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Effect of gillnet twine thickness on capture pattern and efficiency in the Northeast-Arctic cod (*Gadus morhua*) fishery

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ABSTRACT

Gillnets are among the most common fishing gears worldwide. They are often made of thin twine, which is prone to wear and tear, limiting the lifespan of the gillnet. This increases gillnet turnover, and consequently increased risk of gear discarding, gear loss, ghost fishing and marine pollution. This might be mitigated by increasing twine thickness, and thereby breaking strength. However, the tolerable increase in thickness for gillnet durability without compromising the catch efficiency is unknown. Therefore, this study conducted gillnet fishing trials under commercial conditions in the Northeast-Arctic cod gillnet fishery analysing and comparing ways of capture and efficiency between gillnets with two different twine thicknesses for two different mesh sizes. The results demonstrated that a 30 % increase in breaking strength and twine stiffness did not affect catch performance. Therefore, thicker gillnet twine can potentially reduce marine litter by plastic debris from damaged and lost gears without compromising catch performance.

1. Introduction

Plastic pollution is a threat to the marine environment (Barnes et al., 2009; Good et al., 2010; Wang et al., 2019). Plastic litter in the marine environment gradually breaks down, degrading into smaller particles (macro- and microplastics) (Moore, 2008). This can cause severe harm to the marine ecosystems, for instance by being consumed by marine animals, risking blockage of their digestive system (Simmonds, 2012; Gola et al., 2021). Plastics can also enter the food web by releasing toxins, poisoning marine animals (Wang et al., 2019). There are several sources to this pollution, including fishing gear (Richardson et al., 2019; Mepex, 2020; Andrady, 2022). For example, according to a recent study showed that 46 % of the litter found on Norwegian beaches originated from fishing or aquaculture industry (Mepex, 2020). It is estimated that about 380 t of plastic is annually lost in the ocean by the Norwegian fishing fleet alone (Deshpande et al., 2020). The issue is highlighted by the annual retrieving program led by the Norwegian Directorate of Fisheries, who since 1980 have collected >1000 t of lost fishing gear, including 22,000 gillnets (Norwegian Directorate of Fisheries, 2022). This challenge is of global concern, exemplified by ICES/FAO Working Group on Fishing Technology and Fish Behavior which has established a topic group addressing issues relating to lost, abandoned and discarded fishing gear (ICES/FAO, 2023). Specifically, it is claimed in the justification for establishing this topic group that: “Abandoned, lost or otherwise discarded fishing gear (ALDFG) is a substantial source of sea-based marine plastic pollution with a wide range of environmental and socioeconomic impacts” (ICES/FAO, 2023).

Marine pollution caused by lost or abandoned fishing gear can result in an environmental issue, namely, the continued capture of marine animals, also called ghost fishing (Brown and Macfadyen, 2007; Macfadyen et al., 2009; Gilman et al., 2016). Gears such as gillnets and pots have the highest ghost fishing potential, mainly because the capture process is dependent on the fish swimming into the gear (Macfadyen et al., 2009; Gilman et al., 2016). Besides gear loss, some types of fishing gear contribute to plastic pollution by wear and tear of gear components, for instance, bottom trawl and demersal seine (Syversen and Lilleng, 2022; Syversen et al., 2022).

Gillnets are among the most important fishing gears in the world, commonly used by recreational and commercial fisheries (Gilman et al., 2016). A gillnet is a rectangular netting curtain of uniform mesh size that

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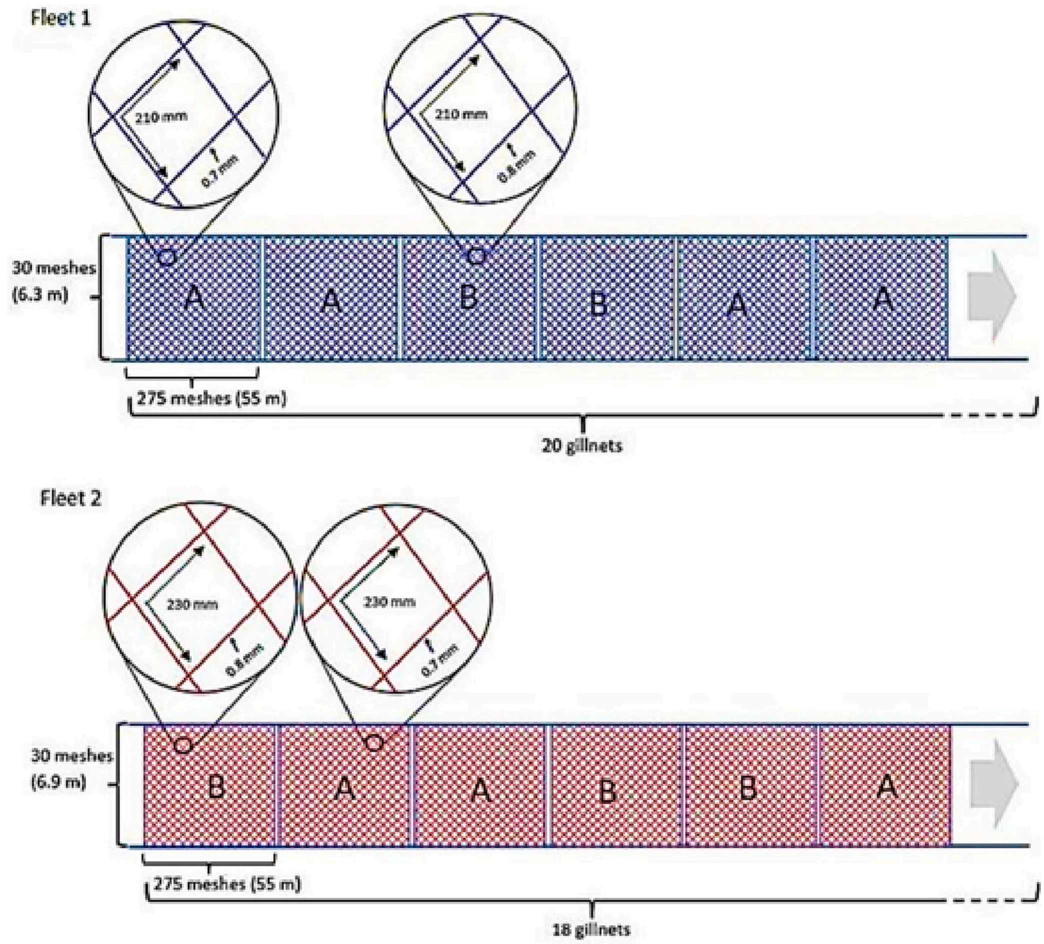

Fig. 1. Experimental gillnet design used in the fishing trials. Fleet 1 (up) and Fleet 2 (down) with monofilament twine thicknesses of 0.7 mm (A) and 0.8 mm (B).

is stretched out in the water column by a floating headrope and a sinking footrope, whereby fish swim into the net without noticing it and are entrapped by the meshes (He and Pol, 2010; Savina et al., 2022). Gillnets are a versatile type of fishing gear, and, compared to other gears, they are relatively cheap, require less fuel consumption and exhibit relatively good size selection (Suuronen et al., 2012). In addition, these static gears are considered to have less impact on benthic habitats compared to active fishing gears such as bottom trawls (Valdemarsen et al., 2007; Lucchetti et al., 2020). Due to its worldwide popularity, gillnets are a major contributor to the ALDFG in the oceans.

One possible way to address the loss of gillnets is by increasing the strength of the gear without compromising the capture efficiency. The capture pattern and efficiency of gillnets are affected by several parameters, such as mesh size, hanging ratio, twine material, number of filaments, and twine thickness (Angelsen et al., 1979; Hovgard, 1996). The twine diameter affects the stiffness and the visibility of the netting in the water, which in turn may affect the capture mechanisms. Typical gillnets are constructed using thin monofilament nylon twine and there is a general assumption that twine thickness affects catch efficiency (He and Pol, 2010). However, only few studies have investigated the effect of twine thickness on capture patterns, and those that exist report contradicting conclusions. Some show that thin twine captures more fish (Holst et al., 2002; Grati et al., 2015) and larger individuals (Holst et al., 2002) compared to thicker twine, while other show that thin twine catches less fish (Yokota et al., 2001) or that twine thickness has no effect on the capture pattern (Gray et al., 2005). Accordingly, since thin twine is less visible than ticker twine (Hansen, 1974), there is a general belief that this contributes to higher catch efficiency. However, thin twine is less durable than thicker twine, because it has a lower breaking strength compared to thicker twine, making it less robust to larger forces. Nylon twine gradually degrades when submerged and laboratory experiments showed signs of degradation after only 200 h (Grimaldo et al., 2020a). Further, gillnets used in commercial fisheries are subjected to wear and tear from deployment, seabed contact, hauling and removal of the fish from the net. Thin twine will be more susceptible to these factors than thicker twine, and consequently gillnets made from thin twine will require more frequent replacement.

