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Effect of the T90-codend on the catch quality of cod (*Gadus morhua*) compared to the conventional codend configuration in the Barents Sea bottom trawl fishery

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ABSTRACT

The aim of this study was to compare the catch quality of Northeast Atlantic cod (*Gadus morhua*) in the Barents Sea bottom trawl fishery caught using the conventional configuration (a sorting grid followed by a diamond mesh (T0) codend) and a T90° turned mesh codend (T90) without a grid. Twenty hauls were conducted, consisting of 10 hauls with the conventional configuration and 10 hauls with the T90-codend. The catch quality was assessed using the catch-damages-index (CDI) and a newly developed method using VIS/NIR hyperspectral imaging to estimate the residual blood abundances in the fish muscle. The probability of obtaining fish with no damage was 23.4% (CI: 16.3–31.1%) for cod captured by the conventional configuration, and 21.2% (CI: 15.4–27.2%) for cod captured by the T90-codend. The average blood abundance (in arbitrary unit) was 0.86 (CI: 0.85–0.87) for cod captured by the conventional configuration and 0.88 (CI: 0.87–0.88) for cod captured by the T90-codend. Catch quality of the hauls obtained using the two gears did not differ significantly in terms of catch damage or residual blood levels in the cod. Hence, this study demonstrated that T90-codends do not compromise catch quality compared to regular diamond meshed codends.

1. Introduction

Northeast Atlantic cod (*Gadus morhua*) is the dominant species in the Barents Sea bottom fishery (Nedreaas et al., 2011; Yaragina et al., 2011), and it is targeted mainly by Russia and Norway (Shamray and Sunnanå, 2011). About 70% of the total annual quota, which is equally divided between these two countries, is caught using bottom trawls (ICES, 2018; Yaragina et al., 2011). In the Barents Sea gadoid fishery, sorting grid systems with a minimum bar spacing of 55 mm are mandatory to ensure the release of juvenile fish (Ministry of Trade, Industry and Fisheries, 2020; Yaragina et al., 2011), followed by a diamond meshed codend with a minimum mesh size of 130 mm (Ministry of Trade, Industry and Fisheries, 2020).

Fish caught by bottom trawls are often associated with reduced quality. For example, Rotabakk et al. (2011) reported that cod caught by bottom trawl have a poorer overall quality compared to cod caught by longline. The most common quality defects in trawl-caught fish are gear marks, skin abrasion, pressure injuries, internal and external bruises, and insufficient exsanguination (Digre et al., 2017; Olsen et al., 2013; Rotabakk et al., 2011). Such quality defects may lead to downgrading of the fish and subsequent economic loss for the producer, as a negative correlation between the number of catch defects and the proportion of high-value products has been reported (Margeirsson et al., 2006). Poor catch quality limits the types of products in which the fish can be used, thus improving the quality of trawl-caught fish could increase its value and potentially expand the bottom trawl fishery market. In addition, catch quality would likely be improved by improving fish welfare in capture fisheries, which has gained increased research interest in recent years (Veldhuizen et al., 2018).

Numerous studies aimed at improving the quality of trawl-caught fish have been conducted in recent years (Brinkhof et al., 2018a, 2018b, 2021; Digre et al., 2010; Svalheim et al., 2019, 2020; Tveit et al., 2019). The general goal is to prevent deterioration of the catch during the capture process, which is key to improving the quality of trawl-caught cod. Tveit et al. (2019) substituted knotless netting for the conventional knotted codend and changed the codend construction from

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a 2-panel to a 4-panel codend. However, these changes did not significantly alter the catch damage of trawl-caught cod compared to the conventional trawl configuration. Brinkhof et al. (2018b) developed a dual sequential codend that improved catch quality; they reported a 14% (confidence interval (CI): 6–24%) higher probability of catching cod without any catch damage compared to cod caught using a conventional trawl. However, the dual sequential codend is expensive and difficult to handle. Therefore, the most optimal solution is to improve catch quality without adding extra expensive equipment.

One simple solution that potentially could improve catch quality is to turn the direction of the codend netting 90 degrees (T90) perpendicular to the towing direction (Fig. 1). In a regular diamond mesh codend, the meshes tend to close when the catch accumulates in the codend. Turning the mesh direction in the codend panels 90 degrees forces the meshes to stay open during the entire capture process regardless of the accumulating catch. Anecdotal information provided by fishers suggests that the T90-codend results in better catch quality. In addition, some fishers argue that the use of a sorting grid, which is compulsory in the bottom trawl fishery in the Barents Sea (Brinkhof et al., 2021; Sistiaga et al., 2016), negatively affects the catch quality.

Previous studies have demonstrated improved size selectivity with the use of the T90-codend compared to the conventional configuration for several species in different fisheries (Cheng et al., 2020; Madsen et al., 2012; Petetta et al., 2020). Brinkhof et al. (2022) demonstrated improved release of juvenile cod while simultaneously increasing catch efficiency in the Barents Sea by removing the compulsory sorting grid and replacing the regular diamond mesh codend with a T90-codend.

