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ARTICLE

Effect of Using Biodegradable Gill Nets on the Catch Efficiency of Greenland Halibut

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Abstract
The effect of using biodegradable polybutylene succinate co-adipate-co-terephthalate (PBSAT) gill nets on the relative catch efficiency was assessed in a commercial gill-net fishery targeting Greenland Halibut *Reinhardtius hippoglossoides* in northern Norway. Compared with conventional polyamide gill nets, the PBSAT gill nets caught fewer fish, and the relative catch efficiency decreased with increasing fish size. For fish larger than 65 cm, the reduction in catch efficiency was significant, as the PBSAT gill nets caught 30% fewer Greenland Halibut in this size range than the conventional polyamide gill nets. Differences in mesh size, breaking strength, and elasticity could contribute to the difference in size-dependent catch efficiency between the two types of gill nets.

When nonbiodegradable plastic materials, which are generally more persistent in the environment than natural materials, get lost, are abandoned, or are discarded at sea, it causes a series of biological, ecological, and socioeconomic problems. In recent decades, numerous studies have focused on assessing the magnitude of the effects of lost fishing gear in the marine environment (Al-Masroori et al. 2004; Brown and Macfadyen 2007; Large et al. 2009; Macfadyen et al. 2009; Gilman 2015; Gilman et al. 2016). Among the mitigating measures proposed to address the problem is the use of biodegradable fishing gear, which should reduce the time frame of ghost fishing (what happens when lost or abandoned gear continues to fish; Macfadyen et al. 2009).

In recent years, many studies have shown that uncolored (transparent) gill nets made of polybutylene succinate resin blended with polybutylene adipate-co-terephthalate resin (PBSAT) can be naturally degraded in seawater by the action of bacteria and algae, and simultaneously these studies documented similar fishing efficiency when compared with conventional polyamide (PA) gill nets (Park et al. 2007a, 2007b, 2010; Park and Bae 2008; Bae et al. 2012, 2013; An and Bae 2013; Kim et al. 2013,

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2016). Kim et al. (2016) reported that within 2 years of being submerged in seawater, gill nets made of PBSAT resin began to degrade and that by then those gill nets would have become weak enough to stop catching fish.

In Norway, gill nets are among the most important fishing methods, especially for the coastal fleet. The main target species are Atlantic Cod *Gadus morhua*, Pollack *Pollachius virens*, Greenland Halibut *Reinhardtius hippoglossoides*, and Monkfish *Lophius piscatorius*, with fisheries for the last two species experiencing the most gear loss (Humborstad et al. 2003). The total international catch of Greenland Halibut in 2015 was 25,250 metric tons. Of this, Norwegian catches accounted for 10,800 metric tons and Russian catches for 12,950 metric tons. In 2015, about 63% of total catches were taken with bottom trawls, 27% with lines, and 12% with gill nets (Hallfredsson 2017). The coastal fleet, which is mostly composed of vessels smaller than 28 m length overall (LOA), can participate in the fishery for Greenland Halibut and can land up to 4,600 metric tons of Greenland Halibut beginning May 23 (from 0000 hours) or until the Norwegian Directorate of Fisheries closes the fishery and up to 2,000 metric tons of Greenland Halibut beginning July 25 (from 0000 hours) or until the Norwegian Directorate of Fisheries closes the fishery (Norwegian Directorate of Fisheries 2015). In addition, the individual quota per vessel size is 17.5, 20.0, and 22.5 metric tons for vessels smaller than 13.99 m LOA, between 14.0 m and 19.99 m LOA, and between 20.0 m and 27.99 m LOA, respectively (Norwegian Directorate of Fisheries 2015).

To date, Norway is one of the few countries in the world that has a program for systematic annual retrieval of lost and abandoned or otherwise discarded fishing gear (Macfadyen et al. 2009) from the most intensively fished areas. Since 1983, more than 20,000 gill nets have been retrieved (Figure 1); however, they represent only about 40–50% of all gill nets that were reported lost. These retrieval operations are highly demanding because of operation depth (500–1,000 m), strong currents in the areas, and uncertainties associated with the accuracy of the lost gear's position. Therefore, and parallel to the gear retrieval program, current research is focused on assessing the possibility of using biodegradable plastic materials to manufacture gill nets.

The Norwegian management institution (i.e., Directorate of Fisheries) sees biodegradable plastic materials as a potential solution to reduce ghost fishing and plastic pollution at sea caused by lost gill nets (G. Langedal, Norwegian Directorate of Fisheries, personal communication). For an application of biodegradable plastics at sea to be environmentally safe, the intermediate breakdown products, even those that are degradable, must not have any ecotoxicological effects on the ecosystem. Simultaneously, for biodegradable gill nets to be adopted by the fishing industry, they must be as efficient as conventional PA gill nets in order to maintain the profitability of the fishing operation. The present study addressed the second concern: fishing efficiency. The specific objective of this study was to compare the relative catch efficiency of biodegradable PBSAT gill nets versus conventional PA gill nets.

