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

Journal:	*ICES Journal of Marine Science*
Manuscript ID	ICESJMS-2018-211.R2
Manuscript Types:	Original Article
Date Submitted by the Author:	n/a
Complete List of Authors:	Grimaldo, Eduardo; SINTEF Ocean, Fisheries Technology Herrmann, Bent; SINTEF Fisheries and Aquaculture, Fishing Gear Technology Vollstad, Jørgen; SINTEF Ocean Su, Biao; SINTEF Ocean Moe Føre, Heidi; SINTEF Ocean, Larsen, Roger; The Arctic University of Norway, Faculty of BioSciences, Fisheries and Economics Tatone, Ivan; University of Tromsø, Norwegian College of Fishery Science
Keyword:	Biodegradable gillnet, Ghost fishing, Gillnet fishery, Catch efficiency, Cod fishery, PBSAT resin, Cod, Saithe

SCHOLARONE™
Manuscripts

1

1   **Fishing efficiency of biodegradable PBSAT gillnets and conventional nylon gillnets used**

2   **in Norwegian cod (*Gadus morhua*) and saithe (*Pollachius virens*) fisheries**

3   Eduardo Grimaldo[1*&], Bent Herrmann[1,2&], Jørgen Vollstad[1], Biao Su[1], Heidi Moe Føre[1],

4   Roger B. Larsen[2], Ivan Tatone[2]

5

6   [1] SINTEF Ocean, Brattørkaia 17C, N-7010 Trondheim, Norway

7   [2] The Arctic University of Norway, UiT, Breivika, N-9037 Tromsø, Norway

8   E-mail address: Eduardo.Grimaldo@sintef.no;

9   * Corresponding author. Tel: +4740624014

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

31

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.,

52 2016; Lusher et al., 2017). Macfadyen et al. (2009) for instance grouped the methods to

53 reduce the effects of ALDFG into: A) preventive methods that reduce the incidence of fishing

54 gear from becoming abandoned, lost and discarded, such as gear marking, on-board

55 technology to avoid or locate lost gear, onshore collection/reception and/or payment for

56 old/retrieved gear, reduced fishing effort and spatial management; B) mitigating measures that

57 reduce the impact of lost gears in the environment, such as reducing ghost fishing (and plastic

58 pollution) through the use of biodegradable gear, reducing ghost fishing of incidental species

59 by providing escape vents; C) curative measures that are intended to remove the lost gear

60 from the environment, such us electronic and/or acoustic technology for locating lost gear,

61 better reporting of lost gear, gear recovery programs and disposal/recycling of retrieved gear.

62 Many scientists argue that efforts focusing on preventive methods and quick recovery of lost

63 gears are likely to be more effective because curative methods can be highly cost demanding

64 and largely time consuming (Matsushita et al., 2008; Suuronen et al., 2012; Ullmann and

65 Broadhurst, 2015). In addition, preventing gear loss would eliminate ghost fishing mortality

66 (Ullmann and Broadhurst, 2015).

67

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

4

77 gillnets made of PBS and PBAT resins have poor tinting properties and therefore can cause

78 catch efficiency problems such as decreased strength and elasticity due to coloration.

79

80 In Norway, gillnetting is one of the most important commercial fishing methods for the

81 coastal fleet, however transparent gillnets are not currently used. Norwegian fishermen prefer

82 coloured gillnets because they provide a better contrast with the metal (aluminium and or

83 stainless steel) sorting boards and make the removal of fish from the nets easier, and also

84 because many fishermen believe that some colours have better catch efficiencies than others

85 depending on the contrast with the seabed. The most important target species in the

86 Norwegian gillnet fishery are cod (*Gadus morhua*) and saithe (*Pollachius virens*). In 2017,

87 4658 fishing boats (less than 14.9 m LOA) were registered and had licences for gillnetting in

88 Norway. This small-scale coastal fleet caught 89460 tonnes of cod, 17635 tonnes of saithe,

89 and 19869 tonnes of haddock (*Melanogrammus aeglefinus)*, representing 22.3%, 14.7% and

90 18.1% of the respective annual quota for these species (Norwegian Directorate of Fisheries,

91 2018). To date, Norway is one of the few countries in the world that has a program for

92 systematic annual retrieval of ALDFG from the most intensively fished areas (Brown et al.,

93 2005; Macfadyen et al., 2009; Cho, 2011). Based on information provided by fishermen, the

94 Norwegian Directorate of Fisheries carry out annual retrieval operations for reported lost

95 fishing gear and deliver it on land to recycling (Humborstad et al., 2003; Gilman et al., 2016).

96 However, these operations are highly challenging because of the depth (500–1000 m) and

97 strong currents in the areas, as well as uncertainties associated with the position of lost gear.

98

99 The development of fishing gears made of biodegradable plastic materials, like PBSAT resin,

100 is considered as a potential solution to reduce ghost fishing and plastic pollution at sea caused

101 by ALDFG (Brown and Macfadyen, 2007; Large et al., 2009; Macfadyen et al., 2009;

102 Gilman, 2015; Gilman et al., 2016); however, for an environmentally safe application of such

103 biodegradable plastics at sea it is important to prove that the intermediate break-down

104 products, even those that are degradable, do not have any ecotoxicological effects on the

105 ecosystem. Simultaneously, for biodegradable gillnets to be adopted by the fishing industry,

106 they should prove to be at least as efficient as conventional nylon gillnets and not compromise

107 the profitability of the fishing operations. The present study addresses the second concern:

108 fishing efficiency. The specific objective of this study was therefore to assess the relative

109 catch efficiency of biodegradable PBSAT gillnets with that of conventional nylon gillnets.

110 Our study covered the consecutive fishing seasons of 2016 and 2017, targeting the fall fishery

111 for cod and saithe in Northern Norway.

112

Materials and Methods

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

115 PBSAT resin is an aliphatic-aromatic co-polyester that is prepared using 1,4-butanediol as an

116 aliphatic glycol (as base materials) and dicarboxylic acids, such as succinic acid and adipic

117 acid (which are aliphatic components) and dimethyl terephthalate (which is an aromatic

118 component) (Kim *et al.*, 2017, patent EP3214133 A1). PBSAT resin is biodegradable,

119 exhibits an excellent coloration effect and does not cause problems such as a decrease in

120 strength due to coloration, as observed in PBS and PBAT resins. The biodegradable PBSAT

121 resin composition includes a colorant at 0.005–0.015 parts by weight. To improve the

122 properties of monofilament yarns formed from the coloured PBSAT resin, additives such as

123 anti-oxidants and UV stabilizers may be included at 0.2–0.5 parts by weight with respect to

124 100 parts by weight of the PBSAT resin (Kim *et al.*, 2017, patent EP3214133 A1).