Since the T90-codend without a grid has exhibited good ability to release juvenile fish, it is also important to investigate the effect of the T90-codend on the catch quality of cod compared to the conventional configuration, which is the purpose of this study.

More specifically, the aims of this study were to i) quantify the extent of catch-related external damage and residual blood levels of cod captured by the conventional trawl configuration (grid & regular, T0-codend), ii) quantify the extent of catch-related external damage and residual blood levels of cod captured by the T90-codend without a grid, and iii) compare the amount and severity of catch-related external damage and residual blood levels between cod caught by the two gear configurations.

2. Materials and methods

2.1. Trawling conditions and trawl design

Experimental fishing was conducted on board the research vessel R/V *Helmer Hanssen* (63.8 m, 4080 horsepower) between 1 and 5 March 2020. The fishing area was located along the coast of Northern Norway in the southern Barents Sea (N 71°21′ E 23°43′ – N 71°21′ E 24°24′). The towing speed varied between 3.0 and 3.5 knots (average 3.3 knots). During towing, the distance between the otter boards, trawl height, and catch volume were monitored by Scanmar sensors.

The trawl contained a set of Injector Scorpion otter boards for bottom trawl (3100 kg, 8 m^2) with 3 m long backstraps and 7 m long connector chains, followed by 60 m long sweeps equipped with an Ø53 cm steel bobbin in the middle to avoid excessive abrasion of the sweeps. The 46.9 m long ground gear consisted of a 14 m long chain (Ø 19 mm) with three equally spaced bobbins (Ø53 cm) on each side and an 18.9 m long rockhopper gear in the center composed of Ø53 cm rubber discs. The trawl used was a two-panel Alfredo 3 fish trawl built from polyethylene (PE) with a 155 mm nominal mesh size with a circumference of 420 meshes. Its fishing line was 19.2 m long, and the headline of the trawl was 35.6 m long and equipped with 170 floats (Ø20 cm).

Two different trawl configurations were applied: a configuration similar to that applied in the commercial fishery and an experimental configuration. The conventional configuration consisted of a flexigrid sorting system inserted between the trawl belly and the extension piece in front of the codend as well as a diamond mesh codend (Fig. 1). The flexigrid is compulsory in the trawl fishery in the Northeast Atlantic and consists of two flexible grids made of high density polypropylene, each 150 cm long and 95.5 cm wide, equipped with fiberglass rods with a bar spacing of 55 mm (Sistiaga et al., 2016). A 9.3 m long extension piece (60 meshes) was inserted between the flexigrid and the codend. The diamond mesh codend (T0) was 11 m long, built from single-braided Ø8 mm PE twine (Euroline Premium, Polar Gold), and had a mesh size of 129.5 ± 4.8 mm (mean ± SD).

The experimental configuration was a T90-codend (Fig. 1). The flexigrid was removed and replaced with a 2-panel extension section followed by a 2- to 4-panel transition section. The T90-codend was built with double-braided Ø4 mm PE twine, was 4 × 12 meshes in circumference and 11 m long, and had a mesh size of 147.6 ± 6.0 mm (mean ± SD). To obtain the same selective properties as with a conventional configuration with a grid, the T90-codend had slightly larger mesh size (Brinkhof et al., 2021 in prep). Mesh sizes in the codends were measured using an OMEGA mesh gauge, and following the procedure described by Wileman et al. (1996).

2.2. Fish sampling

Immediately after each haul 30 cod were randomly sampled from the respective codend on deck. To ensure a representative sample size, fish were randomly collected at the end, middle and beginning of the codend. The fish were stunned by a blow to the head, bled by cutting the isthmus, and exsanguinated in running seawater for 30 min in a 1000 L tank. Next, individual length and weight were recorded. The fish then were gutted, beheaded, cleaned in running seawater, laid in 50 kg blocks in commercial vertical plate freezers, frozen to a core temperature of −18 °C, and finally packed in commercial bags and stored at −30 °C until landing. After the sea trial, the fish were transported to the laboratory at Nofima, Tromsø, and stored for 7 months at −20 °C. Before analyses, the fish were thawed in tanks containing 1000 L of chilled

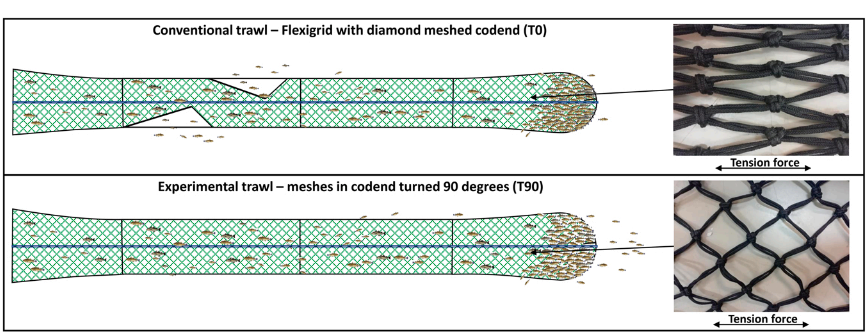

Fig. 1. Setup of the two trawl configurations: the conventional trawl configuration (flexigrid with diamond mesh codend) and the experimental trawl configuration (meshes in codend turned 90 degrees).

water (1 °C) for 24 h and then on ice in 70 L fish crates with the belly cavity facing downward for 48 h. Gentle handling of the fish was emphasized to minimize its influence on quality during processing and analyses. Immediately after thawing, the fish were individually tagged, and length and weight (headed and gutted) were recorded.