Frequent gillnet replacement as a result of wear and tear leads to higher turnover of gillnets, i.e., more production and increased need for waste management. A higher expenditure of gillnets constitutes a potential issue for disposal of worn-out gear in countries lacking sufficient waste management infrastructure. This may result in old nets ending up in the ocean, either through mismanaged waste or by incentives to dump the gear instead of disposing it properly, which would result in marine pollution with recognised negative impacts in marine ecosystems. The typical lifespan of a gillnet varies considerably depending on the fishery (Deshpande et al., 2020; Syversen et al., 2020). For instance, in the Northeast Arctic (NEA) cod (*Gadus morhua*) fishery in Norway, the gillnet lifespan can be as short as one fishing season (Grimaldo et al., 2019). In contrast, in the Greenland halibut (*Reinhardtius hippoglossoides*) fishery in Norway, the gillnet lifespan is typically 5 to 10 years (Syversen et al., 2020). In Norway, approximately 45 % of the commercial fishing fleet uses gillnets, making this fishing gear the most frequently used in the country (Norwegian Directorate of Fisheries, 2021). The economically most important species in Norwegian fisheries is the NEA cod stock, with a TAC of 385,256 tons in 2022 (Norwegian Directorate of Fisheries, 2022), being also the most common species targeted with gillnets, together with Greenland halibut and saithe

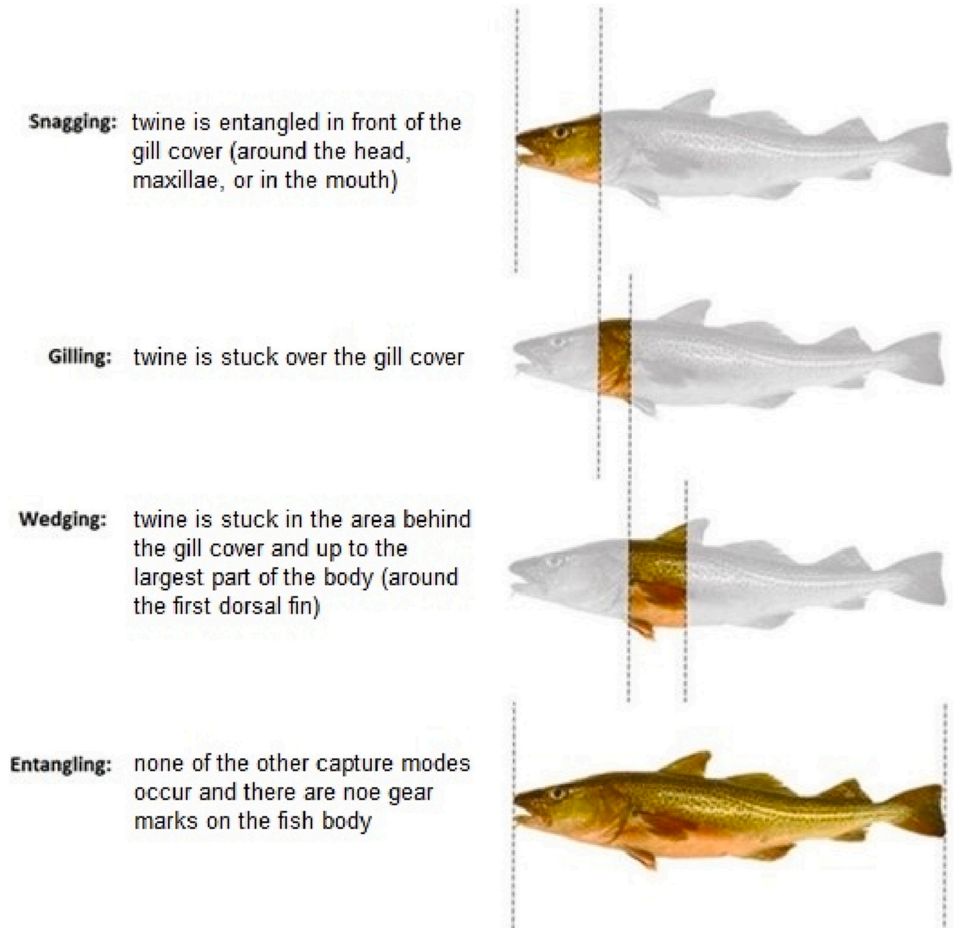

Fig. 2. Capture modes with highlighted areas showing where meshes can get stuck in snagged, gilled, wedged or entangled fish.

Table 1
Number of fish caught in the four different types of gillnets for each capture mode.

	Fleet 1		Fleet 2	
Capture mode	0.7 mm twine	0.8 mm twine	0.7 mm twine	0.8 mm twine
Snagged	200	177	99	87
Gilled	318	273	104	105
Wedged	497	463	177	159
Entangled	12	14	5	6
Total	1027	927	385	357

(*Pollachius virens*).

Challenges of abandoned, lost or discarded gillnets could be related to the common use of thin twine and could thereby potentially be resolved by utilizing thicker twine in the gillnet webbing. However, the tolerable increase in thickness for improving gillnet durability without compromising the catch efficiency is unknown. In general, there is a knowledge gap about the underlying mechanisms that affect gillnet performance, including the effect of twine thickness. Therefore, the present study seeks to investigate the effect of twine thickness by addressing the following research questions: i) how does twine thickness affect capture patterns of cod in gillnets?; ii) what is the effect of twine thickness on gillnet catch efficiency for different mesh sizes?

2. Material and methods

Twine thickness and material are the primary factors defining mechanical properties of gillnet meshes, such as tensile strength and stiffness. Tensile strength is measured as the force per unit cross sectional area required to break the twine. The larger the area, the larger the force required to break the material. The twine stiffness is a measure of the tensile force required to elongate the twine by a certain percentage and increasing twine cross section increases elongation stiffness. Therefore, increasing the twine thickness in a gillnet will result in an increase in the force required to break the gillnet twine and its elongation stiffness, regardless of the properties of its material and thus increase the longevity of gillnets. In the present study, two gillnet twine thicknesses were used, 0.7 and 0.8 mm. By increasing the twine thickness from 0.7 to 0.8 mm, the tensile force to break and elongation stiffness of the twine are increased by approximately 30 %, corresponding to the increase in twine cross-sectional area assuming approximate circular cross-sectional shape (Timoshenko and Goodier, 1970). The 0.7 mm twine is often used in the specific fishery and the 0.8 mm twine was selected as the second thickness since it was commercially available in the same mesh size as for the 0.7 m. Further, an increase in strength and stiffness by 30 % was assumed to provide sufficient contrast for the investigation.

Fish are captured in gillnets in different ways, also called capture modes (Cerbule et al., 2022; Savina et al., 2022), with four different types commonly described in the literature: snagging, gilling, wedging and entangling (He, 2006; Cerbule et al., 2022; Savina et al., 2022):

- o *Snagging*: the twine is entangled in front of the gill cover (around the head, teeth or maxillae);
- o *Gilling*: the twine is stuck over the gill cover;
- o *Wedging*: the twine is stuck in the area behind the gill cover and up to the largest part of the body (around the first dorsal fin);

Table 2
The capture mode probability and fit statistics for snagging, gilling, wedging, and entangling of cod caught with the gillnets with 210 mm mesh size. Numbers in parentheses represent the 95 % confidence intervals. DOF represents the degree of freedom, and deviance represents the model deviance calculated according to Wileman and Ferro (1996).