125

126 Experimental design

127 A set of experiments were designed to cover two consecutive fishing seasons for saithe and

128 cod. Fishing trials were conducted under commercial fishing conditions on board the coastal

6

129 gillnet boat "MS Karoline" (10.9 m LOA). The first fishing season was carried out between

130 24 October 2016 and 11 January 2017, and the second season between 11 October 2017 and

131 17 January 2018, herein referred to as the 2016 and 2017 seasons, respectively. The fishing

132 grounds were off the coast of Troms (Northern Norway) between 69°55′–70°22′N and

133 19°39′–21°05′E, which is a common fishing area for coastal vessels from Troms. The fishing

134 depth varied between 29 and 178 m. The sea water temperature was recorded every hour in

135 2016 with a DST-CTD Star-Oddi logger (Star-Oddi, Iceland) that was set at a depth of

136 approximately 70 m.

137

138 In 2016, the fishing performance of 16 green biodegradable PBSAT gillnets, herein called bio

139 gillnets, and 16 conventional green nylon gillnets, herein called nylon gillnets, was compared

140 during fishing trials carried out under commercial fishing conditions. In 2017, the experiment

141 was repeated with a new set of blue gillnets. Each gillnet sheet was made of double knotted

142 0.55 mm monofilament, had 130 mm nominal mesh opening size and was 50 meshes high by

143 275 meshes long (approx. 55 m stretched length). Each assembled gillnet was approximately

144 27.5 m long and had a hanging ratio of 0.5. Since the density of the gillnets materials was

145 similar (1.12 g ml^{-1} for the bio gillnets and 1.14 g ml^{-1} for nylon gillnets) we provided similar

146 buoyancy to both types of gillnets. Each gillnet sheet was fixed to 26 mm diameter

147 SCANFLYT-800 floatlines (made of braided polypropylene rope with a single core of

148 polyurethane floating elements inside) with a buoyancy of 150 g m^{-1}. To provide weight, they

149 were each attached to a 16 mm diameter DANLINE leadline (made of polypropylene rope

150 with a lead core) with a weight of 360 g m^{-1}. The 32 experimental gillnets were divided into

151 two sets, where each set consisted of eight bio gillnets (B) and eight nylon gillnets (N). The

152 gillnets were attached in such a way that they provided the best information for paired

153 comparison. Set 1 was arranged as B–NN–BB–NN–BB–NN–BB–NN–B and set 2 was

154 arranged as N–BB–NN–BB–NN–BB–NN–BB–N (Fig. 1).

155 FIG. 1

156

157 Actual mesh openings were measured with a Vernier caliper without applying tension to the

158 mesh. Two rows of consecutives 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
$$CC_l = \frac{\sum_{j=1}^{m}\{nt_{lj}\}}{\sum_{j=1}^{m}\{nt_{lj}+nc_{lj}\}} \qquad (1)$$

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

8

181 and bio gillnet of the specific species investigated (cod or saithe) was included in the analysis

182 for that species to avoid overinflating confidence intervals for catch comparisons and catch

183 ratio analyses (Krag et al., 2014, 2016). The functional form for the catch comparison rate

184 *CC(l, v)* (the experimental being expressed by equation 1), was obtained using maximum

185 likelihood estimation by minimizing the following expression:

186
$$-\sum_l \{\sum_{j=1}^m \{nt_{lj} \times ln(CC(l,v)) + nc_{lj} \times ln(1.0 - CC(l,v))\}\} \quad (2)$$

187 where *v* represents the parameters describing the catch comparison curve defined by *CC(l, v)*.

188 The outer summation in the equation is the summation over the length classes *l*. When the

189 catch efficiency of the bio gillnet and nylon gillnet is similar, the expected value for the

190 summed catch comparison rate would be 0.5. Therefore, this baseline can be applied to judge

191 whether or not there is a difference in catch efficiency between the two gillnets. The

192 experimental CC_l was modelled by the function *CC(l, v)*, on the following form:

193
$$CC(l,v) = \frac{exp(f(l,v_0,...,v_k))}{1+exp(f(l,v_0,...,v_k))} \quad (3)$$

194 where *f* is a polynomial of order *k* with coefficients v_0 to v_k. The values of the parameters *v*

195 describing *CC(l, v)* are estimated by minimizing equation (2), which are equivalent to

196 maximizing the likelihood of the observed catch data. We considered *f* of up to an order of 4

197 with parameters v_0, v_1, v_2, v_3 and v_4. Leaving out one or more of the parameters $v_0... v_4$ led to

198 31 additional models that were also considered as potential models for the catch comparison

199 *CC(l,v)*. Among these models, estimations of the catch comparison rate were made using

200 multi-model inference to obtain a combined model (Burnham and Anderson, 2002; Herrmann

201 *et al.*, 2017).

202

203 The ability of the combined model to describe the experimental data was evaluated based on

204 the *p*-value. This *p*-value, which was calculated based on the model deviance and the degrees

205 of freedom, should not be <0.05 for the combined model to describe the experimental data

206 sufficiently well, except from cases where the data were subjected to over-dispersion

207　(Wileman *et al.*, 1996; Herrmann *et al.*, 2017). Based on the estimated catch comparison

208　function *CC(l, v)* we obtained the relative catch efficiency (also named catch ratio) *CR(l, v)*

209　between the two gillnet types by the following relationship:

210 $$CR(l, v) = \frac{CC(l,v)}{(1 - CC(l,v))} \qquad (4)$$

211　The catch ratio is a value that represents the relationship between catch efficiency between the

212　bio gillnet and that of the nylon gillnet. Thus, if the catch efficiency of both gillnets is equal,

213　*CR(l, v)* should always be 1.0. Thus, *CR(l, v)* = 1.5 would mean that the bio gillnet is catching

214　50% more cod or saithe with length *l* than the nylon gillnet. In contrast, if *CR(l, v)* = 0.7 would

215　mean that the bio gillnet is only catching 70% of the cod or saithe with length *l* that the nylon-

216　gillnet is catching.

217

218　The confidence limits for the catch comparison curve and catch ratio curve were estimated

219　using a double bootstrapping method (Herrmann *et al.*, 2017). This bootstrapping method

220　accounts for between-set variability (the uncertainty in the estimation resulting from set

221　deployment variation of catch efficiency in the gillnets and in the availability of cod and

222　saithe) as well as within-set variability (uncertainty about the size structure of the catch for

223　the individual deployments). However, contrary to the double bootstrapping method

224　(Herrmann *et al.*, 2017) the outer bootstrapping loop in the current study accounting for the

225　between deployment-variation was performed paired for the bio and nylon gillnets, taking full

226　advantage of the experimental design in which both types of net were deployed

227　simultaneously (Fig. 1). By multi-model inference in each bootstrap iteration, the method also

228　accounts for the uncertainty in model selection. We performed 1000 bootstrap repetitions and

229　calculated the Efron 95% (Efron, 1982) confidence limits. To identify sizes of cod or saithe

230　with significant differences in catch efficiency, we checked for length classes in which the

231　95% confidence limits for the catch ratio curve did not contain 1.0.

232

233   Finally, a length-integrated average value for the catch ratio ($CR_{average}$) was estimated

234   directly from the experimental catch data by:

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

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**

258   The two experimental gillnets were set at sea 58 and 92 times in the 2016 and 2017 seasons,

259   respectively. Scientists on board the MS Karoline measured the lengths of all fish caught in

260   34 deployments in each fishing season. Fishermen provided logs (dates, positions and setting-

261   retrieving times) of the remaining deployments, except length measurements of fish caught.