2.3. Catch-related damage

Catch-related damage was assessed by two trained experts using the catch-damage-index (CDI) developed by Esaiassen et al. (2013). To avoid any potential bias, the evaluators performed the assessment as a blinded experiment, and the order of the two codends was randomly alternated. The original CDI includes eight different types of catch-related damage: dead in gear, gear-related damage, bruises, gaffing damage, poorly bled, skin abrasion, pressure injuries, and biting injuries (Esaiassen et al., 2013). We omitted dead in gear, gaffing damage, and biting injuries in this study because they are not common in trawl-caught fish. Fish were examined and given a score for each type of damage according to its severity: 0 (flawless), 1 (moderate), or 2 (severe) (Table 1).

2.4. Residual blood measurement by hyperspectral imaging

The muscle residual blood level of each fish was evaluated by hyperspectral imaging using an interactance setup (Sivertsen et al., 2012) in the wavelength range of 400–1000 nm. The hyperspectral camera was a HySpex Baldur V-1024 N (Oslo, Norway), and the illumination consisted of two narrow lines of focused light. The camera's field of view was set in the middle between the light lines such that the signal recorded was mainly due to the light that had travelled some distance into the sample. This setup allows one to measure the properties of fish muscle through the skin.

The blood content in the muscle was analysed using constrained spectral unmixing as described in Skjelvareid et al. (2017). The muscle blood abundances were evaluated for headed and gutted cod. Both sides (left and right) from each fish were subjected to analysis. All image processing was performed using Prediktera's Breeze software (https://prediktera.com/).

2.5. Data analysis

The CDI data were analysed using the method described in Brinkhof et al. (2018a, 2021), using the analysis tool SELNET (Herrmann et al., 2012). The method estimates the probability of obtaining a given score for a given catch damage type as well as the probability of obtaining a given combination of catch damage types. The method also estimates the probability of not exceeding a given score (i.e., the probability of obtaining a given score or lower). The catch damage data were first analysed for each codend separately, and then the potential difference between the two codends was inferred using the method presented and described in Brinkhof et al. (2021). The method described by Brinkhof et al. (2018a, 2021) takes into account both within- and between-haul variation by applying a double bootstrap methodology. The method also includes estimation of uncertainties in the form of 95% CIs (Efron, 1982). It enabled a direct comparison of catch quality between cod caught by the conventional configuration and the T90-codend, which also included the effect size.

The residual blood level data were analysed using R version 4.0.0 (The R Project for Statistical Computing, 2020). Two residual blood values were measured per fish (left and right side). The average residual blood levels (blood abundances) in the left and right sides of each fish were averaged and used as the response variable, while the type of trawl configuration (codend) was used as the predictor variable. In R notation:

$$\textit{Blood abundancy} \sim \textit{Codend} \quad (1)$$

The tilde in expression 1 signifies that the residual blood level (blood abundance) is modelled as a function of the type of trawl configuration (codend type).

Neither catch size nor towing time correlated with the residual blood level, so they were not included as covariates in the model. Analysis of variance (ANOVA) at the 95% CI was applied to this model to test whether the type of trawl configuration affected the residual blood level in the muscle after capture. Model diagnostics were checked to make sure that the ANOVA requirements (homogeneity of variance, normally distributed residuals) were satisfied.

3. Results

We conducted 20 hauls consisting of 10 hauls with the conventional configuration and 10 hauls with the T90-codend (Table 2). From each haul, 30 cod were randomly sampled from the codend, resulting in 600 cod that were evaluated for catch-related damage and residual blood levels. Mean fish weight in the conventional configuration was 2676 ± 783 g (mean ± SD), fish length 68 ± 7 cm (mean ± SD). For the T90-configuration the mean fish weight was 2485 ± 675 g (mean ± SD), and fish length: 67 ± 7 cm (mean ± SD). Table 2 presents the towing time and estimated catch size of each haul.

3.1. Catch-related damage to cod captured by the conventional configuration

Fig. 2 shows catch damage frequency scores for cod caught by the

Table 1
The catch damage index used to evaluate damage to the cod included in the study.

Catch damage	Score			Description
	Flawless	Moderate	Severe	
Poorly bled	0	1	2	Improper bleeding
Bruises	0	1	2	Bruises and discolouration on the skin
Gear marks	0	1	2	Marks on the skin caused by gear contact
Pressure injuries	0	1	2	Injuries caused by crushing
Skin abrasion	0	1	2	Loss of scales

Table 2
Overview of the hauls showing trawl configuration type, towing time, depth, and catch size.