Twine thickness	Fish length (cm)	Capture mode probability (%)			
		Snagging	Gilling	Wedging	Entangling
0.7 mm	70	87.3 (61.0–100.8)	4.0 (0.4–10.1)	15.2 (1.8–36.5)	0.4 (0.1–0.9)
	75	73.6 (50.8–93.6)	5.8 (1.4–11.6)	26.7 (9.0–46.2)	0.4 (0.1–0.8)
	80	53.5 (35.9–73.7)	8.6 (3.6–13.9)	39.6 (25.5–53.1)	0.4 (0.1–0.8)
	85	34.6 (25.7–46.3)	12.5 (7.9–17.0)	50.2 (41.6–58.2)	0.4 (0.1–0.8)
	90	22.4 (16.1–29.0)	17.6 (13.9–21.3)	56.6 (50.0–62.8)	0.5 (0.1–1.0)
	95	16.3 (11.5–20.9)	23.9 (20.1–28.0)	58.4 (52.8–63.9)	0.7 (0.1–1.6)
	100	14.2 (10.6–17.8)	30.6 (25.4–35.7)	55.4 (49.4–60.7)	0.9 (0.0–2.5)
	105	15.0 (11.2–18.8)	37.2 (31.0–43.3)	47.4 (40.7–53.4)	1.3 (0.3–2.7)
	110	19.0 (12.8–26.1)	42.8 (35.9–50.2)	34.6 (27.2–43.2)	1.8 (0.3–3.4)
	115	26.6 (16.4–38.2)	46.8 (38.2–55.5)	20.2 (11.6–29.8)	2.7 (0.4–5.3)
	120	38.4 (21.6–58.6)	48.6 (33.9–61.3)	9.0 (2.3–18.7)	4.5 (0.6–9.4)
	Average	19.5 (15.9–23.2)	31.0 (26.9–35.0)	48.4 (43.9–52.4)	1.8 (0.4–2.2)
	p–value	0.142	0.675	0.526	1.000
	Deviance	68.5	51.7	55.7	26.9
	DOF	57	57	57	57
0.8 mm	70	73.1 (54.8–90.1)	3.9 (0.9–10.4)	18.0 (3.7–40.2)	4.2 (0.2–11.6)
	75	68.9 (54.4–82.2)	5.6 (1.5–12.6)	24.6 (9.9–41.5)	3.4 (0.4–8.1)
	80	56.8 (42.5–71.7)	8.3 (3.2–16.3)	33.5 (17.9–48.8)	2.8 (0.4–6.0)
	85	41.9 (29.5–55.9)	12.1 (6.5–19.2)	43.2 (29.4–56.4)	2.3 (0.4–4.5)
	90	27.5 (18.9–37.3)	17.3 (12.1–22.6)	51.6 (40.7–61.1)	1.9 (0.5–3.6)
	95	17.5 (12.4–23.0)	23.6 (18.7–28.5)	56.9 (49.6–63.9)	1.6 (0.6–2.8)
	100	12.2 (9.1–15.1)	30.4 (25.0–36.4)	57.7 (52.3–63.5)	1.4 (0.6–2.3)
	105	10.6 (7.9–13.4)	36.6 (30.2–43.7)	52.8 (46.1–58.5)	1.2 (0.5–2.1)
	110	12.8 (8.7–17.9)	41.1 (33.8–49.7)	40.6 (32.2–48.1)	1.1 (0.1–2.2)
	115	23.0 (14.8–34.0)	42.6 (32.8–53.1)	22.6 (14.0–31.2)	1.1 (0.1–2.3)
	120	52.7 (35.9–75.9)	40.3 (22.8–53.5)	7.8 (2.2–14.0)	1.0 (−0.1–3.1)
	Average	19.1 (15.6–22.4)	29.5 (24.8–33.7)	49.9 (44.8–55.0)	1.5 (0.7–2.4)
	p–value	0.294	0.839	0.555	0.971
	Deviance	59.1	43.8	51.9	36.0
	DOF	54	54	54	54

- *Entangling*: none of the mentioned capture modes are observed and there are no marks of the net on the fish.

The efficiency of these capture modes can be influenced by the mechanical properties of the gear material and gear design, including the gillnet twine thickness. Therefore, analysing the capture modes might improve the understanding of gillnet fishing performance depending on specific gillnet design parameters. This should supplement traditional research on fishing gear capture efficiency that quantify the fish length-dependent catch ratio and catch comparison rate between different gear designs (Sistiaga et al., 2015; Santos et al., 2016; Herrmann et al., 2017; Grimaldo et al., 2020a).

2.1. Fishing trials and experimental design

Fishing trials were conducted onboard the coastal gillnetter 'Karoline' (Length overall 10.9 m) in the area located north of Vannøya, off the coast of Troms in Northern Norway (between 70°19.69 N –70°22.40 N and 19°38.90E –19°48.75E), at depths of 75–142 m. The fishery in focus was targeting NEA cod. The gillnet trials took place from 29 January to 13 March 2022, using a total of 38 gillnets made of nylon. Each gillnet was mounted on 27.5 m long headropes and footropes, resulting in a hanging ratio of 0.5. The headrope was 23 mm in diameter and 110 g/m buoyancy, whereas the footrope was 14 mm in diameter and 400 g/m buoyancy. The gillnets were divided into two fleets (Fig. 1):

Fleet 1: 20 gillnets with 210 mm mesh size (blue, monofilament twine); 10 nets with 0.7 mm twine thickness (A) and 10 nets with 0.8 mm twine thickness (B). The gillnets were 30 meshes deep and 55 m in stretched length, being arranged as follows: AA-BB-AA-BB-AA-BB-AA-BB-AA-BB.

Fleet 2: 18 gillnets with 230 mm mesh size (red, monofilament twine); 9 nets with 0.7 mm twine thickness (A) and 9 nets with 0.8 mm twine thickness (B). The gillnets were 30 meshes deep and 55 m in stretched length, being arranged as follows: B-AA-BB-AA-BB-AA-BB-AA-BB-A.

Throughout the study period, all gillnets were deployed under commercial conditions (21 deployments). The gillnet fleets had a soaking time of approximately 23 h. All captured cod were measured for total length to the nearest cm below and their capture mode (snagging, gilling, wedging, and entangling) was recorded (Fig. 2). Deployments containing <20 cod were excluded from the statistical analysis, following the procedure of Krag et al. (2014) to avoid reducing the statistical power of the analysis.

Whenever fish fell from the net during hauling, the gear marks on the fish were examined to determine the initial capture mode and in cases of multiple capture modes, the principle of likely sequence was applied (Savina et al., 2022). Considering the cod morphology, where the circumference increases from the snout up to the largest circumference around the first dorsal fin, the primary mode would be the closest to the point of the largest circumference of the fish. For instance, a fish caught by both snagging and gilling would be classified with gilling as the primary capture mode (Fig. 2).

2.2. Capture modes length-dependent probability

The capture modes were analysed using the statistical software SELNET (Herrmann et al., 2012). Conditioned capture, the length-dependent probability for capture by a specific mode, was quantified. Each deployment for both gillnet fleets was considered as the base unit of the analysis. Each capture mode was analysed independently from the others, following the description outlined below (Savina et al., 2022).

Conditioned capture, the expected probability for the capture mode q for fish length l is:

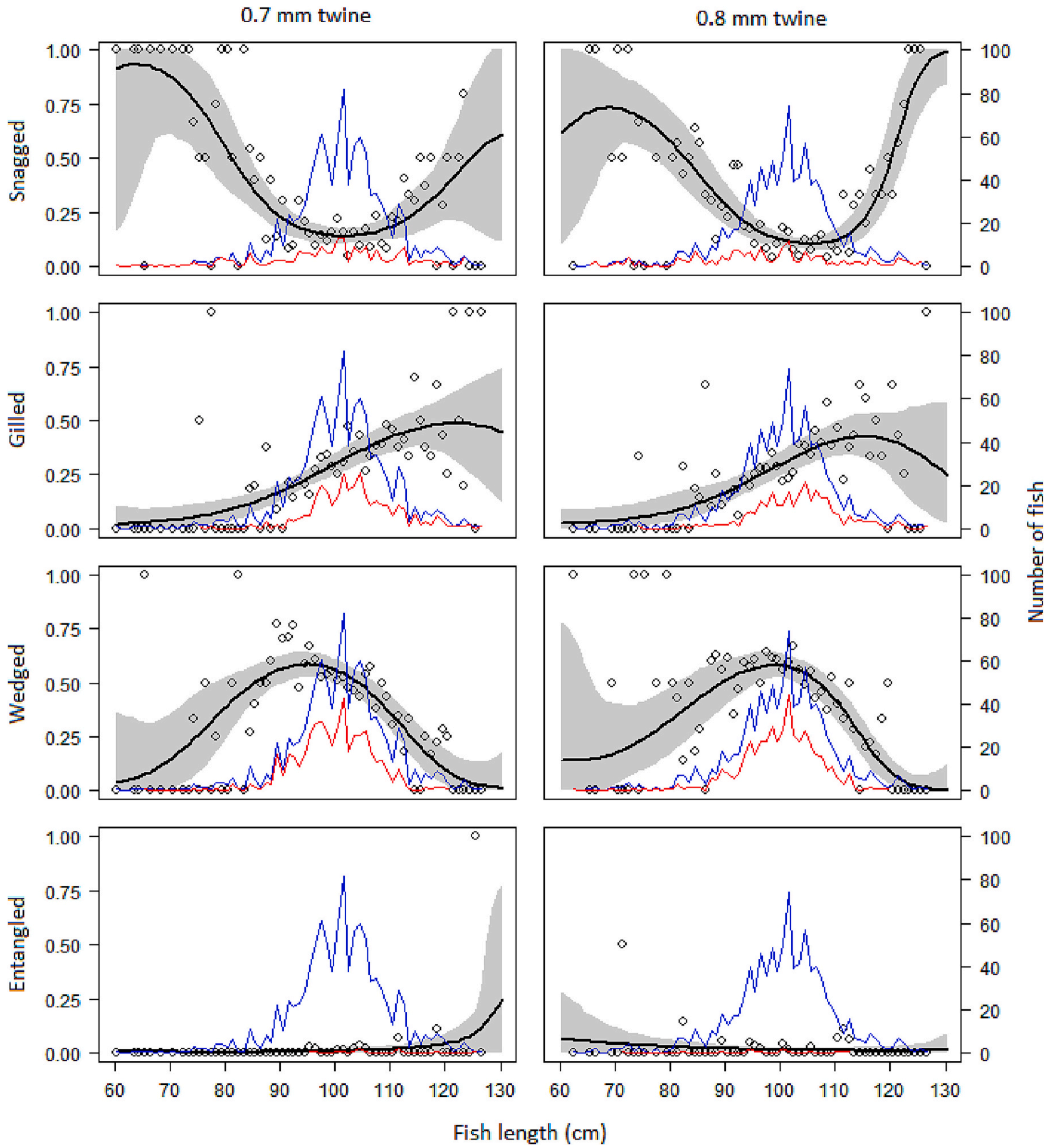

Fig. 3. Population size structure (blue/red line) and capture mode probability (black line) with 95 % confidence intervals of fish caught with the 210 mm mesh gillnets. The red line in the population structure shows the share of the total catch (blue line) for each capture mode. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$$CPq_l = \frac{\sum_{j=1}^{h} n_{qlj}}{\sum_{j=1}^{h}\sum_{i=1}^{Q} n_{ilj}} \tag{1}$$

where n_{qlj} is the number of cod caught for length class l with capture mode q in deployment j. Q equals the four capture modes and h is the total number of gillnet deployments. The functional form for the capture mode probability $CPq(l,\boldsymbol{v})$ was obtained using maximum likelihood estimation by minimizing the expression (2) with respect to parameters $\boldsymbol{v}$:

$$-\sum_{j=1}^{h}\sum_{l}\left\{n_{qlj}\times ln[CPq(l,\boldsymbol{v})]+\left[-n_{qlj}+\sum_{i=1}^{Q}n_{ilj}\right]\times ln[1.0-CPq(l,\boldsymbol{v})]\right\} \tag{2}$$