METHODS

Biodegradable PBSAT resin.— The new PBSAT resin is an aliphatic-aromatic co-polyester prepared using 1.4-butanediol as an aliphatic glycol (the base material) and dicarboxylic acids such as succinic acid and adipic acid (the aliphatic components) and dimethyl terephthalate (the aromatic component). The PBSAT resin includes multiple dicarboxylic acid residue components; for comparison, polybutylene succinate resin contains one dicarboxylic acid residue and polybutylene adipate-co-terephthalate resin includes two dicarboxylic acid residues (Kim et al. 2017; patent EP3214133 A1).

Experimental gill nets.— The relative fishing efficiency of transparent biodegradable PBSAT gill nets was compared with that of conventional yellow PA gill nets during fishing trials. Each gill net had a 210-mm nominal mesh opening, was made of 0.7-mm monofilament, and was 30 meshes in height and 275 meshes long (approximately 55 m stretched length). To provide buoyancy, each gill net was fixed to a 27.5 m long and 26 mm in diameter SCANFLYT-800 float line with a buoyancy of 150 g/m. To provide weight, they were attached to a 27.5 m long and 16 mm in diameter Danline lead line with a weight of 360 g/m. Consequently, an assembled gill net was 27.5 m long and had a hanging ratio of 0.5 (Figure 2).

Because the fishery for Greenland Halibut is carried out at the edge of the continental slope at depths that vary between 500 and 700 m, fishermen commonly use long gill-net sets with 30–40 gill-net sheets. In this study, a single set of experimental gill nets was used. The set consisted of 32 gill nets, with 16 PBSAT gill nets (B) and 16 PA gillnets (N) attached in such a way that they provided information for paired comparison analysis. The sheets of gill nets were arranged as B-NN-BB-NN-BB-NN-BB-NN-BB-NN-BB-NN-BB-NN-BB-NN-B. Actual measurements of the mesh openings (four rows of 20 meshes each) were taken using a Vernier caliper without applying tension to the meshes. The mean mesh openings of PA gill nets and PBSAT gill nets were 198.9 mm (95% CI = 198.4–199.4 mm) and 201.7 mm (95% CI = 201.4–202.0 mm), respectively (Figure 3). The difference in mean mesh sizes between both types of gill net was highly significant (unpaired *t*-test: $P = 6.4 \times 10^{-16}$). So was the difference in variation (*F*-test: $P = 8.4 \times 10^{-10}$).

Fishing vessel and fishing grounds.— The experiment was conducted on board the coastal gill-net boat MS

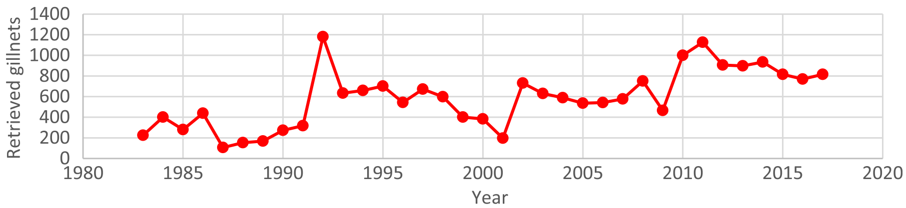

FIGURE 1. Number of retrieved gill nets in Norway (1983–2017). Source: Norwegian Directorate of Fisheries.

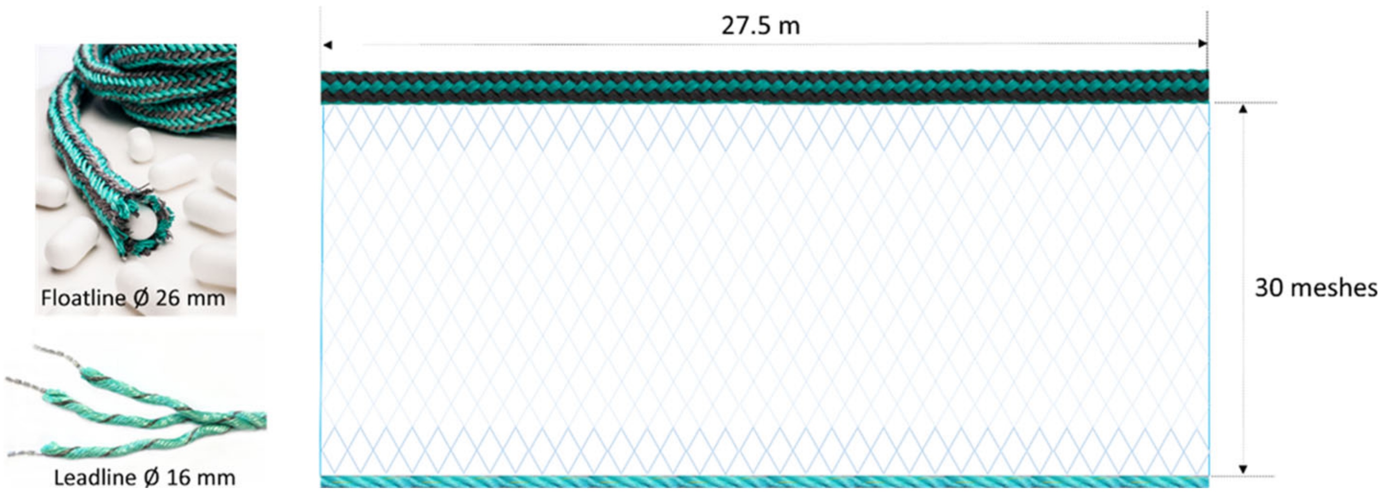

FIGURE 2. One sheet of gill nets illustrating the main components and dimensions.

