



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

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10 & Equal authorship

11
12 **Abstract**

13 Fishing trials were carried out to compare the relative fishing efficiency of gillnets made of a
14 new biodegradable resin (polybutylene succinate co-adipate-co-terephthalate (PBSAT)) with
15 conventional (nylon) nets. The fishing trials covered two consecutive fishing seasons (2016
16 and 2017) for cod (*Gadus morhua*) and saithe (*Pollachius virens*) in northern Norway. Results
17 generally showed better catch rates for the nylon gillnets. The biodegradable PBSAT gillnets
18 caught 50.0% and 26.6% fewer cod, and 41.0% and 22.5% fewer saithe than the nylon
19 gillnets in 2016 and 2017, respectively. Even though the relative catch efficiency of the
20 biodegradable gillnets was slightly better in 2017 than in 2016, the difference with respect to
21 the catch efficiency of nylon gillnets may be too large for bio degradable gillnets to be
22 accepted by fishermen if they were available commercially. Tensile strength measurements of
23 the nylon and bio degradable PBSAT gillnets carried out before and after the fishing trials
24 showed that the both types of gillnets had significant reductions in tensile strength and
25 elongation at break, especially in 2017. Although less catch efficient than nylon gillnets,

26 biodegradable PBSAT gillnets show great potential for reducing ghost fishing and plastic
27 pollution at sea which are major problems in these fisheries.

28

29 **Keywords:** Biodegradable gillnet; Ghost fishing; Gillnet fishery; Catch efficiency; Cod
30 fishery; PBSAT resin; Cod; Saithe.

31

32 **Introduction**

33 Fishing gears that continue fishing after they have been lost (or abandoned) is known as ghost
34 fishing (Breen, 1990). Lost fishing gears, apart from being associated with the catch of target
35 and none-target species, also causes a variety of harmful impacts to coral reefs and benthic
36 fauna, contributes to marine pollution by introducing synthetic (none-biodegradable) plastic
37 materials into the marine food web, causes economic losses from marine species mortalities
38 and due to replacement of lost gears, and diverse costs related to retrieving operations (Al-
39 Masroori et al., 2004; Brown and Macfadyen, 2007; Large et al., 2009; Macfadyen et al.,
40 2009; Gilman, 2015; Gilman et al., 2016; Lusher et al., 2017). From all these problems,
41 marine pollution caused by none-degradable plastics has become one of the most serious
42 problems worldwide (Lusher et al., 2016; Chae and An, 2017). Recognition to all these
43 problems is nowadays demonstrated through the large number of international organizations
44 and agreements that currently focus on reducing the effect of abandoned, lost or otherwise
45 discarded fishing gear (ALDFG) and numerous national initiatives that have being
46 implemented around the world to mitigate their impact on the marine ecosystem (Gilman et
47 al., 2016).

48

49 There is extensive literature presenting mitigating measures and methods to reduce the effects
50 of ALDFG on the environment (Al-Masroori et al., 2004; Matsuoka et al., 2005; Brown and
51 Macfadyen, 2007; Large et al., 2009; Macfadyen et al., 2009; Gilman, 2015; Gilman et al.,

1
2 52 2016; Lusher et al., 2017). Macfadyen et al. (2009) for instance grouped the methods to
3
4 53 reduce the effects of ALDFG into: A) preventive methods that reduce the incidence of fishing
5
6 54 gear from becoming abandoned, lost and discarded, such as gear marking, on-board
7
8 55 technology to avoid or locate lost gear, onshore collection/reception and/or payment for
9
10 56 old/retrieved gear, reduced fishing effort and spatial management; B) mitigating measures that
11
12 57 reduce the impact of lost gears in the environment, such as reducing ghost fishing (and plastic
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14 58 pollution) through the use of biodegradable gear, reducing ghost fishing of incidental species
15
16 59 by providing escape vents; C) curative measures that are intended to remove the lost gear
17
18 60 from the environment, such as electronic and/or acoustic technology for locating lost gear,
19
20 61 better reporting of lost gear, gear recovery programs and disposal/recycling of retrieved gear.
21
22 62 Many scientists argue that efforts focusing on preventive methods and quick recovery of lost
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24 63 gears are likely to be more effective because curative methods can be highly cost demanding
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26 64 and largely time consuming (Matsushita et al., 2008; Suuronen et al., 2012; Ullmann and
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28 65 Broadhurst, 2015). In addition, preventing gear loss would eliminate ghost fishing mortality
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30 66 (Ullmann and Broadhurst, 2015).
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68 In recent years many studies have documented the physical properties, biodegradability and
69 fishing efficiency of transparent gillnets made of poly butylene succinate (PBS) resin blended
70 with poly butylene adipate-co-terephthalate (PBAT) resin and polybutylene succinate co-
71 adipate-co-terephthalate (PBSAT) resin (Park et al., 2007a, b, 2010; Park and Bae, 2008; Bae
72 et al., 2012, 2013; An and Bae, 2013; Kim et al., 2013, 2016). Ishii et al. (2008) reported that
73 within two years of being submerged in seawater, transparent gillnets made of PBSAT resins
74 were degraded by microorganisms (i.e. natural occurring bacteria, algae and fungi), resulting
75 in low-molecular-weight oligomers, dimers and monomers that ultimately were mineralized
76 into carbon dioxide and water (Tokiwa et al., 2009). However, Kim et al. (2017) argues that