262   The mean effective fishing time (± SD) (the time the gillnets remained at the sea bed) was 19

263   h, 10 min ± 6 h, 32 min while in 2017 it was 21 h, 58 min ± 6 h, 06 min. The mean (± SD)

264   fishing depth was significantly deeper in 2017 (109 ± 28.9 m) compared to 2016 (61 ± 55.7

265   m). The temperature of the sea water varied between 8.8ºC and 4.1ºC at the start and end of

266   the experiment. The catch was quite clean, mostly consisting of cod and saithe. These species

267   were caught in sufficient numbers to be included in the analysis. We occasionally caught very

268   few large haddock, but far too few (less than 20 individuals per season) to be included in the

269   study.

270

271   **Cod**

272   A total of 1057 cod were caught over 33 gillnet deployments during the 2016 and 2017

273   fishing seasons, of which 407 were caught by the bio gillnets and 650 were caught by the

274   nylon gillnets. Deployments with at least 10 cod in the catch were used in the analysis

275   because gillnets with less than 10 fish would add little information and increase uncertainties

276   to the catch comparison analyses (Table 1).

277   TABLE 1

278

279   The length distribution of cod that were caught with both types of gillnets was very similar in

280   2016 and 2017. The catch was length-dependent for both types of gillnet, including fish from

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

282   efficiency of the bio gillnets was significantly lower than that of the nylon gillnets for almost

283   all cod sizes except for those below 64 cm, while in 2017 significance was only obtained for

12

284   cod in the size span 90 to 103 cm (Fig. 2). The *CR(l)* was also highly length dependent, with

285   the biggest fish having a lower value for the bio gillnets in 2016, meaning that the nylon

286   gillnets caught significantly more fish in those length classes (Fig. 2). The average *CR* was

287   estimated at 50.0% and 73.4% in 2016 and 2017, respectively, meaning that the bio gillnets

288   on average caught approximately 50.0% fewer fish than the nylon gillnets in 2016 and 26.6%

289   fewer in 2017 (Table 2 and Fig. 2). For 2016 this result was significant as the upper limit for

290   the averaged catch ratio was 73.3% whereas for 2017 it was 102.7% and therefore not

291   significant. The estimated catch ratio curve clearly shows a significant difference in catch

292   efficiency between the bio gillnets and nylon gillnets in 2016, for cod larger than 62 cm. In

293   2017, this difference was not significant, except for the length classes 90 to 103 cm (Fig. 2).

294   FIG. 2

295   TABLE 2.

296

297   **Saithe**

298   A total of 1965 saithe were caught over 45 gillnet deployments during the 2016 and 2017

299   fishing seasons, of which 814 were caught by the bio gillnets and 1151 were caught by the

300   nylon gillnets. Only deployments with at least 10 saithe in the catch were used in the analysis

301   to avoid inflate the confidence limits for the catch comparison analysis (Table 3).

302   TABLE 3.

303

304   The length distribution of saithe caught in 2016 and 2017 was length dependent for both types

305   of gillnet, including fish from 50 to 95 cm, but with most of the fish in the range of 65 to 80

306   cm (Fig. 3). In 2016 and 2017, the catch efficiency of the bio gillnets was very similar to that

307   of the nylon gillnets for fish smaller than 67 cm and 70 cm, respectively. The catch efficiency

308   of the bio gillnets became significant different for larger fish (Fig. 3). The *CR(l)* was also

309   highly length dependent, with the biggest fish having a lower value for the bio gillnets in both

310   2016 and 2017, meaning that the nylon gillnet caught significantly more fish in those length

311   classes (Fig. 3). The average *CR* was estimated at 59.0% and 77.5% in 2016 and 2017,

312   respectively, meaning that the bio gillnets caught on average 41.0% fewer fish in 2016 and

313   22.5% fewer fish in 2017 (Table 4 and Fig. 3). For both 2016 and 2017 this result was

314   significant as the upper limit for the averaged catch ratio was respectively 81.3% and 93.9%.

315   The estimated catch ratio curve clearly shows a significant difference in catch efficiency

316   between the bio gillnets and nylon gillnets in both years, for saithe larger than 69 cm in 2016

317   and larger than 73 cm in 2017 (Fig. 3).

318   FIG 3.

319   TABLE 4.

320

321   **Tensile strength measurements**

322   Tensile strength measurements carried out before and after the fishing experiment showed a

323   significant reduction in tensile strength (t-test, $p < 0.01$) and elongation at break (t-test, $p <$

324   0.01) for both types of gillnet in 2017, but not in 2016 (t-test, $p > 0.05$). In 2017, the nylon

325   gillnets underwent a 13.6% tensile strength reduction (from 11.4 to 9.9 kg) and the bio

326   gillnets underwent an 18.1% strength reduction (from 11.1 to 9.5 kg) (Table 5). Both types of

327   gillnet also showed a significant reduction of elongation at break, 33.9% and 13.2% for the

328   nylon and bio gillnets, respectively.

329   TABLE 5

330

331   **Gillnet damage**

332   The gillnets used in 2017 were more damaged than those used in 2016 (Table 6). The gillnets

333   used in 2017 had more than 26% of badly damaged or broken knots, while this percentage did

334   not exceed 2% in the gillnets used in 2016. The damage in the knots was apparently caused by

335   use and wear throughout the fishing season (i.e. abrasion in the hauling machine, friction due

14

336   to contact with hard surfaces when the gillnets were operated on deck), which turned the

337   smooth surface of the materials (when new) into rough surfaces after the fishing trials (Fig 4).

338   TABLE 6

339   FIG 4.

340

Discussion

342   The bio gillnets caught 50.0% and 26.6% fewer cod, and 41.0% and 22.5% fewer saithe than

343   the nylon gillnets in 2016 and 2017, respectively. Even though the relative catch efficiency of

344   the bio gillnets was slightly better in 2017 than in 2016, the difference with respect to the

345   catch efficiency of nylon gillnets may be too large for bio gillnets to be accepted by fishermen

346   if they were available commercially. Coloured bio gillnets are still in the development process

347   and are not currently a commercial product. The results from these series of experiments at

348   sea suggest the need for further development of biodegradable material to improve their catch

349   efficiency.