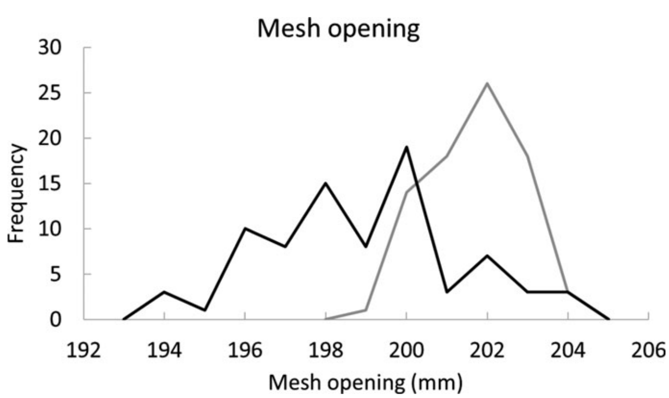

FIGURE 3. Mesh opening distribution for conventional PA gill nets (black line) and biodegradable PBSAT gill nets (gray line).

Skreigrunn (14.9 m LOA, 500 HP) between May 27 and June 23, 2016, and covered almost the entire season for Greenland Halibut. The experiment stopped when the vessel filled its quota. The fishing grounds chosen for the tests were located off the coast of Troms (northern Norway) between 69°24′N and 69°45′N and 16°23′E and 16°37′E, which is a common fishing area for coastal vessels from Troms.

Modelling and comparison of the size-dependent catch efficiency of the gill-net 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. We used the catch information (numbers and sizes of Greenland Halibut) from each gill-net set deployment to determine whether there was a significant difference in the catch efficiency averaged over deployments between the PA gill nets and the PBSAT gill nets. If a difference between the gill nets was present, we also wanted to determine if this difference could be related to the size of the Greenland Halibut. Specifically, to assess the relative length-dependent catch efficiency effect of changing from PA gill nets to PBSAT gill nets, we used the method described in Herrmann et al. (2017) to compare the catch data for the two gill-net types. This method models the length-dependent catch comparison rate (CC_l) summed over gill-net set deployments:

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

where nc_{lj} and nt_{lj} are the numbers of Greenland Halibut caught in each length-class l for the PA gill nets (control and baseline) and the PBSAT gill nets (treatment) in deployment j of a gill-net set; m is the number of deployments carried out. The functional form for the catch comparison rate $CC(l,v)$ (equation 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 the length-classes l. If the catch efficiency of the PBSAT gill nets and PA gill nets was similar, the expected value for the summed catch comparison rate would be 0.5. Therefore, this value was applied to judge whether or not there was a difference in catch efficiency between the two gill-net types. The experimental CC_l was modelled by the function $CC(l,v)$ of the following form:

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

where f is a polynomial of order k with coefficients v_0 to v_k. The values of the parameters v describing $CC(l,v)$ were estimated by minimizing equation (2), which was equivalent to maximizing the likelihood of the observed catch data. We considered f of up to an order of four 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 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, which quantifies the probability of obtaining by coincidence at least as big a discrepancy between the experimental data and the model as what was observed, assuming that the model is correct. Therefore, 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 for cases in which the data were subjected 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 called the catch ratio) $CR(l,v)$ between the two gill-net types using the following relationship:

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

The catch ratio provided a value for the difference in catch efficiency between the PBSAT gill nets and the PA gill nets. If the catch efficiency of both gill nets is equal, $CR(l,v)$ should always be 1.0. Thus, $CR(l,v) = 1.5$ would mean that the PBSAT gill net caught 50% more Greenland Halibut with length l than the PA gill net. In contrast, $CR(l,v) = 0.8$ would mean that the PBSAT gill net caught only 80% of the Greenland Halibut with length l that the PA gill net caught.

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 in catch efficiency in the gill nets and in the availability of Greenland Halibut), 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 described by Herrmann et al. (2017), the outer bootstrapping loop in the current study accounting for the between-deployment variation was performed paired for the PBSAT gill nets and PA gill nets to take full advantage of the experimental design that allowed the two types of gill nets to be deployed simultaneously. By multimodel inference in each bootstrap iteration, this method also accounts for the uncertainty due to uncertainty in model selection. We performed 1,000 bootstrap repetitions and calculated the Efron 95% (Efron 1982) confidence limits. To identify sizes of Greenland Halibut with significant differences in catch efficiency, we checked for length-classes for 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. Equation (5) was applied to the full length span for Greenland Halibut caught and separately for sizes below 65 cm ($CR_{\text{average65}-}$) and above 65 cm ($CR_{\text{average65+}}$) to determine if the average relative catch efficiency differed for the smaller and bigger Greenland Halibut.

