gilman, 2015; Gilman *et al.*, 2016; Lusher *et al.*, 2017). Macfadyen *et al.* (2009) for instance grouped the methods to reduce the effects of ALDFG into: (i) preventive methods that reduce the incidence of fishing gear from becoming abandoned, lost, and discarded, such as gear marking, on-board technology to avoid or locate lost gear, onshore collection/reception and/or payment for old/retrieved gear, reduced fishing effort, and spatial management; (ii) mitigating measures that reduce the impact of lost gears in the environment, such as reducing ghost fishing (and plastic pollution) through the use of biodegradable gear, reducing ghost fishing of incidental species by providing escape vents; (iii) curative measures that are intended to remove the lost gear from the environment, such as electronic and/or acoustic technology for locating lost gear, better reporting of lost gear, gear recovery programs, and disposal/recycling of retrieved gear. Many scientists argue that efforts focusing on preventive methods and quick recovery of lost gears are likely to be more effective because curative methods can be highly cost demanding and largely time consuming (Matsushita *et al.*, 2008; Suuronen *et al.*, 2012; Uhlmann and Broadhurst, 2015). In addition, preventing gear loss would eliminate ghost fishing mortality (Uhlmann and Broadhurst, 2015).

In recent years many studies have documented the physical properties, biodegradability, and fishing efficiency of transparent gillnets made of polybutylene succinate (PBS) resin blended with polybutylene adipate-co-terephthalate (PBAT) resin and polybutylene succinate co-adipate-co-terephthalate (PBSAT) resin (Park *et al.*, 2007a, b, 2010; Park and Bae, 2008; Bae *et al.*, 2012, 2013; An and Bae, 2013; An *et al.*, 2013; Kim *et al.*, 2013, 2016). Ishii *et al.* (2008) reported that within 2 years of being submerged in seawater, transparent gillnets made of PBSAT resins were degraded by microorganisms (i.e. natural occurring bacteria, algae, and fungi), resulting in low-molecular-weight oligomers, dimers, and monomers that ultimately were mineralized into carbon dioxide and water (Tokiwa *et al.*, 2009). However, Kim *et al.* (2017) argues that gillnets made of PBS and PBAT resins have poor tinting properties and therefore can cause catch efficiency problems such as decreased strength and elasticity due to coloration.

In Norway, gillnetting is one of the most important commercial fishing methods for the coastal fleet, however transparent gillnets are not currently used. Norwegian fishermen prefer coloured gillnets because they provide a better contrast with the metal (aluminium and or stainless steel) sorting boards and make the removal of fish from the nets easier, and also because many fishermen believe that some colours have better catch efficiencies than others depending on the contrast with the seabed. The most important target species in the Norwegian gillnet fishery are cod (*Gadus morhua*) and saithe (*Pollachius virens*). In 2017, 4658 fishing boats (less than 14.9 m LOA) were registered and had licences for gillnetting in Norway. This small-scale coastal fleet caught 89 460 tonnes of cod, 17 635 tonnes of saithe, and 19 869 tonnes of haddock (*Melanogrammus aeglefinus*), representing 22.3%, 14.7%, and 18.1% of the respective annual quota for these species (Norwegian Directorate of Fisheries, 2018). To date, Norway is one of the few countries in the world that has a program for systematic annual retrieval of ALDFG from the most intensively fished areas (Brown *et al.*, 2005; Macfadyen *et al.*, 2009; Cho, 2011). Based on information provided by fishermen, the Norwegian Directorate of Fisheries carry out annual retrieval operations for reported lost fishing gear and deliver it on land to recycling (Humborstad *et al.*, 2003; Gilman *et al.*, 2016). However, these operations are highly challenging because of the depth (500–1000 m) and strong currents in the areas, as well as uncertainties associated with the position of lost gear.

The development of fishing gears made of biodegradable plastic materials, like PBSAT resin, is considered as a potential solution to reduce ghost fishing and plastic pollution at sea caused by ALDFG (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 fishing 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. The specific objective of this study was therefore to assess the relative catch efficiency of biodegradable PBSAT gillnets with that of conventional nylon gillnets. Our study covered the consecutive fishing seasons of 2016 and 2017, targeting the fall fishery for cod and saithe in Northern Norway.

Material and methods

Biodegradable polybutylene succinate-co-adipate-co-terephthalate resin

PBSAT resin is an aliphatic-aromatic co-polyester that is 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) (Kim *et al.*, 2017, patent EP3214133 A1). PBSAT resin is biodegradable, exhibits an excellent coloration effect and does not cause problems such as a decrease in strength due to coloration, as observed in 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 yarns formed from the coloured PBSAT 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, patent EP3214133 A1).

Experimental design

A set of experiments were designed to cover two consecutive fishing seasons for saithe and cod. Fishing trials were conducted under commercial fishing conditions on board the coastal gillnet boat "MS Karoline" (10.9 m LOA). The first fishing season was carried out between 24 October 2016 and 11 January 2017, and the second season between 11 October 2017 and 17 January 2018, herein referred to as the 2016 and 2017 seasons, respectively. The fishing grounds were off the coast of Troms (Northern Norway) between 69°55′–70°22′N and 19°39′–21°05′E, which is a common fishing area for coastal vessels from Troms. The fishing depth varied between 29 and 178 m. The seawater temperature was recorded every hour in 2016 with a DST-CTD Star-Oddi logger (Star-Oddi, Iceland) that was set at a depth of approximately 70 m.