350

351   The results generally showed better catch rates for the nylon gillnets than for the bio gillnets,

352   especially for large fish, despite having similar (non-significantly different) mesh sizes. Since

353   similar colours were used in nylon and bio gillnets each year (green gillnets in 2016 and blue

354   gillnets in 2017); colour cannot explain the differences in catch efficiency between both types

355   of gillnets. The physical properties of the gillnets material did change over time and may

356   have affected their fishing efficiency. When new, the strength and the elasticity of both types

357   of nets was very similar. By the end of the fishing season, the reduction in tensile strength and

358   the loss of elasticity can explain the major difference in catch efficiency observed between the

359   nylon gillnets and the bio gillnets, especially for larger fish. In 2017, we measured an 18.1%

360   reduction in tensile strength and a 13.2% reduction in elongation in the bio gillnets; while in

361   2016 these reductions were considerably smaller (Table 5). Visual inspection of the

362 monofilaments and knots of the bio gillnets used in 2017 showed more splintering and other

363 kinds of physical damage than in those used in 2016. Physical damage appeared to be

364 positively correlated with the number of operation days and the fishing depth. In 2017, the

365 experimental gillnets had 59% more deployments, and they were set significantly deeper, than

366 in 2016. Consequently, in 2017 the gillnets were exposed to more physical damage that may

367 have contributed to the greater loss of tensile strength and loss of elasticity which, in turn,

368 made them break more readily. Similar to the bio gillnets, in 2017 the nylon gillnets also

369 experienced a significant reduction in tensile strength (13.2%) and elongation (33.9%),

370 supporting the indication that greater physical damage may be the cause. The reduction in

371 elasticity that was measured in the bio gillnets by the end of the fishing experiments was most

372 likely due to roughening and splintering of the surface due to use and wear of the bio gillnet

373 monofilaments. However, the loss of elasticity is probably also an indication of changes in the

374 physical properties of the PBSAT material due to biodegradation.

375

376 Kim et al. (2016) reported that uncoloured bio gillnets (made of a blending of PBS-PBAT

377 resin) slowly degraded in cold sea water (< 5 ºC). The sea water temperature in our fishing

378 experiments oscillated between 4.1 ºC and 8.8 ºC, suggesting that biological degradation was

379 perhaps also a cause of tensile strength and elasticity reduction of the bio gillnets nets. In our

380 experiment we were unable to separate the degree of strength and elasticity reduction caused

381 by biodegradation from that caused by used and wear. However, when we observed

382 monofilaments samples in the electronic scanning microscope we not only saw physical

383 damages caused by friction in both bio and nylon monofilaments, but also, we saw some

384 degree of roughening and splintering of the surface of the bio material. Roughening and

385 splintering of the monofilament surface of the bio gillnets may actually be a consequence of

386 the biodegradation process. A controlled degradation experiment may avoid the damage

387 caused by use and wear of the material and therefore provide the actual loss of strength and

388 elasticity caused by biodegradation. Also, this experiment can provide the degradation speed

389 of the bio gillnets. It is worth to mention that if biodegradation is combined with daily use and

390 wear of the material, the degradation process may be somehow accelerated.

391

392 When conventional nylon gillnets get lost at sea, the weakening of the material caused by use

393 and wear, or by environmental factors such as UV radiation, virtually ceases and the

394 degradation process therefore continues slowly. It is well documented that nylon gillnets are

395 highly resistant to degradation, but that they do eventually lose their capability for ghost

396 fishing depending on conditions of the seafloor (i.e. type of substrate, sea temperature, light

397 conditions) (Carr *et al*., 1990; Pawson, 2003; Santos *et al*., 2003; Humborstad et al., 2003;

398 Tschernij and Larsson, 2003; Nakashima and Matsuoka, 2004; Pham *et al*., 2014).

399 Furthermore, nylon gillnets do not entirely disappear; they just degrade into smaller plastic

400 particles, commonly known as "micro plastics" that may continue to disturb important

401 processes in marine ecosystems (Moore, 2008; Lee *et al*., 2013; Cole and Galloway, 2015;

402 Desforges *et al*., 2015; Chae and Ann, 2017). Contrary to conventional nylon gillnets, if bio

403 gillnets get lost at sea, bacteria, algae and fungi will much more rapidly degrade the material

404 into carbon dioxide, methane and water, and they would therefore not have any further

405 additional impacts on marine ecosystems (Tokiwa *et al*., 2009; Kim *et al*., 2014a, b).

406 According to Kim *et al*. (2017), bio gillnets start degrading after two years of being immersed

407 in seawater. However, this conclusion is based on a degradation experiment with

408 monofilament samples immersed in sea water, thus the samples were not affected by physical

409 damage from daily use and wear. The question of how fast a bio gillnet can lose its ghost

410 fishing capacity depends greatly on the age of the net when lost and how much it had been

411 used.

412

413 There is limited literature that quantifies the degradation speed of nylon gillnets, and even

414 fewer studies that assess when a lost nylon gillnet loses its ghost fishing capacity. Some

415 available studies show that nylon gillnets continue to fish for several years after being lost

416 (Carr and Cooper, 1987; Puente et al., 2001; Nakashima and Matsuoka, 2004). Our

417 experiment suggest that the degradation time of bio gillnets could even be shorter if the bio

418 gillnets are weakened by used and wear before they get lost.

419

420 Coloured bio gillnets, such as those tested in this study, show potential to become a feasible

421 alternative to conventional nylon gillnets, particularly in the short season Norwegian fisheries

422 like cod, saithe and Greenland halibut, and to reduce the duration of ghost fishing if they do

423 get lost. However, a 26.6% and 22.5% reduction of the cod and saithe catch can considerably

424 affect the cost effectiveness of the fishing operation and the acceptance of bio gillnets by

425 fishermen. Nonetheless, the material is not yet fully developed, and there are challenges and

426 knowledge gaps (i.e. products of degradation, ecotoxicity) that should be addressed before

427 drawing conclusions about the overall benefits of using these new biomaterials in fisheries.

428 Ultimately, it is up to regulatory institutions in Norway to decide whether to introduce bio

429 gillnets in the deep-water gillnet fisheries in order to reduce ghost fishing or let fishermen

430 continue using the most effective nylon gillnets with well-known consequences if they get

431 lost.

432

Acknowledgements

439   Co. Ltd. for their collaboration in this project and for providing the gillnet samples to carry

440   out the experiments at sea.

441

442   **References**

443   Al-Masroori, H. S., Al-Oufi, H., McIlwain, J. L., and McLean, E. 2004. Catches of lost fish

444   traps (ghost fishing) from fishing grounds near Muscat, Sultanate of Oman. Fisheries

445   Research, 69(3): 407–414. doi.org/10.1016/j.fishres.

446   An, H.C. and Bae, J.H., 2013. Catching efficiency of the biodegradable gill net for Pacific

447   herring (*Clupea pallasii*) J. Kor. Soc. Fish. Tech., 49(4), 341－351. doi:

448   10.3796/KSFT.2013.49.4.341.

449   Bae, B. S., Cho, S. K., Park, S. W., and Kim, S. H. 2012. Catch characteristics of the

450   biodegradable gill net for flounder. Journal of the Korean Society of Fisheries Technology,

451   48(4): 310–321. doi:10.3796/KSFT

452   Bae, B. S., Lim, J. H., Park, S. W., Kim, S. H., and Cho, S. K. 2013. Catch characteristics of

453   gillnets for flounder by the physical properties of net filament in the East Sea. Journal of

454   the Korean Society of Fisheries technology, 49(2): 95–105. doi:10.3796/KSFT.

455   Brown, J, Macfadyen, G., Huntington, T., Magnus, J., Tumilty, J. 2005. Ghost Fishing by

456   Lost Fishing Gear. Final Report to DG Fisheries and Maritime Affairs of the European

457   Commission. Fish/2004/20. Institute for European Environmental Policy / Poseidon

458   Aquatic Resource Management Ltd joint report.

459   Brown, J., and Macfadyen, G. 2007. Ghost fishing in EU waters: Impacts and management

460   responses. Marine Policy, 31(4): 488–504. doi.org/10.1016/j.marpol.