Haul no.	Trawl configuration	Towing time (min)	Depth (m)	Catch size (kg)
1	Conventional	62	295	2960
2	Conventional	41	296	1369
3	Conventional	59	290	1391
4	Conventional	29	293	1806
5	Conventional	20	291	1437
6	Conventional	40	288	[a]
7	Conventional	44	295	1869
8	Conventional	42	295	2273
9	Conventional	30	292	2974
10	Conventional	30	297	1380
11	T90 without grid	53	285	2166
12	T90 without grid	45	286	1868
13	T90 without grid	25	282	4669
14	T90 without grid	15	292	5924
15	T90 without grid	18	290	1465
16	T90 without grid	40	288	836
17	T90 without grid	30	290	1680
18	T90 without grid	60	291	2512
19	T90 without grid	25	292	964
20	T90 without grid	33	292	1828

[a] 524 Missing value

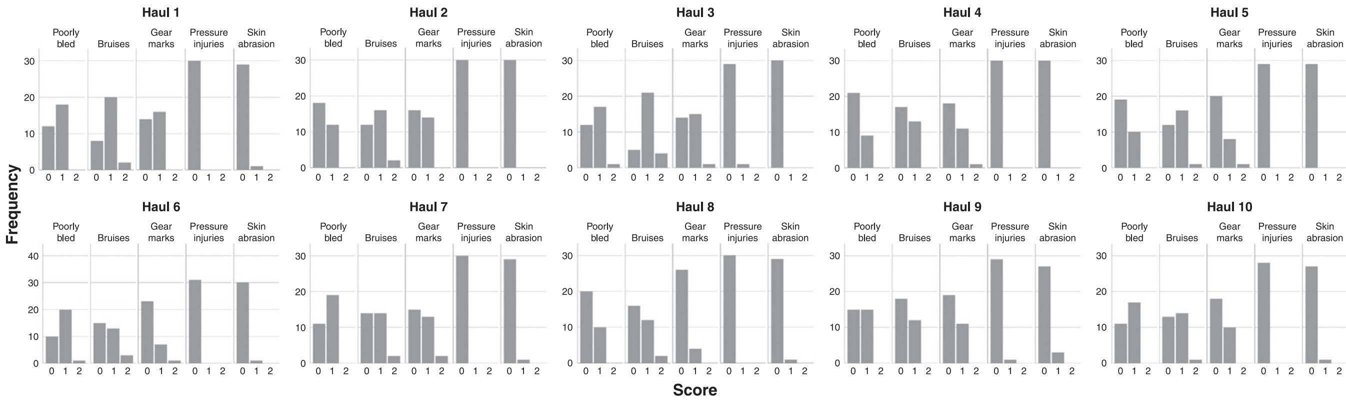

Fig. 2. Catch damage frequency scores for cod caught by the conventional configuration.

conventional configuration in each haul. The probability of obtaining fish with no damage (all categories combined, score = 0) was 23.4% (CI: 16.3–31.1%) (Table 3). Bruising was the type of damage that had the highest probability of being severe (score = 2), but the probability of obtaining fish with severe bruises was only 5.7% (CI: 2.7–9.1%). The probability of obtaining fish that were properly bled (score = 0) was 50.2% (CI: 40.1–%−60.3%), and the probability of obtaining fish that suffered from insufficient exsanguination (score = 2) was only 0.7% (CI: 0.0–2.0%). Pressure injuries and skin abrasion were the damage types that had the lowest probability of being severe (Table 3).

3.2. Catch-related damage to cod captured by the T90-codend

Catch damage frequency scores for cod caught by the T90-codend in each haul are shown in Fig. 3. The probability of obtaining fish with no damage (all categories combined, score = 0) was 21.2% (CI: 15.4–27.2%) (Table 4). Similar to cod caught using the conventional configuration, bruising was the damage type with the highest probability of being severe (score = 2). The probability of obtaining fish with severe bruising damage was 7.1% (CI: 3.8–10.8). The probability of obtaining fish that were properly bled (score = 0) was 49.8% (CI: 42.5–58.7%), and the probability of obtaining fish that suffered from insufficient exsanguination (score = 2) was 0.0% (CI: 0.0–0.0%). Also, like cod caught using the conventional configuration, pressure injuries and skin abrasion were the damage types with the lowest probability of being severe (Table 4).

3.3. Differences in catch-related damage between cod captured by the two gear types

Table 5 presents the difference in catch-related damage between cod caught using the conventional configuration and cod caught using the T90-codend in terms of the estimated probability of obtaining a given catch damage category and score. All differences were minor, and none was significant.

Table 3
Probability (with 95% CIs in brackets) of obtaining cod with different types and levels of catch damage (scores) when captured by the conventional configuration.