In 2016, the fishing performance of 16 green biodegradable PBSAT gillnets, herein called bio gillnets, and 16 conventional green nylon gillnets, herein called nylon gillnets, was compared during fishing trials carried out under commercial fishing conditions. In 2017, the experiment was repeated with a new set of blue gillnets. Each gillnet sheet was made of double knotted 0.55 mm monofilament, had 130 mm nominal mesh opening size and was 50 meshes high by 275 meshes long (approx. 55 m stretched length). Each assembled gillnet was approximately 27.5 m long and had a hanging ratio of 0.5. Since the density of the gillnet materials was similar ($1.12\,\mathrm{g\,ml^{-1}}$ for the bio gillnets and $1.14\,\mathrm{g\,ml^{-1}}$ for nylon gillnets) we provided similar buoyancy to both types of gillnets. Each gillnet sheet was fixed to 26 mm diameter SCANFLYT-800 floatlines (made of braided polypropylene rope with a single core of polyurethane floating elements inside) with a buoyancy of $150\,\mathrm{g\,m^{-1}}$. To provide weight, they were each attached to a 16 mm diameter DANLINE leadline (made of polypropylene rope with a lead core) with a weight of $360\,\mathrm{g\,m^{-1}}$. The 32 experimental gillnets were divided into two sets, where each set consisted of eight bio gillnets (B) and eight nylon gillnets (N). The gillnets were attached in such a way that they provided the best information for paired comparison. Set 1 was arranged as B–NN–BB–NN–BB–NN–BB–NN–B and set 2 was arranged as N–BB–NN–BB–NN–BB–NN–BB–N (Figure 1).

Actual mesh openings were measured with a Vernier calliper without applying tension to the mesh. Two rows of consecutives 20 meshes were measured in each type of gillnet. The mean mesh openings of the bio gillnets and nylon gillnets used in 2016 were 132.8 ± 0.8 mm and 131.4 ± 0.8 mm, respectively. Those used in 2017 were 130.7 ± 0.8 mm and 128.2 ± 0.8 mm, respectively.

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 analyse catch data and conduct length-dependent catch comparisons and catch ratio analyses. Using the numbers and sizes of cod and saithe in each gillnet set deployment we determined whether there was a significant difference in the catch efficiency averaged over deployments between the nylon and bio gillnets. We also determined if a potential difference between the gillnet types could be related to the size of the cod or saithe. 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 types of gillnets. This method models the length-dependent catch comparison rate (CC_l) summed over gillnet set deployments for a full deployment period. The 2016 and 2017 experiments were analysed separately for cod and saithe, respectively:

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

where nc_{lj} and nt_{lj} are the numbers of cod or saithe caught in each length class l for the nylon-gillnet (*control*) and the bio gillnet (*treatment*), in deployment j of a gillnet set. m is the number of deployments carried out for the season (2016 or 2017 experiment separately). Only deployments of the gillnet sets that caught at least 10 individuals in total between the nylon and bio gillnet of the specific species investigated (cod or saithe) was included in the analysis for that species to avoid overinflating confidence intervals for catch comparisons and catch ratio analyses (Krag *et al.*, 2014, 2016). The functional form for the catch comparison rate $\mathrm{CC}(l, \boldsymbol{v})$ [the experimental being expressed by Equation (1)], was obtained using maximum likelihood estimation by minimizing the following expression:

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

where $\boldsymbol{v}$ represents the parameters describing the catch comparison curve defined by $\mathrm{CC}(l, \boldsymbol{v})$. The outer summation in the equation is the summation over the length classes l. When the catch efficiency of the bio gillnet and nylon gillnet is similar, the

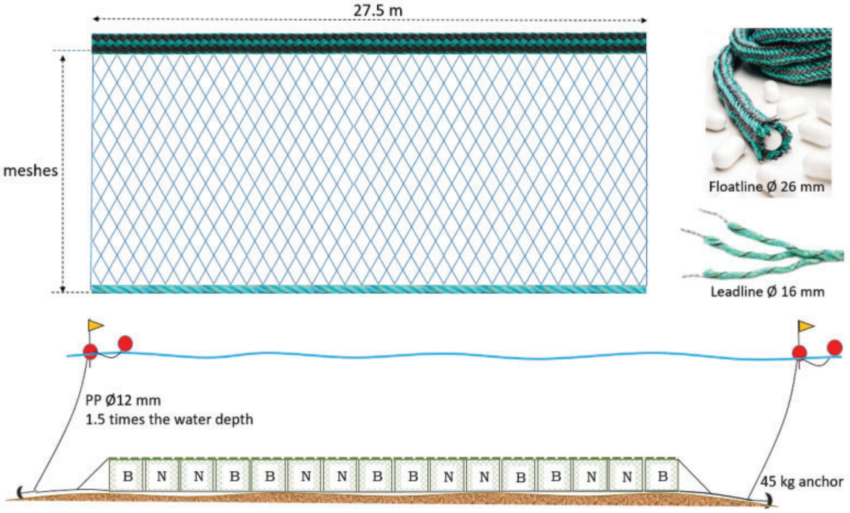

Figure 1. A schematic representation of the experimental gillnets (set 1) showing the layout (N: nylon gillnet; B: bio gillnet) during the fishing trials.