$\boldsymbol{v}$ represents the parameters describing the capture mode probability curve defined by $CPq(l,\boldsymbol{v})$ that has a value ranging from 0.0 to 1.0. Combined, Eq. (1) and expression (2) are similar to those commonly applied for modelling the length-dependent catch comparison rate between two fishing gears (Krag et al., 2014). Therefore, the same approach for modelling $CPq(l,\boldsymbol{v})$ was used, as is often applied for the length dependent catch comparison rate:

$$CPq(l,\boldsymbol{v}) = \frac{exp[f(l,v_0,\ldots,v_4)]}{1+exp[f(l,v_0,\ldots,v_4)]} \tag{3}$$

Table 3
The central points (R_{max}) and correlating fish lengths (LR_{max}) on the bell-shaped capture mode probability curves for gilling and wedging in the fleets with 210- and 230 mm mesh size for both twine thicknesses. Numbers in parentheses represent the 95 % confidence intervals. LR_{max} is measured in cm, and R_{max} quantifies the probability (0.0–1.0).

Mesh size	Capture mode	Parameter	0.7 mm twine	0.8 mm twine
210 mm	Gilling	R_{max}	0.5 (0.3–0.8)	0.4 (0.3–0.6)
		LR_{max}	121.8 (108.3–137.6)	115.2 (108.3–139.3)
	Wedging	R_{max}	0.6 (0.5–0.6)	0.6 (0.5–0.8)
		LR_{max}	94.9 (90.5–98.4)	98.9 (66.7–106.5)
230 mm	Gilling	R_{max}	0.4 (0.2–0.8)	0.4 (0.3–0.5)
		LR_{max}	115.7 (101.6–135.8)	111.3 (101.4–122.6)
	Wedging	R_{max}	0.6 (0.5–0.7)	0.54 (0.4–0.6)
		LR_{max}	106.1 (101.6–110.9)	105.27 (98.6–111.6)

f is a polynomial of order 4 with coefficients $v_0 - v_4$, such that $\boldsymbol{v} = (v_0, \ldots, v_4)$. Excluding one or more parameters $v_0, \ldots, v_4$, at a time resulted in 31 additional candidate models for the capture mode probability function $CPq(l, \boldsymbol{v})$. Multi-model inference was applied when estimating the capture mode probability based on these models to obtain a combined model (Burnham and Anderson, 2002; Herrmann et al., 2017; Savina et al., 2022). The ability of the combined model to describe the experimental data was evaluated based on the *p*-value, model deviance and degrees of freedom. For the combined model to adequately describe the experimental data the *p*-value should ≥0.05, except for cases experiencing data overdispersion (Wileman and Ferro (1996)). For cases with *p*-value <0.05 overdispersion was assumed to be the cause when the modelled curve (3) followed the main trend in the experimental rate (1) without any clear length dependent pattern in the observed deviations (Herrmann et al., 2017).

Uncertainties for $CPq(l, \boldsymbol{v})$, in terms of Efron 95 % percentile confidence intervals (Efron, 1982),were obtained with a double bootstrapping method with 1000 repetitions (Savina et al., 2022). Further, length-integrated value for the capture mode probability ($CPq_{average}$) was estimated directly from the experimental data applying (Cerbule et al., 2022; Savina et al., 2022):

$$CPq_{average} = \frac{\sum_{l}\sum_{j=1}^{h} n_{qlj}}{\sum_{l}\sum_{j=1}^{h}\sum_{i=1}^{Q} n_{ilj}} \tag{4}$$

In Eq. (4) the outer summations include the length classes l for captured cod during the gillnet fishing trials. Contrary to the length-dependent analysis of the capture mode probability described above, the $CPq_{average}$ values are specific for the population structure recorded during the gillnet fishing trials and cannot be extrapolated to other cases where the fish species size structure may be different (Cerbule et al., 2022; Savina et al., 2022). Uncertainties for $CPq_{average}$ were obtained by the same double bootstrap method used for the length dependent capture mode analysis.

2.3. Central points for bell-shaped capture mode probability curves

Some capture model probability curves follow a bell-shaped pattern (Savina et al., 2022) for which it is relevant to estimate two additional parameters, LR_{max} and R_{max}. LR_{max} is the fish length where the curve has its maximum probability, R_{max}. The software SELNET (Herrmann et al., 2012) was used to assess these central points for the probability curves. Values for LR_{max} and R_{max} were achieved using a numerical method in SELNET (Sistiaga et al., 2019).

Table 4
the capture mode probability and fit statistics for snagging, gilling, wedging, and entangling of cod caught with gillnets with 230 mm mesh size. Numbers in parentheses represent the 95 % confidence intervals. DOF represents the degree of freedom, and deviance represents the model deviance calculated according to Wileman and Ferro (1996).

Twine thickness	Fish length (cm)	Capture mode probability (%)			
		Snagging	Gilling	Wedging	Entangling
0.7 mm	70	96.0 (90.0–99.7)	2.3 (0.6–5.7)	4.2 (0.1–9.5)	1.0 (0.4–2.7)
	75	91.8 (82.1–99.2)	3.8 (1.1–7.8)	7.7 (0.9–15.6)	0.9 (0.3–2.4)
	80	82.7 (68.3–95.5)	6.4 (2.1–11.9)	13.9 (3.4–25.0)	0.9 (0.3–2.4)
	85	66.6 (55.0–80.9)	10.7 (3.9–19.0)	23.2 (10.5–35.0)	0.9 (0.3–2.5)
	90	46.1 (37.6–56.5)	16.1 (7.1–25.7)	34.5 (22.8–45.4)	1.0 (0.3–3.0)
	95	28.5 (21.3–36.7)	21.9 (12.8–30.9)	45.2 (35.4–53.6)	1.1 (−0.4–6.0)
	100	17.6 (11.4–24.3)	27.6 (19.6–35.1)	52.9 (45.8–59.9)	1.2 (−0.0–4.9)
	105	12.4 (7.1–18.4)	32.4 (25.7–39.1)	56.1 (48.7–63.4)	1.4 (0.4–3.6)
	110	11.1 (5.8–17.7)	35.8 (27.0–43.8)	53.8 (44.2–63.9)	1.6 (0.2–4.3)
	115	13.8 (6.4–23.5)	37.1 (25.4–49.4)	44.8 (29.6–58.9)	1.8 (−0.6–9.8)
	120	24.8 (9.0–44.3)	35.8 (18.3–57.8)	29.3 (10.7–50.4)	2.1 (1.1–8.4)
	Average	25.7 (19.6–31.7)	27.0 (22.0–32.2)	46.0 (40.1–51.4)	1.3 (0.0–3.0)
	p–value	0.636	0.998	0.862	1.000
	Deviance	48.9	27.8	42.0	19.6
	DOF	53	53	53	53
0.8 mm	70	97.1 (93.6–99.4)	2.8 (−0.3–11.5)	2.0 (0.3–5.0)	2.1 (−0.1–6.4)
	75	91.9 (84.5–97.9)	4.7 (−0.0–15.6)	4.8 (1.1–10.8)	1.8 (−0.2–5.9)
	80	79.6 (66.6–92.7)	7.9 (1.0–19.6)	11.2 (3.1–21.6)	1.6 (−0.5–6.4)
	85	59.8 (45.1–78.2)	12.6 (3.6–23.8)	21.9 (10.2–34.8)	1.4 (−0.3–6.0)
	90	39.3 (27.8–55.3)	18.3 (8.4–29.0)	34.3 (20.0–48.7)	1.3 (−0.2–4.9)
	95	24.6 (16.8–34.0)	24.5 (15.6–33.8)	44.9 (32.5–58.4)	1.3 (0.0–3.7)
	100	16.5 (11.1–22.7)	30.3 (23.1–38.2)	51.5 (41.5–61.0)	1.3 (0.1–3.3)
	105	12.9 (8.3–18.4)	34.6 (28.2–40.9)	53.6 (44.8–61.3)	1.5 (0.2–3.3)
	110	12.7 (7.6–19.2)	36.6 (27.6–44.9)	51.0 (40.0–61.1)	1.8 (0.1–4.5)
	115	16.3 (8.0–26.8)	35.5 (22.2–47.8)	43.6 (31.2–56.5)	2.4 (−0.6–10.7)
	120	27.7 (10.2–48.6)	31.0 (13.3–48.0)	31.8 (16.1–46.6)	3.8 (−1.6–18.9)
	Average	24.4 (17.2–32.0)	29.4 (23.3–35.6)	44.5 (37.1–51.9)	1.7 (0.3–3.4)
	p–value	0.713	0.206	0.227	0.999
	Deviance	44.9	59.0	58.2	26.0
	DOF	51	51	51	51