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2 77 gillnets made of PBS and PBAT resins have poor tinting properties and therefore can cause
3
4 78 catch efficiency problems such as decreased strength and elasticity due to coloration.
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6 79
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8 80 In Norway, gillnetting is one of the most important commercial fishing methods for the
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10 81 coastal fleet, however transparent gillnets are not currently used. Norwegian fishermen prefer
11
12 82 coloured gillnets because they provide a better contrast with the metal (aluminium and or
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14 83 stainless steel) sorting boards and make the removal of fish from the nets easier, and also
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16 84 because many fishermen believe that some colours have better catch efficiencies than others
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18 85 depending on the contrast with the seabed. The most important target species in the
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20 86 Norwegian gillnet fishery are cod (*Gadus morhua*) and saithe (*Pollachius virens*). In 2017,
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22 87 4658 fishing boats (less than 14.9 m LOA) were registered and had licences for gillnetting in
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24 88 Norway. This small-scale coastal fleet caught 89460 tonnes of cod, 17635 tonnes of saithe,
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26 89 and 19869 tonnes of haddock (*Melanogrammus aeglefinus*), representing 22.3%, 14.7% and
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28 90 18.1% of the respective annual quota for these species (Norwegian Directorate of Fisheries,
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30 91 2018). To date, Norway is one of the few countries in the world that has a program for
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32 92 systematic annual retrieval of ALDFG from the most intensively fished areas (Brown et al.,
33
34 93 2005; Macfadyen et al., 2009; Cho, 2011). Based on information provided by fishermen, the
35
36 94 Norwegian Directorate of Fisheries carry out annual retrieval operations for reported lost
37
38 95 fishing gear and deliver it on land to recycling (Humborstad et al., 2003; Gilman et al., 2016).
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40 96 However, these operations are highly challenging because of the depth (500–1000 m) and
41
42 97 strong currents in the areas, as well as uncertainties associated with the position of lost gear.
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44 98
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46 99 The development of fishing gears made of biodegradable plastic materials, like PBSAT resin,
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48 100 is considered as a potential solution to reduce ghost fishing and plastic pollution at sea caused
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50 101 by ALDFG (Brown and Macfadyen, 2007; Large et al., 2009; Macfadyen et al., 2009;
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52 102 Gilman, 2015; Gilman et al., 2016); however, for an environmentally safe application of such
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2 103 biodegradable plastics at sea it is important to prove that the intermediate break-down
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4 104 products, even those that are degradable, do not have any ecotoxicological effects on the
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6 105 ecosystem. Simultaneously, for biodegradable gillnets to be adopted by the fishing industry,
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8 106 they should prove to be at least as efficient as conventional nylon gillnets and not compromise
9
10 107 the profitability of the fishing operations. The present study addresses the second concern:
11
12 108 fishing efficiency. The specific objective of this study was therefore to assess the relative
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14 109 catch efficiency of biodegradable PBSAT gillnets with that of conventional nylon gillnets.
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16
17 110 Our study covered the consecutive fishing seasons of 2016 and 2017, targeting the fall fishery
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19 111 for cod and saithe in Northern Norway.
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23 113 **Materials and Methods**

24 114 **Biodegradable polybutylene succinate-co-adipate-co-terephthalate resin**

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27 115 PBSAT resin is an aliphatic-aromatic co-polyester that is prepared using 1,4-butanediol as an
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29 116 aliphatic glycol (as base materials) and dicarboxylic acids, such as succinic acid and adipic
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31 117 acid (which are aliphatic components) and dimethyl terephthalate (which is an aromatic
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33 118 component) (Kim *et al.*, 2017, patent EP3214133 A1). PBSAT resin is biodegradable,
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35 119 exhibits an excellent coloration effect and does not cause problems such as a decrease in
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37 120 strength due to coloration, as observed in PBS and PBAT resins. The biodegradable PBSAT
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39 121 resin composition includes a colorant at 0.005–0.015 parts by weight. To improve the
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41 122 properties of monofilament yarns formed from the coloured PBSAT resin, additives such as
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43 123 anti-oxidants and UV stabilizers may be included at 0.2–0.5 parts by weight with respect to
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45 124 100 parts by weight of the PBSAT resin (Kim *et al.*, 2017, patent EP3214133 A1).
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51 125 52 126 **Experimental design**

53 127 A set of experiments were designed to cover two consecutive fishing seasons for saithe and
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55 128 cod. Fishing trials were conducted under commercial fishing conditions on board the coastal
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2 129 gillnet boat “MS Karoline” (10.9 m LOA). The first fishing season was carried out between
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4 130 24 October 2016 and 11 January 2017, and the second season between 11 October 2017 and
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6 131 17 January 2018, herein referred to as the 2016 and 2017 seasons, respectively. The fishing
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8 132 grounds were off the coast of Troms (Northern Norway) between 69°55′–70°22′N and
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10 133 19°39′–21°05′E, which is a common fishing area for coastal vessels from Troms. The fishing
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12 134 depth varied between 29 and 178 m. The sea water temperature was recorded every hour in
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14 135 2016 with a DST-CTD Star-Oddi logger (Star-Oddi, Iceland) that was set at a depth of
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16 136 approximately 70 m.
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22 138 In 2016, the fishing performance of 16 green biodegradable PBSAT gillnets, herein called bio
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24 139 gillnets, and 16 conventional green nylon gillnets, herein called nylon gillnets, was compared
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26 140 during fishing trials carried out under commercial fishing conditions. In 2017, the experiment
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28 141 was repeated with a new set of blue gillnets. Each gillnet sheet was made of double knotted
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30 142 0.55 mm monofilament, had 130 mm nominal mesh opening size and was 50 meshes high by
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32 143 275 meshes long (approx. 55 m stretched length). Each assembled gillnet was approximately
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34 144 27.5 m long and had a hanging ratio of 0.5. Since the density of the gillnets materials was
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36 145 similar (1.12 g ml^{-1} for the bio gillnets and 1.14 g ml^{-1} for nylon gillnets) we provided similar
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38 146 buoyancy to both types of gillnets. Each gillnet sheet was fixed to 26 mm diameter
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40 147 SCANFLYT-800 floatlines (made of braided polypropylene rope with a single core of
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42 148 polyurethane floating elements inside) with a buoyancy of 150 g m^{-1} . To provide weight, they
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44 149 were each attached to a 16 mm diameter DANLINE leadline (made of polypropylene rope
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46 150 with a lead core) with a weight of 360 g m^{-1} . The 32 experimental gillnets were divided into
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48 151 two sets, where each set consisted of eight bio gillnets (B) and eight nylon gillnets (N). The
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50 152 gillnets were attached in such a way that they provided the best information for paired
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52 153 comparison. Set 1 was arranged as B–NN–BB–NN–BB–NN–BB–NN–B and set 2 was
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54 154 arranged as N–BB–NN–BB–NN–BB–NN–BB–N (Fig. 1).
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155 FIG. 1

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157 Actual mesh openings were measured with a Vernier caliper without applying tension to the
 158 mesh. Two rows of consecutive 20 meshes were measured in each type of gillnet. The mean
 159 mesh openings of the bio gillnets and nylon gillnets used in 2016 were 132.8 ± 0.8 mm and
 160 131.4 ± 0.8 mm, respectively. Those used in 2017 were 130.7 ± 0.8 mm and 128.2 ± 0.8 mm,
 161 respectively.