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 gillnets. The experimental CC_l was modelled by the function $CC(l, \boldsymbol{v})$, on the following form:

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

where f is a polynomial of order k with coefficients v_0 to v_k. The values of the parameters $\boldsymbol{v}$ describing $CC(l, \boldsymbol{v})$ are estimated by minimizing Equation (2), which are 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 $CC(l, \boldsymbol{v})$. Among these models, estimations of the catch comparison rate were made using multimodel 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. This *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 from cases where the data were subjected to over-dispersion (Wileman *et al.*, 1996; Herrmann *et al.*, 2017). Based on the estimated catch comparison function $CC(l, \boldsymbol{v})$ we obtained the relative catch efficiency (also named catch ratio) $CR(l, \boldsymbol{v})$ between the two gillnet types by the following relationship:

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

The catch ratio is a value that represents the relationship between catch efficiency between the bio gillnet and that of the nylon gillnet. Thus, if the catch efficiency of both gillnets is equal, $CR(l, \boldsymbol{v})$ should always be 1.0. Thus, $CR(l, \boldsymbol{v}) = 1.5$ would mean that the bio gillnet is catching 50% more cod or saithe with length l than the nylon gillnet. In contrast, if $CR(l, \boldsymbol{v}) = 0.7$ would mean that the bio gillnet is only catching 70% of the cod or saithe 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 and saithe) 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 and nylon gillnets, taking full advantage of the experimental design in which both types of net were deployed simultaneously (Figure 1). By multimodel inference in each bootstrap iteration, the method also accounts for the uncertainty in model selection. We performed 1000 bootstrap repetitions and calculated the Efron 95% (Efron, 1982) confidence limits. To identify sizes of cod or saithe 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 (CR_{average}) was estimated directly from the experimental catch data by:

$$CR_{\text{average}} = \frac{\sum_l \sum_{j=1}^{m} \{nt_{lj}\}}{\sum_l \sum_{j=1}^{m} \{nc_{lj}\}} \tag{5}$$

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

Tensile strength tests

Tensile strength tests were carried out on all the bio and nylon gillnets used in the fishing experiments using a H10KT universal tensile testing machine (Tinius Olsen TMC, PA, USA) equipped with a load cell with 5000 N rated force. The tests were performed in wet conditions on samples collected before and after the experimental fishing (at least 40 replicates for each case) according to ISO 1806: 2002. 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 is given relative to the initial mesh size in percentage.

Assessment of gillnet damage

We assessed the degree of damage in the knots as an indication of the degree of damage of the gillnets. Samples from each type of gillnets used in 2016 and 2017, each measuring 20 × 20 meshes (approx. 2200 mm × 2200 mm) were visually inspected using a Nalakuvara magnifying glass 3× 45×. All 420 knots from each gillnet sample were individually assessed. The degree of damage was divided into four categories: (1) No damage, (2) slightly damaged, (3) badly damaged, and (4) broken knot. The results are given as percentages of the total amount of knots form the sample.

Results

The two experimental gillnets were set at sea 58 and 92 times in the 2016 and 2017 seasons, respectively. Scientists on board the MS Karoline measured the lengths of all fish caught in 34 deployments in each fishing season. Fishermen provided logs (dates, positions, and setting-retrieving times) of the remaining deployments, except length measurements of fish caught. The mean effective fishing time (± SD) (the time the gillnets remained at the sea bed) was 19 h, 10 min ± 6 h, 32 min while in 2017 it was 21 h, 58 min ± 6 h, 06 min. The mean (± SD) fishing depth was significantly deeper in 2017 (109 ± 28.9 m) compared with 2016 (61 ± 55.7 m). The temperature of the seawater varied between 8.8°C and 4.1°C at the start and end of the experiment. The catch was quite clean, mostly consisting of cod and saithe. These species were caught in sufficient numbers to be included in the analysis. We occasionally caught very few large haddock, but far too few (less than 20 individuals per season) to be included in the study.

Cod

A total of 1057 cod were caught over 33 gillnet deployments during the 2016 and 2017 fishing seasons, of which 407 were caught by the bio gillnets and 650 were caught by the nylon gillnets. Deployments with at least 10 cod in the catch were used in the analysis because gillnets with less than 10 fish would add little

Table 1. Catch data for cod.

Set ID cod	Year	Minimum size (cm)	Maximum size (cm)	Number of cod in bio gillnet	Number of cod in nylon gillnet
1	2016	51	89	49	60
2	2016	52	85	7	13
3	2016	52	88	8	9
4	2016	54	90	6	11
5	2016	60	82	3	13
6	2016	56	85	4	7
7	2016	58	86	5	10
8	2016	54	88	8	13
9	2016	57	84	13	29
10	2016	52	87	10	17
11	2016	60	76	3	9
12	2016	58	109	13	60
13	2016	57	100	21	49
14	2017	48	108	13	9
15	2017	58	97	13	32
16	2017	51	78	10	5
17	2017	50	86	9	23
18	2017	59	99	32	25
19	2017	58	94	15	43
20	2017	57	95	44	54
21	2017	50	100	7	7
22	2017	64	91	10	13
23	2017	64	105	8	11
24	2017	54	106	31	12
25	2017	60	104	17	24
26	2017	59	104	5	13
27	2017	58	92	8	13
28	2017	56	94	4	7
29	2017	62	104	2	9
30	2017	62	99	8	15
31	2017	51	100	15	20
32	2017	70	105	3	7
33	2017	62	95	3	8

Only sets with at least 10 cod caught were used in the analysis.

information and increase uncertainties to the catch comparison analyses (Table 1).