461   Burnham, K. P., and Anderson, D. R. 2002. Model selection and multimodel inference: a

462   practical information-theoretic approach, 2nd ed. Springer-Verlag, New York. ISBN 978-

463   0-387-22456-5.

464   Carr, H.A., Cooper, R.A., 1987. Manned submersible and ROV assessment of ghost gillnets

465   in the Gulf of Maine. In: Proceedings of the Oceans'87, The Ocean—An International

466   Workplace, vol. 2, Halifax, NS, pp. 622–624. doi: 10.1109/OCEANS.1987.1160764.

467   Carr, H. A., Amaral, E. H., Hulbert, A. W., and Cooper, R. 1990. Underwater survey of

468   simulated lost demersal and lost commercial gill nets off New England. *In*: Marine debris:

469   sources, impacts and solutions: 171–186. J. M. Coe, and D. B. Rogers (Eds). Springer,

470   New York. ISBN-13: 978-1461384885.

471   Chae, Y., and An, J. Y. 2017. Effects of micro- and nanoplastics on aquatic ecosystems:

472   Current research trends and perspectives. Marine Pollution Bulletin, 30 November 2017,

473   124(2): 624–632. doi: 10.1016/j.marpolbul.2017.01.070.

474   Cho, D.O. 2011. Removing derelict fishing gear from the deep seabed of the East Sea. Marine

475   Policy 35, 610–614. doi.org/10.1016/j.marpol.2011.01.022.

476   Cole, M., and Galloway, T. S. 2015. Ingestion of nanoplastics and microplastics by Pacific

477   oyster larvae. Environmental Science Technology, 49(24): 14625–14632. doi:

478   10.1021/acs.est.5b04099

479   Desforges, J. P. W., Galbraith, M., and Ross, P. S. 2015. Ingestion of microplastics by

480   zooplankton in the Northeast Pacific Ocean. Archives of Environmental Contamination and

481   Toxicology, 69(3): 320–330. doi: 10.1007/s00244-015-0172-5.

482   Efron, B. 1982. The jackknife, the bootstrap and other resampling plans. *In*: SIAM

483   Monograph No. 38, CBSM-NSF Regional Conference Series in Applied Mathematics,

484   Philadelphia. ISBN: 978-0-89871-179-0.

485   Gilman, E. 2015. Status of international monitoring and management of abandoned, lost and

486   discarded fishing gear and ghost fishing. Marine Policy, 60: 225–239.

487   doi.org/10.1016/j.marpol.

488   Gilman, E., Chopin, F., Suuronen, P., and Kuemlangan, B. 2016. Abandoned, lost or

489   otherwise discarded gillnets and trammel nets. Methods to estimate ghost fishing mortality,

20

490   and the status of regional monitoring and management. FAO Technical paper 600. ISSN

491   2070-7010.

492   Herrmann, B., Krag, L. A., Feekings, J., and Noack, T. 2016. Understanding and predicting

493   size selection in diamond-mesh cod ends for Danish seining: a study based on sea trials

494   and computer simulations. Marine and Coastal Fisheries: Dynamics, Management, and

495   Ecosystem Science, 8: 277–291. doi:10.1080/19425120.2016.1161682.

496   Herrmann, B., Sistiaga, M., Nielsen, K.N., and Larsen, R.B. 2012. Understanding the size

497   selectivity of redfish (*Sebastes* spp.) in North Atlantic trawl codends. Journal of Northwest

498   Atlantic Fishery Science, 44: 1–13. doi:10.2960/J.v44.m680.

499   Herrmann, B., Sistiaga, M., Rindahl, L., and Tatone, I. 2017. Estimation of the effect of gear

500   design changes on catch efficiency: methodology and a case study for a Spanish longline

501   fishery targeting hake (*Merluccius merluccius*). Fisheries Research, 185: 153–160.

502   doi.org/10.1016/j.fishres.

503   Humborstad, O. B., Løkkeborg, S., Hareide, N. R., and Furevik, D. M. 2003. Catches of

504   Greenland halibut (*Reinhardtius hippoglossoides*) in deep-water ghost fishing gillnets on

505   the Norwegian continental slope. Fisheries Research, 64: 163–170. doi.org/10.1016/S0165-

506   7836(03)00215-7.

507   Ishii, N., Inoue, Y., Tagaya, T., Mitomo, H., Nagai, D., and Kasuya, K. 2008. Isolation and

508   characterization of poly (butylene succinate)-degrading fungi. Polymer Degradation and

509   Stability, 93: 883–888. doi.org/10.1016/j.polymdegradstab.

510   ISO 1806:2002. Fishing nets – Determination of mesh breaking force of netting. International

511   Organization for Standardization. 6 p.

512   Kim, S., Kim, P., Lim, J., An, H., and Suuronen, P. 2016. Use of biodegradable driftnets to

513   prevent ghost fishing: physical properties and fishing performance for yellow croaker.

514   Animal Conservation, 19: 309–319. doi: 10.1111/acv.12256.

515   Kim, S., Park, S., Lee, K., and Lim, J. 2013. Characteristics on the fishing performance of a

516   drift net for yellow croaker (*Larimichthys polyactis*) in accordance with the thickness of a

517   net twine. Journal of the Korean Society of Fisheries Technology, 49: 218–226. doi:

518   10.3796/KSFT.

519   Kim, S., Park, S., and Lee, K. 2014a. Fishing performance of an Octopus minor net pot made

520   of biodegradable twines. Turkish Journal of Fisheries and Aquatic Sciences, 14: 21–30.

521   doi: 10.4194/1303-2712-v14_1_03.

522   Kim, S., Park, S., and Lee, K. 2014b. Fishing performance of environmentally friendly

523   tubular pots made of biodegradable resin (PBS/PBAT) for catching the conger eel Conger

524   Myriaster. Fisheries Science, 80: 887–895. doi.org/10.1007/s12562-014-0785-z.

525   Kim, M. K., Yun, K. C., Kang, G. D., Ahn, J. S., Kang, S. M., Kim, Y. J., Yang, M. H. and

526   Byun, K. S. 2017. Biodegradable resin composition and fishing net produced from same.

527   US Patent application publication, US 2017/0112111A1.

528   Krag L.A., Herrmann B., Karlsen J.D. 2014. Inferring escape behaviour in trawls based on

529   catch comparison data: Model development and evaluation based on data from Skagerrak,

530   Denmark. PLoS One, Vol. 9, Issue, 2, e88819. doi.org/10.1371/journal.pone.0088819.

531   Krag, L., Herrmann, B., Feekings, J., Karlsen, J. 2016. Escape panels in trawls – a consistent

532   management tool? Aquatic Living Resources 29, 306. doi: 10.1051/alr/2016028.

533   Large, P. A., Graham, N. G., Hareide, N. R., Misund, R., Rihan, D. J., Mulligan, M. C.,

534   Randall, P. J., Peach, D. J., McMullen, P. H., and Harlay, X. 2009. Lost and abandoned

535   nets in deep-water gillnet fisheries in the Northeast Atlantic: retrieval exercises and

536   outcomes. ICES Journal of Marine Science, 66: 323–333. doi.org/10.1093/icesjms/fsn220.