162

163 **Modelling the size-dependent catch efficiency between gillnet types**

164 We used the statistical analysis software SELNET (Sistiaga *et al.*, 2010; Herrmann *et al.*,
 165 2012, 2016) to analyse catch data and conduct length-dependent catch comparisons and catch
 166 ratio analyses. Using the numbers and sizes of cod and saithe in each gillnet set deployment
 167 we determined whether there was a significant difference in the catch efficiency averaged
 168 over deployments between the nylon and bio gillnets. We also determined if a potential
 169 difference between the gillnet types could be related to the size of the cod or saithe.
 170 Specifically, to assess the relative length-dependent catch efficiency effect of changing from
 171 nylon gillnet to bio gillnet, we used the method described in Herrmann *et al.* (2017) and
 172 compared the catch data for the two types of gillnets. This method models the length-
 173 dependent catch comparison rate (CC_l) summed over gillnet set deployments for a full
 174 deployment period. The 2016 and 2017 experiments were analysed separately for cod and
 175 saithe, respectively:

$$176 \quad CC_l = \frac{\sum_{j=1}^m \{nt_{lj}\}}{\sum_{j=1}^m \{nt_{lj} + nc_{lj}\}} \quad (1)$$

177 where nc_{lj} and nt_{lj} are the numbers of cod or saithe caught in each length class l for the nylon-
 178 gillnet (*control*) and the bio gillnet (*treatment*), in deployment j of a gillnet set. m is the
 179 number of deployments carried out for the season (2016 or 2017 experiment separately). Only
 180 deployments of the gillnet sets that caught at least 10 individuals in total between the nylon

1
2 181 and bio gillnet of the specific species investigated (cod or saithe) was included in the analysis
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4 182 for that species to avoid overinflating confidence intervals for catch comparisons and catch
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6 183 ratio analyses (Krag et al., 2014, 2016). The functional form for the catch comparison rate
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8 184 $CC(l, \mathbf{v})$ (the experimental being expressed by equation 1), was obtained using maximum
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10 185 likelihood estimation by minimizing the following expression:

$$11 \quad -\sum_l \left\{ \sum_{j=1}^m \{ n t_{lj} \times \ln(CC(l, \mathbf{v})) + n c_{lj} \times \ln(1.0 - CC(l, \mathbf{v})) \} \right\} \quad (2)$$

12
13 186 where \mathbf{v} represents the parameters describing the catch comparison curve defined by $CC(l, \mathbf{v})$.
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15 187 The outer summation in the equation is the summation over the length classes l . When the
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17 188 catch efficiency of the bio gillnet and nylon gillnet is similar, the expected value for the
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19 189 summed catch comparison rate would be 0.5. Therefore, this baseline can be applied to judge
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21 190 whether or not there is a difference in catch efficiency between the two gillnets. The
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23 191 experimental CC_l was modelled by the function $CC(l, \mathbf{v})$, on the following form:
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$$26 \quad CC(l, \mathbf{v}) = \frac{\exp(f(l, v_0, \dots, v_k))}{1 + \exp(f(l, v_0, \dots, v_k))} \quad (3)$$

27
28 193 where f is a polynomial of order k with coefficients v_0 to v_k . The values of the parameters \mathbf{v}
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30 194 describing $CC(l, \mathbf{v})$ are estimated by minimizing equation (2), which are equivalent to
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32 195 maximizing the likelihood of the observed catch data. We considered f of up to an order of 4
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34 196 with parameters v_0, v_1, v_2, v_3 and v_4 . Leaving out one or more of the parameters $v_0 \dots v_4$ led to
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36 197 31 additional models that were also considered as potential models for the catch comparison
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38 198 $CC(l, \mathbf{v})$. Among these models, estimations of the catch comparison rate were made using
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40 199 multi-model inference to obtain a combined model (Burnham and Anderson, 2002; Herrmann
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42 200 *et al.*, 2017).
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48 203 The ability of the combined model to describe the experimental data was evaluated based on
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50 204 the p -value. This p -value, which was calculated based on the model deviance and the degrees
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52 205 of freedom, should not be <0.05 for the combined model to describe the experimental data
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54 206 sufficiently well, except from cases where the data were subjected to over-dispersion
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1
2 207 (Wileman *et al.*, 1996; Herrmann *et al.*, 2017). Based on the estimated catch comparison
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4 208 function $CC(l, \nu)$ we obtained the relative catch efficiency (also named catch ratio) $CR(l, \nu)$
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6 209 between the two gillnet types by the following relationship:
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8
9 210
$$CR(l, \nu) = \frac{CC(l, \nu)}{(1 - CC(l, \nu))} \quad (4)$$