The length distribution of cod that were caught with both types of gillnets was very similar in 2016 and 2017. The catch was length-dependent for both types of gillnet, including fish from 50 to 103 cm, but with most of the fish in the range of 65–85 cm (Figure 2). In 2016, the catch efficiency of the bio gillnets was significantly lower than that of the nylon gillnets for almost all cod sizes except for those below 64 cm, while in 2017 significance was only obtained for cod in the size span 90 to 103 cm (Figure 2). The CR(l) was also highly length dependent, with the biggest fish having a lower value for the bio gillnets in 2016, meaning that the nylon gillnets caught significantly more fish in those length classes (Figure 2). The average CR was estimated at 50.0% and 73.4% in 2016 and 2017, respectively, meaning that the bio gillnets on average caught approximately 50.0% fewer fish than the nylon gillnets in 2016 and 26.6% fewer in 2017 (Table 2 and Figure 2). For 2016 this result was significant as the upper limit for the averaged catch ratio was 73.3% whereas for 2017 it was 102.7% and therefore not significant. The estimated catch ratio curve clearly shows a significant difference in catch efficiency between the bio gillnets and nylon gillnets in 2016, for cod larger than 62 cm. In 2017, this difference was not significant, except for the length classes 90 to 103 cm (Figure 2).

Saithe

A total of 1965 saithe were caught over 45 gillnet deployments during the 2016 and 2017 fishing seasons, of which 814 were caught by the bio gillnets and 1151 were caught by the nylon gillnets. Only deployments with at least 10 saithe in the catch were used in the analysis to avoid inflate the confidence limits for the catch comparison analysis (Table 3).

The length distribution of saithe caught in 2016 and 2017 was length dependent for both types of gillnet, including fish from 50 to 95 cm, but with most of the fish in the range of 65–80 cm (Figure 3). In 2016 and 2017, the catch efficiency of the bio gillnets was very similar to that of the nylon gillnets for fish smaller than 67 cm and 70 cm, respectively. The catch efficiency of the bio gillnets became significant different for larger fish (Figure 3). The CR(l) was also highly length dependent, with the biggest fish having a lower value for the bio gillnets in both 2016 and 2017, meaning that the nylon gillnet caught significantly more fish in those length classes (Figure 3). The average CR was estimated at 59.0% and 77.5% in 2016 and 2017, respectively, meaning that the bio gillnets caught on average 41.0% fewer fish in 2016 and 22.5% fewer fish in 2017 (Table 4 and Figure 3). For both 2016 and 2017 this result was significant as the upper limit for the averaged catch ratio was 81.3% and 93.9%, respectively. The estimated catch ratio curve clearly shows a significant difference in