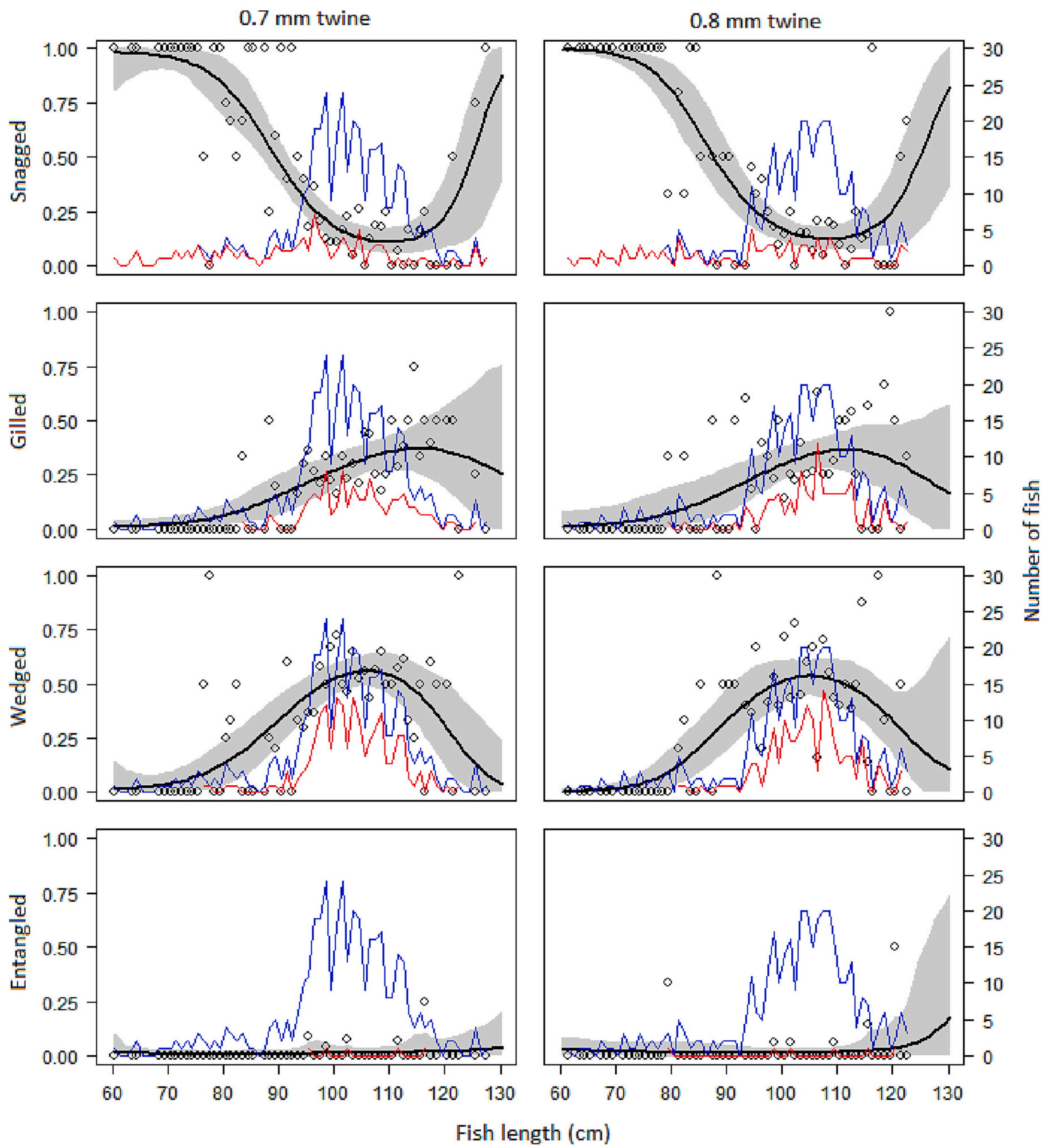

Fig. 4. Population size structure (blue/red line) and capture mode probability (black line) with 95 % confidence intervals of fish caught with the 230 mm mesh gillnets. The red line in the population structure shows the share of the total catch (blue line) for each capture mode. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.4. Difference in the length-dependent probability for capture modes between gillnet designs

To investigate the effect of changing from gillnet (Y) to gillnet (Z) on the capture mode probability curve $CP_{q,gillnett}(l, \boldsymbol{v}_{gillnet})$ for mode q, the length-dependent change $\Delta CPq(l)$ in the values was estimated as follows:

$$\Delta CPq(l) = CP_{q,Z}(l) - CP_{q,Y}(l) \tag{5}$$

In Eq. (5) $CP_{q,Y}(l)$ represents the probability for gillnet design (Y) and $CP_{q,Z}(l)$ represents the probability for gillnet design (Z). The bootstrap populations (both containing 1000 repetitions) of results for both $CP_{q,Y}(l)$ and $CP_{q,Z}(l)$ were used to estimate 95 % confidence limits for $\Delta CPq(l)$. Because these were obtained independently, a new bootstrap population of results was created for $\Delta CPq(l)$:

$$\Delta CP_q(l)_i = CP_{q,Z}(l)_i - CP_{q,Y}(l)_i \; i \in [1\ldots1000] \tag{6}$$

In Eq. (6) i denotes the bootstrap repetition index. As the bootstrap resampling was random and independent for the two groups of results, it is valid to generate the bootstrap population of results for the difference based on the two independently generated bootstrap files (Herrmann et al., 2018). Based on the bootstrap population, Efron 95 % percentile confidence limits were obtained for$\Delta CPq(l)$ as described above. The methodology applied in this section for the difference in capture mode probability is similar to that applied by Larsen et al. (2018) for inferring difference in size selectivity.