10

11 211 The catch ratio is a value that represents the relationship between catch efficiency between the
12
13 212 bio gillnet and that of the nylon gillnet. Thus, if the catch efficiency of both gillnets is equal,
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15 213 $CR(l, \nu)$ should always be 1.0. Thus, $CR(l, \nu) = 1.5$ would mean that the bio gillnet is catching
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17 214 50% more cod or saithe with length l than the nylon gillnet. In contrast, if $CR(l, \nu) = 0.7$ would
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19 215 mean that the bio gillnet is only catching 70% of the cod or saithe with length l that the nylon-
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21 216 gillnet is catching.
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26 218 The confidence limits for the catch comparison curve and catch ratio curve were estimated
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28 219 using a double bootstrapping method (Herrmann *et al.*, 2017). This bootstrapping method
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30 220 accounts for between-set variability (the uncertainty in the estimation resulting from set
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32 221 deployment variation of catch efficiency in the gillnets and in the availability of cod and
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34 222 saithe) as well as within-set variability (uncertainty about the size structure of the catch for
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36 223 the individual deployments). However, contrary to the double bootstrapping method
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38 224 (Herrmann *et al.*, 2017) the outer bootstrapping loop in the current study accounting for the
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40 225 between deployment-variation was performed paired for the bio and nylon gillnets, taking full
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42 226 advantage of the experimental design in which both types of net were deployed
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44 227 simultaneously (Fig. 1). By multi-model inference in each bootstrap iteration, the method also
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46 228 accounts for the uncertainty in model selection. We performed 1000 bootstrap repetitions and
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48 229 calculated the Efron 95% (Efron, 1982) confidence limits. To identify sizes of cod or saithe
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50 230 with significant differences in catch efficiency, we checked for length classes in which the
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52 231 95% confidence limits for the catch ratio curve did not contain 1.0.
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233 Finally, a length-integrated average value for the catch ratio ($CR_{average}$) was estimated
234 directly from the experimental catch data by:

$$235 \quad CR_{average} = \frac{\sum_l \sum_{j=1}^m \{nt_{lj}\}}{\sum_l \sum_{j=1}^m \{nc_{lj}\}} \quad (5)$$

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

238

239 **Tensile strength tests**

240 Tensile strength tests were carried out on all the bio and nylon gillnets used in the fishing
241 experiments using a H10KT universal tensile testing machine (Tinius Olsen TMC, PA, USA)
242 equipped with a load cell with 5000 N rated force. The tests were performed in wet conditions
243 on samples collected before and after the experimental fishing (at least 40 replicates for each
244 case) according to ISO 1806:2002. Tensile strength, defined as the stress needed to break the
245 sample, is given in kg, and elongation at break, defined as the length of the sample after it had
246 stretched right when it breaks is given relative to the initial mesh size in percentage.

247

248 **Assessment of gillnet damage**

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

256

257 **Results**

1
2 258 The two experimental gillnets were set at sea 58 and 92 times in the 2016 and 2017 seasons,
3
4 259 respectively. Scientists on board the MS Karoline measured the lengths of all fish caught in
5
6 260 34 deployments in each fishing season. Fishermen provided logs (dates, positions and setting-
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8 261 retrieving times) of the remaining deployments, except length measurements of fish caught.
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10 262 The mean effective fishing time (\pm SD) (the time the gillnets remained at the sea bed) was 19
11
12 263 h, 10 min \pm 6 h, 32 min while in 2017 it was 21 h, 58 min \pm 6 h, 06 min. The mean (\pm SD)
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14 264 fishing depth was significantly deeper in 2017 (109 ± 28.9 m) compared to 2016 (61 ± 55.7
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16 265 m). The temperature of the sea water varied between 8.8°C and 4.1°C at the start and end of
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18 266 the experiment. The catch was quite clean, mostly consisting of cod and saithe. These species
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20 267 were caught in sufficient numbers to be included in the analysis. We occasionally caught very
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22 268 few large haddock, but far too few (less than 20 individuals per season) to be included in the
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24 269 study.
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30 271 **Cod**

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32 272 A total of 1057 cod were caught over 33 gillnet deployments during the 2016 and 2017
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34 273 fishing seasons, of which 407 were caught by the bio gillnets and 650 were caught by the
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36 274 nylon gillnets. Deployments with at least 10 cod in the catch were used in the analysis
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38 275 because gillnets with less than 10 fish would add little information and increase uncertainties
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40 276 to the catch comparison analyses (Table 1).
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43 277 TABLE 1

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47 279 The length distribution of cod that were caught with both types of gillnets was very similar in
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49 280 2016 and 2017. The catch was length-dependent for both types of gillnet, including fish from
50
51 281 50 to 103 cm, but with most of the fish in the range of 65 to 85 cm (Fig. 2). In 2016, the catch
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53 282 efficiency of the bio gillnets was significantly lower than that of the nylon gillnets for almost
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55 283 all cod sizes except for those below 64 cm, while in 2017 significance was only obtained for
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1
2 284 cod in the size span 90 to 103 cm (Fig. 2). The $CR(l)$ was also highly length dependent, with
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4 285 the biggest fish having a lower value for the bio gillnets in 2016, meaning that the nylon
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6 286 gillnets caught significantly more fish in those length classes (Fig. 2). The average CR was
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8 287 estimated at 50.0% and 73.4% in 2016 and 2017, respectively, meaning that the bio gillnets
9
10 288 on average caught approximately 50.0% fewer fish than the nylon gillnets in 2016 and 26.6%
11
12 289 fewer in 2017 (Table 2 and Fig. 2). For 2016 this result was significant as the upper limit for
13
14 290 the averaged catch ratio was 73.3% whereas for 2017 it was 102.7% and therefore not
15
16 291 significant. The estimated catch ratio curve clearly shows a significant difference in catch
17
18 292 efficiency between the bio gillnets and nylon gillnets in 2016, for cod larger than 62 cm. In
19
20 293 2017, this difference was not significant, except for the length classes 90 to 103 cm (Fig. 2).
21
22

23
24 294 FIG. 2

25
26 295 TABLE 2.

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28 296

29
30 297 **Saithe**

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33 298 A total of 1965 saithe were caught over 45 gillnet deployments during the 2016 and 2017
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35 299 fishing seasons, of which 814 were caught by the bio gillnets and 1151 were caught by the
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37 300 nylon gillnets. Only deployments with at least 10 saithe in the catch were used in the analysis
38
39 301 to avoid inflate the confidence limits for the catch comparison analysis (Table 3).
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41 302 TABLE 3.