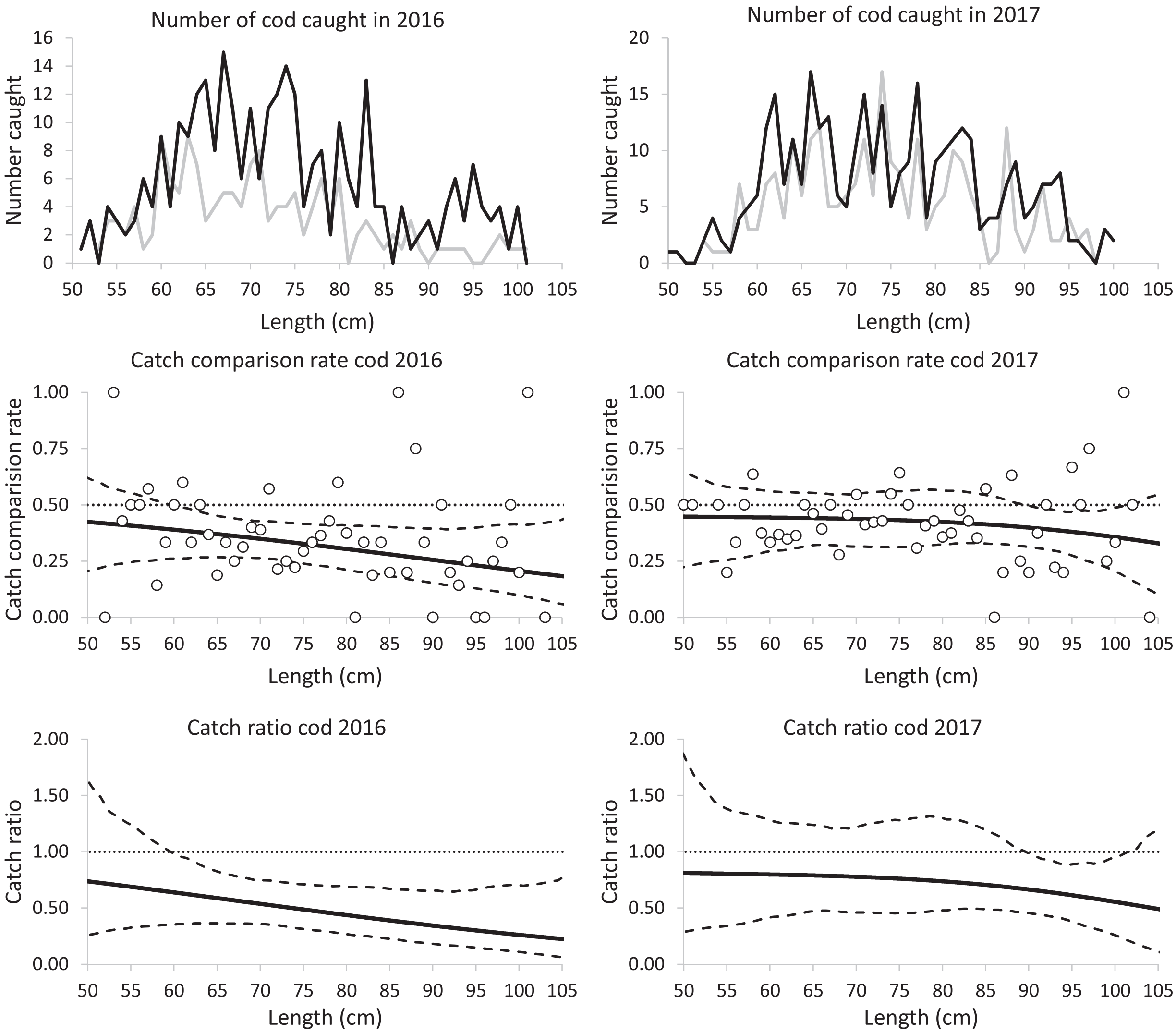

Figure 2. Top: size distribution of cod caught with each type of gillnet (the black and grey curves represent nylon and bio gillnets, respectively). Centre: Catch comparison rate (CC) based on all deployments for 2016 (left) and 2017 (right) with circle marks representing the experimental rate and the curve representing the modelled CC. The dotted line at 0.5 represents the baseline at which both types of gillnet have equal catch rates. Stippled curves represent 95% confidence limits for the estimated catch comparison curve. Bottom: Estimated catch ratio (CR) curve based on all deployments. The dotted line at 1.0 represents the baseline at which both types of gillnet have equal catch rates. Stippled curves represent 95% confidence limits for the estimated catch ratio curve.

Table 2. Catch ratio (CR(*l*)) for cod (%) and fit statistics obtained for the bio gillnets relative to for nylon gillnets in 2016 and 2017.

Length (cm)	**CR(*l*) (%) 2016**	**CR(*l*) (%) 2017**
55	68.9 (33.3–121.9)	80.5 (34.8–136.4)
60	63.9 (35.6–96.2)	79.8 (42.2–127.0)
65	58.8 (36.4–81.2)	79.0 (47.5–123.5)
70	53.7 (35.7–74.6)	77.8 (46.0–122.9)
75	48.7 (31.0–70.9)	76.1 (45.7–127.9)
80	43.7 (26.2–68.6)	73.8 (47.9–128.8)
85	39.9 (22.3–66.8)	70.6 (48.5–117.6)
90	34.4 (17.8–65.6)	66.4 (45.0–96.9)
95	30.1 (14.4–67.1)	61.4 (36.7–89.2)
100	26.1 (10.6–69.6)	55.5 (24.4–96.2)
Average	50.0 (31.4–73.3)	73.4 (51.9–102.7)
p-value	0.2208	0.7037
Deviance	55.21	45.16
DF	48	51

Values in brackets represent 95% confidence limits.

DF, degrees of freedom.

Table 3. Catch data for saithe.

Set ID saithe	Year	Minimum size (cm)	Maximum size (cm)	Number of saithe in Bio gillnet	Number of saithe in Nylon gillnet
1	2016	60	83	18	13
2	2016	60	80	17	8
3	2016	52	80	9	2
4	2016	56	87	10	14
5	2016	57	87	27	45
6	2016	63	89	9	12
7	2016	63	90	16	21
8	2016	60	82	9	13
9	2016	56	90	12	56
10	2016	64	85	7	15
11	2016	58	82	7	16
12	2016	64	88	3	11
13	2016	61	88	25	29
14	2016	58	83	12	19
15	2016	68	80	5	8
16	2016	59	78	4	7
17	2016	57	80	7	18
18	2016	57	86	12	18
19	2016	65	85	8	10
20	2016	55	83	25	61
21	2016	62	82	7	26
22	2017	52	92	43	41
23	2017	64	82	5	13
24	2017	54	92	38	51
25	2017	52	88	15	21
26	2017	50	97	27	44
27	2017	62	99	22	37
28	2017	52	85	21	25
29	2017	61	76	7	3
30	2017	51	88	10	16
31	2017	62	94	6	11
32	2017	64	82	7	6
33	2017	52	82	17	24
34	2017	54	86	14	14
35	2017	54	92	39	42
36	2017	54	97	37	19
37	2017	56	87	25	59
38	2017	54	86	41	36
39	2017	54	91	18	27
40	2017	56	82	36	47
41	2017	58	82	4	11
42	2017	55	90	77	78
43	2017	51	84	48	86
44	2017	61	80	3	7
45	2017	58	81	5	11

Only sets with at least 10 saithe caught were used in the analysis.

catch efficiency between the bio gillnets and nylon gillnets in both years, for saithe larger than 69 cm in 2016 and larger than 73 cm in 2017 (Figure 3).