	0	1	2	≤ 1
All categories	23.41% (16.33–31.08%)	0.33% (0.00–1.67%)	0.33% (0.00–1.67%)	92.98% (88.59–96.66%)
Poorly bled	50.17% (40.13–60.27%)	48.83% (38.67–58.61%)	0.67% (0.00–2.01%)	99.00% (97.32–100.00%)
Bruises	43.48% (34.11–52.01%)	50.50% (42.67–58.67%)	5.69% (2.68–9.09%)	93.98% (90.33–97.00%)
Gear marks	61.20% (52.19–70.71%)	36.45% (27.24–45.67%)	2.01% (0.33–4.04%)	97.66% (95.30–99.66%)
Pressure injuries	99.00% (97.30–97.30%)	0.67% (0.00–2.03%)	0.00% (0.00–0.00%)	99.67% (98.33–100.00%)
Skin	96.99% (93.92–99.33%)	2.68% (0.66–5.65%)	0.00% (0.00–0.00%)	99.67% (98.33–100–00%)
Poorly & Bruises	27.76% (20.07–36.45%)	29.10% (21.55–36.7%)	0.33% (0.00–1.67%)	93.65% (89.30–97.32%)
Poorly & Gear	35.45% (26.76–45.15%)	22.07% (13.95–29.87%)	0.33% (0.00–1.68%)	97.32% (94.61–99.66%)
Poorly & Press	50.17% (41.00–60.34%)	0.67% (0.00–2.35%)	0.33% (0.00–1.67%)	99.33% (97.67–100.00%)
Poorly & Skin	50.17% (40.47–59.20%)	2.68% (0.66–5.65%)	0.33% (0.00–1.67%)	99.33% (97.99–100.00%)
Bruises & Gear	34.78% (25.83–44.48%)	25.08% (17.67–32.11%)	1.67% (0.00–3.72%)	93.65% (89.60–96.98%)
Bruises & Press	43.81% (34.23–52.82%)	1.00% (0.00–2.69%)	0.33% (0.00–1.36%)	94.31% (91.00–97.64%)
Bruises & Skin	43.14% (33.77–52.00%)	1.67% (0.00–3.99%)	0.33% (0.00–1.35%)	94.31% (90.67–97.65%)
Gear & Press	61.20% (51.51–71.14%)	0.67% (0.00–2.33%)	0.33% (0.00–1.35%)	97.99% (95.96–99.67%)
Gear & Skin	60.54% (52.01–70.17%)	1.67% (0.00–4.38%)	0.33% (0.00–1.67%)	97.99% (95.95–99.67%)
Press & Skin	96.66% (93.29–99.33%)	0.33% (0.00–1.68%)	0.33% (0.00–1.68%)	100.00% (100.00–100.00%)
Poorly, Bruises & Gear	23.75% (16.56–31.76%)	15.72% (9.90–21.89%)	0.33% (0.00–1.67%)	92.98% (88.12–96.98%)
Poorly, Bruises & Press	27.76% (20.00–35.91%)	0.67% (0.00–2.35%)	0.33% (0.00–1.68%)	93.65% (89.33–97.32%)
Poorly, Bruises & Skin	27.42% (19.60–35.91%)	1.67% (0.00–4.03%)	0.33% (0.00–1.67%)	93.65% (89.11–97.65%)
Poorly, Gear & Press	35.12% (26.00–44.33%)	0.67% (0.00–2.03%)	0.33% (0.00–1.35%)	97.32% (94.65–99.66%)
Poorly, Gear & Skin	35.12% (26.76–44.78%)	1.67% (0.00–4.35%)	0.33% (0.00–1.35%)	97.32% (94.65–99.33%)
Poorly, Press & Skin	49.83% (40.67–60.20%)	0.33% (0.00–1.68%)	0.33% (0.00–1.68%)	99.33% (97.67–100.00%)
Bruises, Gear & Press	34.78% (25.83–43.62%)	0.67% (0.00–2.03%)	0.33% (0.00–1.35%)	93.65% (89.33–96.99%)
Bruises, Gear & Skin	34.45% (25.58–43.33%)	1.34% (0.00–3.68%)	0.33% (0.00–1.36%)	93.65% (89.67–97.00%)
Bruises, Press & Skin	43.14% (34.00–52.33%)	0.33% (0.00–1.67%)	0.33% (0.00–1.67%)	94.31% (90.40–97.65%)
Gear, Press & Skin	60.20% (51.34–69.10%)	0.33% (0.00–1.68%)	0.33% (0.00–1.68%)	97.99% (95.70–99.67%)
Poorly, Bruises, Gear & Press	23.75% (16.33–30.98%)	0.67% (0.00–2.34%)	0.33% (0.00–1.68%)	92.98% (87.92–96.97%)
Poorly, Bruises, Gear & Skin	23.41% (16.28–31.31%)	1.34% (0.00–3.69%)	0.33% (0.00–1.35%)	92.98% (88.12–96.98%)
Poorly, Bruises, Press & Skin	27.42% (20.67–35.14%)	0.33% (0.00–1.67%)	0.33% (0.00–1.67%)	93.65% (89.70–97.33%)
Poorly, Gear, Press & Skin	34.78% (25.25–44.26%)	0.33% (0.00–1.68%)	0.33% (0.00–1.68%)	97.32% (94.70–99.33%)
Bruises, Gear, Press & Skin	34.45% (25.08–43.62%)	0.33% (0.00–1.36%)	0.33% (0.00–1.36%)	93.65% (89.97–96.67%)