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45
46 304 The length distribution of saithe caught in 2016 and 2017 was length dependent for both types
47
48 305 of gillnet, including fish from 50 to 95 cm, but with most of the fish in the range of 65 to 80
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50 306 cm (Fig. 3). In 2016 and 2017, the catch efficiency of the bio gillnets was very similar to that
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52 307 of the nylon gillnets for fish smaller than 67 cm and 70 cm, respectively. The catch efficiency
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54 308 of the bio gillnets became significant different for larger fish (Fig. 3). The $CR(l)$ was also
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56 309 highly length dependent, with the biggest fish having a lower value for the bio gillnets in both
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1
2 310 2016 and 2017, meaning that the nylon gillnet caught significantly more fish in those length
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4 311 classes (Fig. 3). The average *CR* was estimated at 59.0% and 77.5% in 2016 and 2017,
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6 312 respectively, meaning that the bio gillnets caught on average 41.0% fewer fish in 2016 and
7
8 313 22.5% fewer fish in 2017 (Table 4 and Fig. 3). For both 2016 and 2017 this result was
9
10 314 significant as the upper limit for the averaged catch ratio was respectively 81.3% and 93.9%.
11
12 315 The estimated catch ratio curve clearly shows a significant difference in catch efficiency
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14 316 between the bio gillnets and nylon gillnets in both years, for saithe larger than 69 cm in 2016
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16 317 and larger than 73 cm in 2017 (Fig. 3).
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19 318 FIG 3.

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21 319 TABLE 4.

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23 320

24 321 **Tensile strength measurements**

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28 322 Tensile strength measurements carried out before and after the fishing experiment showed a
29
30 323 significant reduction in tensile strength (t-test, $p < 0.01$) and elongation at break (t-test, $p <$
31
32 324 0.01) for both types of gillnet in 2017, but not in 2016 (t-test, $p > 0.05$). In 2017, the nylon
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34 325 gillnets underwent a 13.6% tensile strength reduction (from 11.4 to 9.9 kg) and the bio
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36 326 gillnets underwent an 18.1% strength reduction (from 11.1 to 9.5 kg) (Table 5). Both types of
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38 327 gillnet also showed a significant reduction of elongation at break, 33.9% and 13.2% for the
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40 328 nylon and bio gillnets, respectively.
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43 329 TABLE 5

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46 331 **Gillnet damage**

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48 332 The gillnets used in 2017 were more damaged than those used in 2016 (Table 6). The gillnets
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50 333 used in 2017 had more than 26% of badly damaged or broken knots, while this percentage did
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52 334 not exceed 2% in the gillnets used in 2016. The damage in the knots was apparently caused by
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54 335 use and wear throughout the fishing season (i.e. abrasion in the hauling machine, friction due
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2 336 to contact with hard surfaces when the gillnets were operated on deck), which turned the
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4 337 smooth surface of the materials (when new) into rough surfaces after the fishing trials (Fig 4).

5
6 338 TABLE 6

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8 339 FIG 4.

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11 341 **Discussion**

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13 342 The bio gillnets caught 50.0% and 26.6% fewer cod, and 41.0% and 22.5% fewer saithe than
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15 343 the nylon gillnets in 2016 and 2017, respectively. Even though the relative catch efficiency of
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17 344 the bio gillnets was slightly better in 2017 than in 2016, the difference with respect to the
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19 345 catch efficiency of nylon gillnets may be too large for bio gillnets to be accepted by fishermen
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21 346 if they were available commercially. Coloured bio gillnets are still in the development process
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23 347 and are not currently a commercial product. The results from these series of experiments at
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25 348 sea suggest the need for further development of biodegradable material to improve their catch
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27 349 efficiency.

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31 351 The results generally showed better catch rates for the nylon gillnets than for the bio gillnets,
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33 352 especially for large fish, despite having similar (non-significantly different) mesh sizes. Since
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35 353 similar colours were used in nylon and bio gillnets each year (green gillnets in 2016 and blue
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37 354 gillnets in 2017); colour cannot explain the differences in catch efficiency between both types
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39 355 of gillnets. The physical properties of the gillnets material did change over time and may
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41 356 have affected their fishing efficiency. When new, the strength and the elasticity of both types
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43 357 of nets was very similar. By the end of the fishing season, the reduction in tensile strength and
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45 358 the loss of elasticity can explain the major difference in catch efficiency observed between the
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47 359 nylon gillnets and the bio gillnets, especially for larger fish. In 2017, we measured an 18.1%
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49 360 reduction in tensile strength and a 13.2% reduction in elongation in the bio gillnets; while in
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51 361 2016 these reductions were considerably smaller (Table 5). Visual inspection of the