Finally, for explorative purposes, we looked for any sign of loss in relative fishing efficiency for the PBSAT gill nets compared with the PA gill nets during the deployment period by comparing catch ratios for the last three deployments with those obtained for the first three deployments.

Tensile strength tests.— To compare the physical properties of the biodegradable PBSAT and conventional PA monofilaments, tensile strength measurements were carried out on samples before and after the fishing experiments using a H10KT universal tensile testing machine (Tinius Olsen TMC, Horsham, Pennsylvania). Spools of monofilament were provided by the producers of the gill nets. Samples of gill nets measuring approximately 20 meshes × 20 meshes were cut from the center of the new and used gill nets. The tests were performed in dry and wet conditions (at least 40 replicates for each case) according to ISO 1806 (International Organization for Standardization 2002). Tensile strength, defined as the stress needed to break the sample, is given in kilograms, and elongation at break, defined as the length of the sample after it has stretched and right when it breaks, is given relative to the initial size in percentage. The *t*-tests were used to compare the means of the two populations (PA or PBSAT), and *F*-tests were performed to determine the equality of the variances of the two populations.

RESULTS

The experimental gill-net set was lost on the first deployment carried out on May 27, 2016, and was recovered 3 d later on May 30, 2016. The length measurements of Greenland Halibut caught in this set of gill nets were not recorded and therefore not included in the analysis. Scientists on board the MS *Skreigrunn* measured the lengths of all fish caught in the next seven deployments. A total of 698 Greenland Halibut were caught, with 316 caught in the PBSAT gill nets and 382 in the PA gill nets. The mean ± SD effective soaking time was 21 h 29 min ± 0 h 52 min. The mean ± SD fishing depth was 664.1 ± 12.6 m, and sea temperature varied between 5°C and 6°C. Table 1 shows catch data including set number, date, soaking time, number of fish caught, and minimum and maximum length of fish caught.

Length-Dependent Catch Efficiency

The catch comparison rate was highly length dependent, with Greenland Halibut larger than 65 cm having a lower value for the bio gill nets; this means that the PA gill nets caught significantly more fish in those length classes (Figure 4). The modeled catch comparison curve follows the main trend of the experimental points, which is supported by the fit statistics presented in Table 2. When analyzing the size-dependent catch efficiency in the first three and the last three gill-net deployments, the results show a very similar tendency to when including all seven deployments. The size-dependent catch efficiency from the first three deployments shows that for fish larger than 65 cm in length, the catch rates for the PBSAT gill nets were significantly lower than those for the PA gill nets. The size-dependent catch efficiency from the last three deployments shows that catch rates for the PBSAT gill nets were significantly lower than those for the PA gill nets for fish between 64 and 74 cm (Figure 4).

The length-integrated average value for the catch ratio of the PBSAT gill nets with respect to the PA gill nets (including all deployments) was 82.7%, meaning that the PBSAT gill nets caught 17.3% fewer fish than the PA gill nets. However, this difference was not statistically significant, as expressed by the wide confidence limits (62.4–110.2) (Table 2). However, the average catch ratio for sizes of Greenland Halibut above 65 cm ($CR_{\text{average65+}}$) was 29.8% (CI = 15.5–44.4), which indicates that the PBSAT gill nets were catching significantly fewer bigger fish than the PA gill nets. For sizes of Greenland Halibut below 65 cm, the average catch efficiency ($CR_{\text{average65}-}$) was similar between the two gill-net types (Table 2). Individual analysis of the length-classes of 45, 50, 55, 60, 65, 70, 75, and 80 cm revealed significant differences in the catch ratio for fish larger than 65 cm. In the length-classes of 70 and 80 cm, for instance, the PBSAT gill nets caught 23.5% (CI = 1.2–43.3) and 2.1% (CI = 0.0–17.5) of what the PA gill nets caught, respectively (Table 2).

The length-integrated average values for the catch ratio of the PBSAT gill nets with respect to the PA gill nets for the first three and the last three deployments were 94.6% (CI = 81.8–173.7%) and 75.0% (CI = 60.5–123.8%), respectively. This means that the PBSAT gill nets caught 5.4% and 25.0% fewer fish than the PA gill nets in the first three and the last three deployments, respectively (Table 2). However, as is evident from the highly overlapping confidence bands, this result was not significant and likely was a coincidence.

Tensile Strength

The average breaking strength of the dry knotless PA monofilaments was 27.6 kg (CI = 27.4–27.8 kg) and that of dry biodegradable monofilaments was 17.7 kg (CI = 17.5–17.8 kg). Thus, the PA monofilaments were significantly 35.8% stronger (*t*-test: $P = 7.7 \times 10^{-21}$) than the biodegradable monofilaments. The average elongation at break of dry PA monofilaments was 27.7% (26.9–28.5%) and that of dry biodegradable monofilaments was 25.2% (CI = 25.1–25.2%), meaning that the dry PBSAT monofilaments were significantly (*t*-test: $P = 3.3 \times 10^{-4}$)

TABLE 1. Information about the seven gill-net deployments in 2016 comparing biodegradable PBSAT gill nets with conventional PA gill nets. The catch data includes the set number, date, fishing depth, soaking time, minimum and maximum length of fish caught, and number of fish caught in each net type.