537   Lee, K. W., Shim, W. J., Kwon, O. Y., and Kang, J. H. 2013. Size-dependent effects of micro

538   polystyrene particles in the marine copepod *Tigriopus japonicus*. Environmental Science

539   Technology 47(19): 11278–11283. doi: 10.1021/es401932b.

22

540 Lusher, A.L., Hollman, P.C.H., Mendoza-Hill, J.J. 2017. Microplastics in fisheries and

541   aquaculture: status of knowledge on their occurrence and implications for aquatic

542   organisms and food safety. FAO Fisheries and Aquaculture Technical Paper, 615: 126p.

543   ISBN 978-92-5-109882-0.

544 Macfadyen, G., Huntington, T., and Cappell, R. 2009. Abandoned, lost or otherwise discarded

545   fishing gear. FAO Fisheries and Aquaculture Technical Paper, 523: 115p. ISBN 978-92-5-

546   106196-1.

547 Matsuoka, T., Nakashima, T., Nagasawa, N. 2005. A review of ghost fishing: scientific

548 approaches to evaluation and solutions. Fisheries Science 71: 691-702.

549 doi.org/10.1111/j.1444-2906.2005.01019.x.

550 Matsushita, Y., Machida, S., Kanehiro, H., Nakamura, F., Honda. N. 2008. Analysis of mesh

551   breaking loads in cotton gill nets: possible solution to ghost fishing. Fisheries Science 74:

552   230-235 doi.org/10.1111/j.1444-2906.2008.01517.x

553 Moore, C. 2008. Synthetic polymers in the marine environment: a rapidly increasing, long-

554   term threat. Environmental Research, 108: 131–139. doi: 10.1016/j.envres.2008.07.025.

555 Moore, D. S, McCabe, G. P., Duckworth, W. M., and Sclove, S. L. 2003. Practice of Business

556   Statistics using data for decisions. Published by W. H. Freeman. ISBN 10: 0716757230

557   /ISBN 13: 9780716757238.

558 Nakashima, T., and Matsuoka, T. 2004. Ghost fishing ability decreasing over time for lost

559   bottom-gillnet and estimation of total number of mortality. Nippon Suisan Gakkaishi, 70:

560   728–737. doi.org/10.2331/suisan.70.728.

561 Norwegian Directorate of Fisheries 2018. Economic and biological figures from Norwegian

562   fisheries. Report from the Norwegian Directorate of Fisheries, ISSN 2464-3157, 38p. (In

563   Norwegian) https://www.fiskeridir.no/Yrkesfiske/Statistikk-yrkesfiske/Statistiske-

564   publikasjoner/Noekkeltall-for-de-norske-fiskeriene

565 Park, S. W., and Bae, J. H. 2008. Weather ability of biodegradable polybutylene succinate

566 (PBS) monofilaments. Journal of the Korean Society of Fisheries Technology, 44(4): 265–

567 272. doi: 10.3796/KSFT.2008.44.4.265

568 Park, S. W., Bae, J. H., Lim, J. H., Cha, B. J., Park, C. D., Yang, Y. S., and Ahn, H. C. 2007a.

569 Development and physical properties on the monofilament for gill nets and traps using

570 biodegradable aliphatic polybutylene succinate resin. Journal of the Korean Society of

571 Fisheries Technology, 43(4): 281–290. doi: 10.3796/KSFT.

572 Park, S. W., Kim, S. H., Choi, H. S., and Cho, H. H., 2010. Preparation and physical

573 properties of biodegradable polybutylene succinate/polybutylene adipate-co-terephthalate

574 blend monofilament by melt spinning. Journal of the Korean Society of Fisheries

575 Technology, 46: 257–264. doi: 10.3796/KSFT.2010.46.3.257.

576 Park, S. W., Park, C. D., Bae, J. H., and Lim, J. H. 2007b. Catching efficiency and

577 development of the biodegradable monofilament gill net for snow crab *Chionoecetes*

578 *opilio*. Journal of the Korean Society of Fisheries Technology, 43: 28–37. doi:

579 10.3796/KSFT.2007.43.1.028.

580 Pawson, M. 2003. The catching capacity of lost static fishing gears: Introduction. Fisheries

581 Research, 64: 101–105. doi.org/10.1016/S0165-7836(03)00208-X.

582 Pham, C. K., Ramirez-Llodra, E., Alt, C. H. S., Amaro, T., Bergmann, M., Canals, M.,

583 Company, J. B., Davies, J., Duineveld, G., Galgani, F., Howell, K. L., Huvenne, V. A. I.,

584 Isidro, E., Jones, D. O. B., Lastras, G., Morato, T., Gomes-Pereira, J. N., Purser, A.,

585 Stewart, H., Tojeira, I., Tubau, X., Van Rooij, D., and Tyler, P.A. 2014. Marine Litter

586 distribution and density in European Seas, from the Shelves to Deep Basins. PLoS One, 9:

587 e95839. doi.org/10.1371/journal.pone.0095839.

588 Puente, E., Arregi, L., Gomez, E., Sancho, G., 2001. An experimental approach to study the

589 effects of lost static fishing gear on the Bay of Biscay benthic communities: FANTARED-

590 2. ICES CM 2001/R:04.

591   Santos, M., Saldanha, H., Gaspar, M., and Monteiro, C. 2003. Causes and rates of net loss off

592   the Algarve (southern Portugal). Fisheries Research, 64: 115–118. doi.org/10.1016/S0165-

593   7836(03)00210-8.

594   Sistiaga, M., Herrmann, B., Grimaldo, E., and Larsen, R. B. 2010. Assessment of dual

595   selection in grid-based selectivity systems. Fisheries Research, 105: 187–199.

596   doi.org/10.1016/j.fishres.

597   Suuronen, P., Chopin, F., Glass, C., Løkkeborg, S., Matsushita, Y., Queirolo, D., Rihan, D.

598   2005. Low impact and fuel-efficient fishing—Looking beyond the horizon. Fisheries

599   Research, Volumes 119–120: 135-146. doi.org/10.1016/j.fishres.2011.12.009.

600   Tokiwa, Y., Calabia, B. P., Ugwu, C. U., and Aiba, S. 2009. Biodegradability of plastics.

601   International Journal of Molecular Sciences, 10: 3722–3742. doi:10.3390/ijms10093722.

602   Tschernij, V., and Larsson, P. O. 2003. Ghost fishing by lost cod gill nets in the Baltic Sea.

603   Fisheries Research, 64: 151–162. doi.org/10.1016/S0165-7836(03)00214-5.

604   Uhlmann, S., Broadhurst, M.K. 2015. Mitigating unaccounted fishing mortality from gillnets

605   and traps Fish and Fisheries 16, 183–229. doi: 10.1111/faf.12049.

606   Wileman, D. A., Ferro, R. S. T., Fonteyne, R., and Millar, R. B. (Ed.) 1996. manual of

607   methods of measuring the selectivity of towed fishing gears. ICES Coop. Res. Rep. No.