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2 362 monofilaments and knots of the bio gillnets used in 2017 showed more splintering and other
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4 363 kinds of physical damage than in those used in 2016. Physical damage appeared to be
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6 364 positively correlated with the number of operation days and the fishing depth. In 2017, the
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8 365 experimental gillnets had 59% more deployments, and they were set significantly deeper, than
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10 366 in 2016. Consequently, in 2017 the gillnets were exposed to more physical damage that may
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12 367 have contributed to the greater loss of tensile strength and loss of elasticity which, in turn,
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14 368 made them break more readily. Similar to the bio gillnets, in 2017 the nylon gillnets also
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16 369 experienced a significant reduction in tensile strength (13.2%) and elongation (33.9%),
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18 370 supporting the indication that greater physical damage may be the cause. The reduction in
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20 371 elasticity that was measured in the bio gillnets by the end of the fishing experiments was most
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22 372 likely due to roughening and splintering of the surface due to use and wear of the bio gillnet
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24 373 monofilaments. However, the loss of elasticity is probably also an indication of changes in the
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26 374 physical properties of the PBSAT material due to biodegradation.
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32 376 Kim et al. (2016) reported that uncoloured bio gillnets (made of a blending of PBS-PBAT
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34 377 resin) slowly degraded in cold sea water (< 5 °C). The sea water temperature in our fishing
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36 378 experiments oscillated between 4.1 °C and 8.8 °C, suggesting that biological degradation was
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38 379 perhaps also a cause of tensile strength and elasticity reduction of the bio gillnets nets. In our
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40 380 experiment we were unable to separate the degree of strength and elasticity reduction caused
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42 381 by biodegradation from that caused by used and wear. However, when we observed
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44 382 monofilaments samples in the electronic scanning microscope we not only saw physical
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46 383 damages caused by friction in both bio and nylon monofilaments, but also, we saw some
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48 384 degree of roughening and splintering of the surface of the bio material. Roughening and
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50 385 splintering of the monofilament surface of the bio gillnets may actually be a consequence of
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52 386 the biodegradation process. A controlled degradation experiment may avoid the damage
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54 387 caused by use and wear of the material and therefore provide the actual loss of strength and
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2 388 elasticity caused by biodegradation. Also, this experiment can provide the degradation speed
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4 389 of the bio gillnets. It is worth to mention that if biodegradation is combined with daily use and
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6 390 wear of the material, the degradation process may be somehow accelerated.
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10 392 When conventional nylon gillnets get lost at sea, the weakening of the material caused by use
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12 393 and wear, or by environmental factors such as UV radiation, virtually ceases and the
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14 394 degradation process therefore continues slowly. It is well documented that nylon gillnets are
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16 395 highly resistant to degradation, but that they do eventually lose their capability for ghost
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18 396 fishing depending on conditions of the seafloor (i.e. type of substrate, sea temperature, light
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20 397 conditions) (Carr *et al.*, 1990; Pawson, 2003; Santos *et al.*, 2003; Humborstad *et al.*, 2003;
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22 398 Tschernij and Larsson, 2003; Nakashima and Matsuoka, 2004; Pham *et al.*, 2014).

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24 399 Furthermore, nylon gillnets do not entirely disappear; they just degrade into smaller plastic
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26 400 particles, commonly known as “micro plastics” that may continue to disturb important
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28 401 processes in marine ecosystems (Moore, 2008; Lee *et al.*, 2013; Cole and Galloway, 2015;
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30 402 Desforges *et al.*, 2015; Chae and Ann, 2017). Contrary to conventional nylon gillnets, if bio
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32 403 gillnets get lost at sea, bacteria, algae and fungi will much more rapidly degrade the material
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34 404 into carbon dioxide, methane and water, and they would therefore not have any further
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36 405 additional impacts on marine ecosystems (Tokiwa *et al.*, 2009; Kim *et al.*, 2014a, b).