Set ID	Date	Fishing depth (m)	Soaking time (h:min)	Minimum length (cm)	Maximum length (cm)	Number of fish in PBSAT gill nets	Number of fish in PA gill nets
Lost[a]	May 27						
1	May 31	640–672	22:30	47	68	45	55
2	June 1	655–687	22:10	52	67	33	19
3	June 2	645–689	22:56	48	73	62	74
4	June 13	630–657	21:45	53	80	32	42
5	June 16	658–664	22:15	54	73	26	21
6	June 20	670–698	21:25	52	71	95	133
7	June 23	655–678	20:05	54	68	23	38

[a]The experimental gill-net set got lost and was recovered on May 30, 2016. The catch data was not recorded and therefore was not included in the analysis.

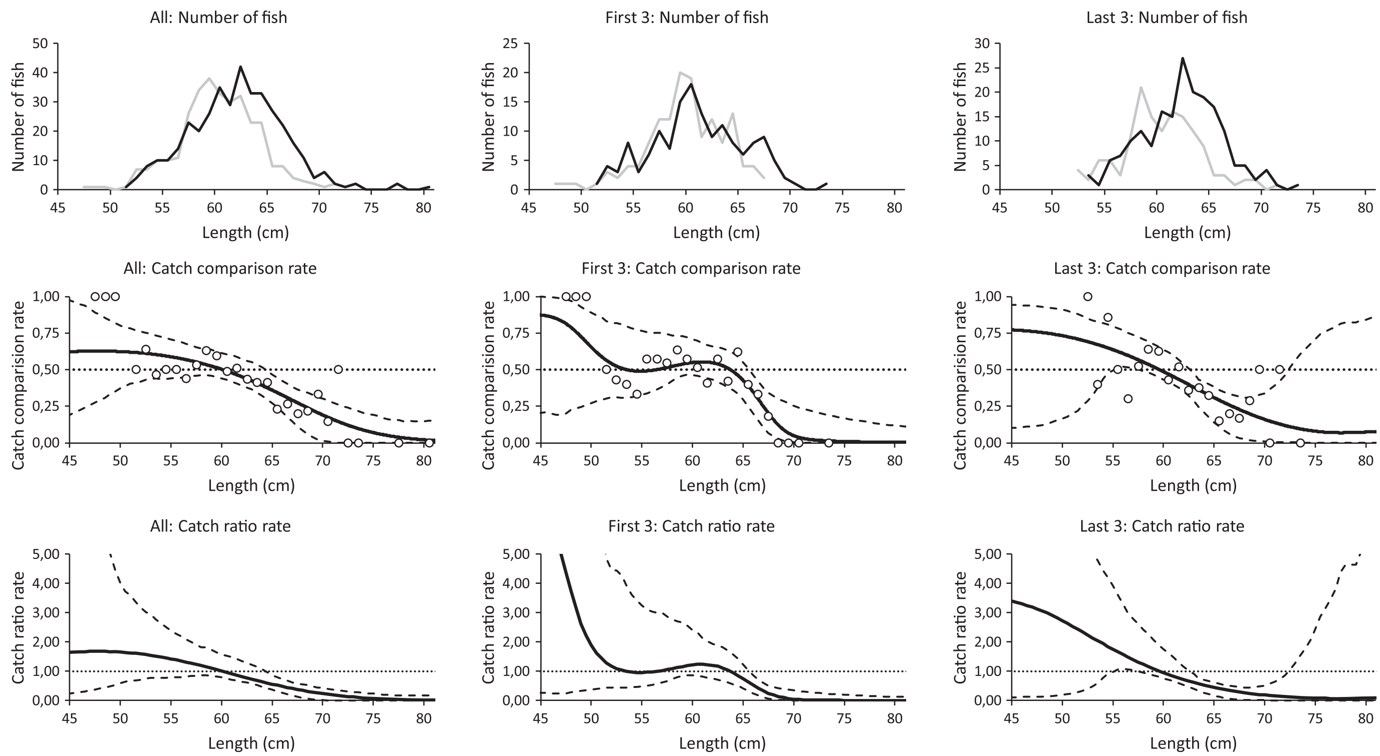

FIGURE 4. Size distribution, catch comparison rate, and catch ratio rate for Greenland Halibut catches for all seven gill-net deployments, in the first three deployments, and in the last three deployments. The top panels show the size distribution of Greenland Halibut caught with each type of gill net (black = PA gill nets, gray = PBSAT gill nets). The center panels show the catch comparison rate, with circle marks representing the experimental rate and the curve representing the modeled catch comparison rate. The dotted line at 0.5 represents the baseline, where both types of gill nets catch equally for Greenland Halibut. The dashed curves represent 95% confidence limits for the estimated catch comparison curve. The bottom panels show the estimated catch ratio curve. The dotted line at 1.0 represents the baseline, where both types of gill nets catch equally for Greenland Halibut. The dashed curves represent 95% confidence limits for the estimated catch ratio curve.