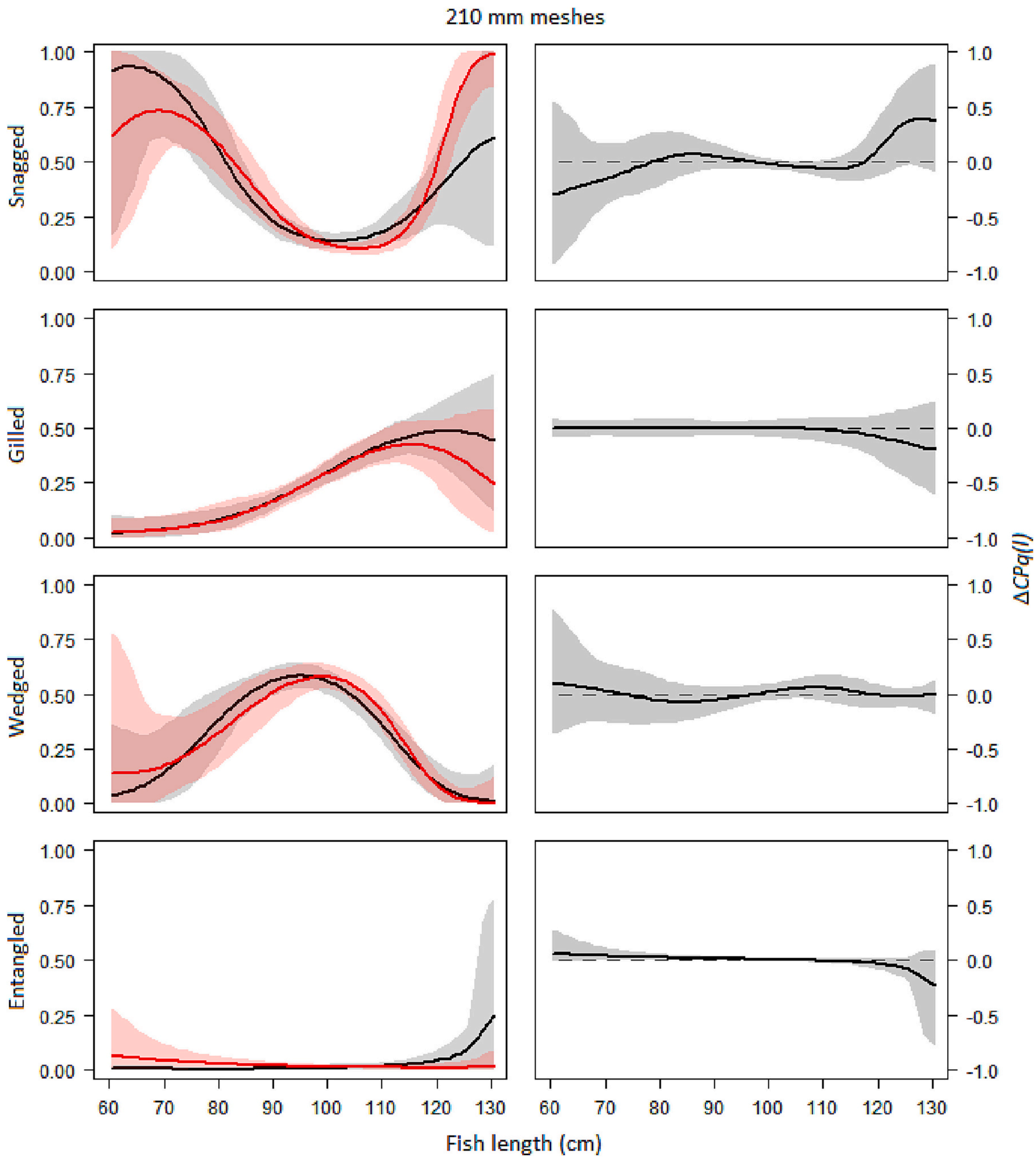

Fig. 5. Left: Capture mode probability curves for 0.7 mm (black) and 0.8 mm (red) twine thickness for gillnets with 210 mm mesh size. Right: Delta plots showing the effect on capture mode probability (ΔCPq(l)) when increasing twine thickness. The grey shaded areas show the 95 % confidence interval. The horizontal dotted line at 0 in the right column shows the baseline where there is no difference between the two twine thicknesses. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.5. Size-dependent catch efficiency between gillnets with different twine thickness

Assessing the difference in relative length-dependent catch efficiency between gillnets with different twine thickness was performed separately for each mesh size. This was done by comparing the catch data between gillnet types using the method described in Cerbule et al. (2022), which models the length dependent catch comparison rate (CC_l) summed over all gillnet fleet deployments during the entire study period. CC_l is expressed by the following equation:

$$CC_l = \frac{\sum_{j=1}^{m}\{nt_{lj}\}}{\sum_{j=1}^{m}\{nt_{lj}+nc_{lj}\}} \quad (7)$$

where nt_{lj} and nc_{lj} are the numbers of cod caught in each length class l for gillnets with respectively 0.7 mm and 0.8 mm thickness in deployment j of a gillnet fleet (1 or 2). m is the number of deployments carried out with each fleet. The functional form for the catch comparison rate $CC(l, \boldsymbol{v})$ was obtained using maximum likelihood estimation by minimizing the following expression:

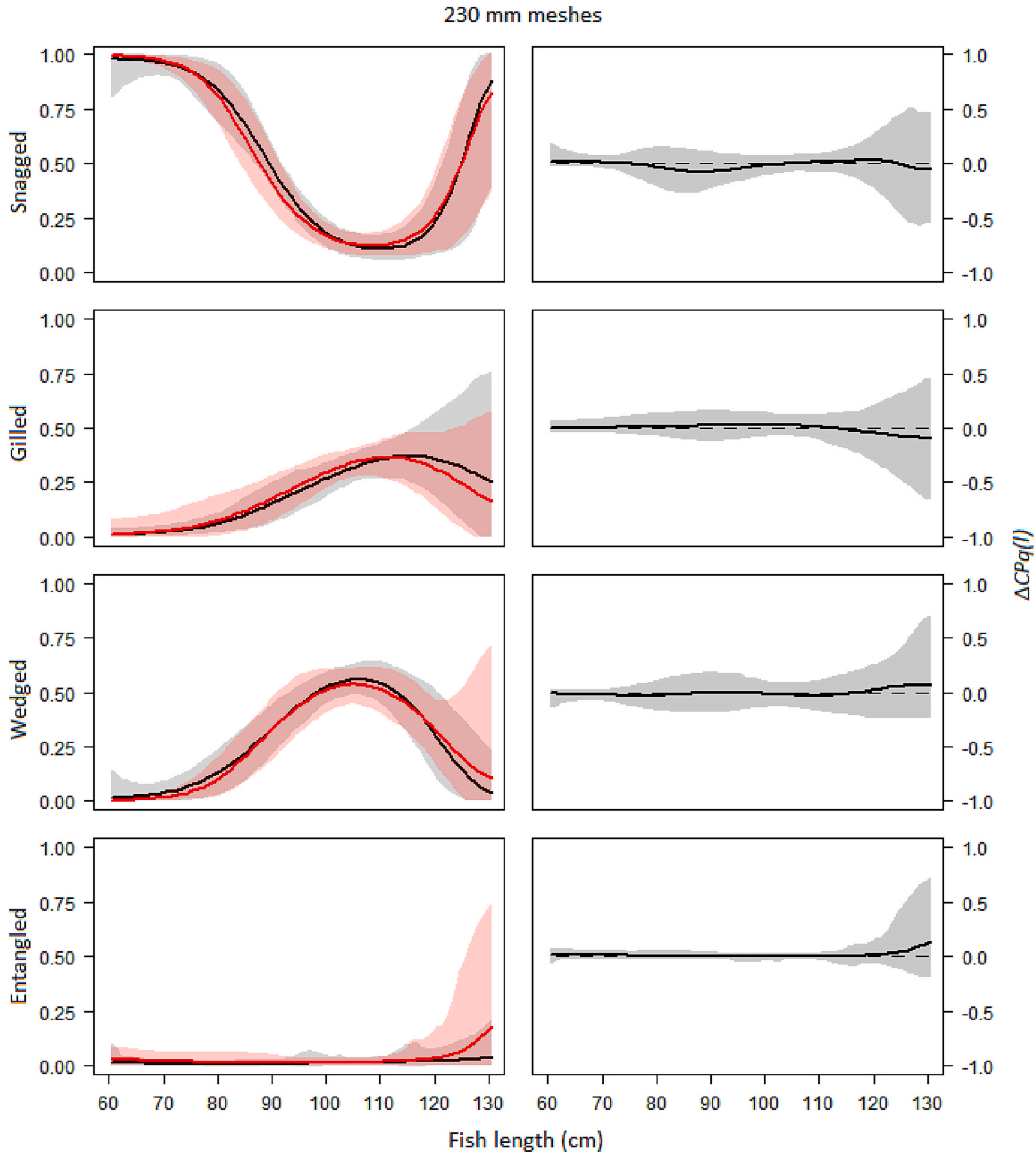

Fig. 6. Left: Capture mode probability curves for 0.7 mm (black) and 0.8 mm (red) twine thickness for gillnets with 230 mm mesh size. Right: Delta plots showing the effect on capture mode probability (ΔCPq(l)) when increasing twine thickness. The grey shaded areas show the 95 % confidence interval. The horizontal dotted line at 0 in the right column shows the baseline where there is no difference between the two twine thicknesses. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$$-\sum_{l}\left\{\sum_{j=1}^{m}\left\{nt_{lj}\times ln(CC(l,\mathbf{v}))+nc_{lj}\times ln(1.0-CC(l,\mathbf{v}))\right\}\right\} \quad (8)$$

where $\mathbf{v}$ represents the parameters describing the catch comparison curve defined by $CC(l,\mathbf{v})$. The outer summation in expression (8) is the summation over length classes l. If the 0.7 and 0.8 mm twines have the same catch efficiency, the value for the summed catch comparison rate is 0.5, which acts as a baseline. The experimental CC_l (Eq. (7)) was modelled by the function $CC(l,\mathbf{v})$ using the following equation (Krag et al., 2014):