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38 406 According to Kim *et al.* (2017), bio gillnets start degrading after two years of being immersed
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40 407 in seawater. However, this conclusion is based on a degradation experiment with
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42 408 monofilament samples immersed in sea water, thus the samples were not affected by physical
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44 409 damage from daily use and wear. The question of how fast a bio gillnet can lose its ghost
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46 410 fishing capacity depends greatly on the age of the net when lost and how much it had been
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48 411 used.
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2 413 There is limited literature that quantifies the degradation speed of nylon gillnets, and even
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4 414 fewer studies that assess when a lost nylon gillnet loses its ghost fishing capacity. Some
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6 415 available studies show that nylon gillnets continue to fish for several years after being lost
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8 416 (Carr and Cooper, 1987; Puente et al., 2001; Nakashima and Matsuoka, 2004). Our
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10 417 experiment suggest that the degradation time of bio gillnets could even be shorter if the bio
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12 418 gillnets are weakened by used and wear before they get lost.
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17 420 Coloured bio gillnets, such as those tested in this study, show potential to become a feasible
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19 421 alternative to conventional nylon gillnets, particularly in the short season Norwegian fisheries
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21 422 like cod, saithe and Greenland halibut, and to reduce the duration of ghost fishing if they do
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23 423 get lost. However, a 26.6% and 22.5% reduction of the cod and saithe catch can considerably
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25 424 affect the cost effectiveness of the fishing operation and the acceptance of bio gillnets by
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27 425 fishermen. Nonetheless, the material is not yet fully developed, and there are challenges and
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29 426 knowledge gaps (i.e. products of degradation, ecotoxicity) that should be addressed before
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31 427 drawing conclusions about the overall benefits of using these new biomaterials in fisheries.
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33 428 Ultimately, it is up to regulatory institutions in Norway to decide whether to introduce bio
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35 429 gillnets in the deep-water gillnet fisheries in order to reduce ghost fishing or let fishermen
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37 430 continue using the most effective nylon gillnets with well-known consequences if they get
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39 431 lost.
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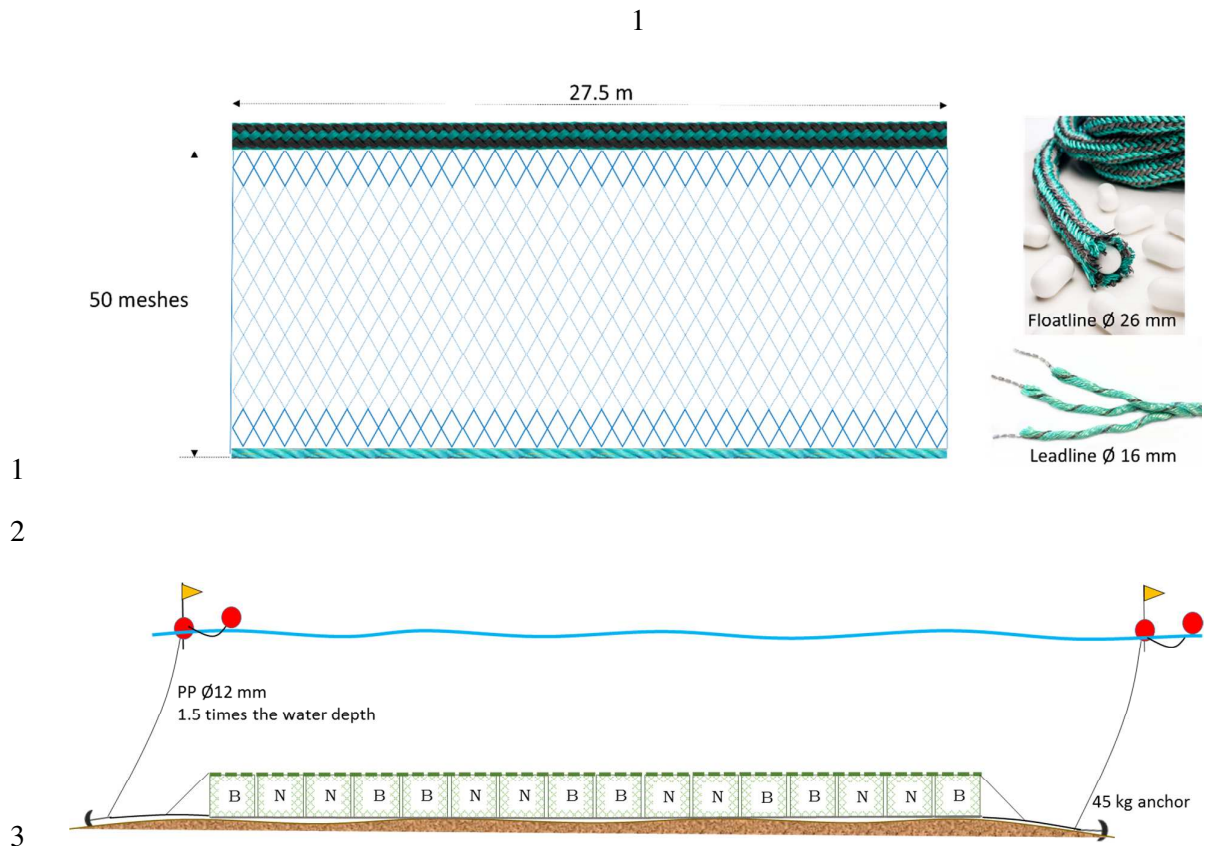
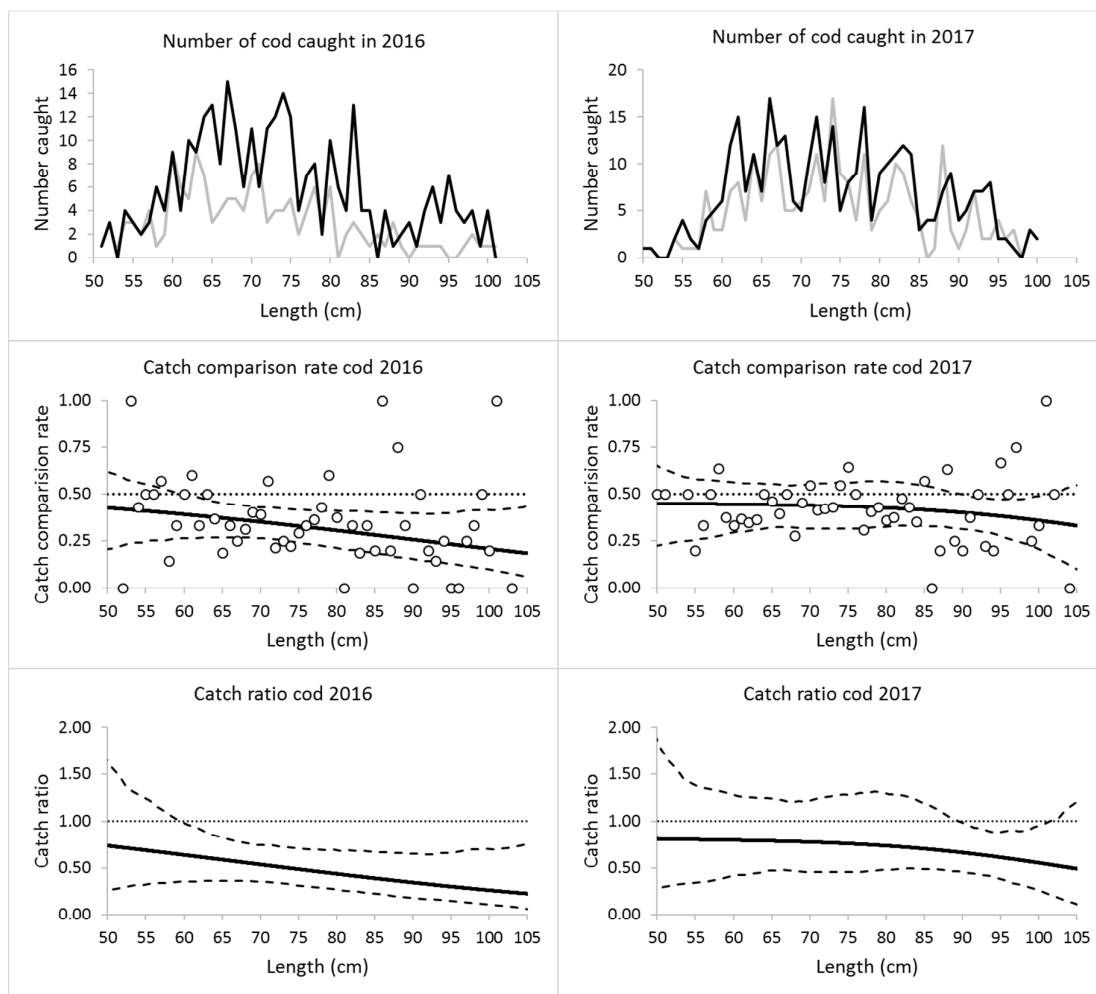


Fig. 1 A schematic representation of the experimental gillnets (set 1) showing the layout (N: nylon gillnet; B: bio gillnet) during the fishing trials.