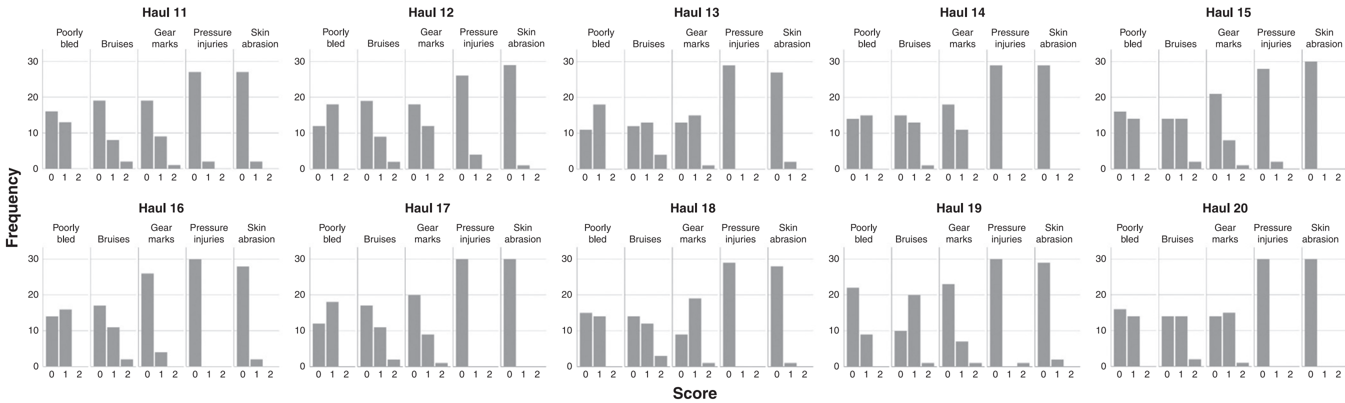

Fig. 3. Catch damage frequency scores for cod caught by the T90-codend without a sorting grid.

Table 4
Probability (with 95% CIs in brackets) of obtaining cod with different types and levels of catch damage (scores) when captured using the T90-codend.