608   215, ICES, Copenhagen, Denmark. ISSN 1017-6195.

1

1

2

3

4
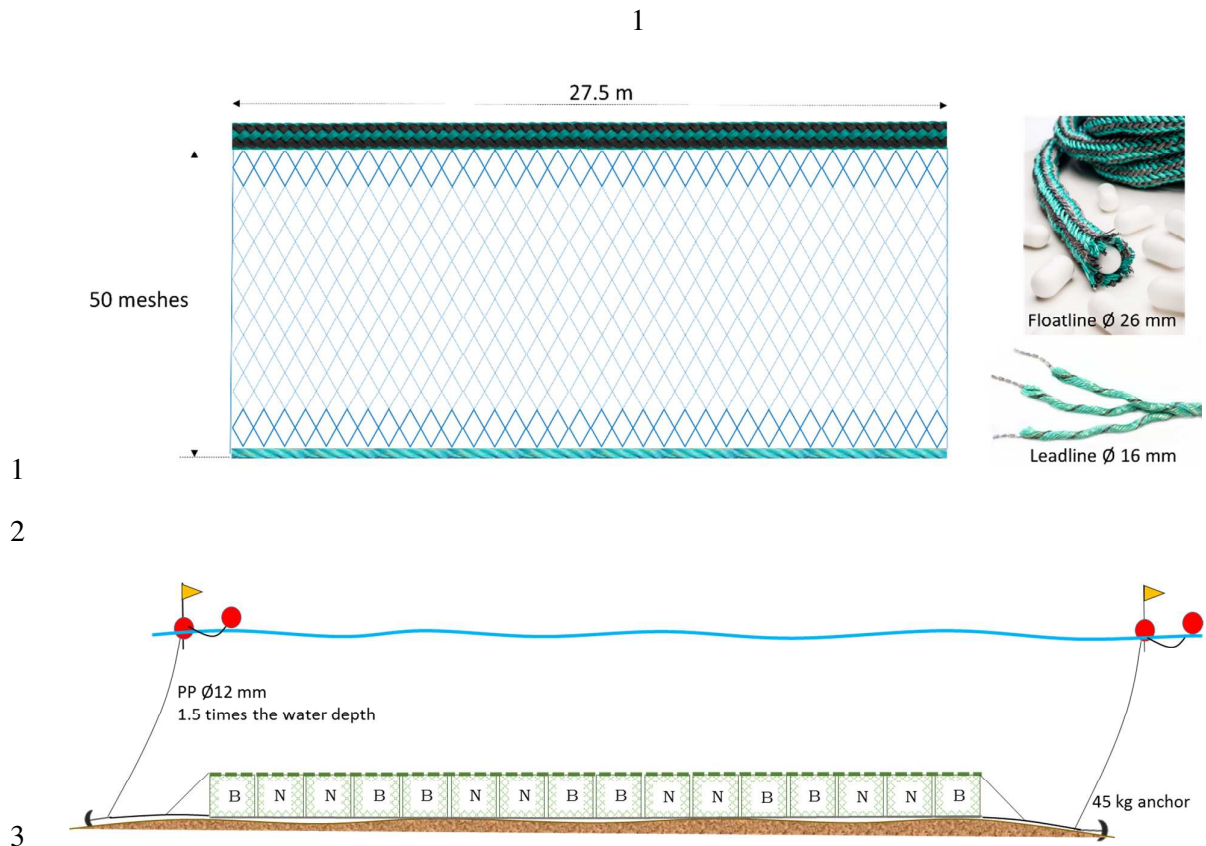
5 **Fig. 1** A schematic representation of the experimental gillnets (set 1) showing the layout (N:

6 nylon gillnet; B: bio gillnet) during the fishing trials.

7

2
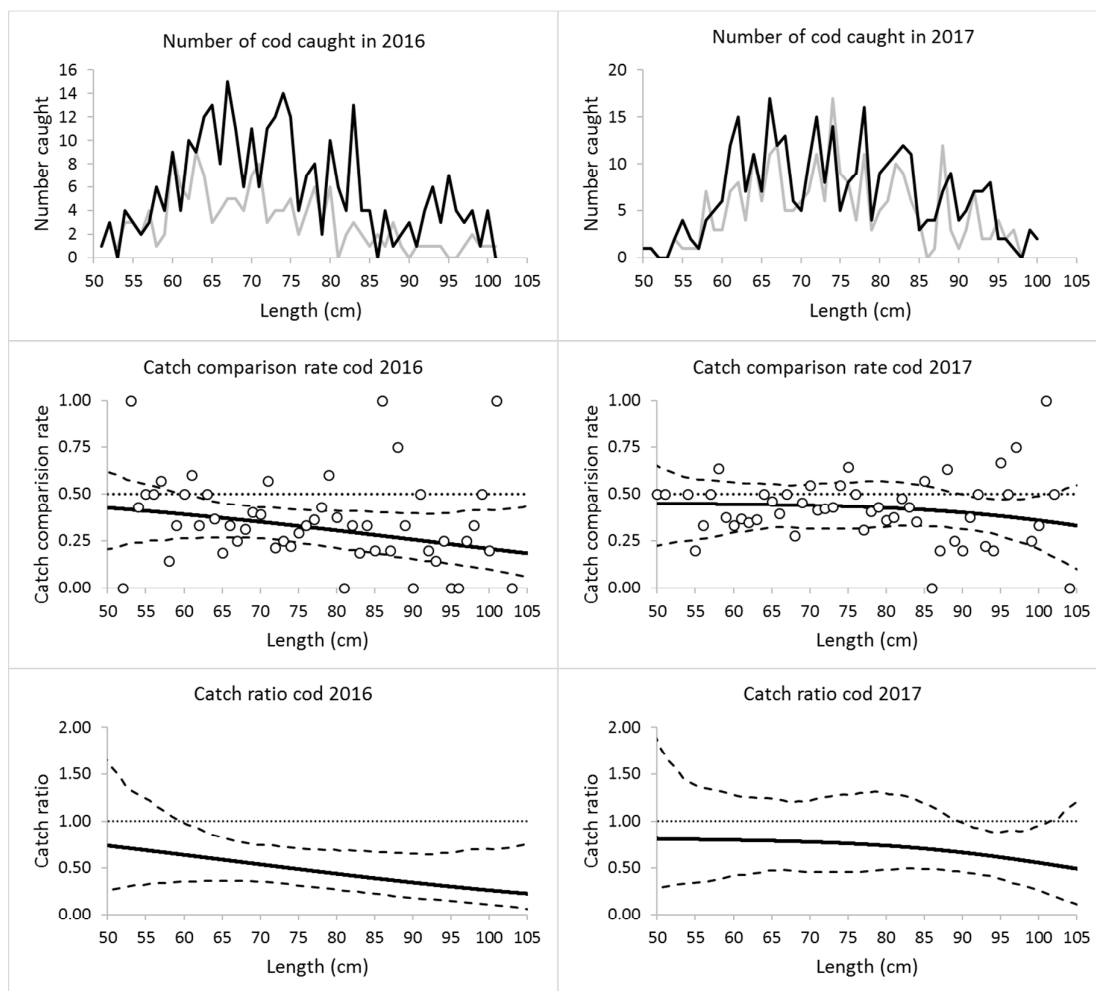
Fig. 2. Top: size distribution of cod caught with each type of gillnet (the black and grey

curves represent nylon and bio gillnets, respectively). Centre: Catch comparison rate (*CC*)

based on all deployments for 2016 (left) and 2017 (right) with circle marks representing the

experimental rate and the curve representing the modelled *CC*. The dotted line at 0.5

represents the baseline at which both types of gillnet have equal catch rates. Stippled curves

represent 95% confidence limits for the estimated catch comparison curve. Bottom: Estimated

catch ratio (*CR*) curve based on all deployments. The dotted line at 1.0 represents the baseline

at which both types of gillnet have equal catch rates. Stippled curves represent 95%