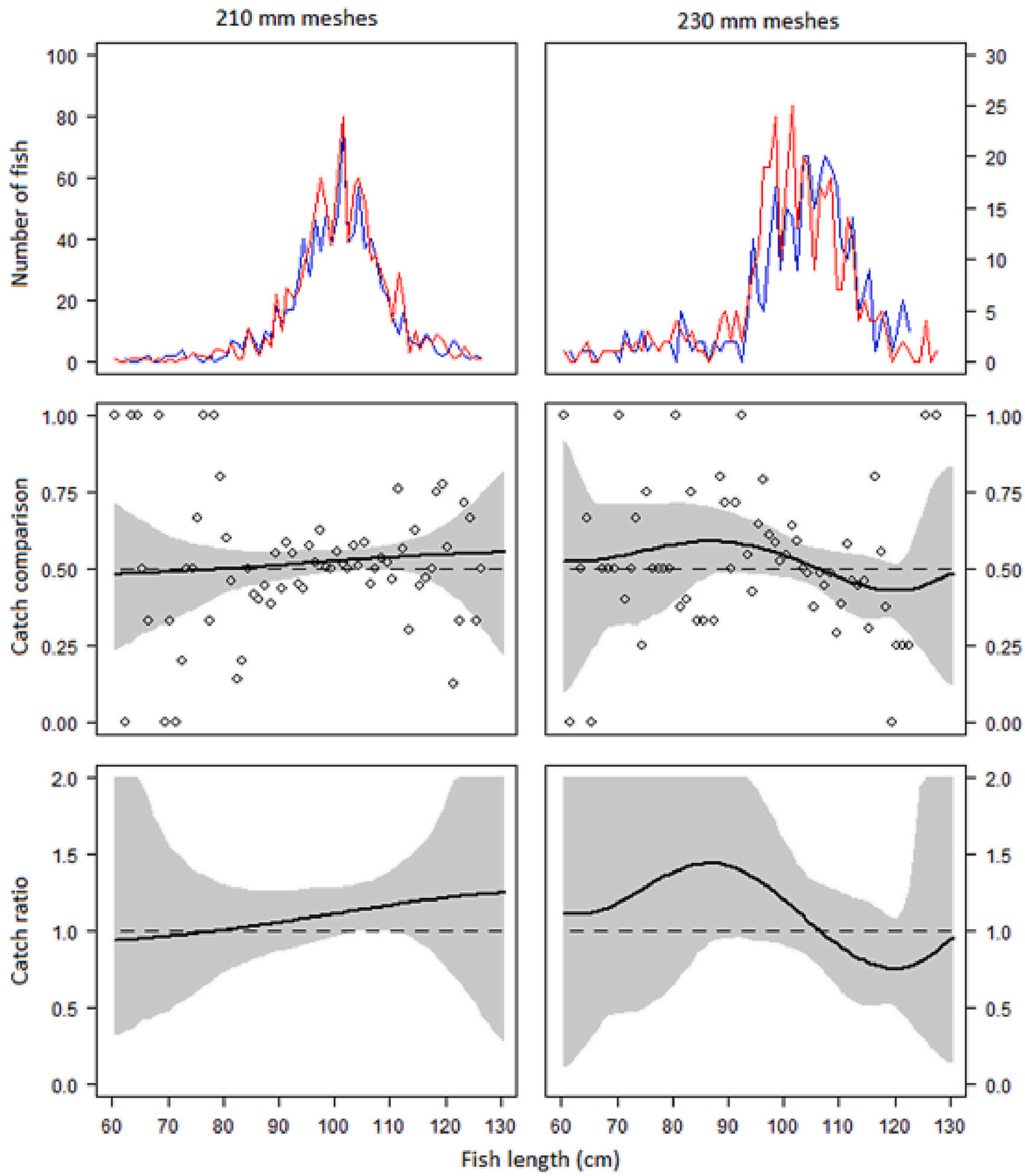

Fig. 7. Catch comparison rate (CC) and catch ratio (CR) for gillnets with 210 mm (left) and with 230 mm meshes (right). Upper graphs show the number of cod caught with the 0.7 mm (red) and 0.8 mm twine (blue). Middle graph shows the catch comparison rate. Bottom graph shows the catch ratios. Grey shaded areas mark the 95 % confidence intervals. Horizontal dotted lines at 0.5 in the CC-plot and at 1.0 in the CR-plot represent the baseline where gillnets with different twine thicknesses catch equally. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$$CC(l,\boldsymbol{v}) = \frac{exp(f(l, v_0, \ldots, v_k))}{1 + exp(f(l, v_0, \ldots, v_k))} \tag{9}$$

where f is a polynomial of order k with coefficients v_0 to v_k, and order k was set to 4. The values of the parameters v describing $CC(l,\boldsymbol{v})$ were estimated by minimizing expression (8) and multi-model inference was used to obtain a combined model (Burnham and Anderson, 2002; Herrmann et al., 2017). Just like for the capture mode analysis, the ability to describe the experimental data of the combined model for the catch comparison rate was evaluated based on the p-value.

Based on the estimated catch comparison function $CC(l,\boldsymbol{v})$, the relative catch efficiency (or catch ratio) $CR(l,\boldsymbol{v})$ between the two gillnet types was obtained using the following equation (Cerbule et al., 2022):

$$CR(l,\boldsymbol{v}) = \frac{CC(l,\boldsymbol{v})}{(1 - CC(l,\boldsymbol{v}))} \tag{10}$$

If the two gillnet types have an identical catch efficiency, then this value is 1.0. If $CR(l,\boldsymbol{v}) = 1.5$ the gillnets with 0.7 mm twine would catch 50 % more cod with length l than those with 0.8 mm twine. On the other hand, if $CR(l,\boldsymbol{v}) = 0.8$ the gillnet with 0.7 mm twine would catch 80 % of the cod with length l compared to those with 0.8 mm twine.

The confidence limits for $CC(l,\boldsymbol{v})$ and $CR(l,\boldsymbol{v})$ were estimated using the double bootstrapping method also applied for the capture mode analysis described above. To identify the cod sizes with significant differences in catch efficiency between gillnet types, the length classes in which the 95 % confidence limits for the catch ratio curve did not contain 1.0 were checked.

The length-integrated average catch ratio ($CR_{average}$) was estimated

Table 5
Catch ratios and fit statistics for fleets 1 and 2. Numbers in parentheses represent 95 % confidence intervals. Significant differences are highlighted in bold.

Length (cm)	Catch ratio (%)	
	Fleet 1	Fleet 2
70	96.4 (48.1–154.2)	118.8 (46.2–248.6)
75	98.4 (60.4–138.1)	129.2 (51.2–250.3)
80	100.6 (73.7–129.5)	138.7 (67.1–251.9)
85	103.0 (81.3–126.0)	143.6 (87.9–242.4)
90	105.6 (87.1–125.8)	141.7 (94.7–217.5)
95	108.4 (92.1–127.9)	132.8 (93.0–190.5)
100	111.2 (97.0–128.1)	118.8 (90.0–156.6)
105	**114.0 (100.3–131.6)**	103.1 (80.3–132.5)
110	116.7 (99.3–139.7)	88.9 (60.2–124.5)
115	119.3 (92.2–154.6)	78.8 (50.8–118.4)
120	121.2 (74.9–187.3)	75.2 (49.9–107.4)
Average	110.9 (99.3–123.7)	107.8 (84.9–130.7)
p–value	0.090	0.683
Deviance	75.1	51.4
DOF	60	57

directly from the experimental catch data using the following equation:

$$CR_{average} = \frac{\sum_{l}\sum_{j=1}^{m}\{nt_{lj}\}}{\sum_{l}\sum_{j=1}^{m}\{nc_{lj}\}} \tag{11}$$

where the outer summation covers the length classes in the catches during the experimental fishing trials.

3. Results

The catch consisted nearly of only cod, representing >90 % of the total catch. The bycatch consisted of a few haddock (*Melanogrammus aeglefinus*) and halibut (*Hippoglossus hippoglossus*). Therefore, only data on cod was included in this investigation. A total of 2819 cod, all above the minimum landing size of 44 cm, were captured during the gillnet fishing trials and 2696 cod were used in the analysis, after omitting 123 cod caught in hauls containing <20 individuals. From these, 72 % were captured by the gillnet with 210 mm meshes (53 % with 0.7 mm twine and 47 % with 0.8 mm twine), and 28 % were captured by the gillnet with 230 mm meshes (52 % with 0.7 mm twine and 48 % with 0.8 mm twine) (Table 1).

3.1. Capture pattern for gillnets with 210 mm mesh size

The fit statistics for the capture modes showed that the deviations between the experimental data and the modelled data were acceptable. The *p*-value exceeded 0.05 for all cases (Table 2), implying that the modelled capture mode curves represent well the collected data.

Clear length-dependent capture patterns were observed for the different capture modes in gillnets with 210 mm meshes (Fig. 3). For those with 0.7 mm twine, snagging was the dominant mode of capture for cod in smaller length classes. The snagging probability decreases with increasing fish length, after which wedging becomes the capture mode with highest catching probability. The latter has its highest probability (58 %) of capture for cod around 95 cm (Fig. 3, Table 3). When fish length exceeds 100 cm, gilling becomes the most likely capture mode, reaching its highest probability (49 %) for cod of 122 cm (Fig. 3, Table 3). For largest individuals, snagging becomes again the predominant capture mode. However, since few fish larger than 120 cm were captured, the trend for these individuals is uncertain. Entangling only occurred in 26 cods (1.3 %) caught by 210 mm meshed gillnets and no length-dependent trend was detected. For the gillnets with 0.8 mm twine thickness, the length-dependent trend in capture mode was similar to that of the gillnets with 0.7 mm twine thickness. This was only distinguishable by the curves for the gillnets with 0.8 mm twine, being slightly skewed towards larger length classes (Fig. 3).

3.2. Capture pattern for gillnets with 230 mm mesh size

The fit statistics for the capture modes showed that the deviations between the experimental data and the modelled data were acceptable. The *p*-value exceeded 0.05 for all cases (Table 4), implying that the modelled capture modes curves represent well the collected data.

For the gillnets with 230 mm meshes there is clear proof of length-dependent capture mode probabilities (Fig. 4). For those with 0.7 mm twine thickness, snagging had the highest probability for cod in the smaller length classes. Wedging becomes the predominant capture mode as fish length increases, reaching a maximum probability (56 %) for cod with 106 cm long (Fig. 4, Table 3). For even larger fish, gilling becomes the most likely capture mode, reaching its highest probability (37 %) for fish with 116 cm long (Fig. 4, Table 3). For the largest individuals snagging again becomes the most probable way of capture. In these gillnets, entangling constituted a minor proportion (1.5 %) of the total fish caught. Similarly to the gillnets with 210 mm meshes, the differences between twine thicknesses in the fleet with 230 mm meshes were only distinguishable by the probability curves for the thicker twine, being also slightly skewed towards larger length classes (Fig. 4).