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

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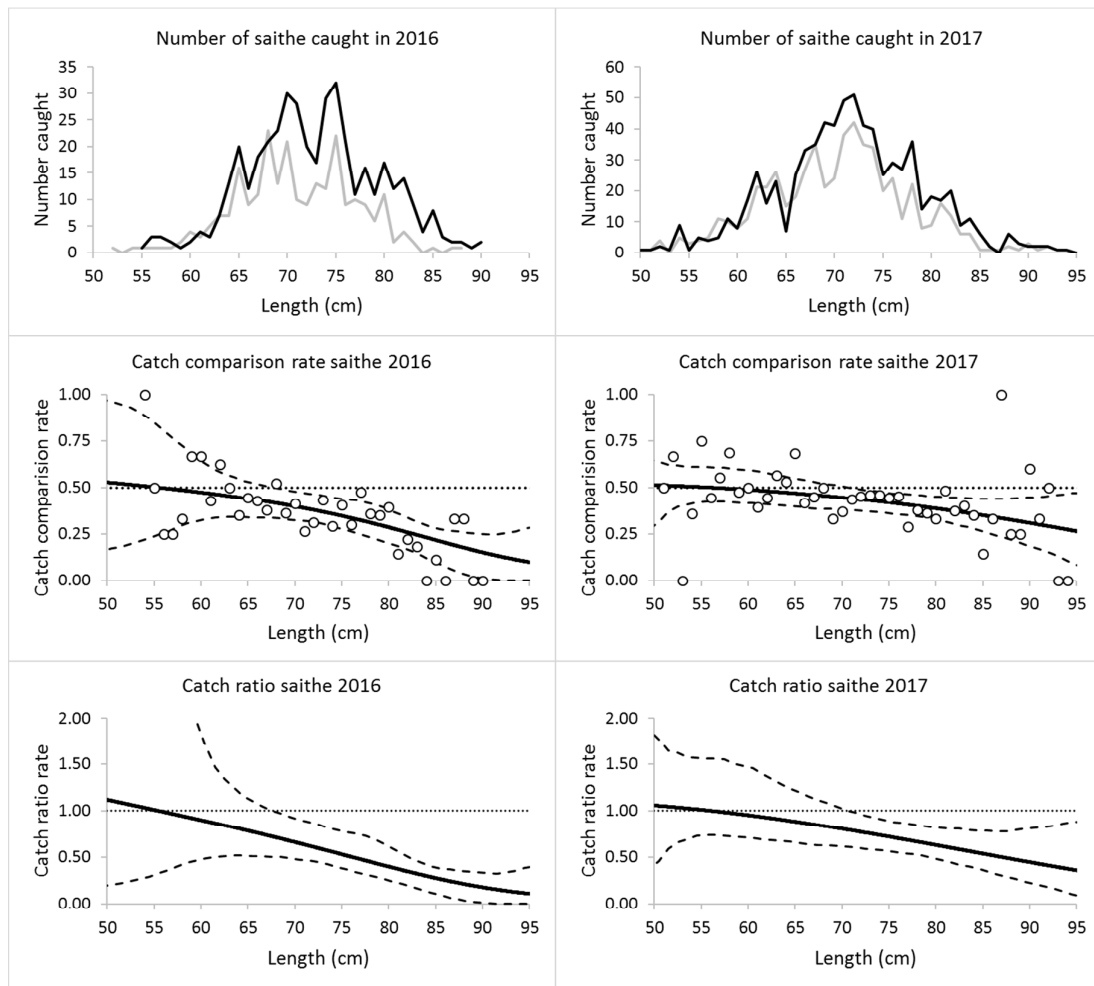


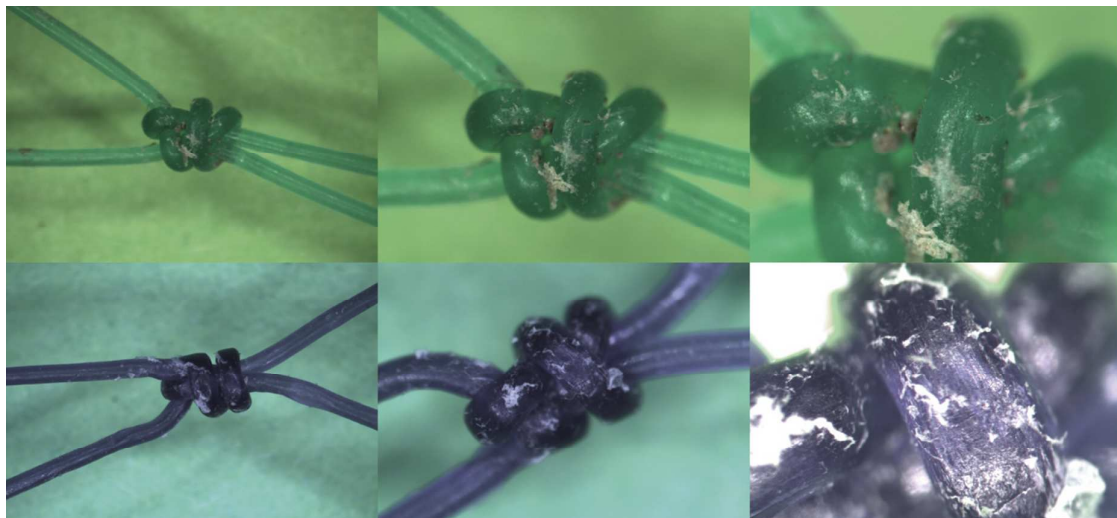
Fig. 3. Top: size distribution of saithe caught with each type of gillnet (the black and grey curves represent nylon and bio gillnets, respectively). Centre: Catch comparison rate (CC) based on all deployments for 2016 (left) and 2017 (right) with circle marks representing the experimental rate and the 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.

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37 **Fig. 4.** Images of the bio gillnets from 2016 (green) and 2017 (blue) showing physical

38 damage of the knots.

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1 **Table 1.** Catch data for cod. Only sets with at least 10 cod caught were used in the analysis.

Set ID	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

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

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

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16 **Table 3.** Catch data for saithe. Only sets with at least 10 saithe caught were used in the
 17 analysis.

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

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19 **Table 4.** Catch ratios ($CR(l)$) for saithe (%) and fit statistics obtained for the bio gillnets
 20 relative to for nylon gillnets in 2016 and 2017. Values in brackets represent 95% confidence
 21 limits. DF, degrees of freedom.

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

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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

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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 %

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