9.2% less elastic than dry PA monofilaments (Table 3; Figure 5).

The average breaking strength of the wet knotless PA monofilaments was 22.2 kg (CI = 22.1–22.4 kg) and that of wet biodegradable monofilaments was 19.3 kg (CI = 19.2–19.4 kg), representing a significant difference (t-test: $P = 3.3 \times 10^{-4}$) of 13.2% in favor of the PA monofilament. The average elongation at break of the wet knotless PA monofilaments was 32.1% (31.4–32.8%) and that of biodegradable monofilaments was 25.0% (CI =

TABLE 2. Catch ratio (%; 95% confidence limits in parentheses) and fit statistics obtained for the biodegradable PBSAT design versus the conventional PA design for all data, the first three sets, and the last three sets. The catch ratio provided value for the difference in catch efficiency between the PBSAT gill nets and the PA gill nets. If the catch efficiency of both gill nets is equal, the catch ratio should always be 100%. Thus, a catch ratio of 150% would mean that the PBSAT gill nets caught 50% more Greenland Halibut than the PA gill nets. In contrast, a catch ratio of 80% would mean that the PBSAT gill nets caught only 80% of the Greenland Halibut with length *l* that the PA gill nets caught.

Length (cm) and statistics	Catch ratio (%)		
	All data	First three sets	Last three sets
45	164.9 (24.0–363.1)	690.8 (25.8–67,920.1)	338.9 (11.4–1,634.4)
50	165.7 (59.5–400.6)	188.7 (37.4–803.9)	273.4 (19.4–1,012.8)
55	142.7 (78.9–239.1.7)	95.9 (49.2–324.3)	175.2 (98.0–392.9)
60	101.0 (79.0–158.1)	121.7 (86.6–241.0)	94.8 (76.5–174.6)
65	56.2 (37.4–86.9)	74.6 (42.0–123.7)	44.7 (15.9–62.0)
70	23.5 (1.2–43.3)	5.2 (0.3–34.3)	19.0 (1.0–51.5)
75	7.5 (0.0–23.7)	0.9 (0.0–20.1)	8.6 (0.1–243.2)
80	2.1 (0.0–17.5)	0.4 (0.0–13.4)	31.3 (0.0–532.8)
Average, fish <65 cm	100.0 (85.9–129.5)	112.1 (90.9–202.0)	91.0 (71.9–173.2)
Average, fish >65 cm	29.8 (15.5–44.4)	31.3 (0.0–55.6)	25.5 (0.0–44.4)
Average	82.7 (62.1–112.9)	94.6 (81.8–173.7)	75.0 (60.5–123.8)
P-value	0.7141	0.9082	0.1143
Deviance	18.78	11.44	22.98
df	23	19	16

24.7–25.3%), meaning that the wet biodegradable monofilaments were significantly (*t*-test: $P = 1.9 \times 10^{-8}$) 22.3% less elastic than the wet PA monofilaments (Table 3; Figure 5).

The average breaking strength of the wet PA netting was 22.5 kg (CI = 22.0–23.0 kg), while that of biodegradable netting was 20.0 kg (CI = 19.1–20.9 kg), representing a significant difference (*t*-test: $P = 7.9 \times 10^{-4}$) of 11.0% in favor of the PA netting. The average elongation at break of PA netting was 30.6% (29.9–31.3%), while that of biodegradable netting was 34.2% (CI = 33.4–35.0%), meaning that the biodegradable netting was significantly (*t*-test: $P = 3.2 \times 10^{-6}$) 11.6% less elastic than PA netting (Table 3; Figure 5).

The difference in the average tensile strength between new and used gill nets (measured in wet conditions) was significant for PA gill nets (*t*-test: $P = 3.2 \times 10^{-10}$) and for PBSAT gill nets (*t*-test: $P = 3.2 \times 10^{-2}$). The elasticity of used PBSAT gill nets (32.9%, CI = 31.6–34.1%) was significantly reduced (*t*-test: $P = 2.7 \times 10^{-2}$) by 3.9% with respect to new PBSAT nets (34.2%, CI = 33.4–35.0%) (Table 3; Figure 5). Used PBSAT gill nets were significantly (12.3%) weaker and 8.5% less elastic than used PA gill nets.