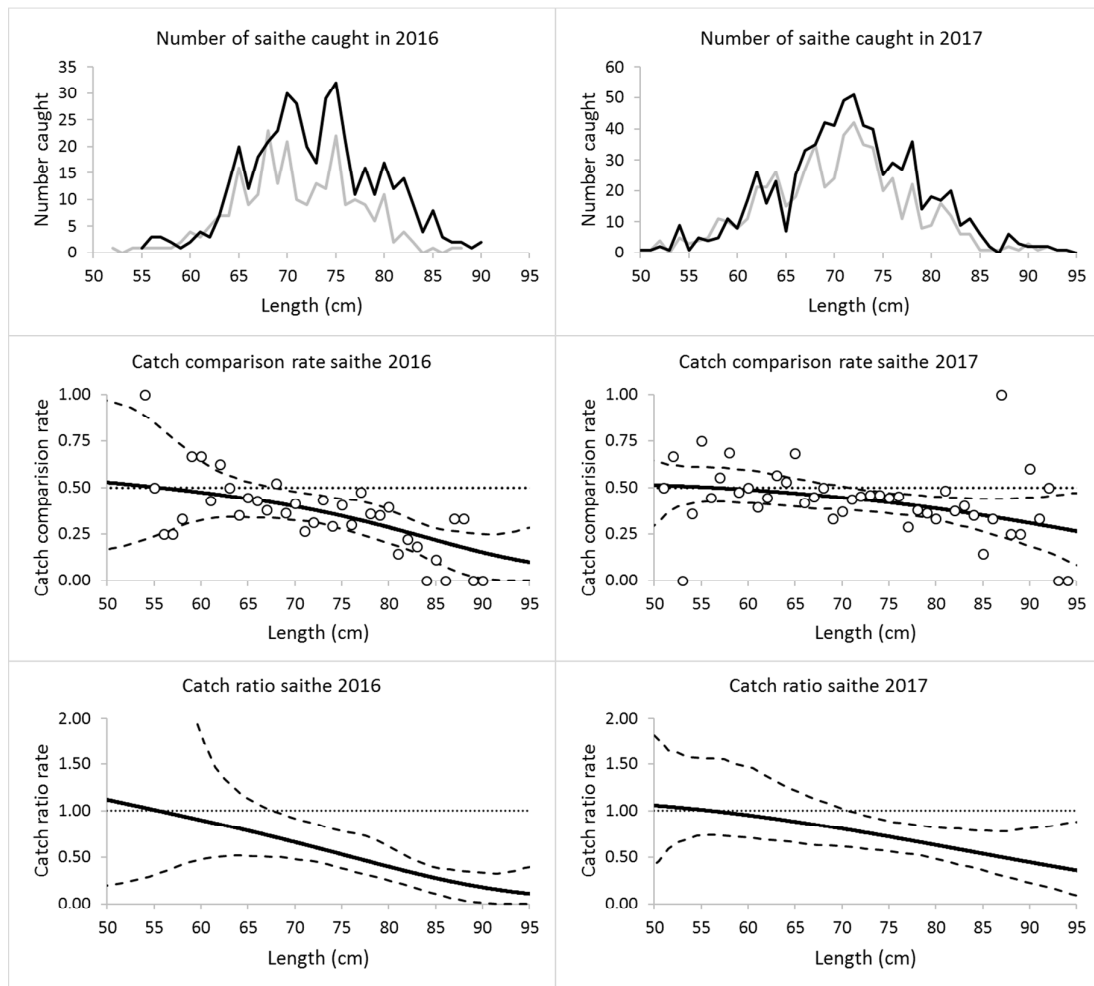confidence limits for the estimated catch ratio curve.

3

20

21

22

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%
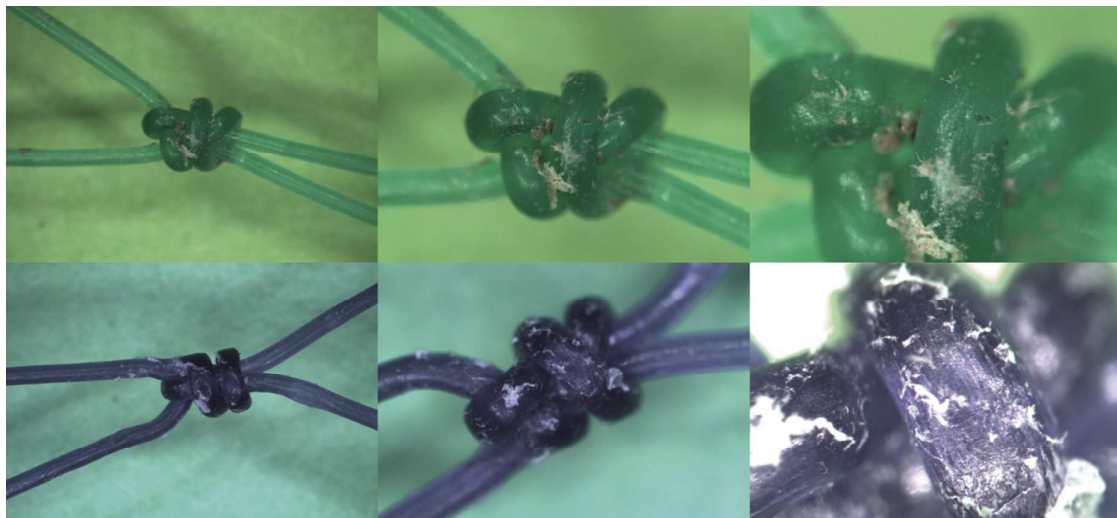
confidence limits for the estimated *CR* curve.

23

24

25

26

27

28

29

30

31

4

32

33

34

35

36

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

38 damage of the knots.

39

40

1

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

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

2

2

3 **Table 2.** Catch ratio (*CR(l)*) for cod (%) and fit statistics obtained for the bio gillnets relative

4 to for nylon gillnets in 2016 and 2017. Values in brackets represent 95% confidence limits.

5 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

6

7

8

9

10

11

12

13

14

15

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

18

4

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

22

23

24

25

26

27

28

29

30

5

31

32

33

34

35 **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

36

37

38

39

40

41

42

6

43

44

45 **Table 6.** Percentage of knots with no damage, slightly damaged, badly damaged, and broken

46 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 %

47

48