3.3. Twine thickness effect on length-dependent capture mode probability

The effect of twine thickness on the length-dependent capture mode probability is presented in Fig. 5 (gillnets with 210 mm mesh size) and Fig. 6 (gillnets with 230 mm mesh size).

Figs. 5 and 6 show that the baseline for all capture modes, i.e., marking where there is no difference between the 0.7 and 0.8 mm twine, is within the 95 % confidence interval. This implies that increasing the twine thickness from 0.7 to 0.8 mm, and consequently improving the breaking strength and twine stiffness by approximately 30 %, has no significant effect on the way cod of diverse sizes is captured by gillnets.

3.4. Twine thickness effect on catch efficiency

The effect of twine thickness on gillnet catch efficiency is presented in Fig. 7 and Table 5. The fit statistics for the catch comparison analyses showed that the deviations between the experimental data and the modelled data were acceptable. The *p*-value exceeded 0.05 for all cases (Table 5), implying that the modelled catch comparison curves represent well the collected data.

Increased twine thickness did not prove to have a significant effect on the overall catch efficiency for either mesh size. However, for specific length classes, a significant variation was observed in the gillnets with 210 mm mesh size, where the gears with thin twine captured 14 % more cod in the length class of 105 cm (Fig. 7). For gillnets with 210 mm meshes the average catch ratio value was 110.9 (CI: 99.3–123.7). Furthermore, there is a weak, non-significant, trend which could indicate a positive correlation between fish length and catch efficiency for the thinner twine.

The average catch ratio for gillnets with 230 mm meshes was 107.8 (CI: 84.9–130.7). Furthermore, a weak, non-significant, trend indicates that thin twine is more efficient for smaller cod, while the opposite trend occurred for larger cod. Comparing the two fleets revealed weak opposing trends for fish in the size range of 80–120 cm. For increasing fish length within this range, the gillnets with 210 mm meshes caught more fish, while the opposite was estimated for gillnets with 230 mm meshes. However, the gillnets with 230 mm meshes captured fewer fish, making any speculations about the trends estimated for large cod uncertain.

4. Discussion

The results of this study demonstrated that an increase in twine thickness does not significantly affect the catch performance of the gear. Modifying fishing gear is thought to be a plausible measure to address ALDFG (ICES/FAO, 2023). When it comes to gillnets this can be done by finding the tolerable increase filament thickness for gillnet durability without compromising the catch efficiency. This may increase the lifetime of the gear, and thereby lead to a reduction in gillnet turnover. Consequently, this could reduce the risk of gear discarding, gear loss, ghost fishing and ultimately marine pollution.

This study investigated the effect of gillnet twine thickness on capture pattern and efficiency in the NEA cod fishery. The results demonstrated that a 30 % increase in breaking strength and twine stiffness did not affect the catch performance. Therefore, thicker gillnet twine can potentially reduce marine litter by plastic debris from damaged and lost gears without compromising catch performance.

Investigating the effect of twine thickness on different mesh sizes showed that increasing twine thickness did not have a significant effect on the overall catch efficiency for gillnets with 210 and 230 mm mesh sizes. However, a weak non-significant trend was recorded for the gillnets with 210 mm mesh size, appearing that the thinner twine (0.7 mm) caught slightly more fish compared to the thicker twine (0.8 mm) with increasing fish length. Several previous studies corroborate this observation (Hansen, 1974; Turunen, 1996; Yokota et al., 2001; Kim et al., 2016) and there are several possible explanations for this pattern. Thin twine requires less force to be stretched compared to thick twine, and this may result in thinner twine retaining fish belonging to larger length classes. Also, large fish can exert more force on the twine resulting in more stretch, and therefore it is possible to assume that a thin twine can capture more large fish, as long the twine does not break. On the other hand, thick twine on the other hand, requires more force to be stretched, and depending on the population size structure in a specific area, only fish in a narrower length range will be able to stretch enough the material to be retained in the gillnet. It is also possible that thicker twine is more easily detectable (Hansen, 1974; Gabriel et al., 2005), which would explain why thicker twine might have a slightly lower capture efficiency compared to thinner twine.

The analysis of the effect of twine thickness on the way cod was captured (capture modes) showed clear length-dependent trends for both twine thicknesses. Small cod have the highest likelihood of being caught by snagging, whereas with increasing length, wedging becomes the most probable cause of capture followed by gilling. Then, snagging becomes again the most probable capture mode for the largest cods. This capture pattern reflects the cod morphology, with gradually increasing circumference perimeter from the snout to the first dorsal fin. In practice, the smaller the cod, the further back on the fish body the mesh will match the first fish circumference, and the larger the cod, the further towards the fish snout will be the case. The U-shaped form of the probability curve for snagging and the bell-shaped curves for wedging and gilling clearly confirm that these ways of capture are length-dependent. Only fish within a certain length range can get captured in a distinct way by a specific mesh size, a trend that corroborates previous studies analysing modes of capture in gillnets (Cerbule et al., 2022; Savina et al., 2022). The capture mode curves showed similar trends regarding length-dependency for the gillnet with 210 mm mesh size and the gillnets with 230 mm mesh size. The only difference between mesh sizes was that the curves were slightly skewed towards larger length classes for the largest mesh size. This can be explained by larger cod having a larger body circumference, and therefore gillnets with large meshes will catch fish belonging to larger length classes. No differences were observed between the catches of gillnets with 0.7 and 0.8 mm twine, revealing that twine thickness did not significantly influence the way cod became captured in gillnets.

Combining the findings from the capture mode- and catch efficiency showed that an increase in twine thickness, equivalent to approximately 30 % increase in breaking strength, had no significant effect on the catch efficiency of the gillnet. These results are in accordance with a study by Grimaldo et al. (2020b) that compared two different biodegradable polybutylene succinate *co*-adipate-co-terephthalate (PBSAT) twine thicknesses (0.55 and 0.60 mm, equivalent to 18 % difference in breaking strength). Corroborating Grimaldo et al. (2020b), the present study further contributed to fill the knowledge gap regarding the underlying mechanisms that influence the gillnet capture process for cod. This information might be useful for future gillnet design, since using thicker twine in gillnet construction will not compromise the catch efficiency of the gear. Utilizing thicker twine might therefore potentially increase the gillnets lifetime. For instance, thicker twine will make it harder for large fish to stress and eventually break the twine. Also, thicker twine will make the gear more robust when it comes to wear down from general use, including hauling and removing fish from the net. Increasing the gears lifetime will consequently reduce the turnover and gillnet production. As a result, this could reduce waste and, especially in countries lacking sufficient waste management infrastructure, it could also help decreasing marine pollution by abandoned or discarded gears. Increased gillnet lifetime could also reduce the amount of gillnets that are lost due to malfunctioning gear, thereby further reducing marine pollution and its associated environmental and socioeconomic consequences.

Another way the environmental impacts of discarded or lost gillnets could be reduced is by developing a biodegradable material to replace nylon in gillnet twine. However, previous investigations of biodegradable PBSAT gillnets have shown a significantly lower catch efficiency compared to polyamide gillnets (Grimaldo et al., 2018a, 2018b, 2019, 2020a, 2020b). The lower catch efficiency in these studies have been explained in connection to the physical properties of the gear material, like elasticity and breaking strength which are determined by twine thickness. However, the findings in the present study prove that it is possible to fish within a range of twine thicknesses without reducing the efficiency of gillnets. Thus, future biodegradable gillnets can possibly be made of thicker twine to compensate for the loss of catch efficiency described in Grimaldo et al. (2018a). In this way, the knowledge obtained in the present study can potentially have positive effects for the mitigation of marine pollution by encouraging further development of biodegradable material and the production of more durable gillnet twines that would reduce the amount of plastic waste resulting from abandoned and lost gear.

CRediT authorship contribution statement

Ilmar Brinkhof: Conceptualization, Methodology, Validation, Formal Analysis, Investigation, Data curation, Writing – Original Draft, Writing – Review and editing, Visualization.

Bent Herrmann: Conceptualization, Methodology, Software, Validation, Formal Analysis, Investigation, Writing – Original Draft, Writing – Review and editing, Visualization.

Roger B. Larsen: Conceptualization, Methodology, Resources, Investigation, Writing – Original Draft.

Jesse Brinkhof: Validation, Resources, Investigation, Data curation, Writing – Original Draft, Writing – Review and editing, Visualization.

Eduardo Grimaldo: Conceptualization, Methodology, Investigation, Data curation, Writing – Original Draft, Review and editing.

Jørgen Vollstad: Conceptualization, Methodology, Data curation, Resources.

Declaration of competing interest

The authors declare that they have no competing financial interests or personal relationships that could have influenced the work reported in this paper.

Data availability

Data will be made available on request.

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