DISCUSSION

Compared to conventional PA gill nets, the PBSAT gill nets caught fewer Greenland Halibut, the relative catch efficiency decreased with increasing fish size, and for sizes above 65 cm in length this reduction in catch efficiency was statistically significant. Specifically, it was estimated that the PBSAT gill nets caught 30% fewer Greenland Halibut above 65 cm than the conventional PA gill nets (Table 2). The difference in tensile strength and elasticity between the two net types could have had a strong effect on their relative catch efficiencies. Material testing revealed that the PBSAT gill nets were considerably weaker (11.0%) and less elastic (11.9%) than the PA gill nets. Thus, large Greenland Halibut (>65 cm) may have managed to break the meshes of PBSAT gill nets and avoid getting caught. Our results agree with those reported by Grimaldo et al. (2018), who assessed the catch characteristics of PBSAT gill nets for Atlantic Cod and Pollack, with Bae et al. (2013) for flounder *Cleisthenes pinetorum*, and with Kim et al. (2013, 2016) for Yellow Croaker *Larimichthys polyactis*. These scientists reported that the catch efficiency of PA gill nets was 1.1–1.4 times greater than that of the biodegradable nets and concluded that the flexibility of PBSAT gill nets was positively correlated with fishing capacity (i.e., greater flexibility means greater fishing capacity).

We also investigated whether there were any signs of temporal loss in relative fishing efficiency for the PBSAT gill nets and the PA gill nets during the deployment period by comparing catch ratios for the last three deployments with those obtained for the first three deployments. We did not find any clear signs of such an effect. However, the deployment period during this study was short, so this result cannot be taken as evidence that PBSAT gill nets

TABLE 3. Average tensile strength (kg) and elongation at break (%) measurements (with 95% confident intervals in parentheses) for the monofilaments and meshes of new and used gill nets used for fishing Greenland Halibut in 2016.

	Tensile strength (kg)		Elongation at break (%)	
Type of material	New	Used	New	Used
Dry PA monofilament	27.6 (27.4–27.8)		27.7 (26.9–28.5)	
Dry biodegradable monofilament	17.7 (17.5–17.8)		25.2 (25.1–25.2)	
Wet PA monofilament	22.2 (22.1–22.4)		32.1 (31.4–32.8)	
Wet biodegradable monofilament	19.3 (19.2–19.4)		25.0 (24.7–25.3)	
Wet PA netting	22.5 (22.0–23.0)	21.1 (21.1–21.1)	30.6 (29.9–31.3)	30.1 (30.1–30.2)
Wet biodegradable netting	20.0 (19.1–20.9)	18.5 (18.5–18.6)	34.2 (33.4–35.0)	32.9 (32.9–32.9)

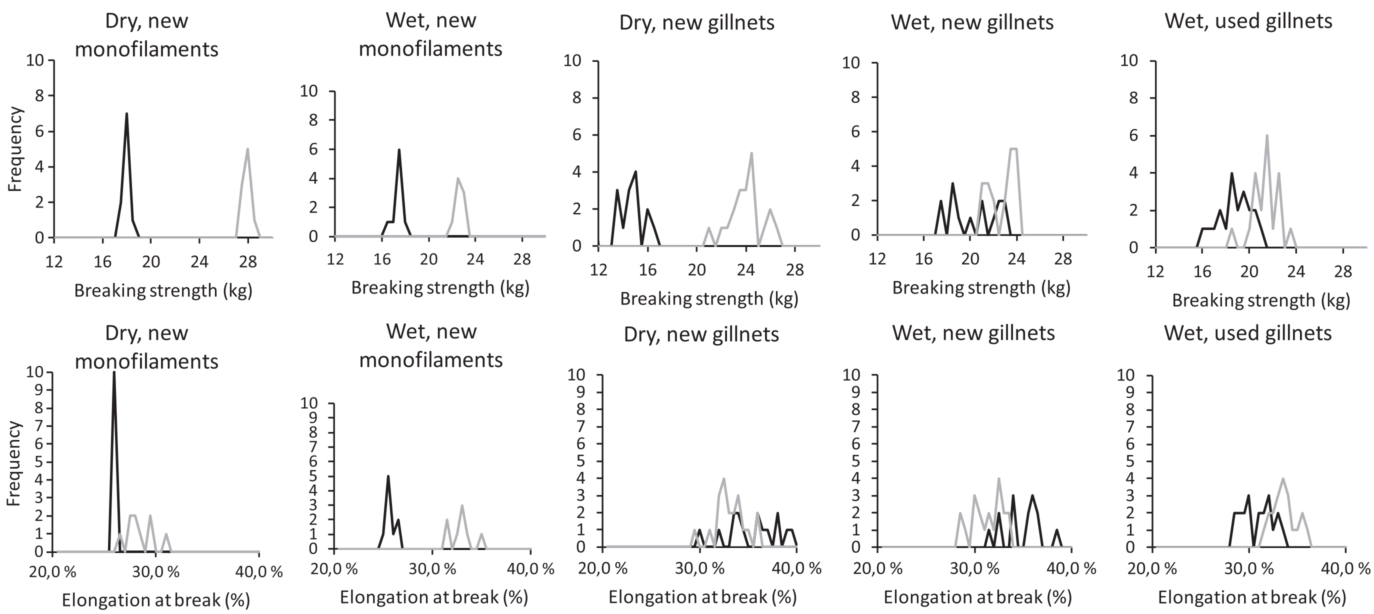

FIGURE 5. Tensile strength (top panels) and elongation at break (bottom panels) of monofilaments and netting for measurements carried out in dry and wet conditions for PA (gray lines) and biodegradable (black lines) materials.

do not lose catch efficiency compared with the traditional gill nets over the course of a complete fishing season that consists of many more deployments.