Tensile strength measurements

Tensile strength measurements carried out before and after the fishing experiment showed a significant reduction in tensile strength (t-test, $p < 0.01$) and elongation at break (t-test, $p < 0.01$) for both types of gillnet in 2017, but not in 2016 (t-test, $p > 0.05$). In 2017, the nylon gillnets underwent a 13.6% tensile strength reduction (from 11.4 to 9.9 kg) and the bio gillnets underwent an 18.1% strength reduction (from 11.1 to 9.5 kg) (Table 5). Both types of gillnet also showed a significant reduction of elongation at break, 33.9% and 13.2% for the nylon and bio gillnets, respectively.

Gillnet damage

The gillnets used in 2017 were more damaged than those used in 2016 (Table 6). The gillnets used in 2017 had more than 26% of badly damaged or broken knots, while this percentage did not exceed 2% in the gillnets used in 2016. The damage in the knots was apparently 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 surface of the materials (when new) into rough surfaces after the fishing trials (Figure 4).

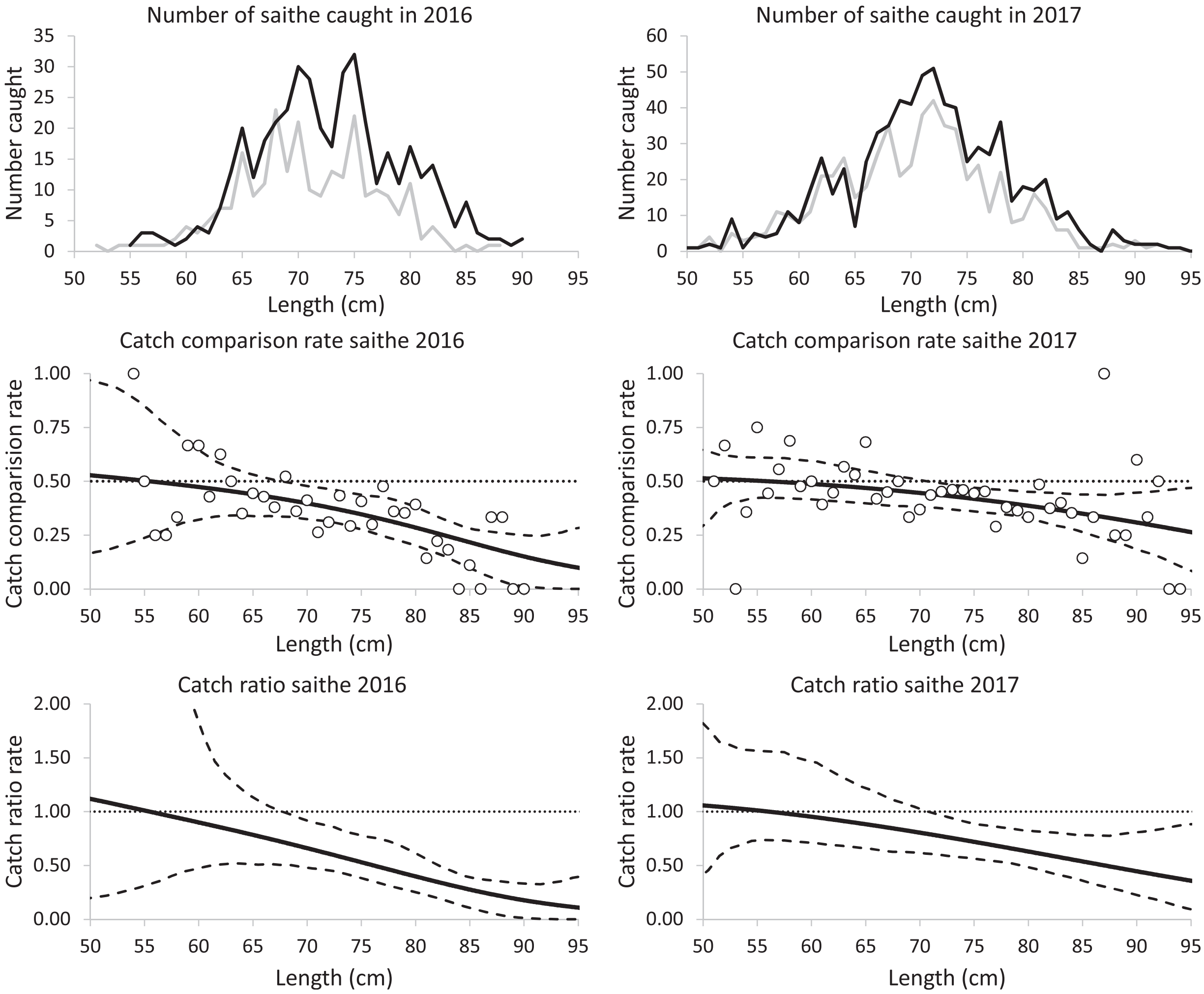

Figure 3. Top: size distribution of saithe caught with each type of gillnet (the black and grey curves represent nylon and bio gillnets, respectively). Centre: Catch comparison rate (CC) based on all deployments for 2016 (left) and 2017 (right) with circle marks representing the experimental rate and the curve representing the modelled (CC). The dotted line at 0.5 represents the baseline at which both types of gillnet have equal catch rates. Stippled curves represent 95% confidence limits for the estimated catch comparison curve. Bottom: Estimated catch ratio (CR) curve based on all deployments. The dotted line at 1.0 represents the baseline at which both types of gillnet have equal catch rates. Stippled curves represent 95% confidence limits for the estimated CR curve.

Table 4. Catch ratios (CR(*l*)) for saithe (%) and fit statistics obtained for the bio gillnets relative to for nylon gillnets in 2016 and 2017.