	0	1	2	≤ 1
All categories	21.21% (15.44–27.15%)	0.00% (0–0.00%)	0.00% (0–0.00%)	90.91% (86.96–94.59%)
Poorly bled	49.83% (42.47–58.67%)	50.17% (41.33–57.53%)	0.00% (0–0.00%)	100.00% (100–100.00.00%)
Bruises	50.84% (42.28–58.98%)	42.09% (33.67–50.84%)	7.07% (3.77–10.81%)	92.93% (89.19–96.23%)
Gear marks	60.94% (49.15–71.48%)	36.70% (26.51–47.62%)	2.36% (0.67–4.42%)	97.64% (95.58–99.33%)
Pressure injuries	96.97% (93.33–99.66%)	2.69% (0.00–6.40%)	0.34% (0–1.67%)	99.66% (98.33–100.00%)
Skin abrasion	96.63% (93.67–98.99%)	3.37% (1.01–6.33%)	0.00% (0–0.00%)	100.00% (100–100.00%)
Poorly & Bruises	26.60% (20.67–33.00%)	20.88% (15.31–26.94%)	0.00% (0–0.00%)	92.93% (89.19–96.03%)
Poorly & Gear marks	34.68% (26.62–42.09%)	22.56% (15.56–30.98%)	0.00% (0–0.00%)	97.64% (95.58–99.33%)
Poorly & Press	48.82% (41.28–56.23%)	2.02% (0.00–4.73%)	0.00% (0–0.00%)	99.66% (98.33–100.00%)
Poorly & Skin	48.15% (40.2–55.63%)	1.68% (0.00–3.75%)	0.00% (0–0.00%)	100.00% (100–100.00%)
Bruises & Gear	36.36% (26.69–45.27%)	18.86% (13.47–24.75%)	0.67% (0–2.34%)	91.25% (87.16–94.63%)
Bruises & Press	49.83% (41.33–58.05%)	1.35% (0.00–3.37%)	0.00% (0–0.00%)	92.59% (88.93–95.64%)
Bruises & Skin	49.16% (41.41–56.61%)	1.68% (0.00–4.05%)	0.00% (0–0.00%)	92.93% (89.08–95.97%)
Gear & Press	60.61% (49.15–71.28%)	2.02% (0.00–5.03%)	0.00% (0–0.00%)	97.31% (94.92–99.32%)
Gear & Skin	58.59% (46.94–68.69%)	0.67% (0.00–2.04%)	0.00% (0–0.00%)	97.64% (95.58–99.33%)
Press & Skin	93.60% (89.15–97.97%)	0.00% (0.00–0.00%)	0.00% (0–0.00%)	99.66% (98.34–100.00%)
Poorly, Bruises & Gear	21.89% (16.27–27.80%)	10.77% (6.69–15.77%)	0.00% (0–0.00%)	91.25% (87.07–94.92%)
Poorly, Bruises & Press	25.93% (20.27–32.54%)	1.35% (0.00–3.39%)	0.00% (0–0.00%)	92.59% (89.15–95.96%)
Poorly, Bruises & Skin	25.59% (19.93–31.42%)	1.01% (0.00–3.38%)	0.00% (0–0.00%)	92.93% (89.19–95.97%)
Poorly, Gear & Press	34.68% (27.21–42.62%)	1.35% (0.00–4.03%)	0.00% (0–0.00%)	97.31% (94.65–99.32%)
Poorly, Gear & Skin	33.67% (25.85–41.22%)	0.34% (0.00–1.35%)	0.00% (0–0.00%)	97.64% (95.33–99.33%)
Poorly, Press & Skin	47.14% (39.53–55.15%)	0.00% (0.00–0.00%)	0.00% (0–0.00%)	99.66% (98.65–100.00%)
Bruises, Gear & Press	36.36% (27.00–44.97%)	1.01% (0.00–3.03%)	0.00% (0–0.00%)	90.91% (86.91–94.24%)
Bruises, Gear & Skin	35.02% (26.76–43.39%)	0.34% (0.00–1.35%)	0.00% (0–0.00%)	91.25% (87.07–94.63%)
Bruises, Press & Skin	48.15% (40.60–56.12%)	0.00% (0.00–0.00%)	0.00% (0–0.00%)	92.59% (88.89–95.64%)
Gear, Press & Skin	58.25% (46.76–68.46%)	0.00% (0.00–0.00%)	0.00% (0–0.00%)	97.31% (94.95–99.32%)
Poorly, Bruises, Gear & Press	21.89% (15.82–27.95%)	1.01% (0.00–3.06%)	0.00% (0–0.00%)	90.91% (86.82–94.58%)
Poorly, Bruises, Gear & Skin	21.21% (15.70–27.33%)	0.34% (0.00–1.67%)	0.00% (0–0.00%)	91.25% (87.12–94.65%)
Poorly, Bruises, Press & Skin	24.92% (19.46–30.41%)	0.00% (0.00–0.00%)	0.00% (0–0.00%)	92.59% (88.93–95.95%)
Poorly, Gear, Press & Skin	33.67% (25.68–41.06%)	0.00% (0.00–0.00%)	0.00% (0–0.00%)	97.31% (94.7–99.32%)
Bruises, Gear, Press & Skin	35.02% (26.44–43.88%)	0.00% (0.00–0.00%)	0.00% (0–0.00%)	90.91% (86.82–94.28%)

3.4. Residual blood levels

We did not detect any significant difference in the amount of residual blood between fish caught using the two different trawl configurations. The residual blood level did not correlate with either catch size or towing time (Fig. 4), which was also verified by the linear model.

When data from hauls 1–10 (conventional configuration) were merged and those from hauls 11–20 (T90-codend) were merged, the average blood abundance (in arbitrary unit) with 95% CIs for all hauls for each codend were 0.86 (CI: 0.85–0.87) and 0.88 (CI: 0.87–0.88), respectively. Fig. 5 shows the overall average blood abundance for cod caught by each gear when the hauls from each trawl configuration were merged.

4. Discussion

It is difficult to improve catch quality if damage occurs during the catching process. Hence, preventing the deterioration of the catch during the capture process is of utmost importance for improving the quality of trawl-caught cod. Brinkhof et al.,2022 demonstrated that the trawl configuration with the T90-codend improved the release of juvenile fish. Thus, the goal in this study was to determine whether this configuration could compromise catch quality. Our results demonstrate that cod caught by the T90-codend had the same amount and severity of catch-related damage as cod caught by the conventional trawl configuration. Our results also show that there was no significant difference in residual blood levels between cod caught with the two different trawl configurations.

Digre et al. (2010) investigated the effect of a partial T90-codend on the catch quality of cod and haddock (*Melanogrammus aeglefinus*). However, their experimental trawl setup included a sorting grid and diamond knotless meshes in the last four meters of the codend. These additions make it difficult to document the potential effect of the T90-codend on catch quality specifically.

Table 5
Differences in probability for different types and levels of catch damage (scores) between cod captured by the conventional configuration and cod captured by the experimental T90-codend.