The results obtained in this study need to be interpreted with caution, as they are based on a data set composed of only seven gill-net deployments that caught 698 Greenland Halibut. This small sample size leads to uncertainties regarding the estimated catch ratios of the PBSAT gill nets and the PA gill nets. However, these uncertainties are reflected in the confidence bands around the catch ratio curves. Therefore, as long as these confidence bands are considered when drawing conclusions, the limited number of Greenland Halibut caught should not be a major problem if it is valid to assume that the seven gill-net deployments reflect how the two gill-net types on average would perform, at least relative to each other regarding catch efficiency for Greenland Halibut. We have no reason to believe that our gill-net deployments were atypical for the fishery. Therefore, despite the limited data set we believe that this study provides relevant and reliable information as long as the above-described precautions are respected.

Tensile strength measurements of the used PBSAT gill nets showed that some meshes broke at a 15.6-kg load, whereas the weakest PA mesh broke at a 18.2-kg load. Based on the length distributions of fish caught with both types of gill nets, it seems possible that the weakest PA meshes were still strong enough to retain Greenland Halibut of large length-classes, whereas the weakest PBSAT gill-net meshes were not. The elasticity of the used PA gill nets was unchanged over time (around 30%) but that of the used PBSAT gill nets was significantly reduced by 3.9% with respect to new nets. This reduction in elasticity in the PBSAT gill nets (and not in the PA gill nets) over the course of the 4-week experiment (May 27 to June 23, 2016) suggests that changes in the physical properties of the PBSAT gill nets occur over time due to degradation.

Biological degradation was not assessed in this study, but it should be studied because it may confound the effect of use and wear of the gill nets on the weakening of the PBSAT gill nets.

If lost, both PBSAT and PA gill nets are no longer affected by use and wear (i.e., abrasion in the hauling machine, friction due to contact with hard surfaces when gill nets are operated on deck). In the case of PBSAT gill nets, bacteria, algae, and fungi 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 the marine ecosystems (Tokiwa et al. 2009; Kim et al. 2014a, 2014b). In the case of PA gill nets, weakening of the material nearly stops when the gear is lost, and degradation then occurs very slowly. The PA gill nets are highly resistant to degradation, but 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, PA gill nets 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. (2017), biodegradable PBSAT gill nets would stop catching fish after 2 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 use and wear. The question of "how fast a biodegradable gill net loses its ghost fishing capacity" depends greatly on when it is lost (new or old gill net) and how much it has been used (use and wear).

The lifespan of gill nets, in this case defined as the amount of time they can be used for fishing, depends greatly on their durability and the degree of damage that they suffer when fishing. In the Norwegian deepwater gill-net fishery for Greenland Halibut, a conventional PA gill net generally is used for one season, and one season normally lasts between 1 and 2 months depending on the boat, the quota, and the availability and catchability of fish. When the fishing season is over, fishermen normally exchange most of the sheets of nets for new ones because the cost of repairing the nets is much greater than the cost of buying new, relatively inexpensive PA gill nets. Therefore, the use of short-lifespan PBSAT gill nets could be an alternative to conventional PA gill nets if the profitability of the fishing operations is not compromised.

However, in the current study, the cost of the PBSAT gill nets was approximately twice that of PA gill nets, and the catch of Greenland Halibut obtained with the PBSAT gill nets was approximately 19% lower than that caught with PA gill nets. One set of PA gill nets (32 sheets) for fishing Greenland Halibut costs approximately US$3,104; thus, the cost of replacing them with PBSAT gill nets would have been approximately $6,208. Based on the length–weight relationship for Greenland Halibut ($w = 4.538 \times 10^{-6} \times l^{3,158}$; Gundersen and Brodie 1999), the weight of the fish caught with the experimental gill nets was approximately 1,390 kg, and according to the price in June 2016 ($3.06/kg) the catch had a value of $5,006. The fact that the PBSAT gill nets caught only 82.3% of what the PA gill nets did was equivalent to approximately 197 kg less of Greenland Halibut, which represented a loss of $709. The MS *Skreigrunn* used five sets of gill nets in the 2016 fishing season (one of which was the experimental gill-net set) and landed 16,136 kg of Greenland Halibut in the period of May 27 to June 23, 2016, with a value of $58,225. If all gill nets used in this period had been PBSAT gill nets, the 19% reduction in catch would have represented approximately $8,150 less income for the crew of the MS *Skreigrunn*.

In conclusion, biodegradable PBSAT gill nets have potential to be used as a feasible alternative to conventional PA gill nets, especially in short-seasoned fisheries such as that for Greenland Halibut, and they would reduce the effect of ghost fishing if they are lost. However, a 17.3% reduction of the catch would negatively impact the cost-effectiveness of the fishing operation and the acceptance of biodegradable gill nets 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 gill-net fisheries.

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