Length (cm)	CR(*l*) (%) 2016	CR(*l*) (%) 2017
50	111.9 (20.7–2599.0)	105.8 (45.8–176.9)
55	101.1 (32.8–481.2)	101.2 (73.6–156.3)
60	90.0 (48.7–169.2)	95.3 (70.8–145.4)
65	78.5 (50.9–110.4)	88.4 (65.5–120.1)
70	66.1 (47.4–90.1)	80.5 (61.1–100.7)
75	53.1 (36.9–76.8)	72.0 (55.7–87.9)
80	39.9 (24.0–58.8)	63.0 (47.3–81.9)
85	27.7 (9.4–38.0)	53.8 (34.5–78.2)
90	17.8 (1.0–33.0)	44.7 (21.3–81.3)
95	11.0 (0.1–40.3)	35.9 (8.1–88.6)
Average	59.0 (43.1–81.3)	77.5 (62.7–93.9)
p-value	0.7098	0.7127
Deviance	28.10	37.38
DF	33	43

Values in brackets represent 95% confidence limits.
DF, degrees of freedom.

Discussion

The bio gillnets caught 50.0% and 26.6% fewer cod, and 41.0% and 22.5% fewer saithe than the nylon gillnets in 2016 and 2017, respectively. Even though the relative catch efficiency of the bio gillnets was slightly better in 2017 than in 2016, the difference with respect to the catch efficiency of nylon gillnets may be too large for bio gillnets to be accepted by fishermen if they were available commercially. Coloured bio gillnets are still in the development process and are not currently a commercial product. The results from these series of experiments at sea suggest the need for further development of biodegradable material to improve their catch efficiency.

The results generally showed better catch rates for the nylon gillnets than for the bio gillnets, especially for large fish, despite having similar (non-significantly different) mesh sizes. Since similar colours were used in nylon and bio gillnets each year (green gillnets in 2016 and blue gillnets in 2017); colour cannot explain the differences in catch efficiency between both types of gillnets.

Table 5. Tensile strength (kg) and elongation at break (%), with 95% confident intervals (in brackets) for the gillnets used in 2016 and 2017.

Material	Test	2016				2017			
		New	Used	% reduction	*p*-value	New	Used	% reduction	*p*-value
Nylon	Tensile strength	11.9 (0.54)	11.8 (0.68)	−0.8	0.1223	11.4 (0.42)	9.9 (0.97)	−13.2	0.0001
	Elongation at break	36.8 (0.79)	35.9 (1.11)	−2.4	0.0757	36.6 (0.83)	26.2 (1.78)	−33.9	0.0000
Biodegradable	Tensile strength	11.8 (0.39)	11.8 (0.51)	0.0	0.1028	11.1 (0.24)	9.5 (0.66)	−18.1	0.0001
	Elongation at break	39.7 (1.06)	38.4 (1.16)	−3.3	0.0707	38.5 (0.69)	33.4 (2.33)	−13.2	0, 0011

Table 6. Percentage of knots with no damage, slightly damaged, badly damaged, and broken knots for gillnets used in 2016 and 2017.

	2016				2017			
	No damage	Slightly damaged	Badly damaged	Broken	No damage	Slightly damaged	Badly damaged	Broken
Bio gillnet	25.95 %	71.90 %	1.90 %	0.00 %	3.81 %	68.57 %	18.81 %	8.57 %
Nylon gillnet	28.81 %	69.76 %	0.48 %	0.00 %	37.38 %	35.24 %	19.52 %	7.86 %

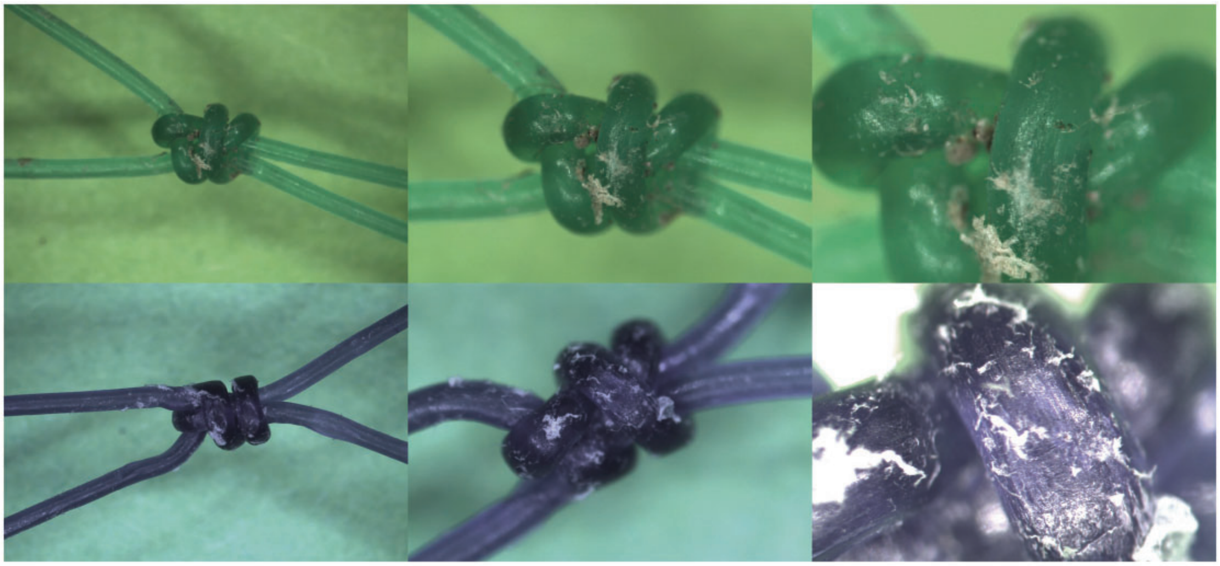

Figure 4. Images of the bio gillnets from 2016 (green) and 2017 (blue) showing physical damage of the knots.

The physical properties of the gillnets material did change over time and may have affected their fishing efficiency. When new, the strength and the elasticity of both types of nets was very similar. By the end of the fishing season, the reduction in tensile strength and the loss of elasticity can explain the major difference in catch efficiency observed between the nylon gillnets and the bio gillnets, especially for larger fish. In 2017, we measured an 18.1% reduction in tensile strength and a 13.2% reduction in elongation in the bio gillnets; while in 2016 these reductions were considerably smaller (Table 5). Visual inspection of the monofilaments and knots of the bio gillnets used in 2017 showed more splintering and other kinds of physical damage than in those used in 2016. Physical damage appeared to be positively correlated with the number of operation days and the fishing depth. In 2017, the experimental gillnets had 59% more deployments, and they were set significantly deeper, than in 2016. Consequently, in 2017 the gillnets were exposed to more physical damage that may have contributed to the greater loss of tensile strength and loss of elasticity which, in turn, made them break more readily. Similar to the bio gillnets, in 2017 the nylon gillnets also experienced a significant reduction in tensile strength (13.2%) and elongation (33.9%), supporting the indication that greater physical damage may be the cause. 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 bio gillnets (made of a blending of PBS-PBAT resin) slowly degraded in cold sea water (<5°C). The seawater temperature in our fishing experiments oscillated between 4.1°C and 8.8°C, suggesting that biological degradation was perhaps also a cause of tensile strength and elasticity reduction of the bio gillnets nets. In our experiment we were unable to separate the degree of strength and elasticity reduction caused by biodegradation from that caused by used and wear. However, when we observed monofilaments samples in the electronic scanning microscope we not only saw physical damages caused by friction in both bio and nylon monofilaments, but also, we saw some degree of roughening and splintering of the surface of the bio material. Roughening and splintering of the monofilament surface of the bio gillnets may actually be a consequence of the biodegradation process. A controlled degradation experiment may avoid the damage caused by use and wear of the material and therefore provide the actual loss of strength and elasticity caused by biodegradation. Also, this experiment can provide the degradation speed of the bio gillnets. It is worth to mention that if biodegradation is combined with daily use and wear of the material, the degradation process may be somehow accelerated.

When conventional nylon gillnets get lost at sea, the weakening of the material caused by use and wear, or by environmental factors such as UV radiation, virtually ceases and the degradation process therefore continues slowly. It is well-documented that nylon gillnets are highly resistant to degradation, but that they do eventually lose their capability for ghost fishing depending on conditions of the seafloor (i.e. type of substrate, sea temperature, light conditions) (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, commonly known as “micro plastics” that may continue to disturb important processes in marine ecosystems (Moore, 2008; Lee *et al.*, 2013; Cole and Galloway, 2015; Desforges *et al.*, 2015; Chae and An, 2017). Contrary to conventional nylon gillnets, if bio gillnets get lost at sea, bacteria, algae, and fungi will much more rapidly degrade the material into carbon dioxide, methane and water, and they would therefore not have any further additional impacts on marine ecosystems (Tokiwa *et al.*, 2009; Kim *et al.*, 2014a, b). According to Kim *et al.* (2017), bio gillnets start degrading after two years of being immersed in seawater. However, this conclusion is based on a degradation experiment with monofilament samples immersed in seawater, thus the samples were not affected by physical damage from daily use and wear. The question of how fast a bio gillnet can lose its ghost fishing capacity depends greatly on the age of the net when lost and how much it had been used.

There is limited literature that quantifies the degradation speed of nylon gillnets, and even fewer studies that assess when a lost nylon gillnet loses its ghost fishing capacity. Some available studies show that nylon gillnets continue to fish for several years after being lost (Carr and Cooper, 1987; Puente *et al.*, 2001; Nakashima and Matsuoka, 2004). Our experiment suggest that the degradation time of bio gillnets could even be shorter if the bio gillnets are weakened by used and wear before they get lost.

Coloured bio gillnets, such as those tested in this study, show potential to become a feasible alternative to conventional nylon gillnets, particularly in the short season Norwegian fisheries like cod, saithe and Greenland halibut, and to reduce the duration of ghost fishing if they do get lost. However, a 26.6% and 22.5% reduction of the cod and saithe catch can considerably affect the cost effectiveness of the fishing operation and the acceptance of bio gillnets by fishermen. Nonetheless, the material is not yet fully developed, and there are challenges and knowledge gaps (i.e. products of degradation, ecotoxicity) that should be addressed before drawing conclusions about the overall benefits of using these new biomaterials in fisheries. Ultimately, it is up to regulatory institutions in Norway to decide whether to introduce bio gillnets in the deep-water gillnet fisheries in order to reduce ghost fishing or let fishermen continue using the most effective nylon gillnets with well-known consequences if they get lost.

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