	0	1	2	≤ 1
All categories	− 2.20% (−11.04 to 7.81%)	− 0.33% (−1.67 to 0.00%)	− 0.33% (−1.67 to 0.00%)	− 2.07% (−7.66 to 3.3%)
Poorly bled	−0.34% (−12.50 to 13.03%)	1.34% (−11.75 to 13.52%)	− 0.67% (−2.01 to 0.00%)	1.00% (0.00–2.68%)
Bruises	7.36% (−4.93 to 20.67%)	− 8.41% (−20.64 to 3.61%)	1.39% (−3.00 to 6.24%)	− 1.05% (−5.78 to 3.57%)
Gear marks	− 0.26% (−15.4 to 13.11%)	0.25% (−12.62 to 15.05%)	0.35% (−2.62 to 3.07%)	− 0.02% (−2.77 to 2.96%)
Pressure injuries	− 2.03% (−5.75 to 1.34%)	2.02% (−1.00 to 5.74%)	0.34% (0.00–1.67%)	0.00% (−1.34 to 1.35%)
Skin abrasion	− 0.36% (−4.00 to 3.67%)	0.69% (−3.00 to 4.37%)	0.00% (0.00–0.00.00%)	0.33% (0.00–1.67%)
Poorly & Bruises	− 1.16% (−11.23 to 8.61%)	− 8.22% (−17.84 to 1.49%)	− 0.33% (−1.67 to 0.00%)	− 0.72% (−5.81 to 4.75%)
Poorly & Gear	− 0.77% (−13.62 to 10.35%)	0.49% (−9.77 to 11.76%)	− 0.33% (−1.68 to 0.00%)	0.32% (−3.00 to 3.66%)
Poorly & Press	− 1.35% (−13.65 to 10.18%)	1.35% (−1.35 to 4.38%)	− 0.33% (−1.67 to 0.00%)	0.33% (−1.33 to 1.99%)
Poorly & Skin	− 2.02% (−14.3 to 11.17%)	− 0.99% (−4.67 to 2.03%)	− 0.33% (−1.67 to 0.00%)	0.67% (0.00–2.01%)
Bruises & Gear	1.58% (−12.06 to 14.26%)	− 6.23% (−15.27 to 3.17%)	− 1.00% (−3.38 to 1.34%)	− 2.40% (−7.89 to 3.15%)
Bruises & Press	6.02% (−5.92 to 18.30%)	0.34% (−2.01 to 2.68%)	− 0.33% (−1.36 to 0.00%)	− 1.72% (−6.81 to 2.89%)
Bruises & Skin	6.01% (−6.21 to 17.91%)	0.01% (−3.01 to 3.03%)	− 0.33% (−1.35 to 0.00%)	− 1.39% (−6.45 to 3.49%)
Gear & Press	− 0.60% (−16.61 to 13.26%)	1.35% (−1.34 to 4.67%)	− 0.33% (−1.35 to 0.00%)	− 0.69% (−3.74 to 2.29%)
Gear & Skin	− 1.95% (−16.50 to 10.73%)	− 1.00% (−4.02 to 1.32%)	− 0.33% (−1.67 to 0.00%)	− 0.35% (−3.34 to 2.32%)
Press & Skin	− 3.05% (−8.15 to 2.68%)	− 0.33% (−1.68 to 0.00%)	− 0.33% (−1.68 to 0.00%)	− 0.34% (−1.66 to 0.00%)
Poorly, Bruises & Gear	− 1.86% (−11.57 to 7.07%)	− 4.94% (−12.78 to 2.65%)	− 0.33% (−1.67 to 0.00%)	− 1.73% (−7.41 to 4.03%)
Poorly, Bruises & Pressure	− 1.83% (−12.26 to 8.26%)	0.68% (−1.67 to 3.04%)	− 0.33% (−1.68 to 0.00%)	− 1.05% (−6.06 to 4.49%)
Poorly, Bruises & Skin	− 1.84% (−12.74 to 8.39%)	− 0.66% (−3.34 to 2.04%)	− 0.33% (−1.67 to 0.00%)	− 0.72% (−6.23 to 4.87%)
Poorly, Gear & Press	− 0.44% (−12.57 to 11.02%)	0.68% (−1.67 to 3.42%)	− 0.33% (−1.35 to 0.00%)	− 0.02% (−3.36 to 3.32%)
Poorly, Gear & Skin	− 1.45% (−13.51 to 10.07%)	− 1.34% (−4.05 to 0.67%)	− 0.33% (−1.35 to 0.00%)	0.32% (−2.73 to 3.34%)
Poorly, Press & Skin	− 2.69% (−15.62 to 8.88%)	− 0.33% (−1.68 to 0.00%)	− 0.33% (−1.68 to 0.00%)	0.33% (−1.33 to 2.01%)
Bruises, Gear & Press	1.58% (−11.05 to 13.47%)	0.34% (−1.67 to 2.69%)	− 0.33% (−1.35 to 0.00%)	− 2.74% (−8.08 to 2.58%)
Bruises, Gear marks & Skin	0.57% (−12.08 to 13.59%)	− 1.00% (−3.36 to 0.68%)	− 0.33% (−1.36 to 0.00%)	− 2.40% (−7.76 to 2.87%)
Bruises, Press & Skin	5.00% (−7.07 to 16.84%)	− 0.33% (−1.67 to 0.00%)	− 0.33% (−1.67 to 0.00%)	− 1.72% (−6.84 to 2.61%)
Gear, Press & Skin	− 1.95% (−17.37 to 12.04%)	− 0.33% (−1.68 to 0.00%)	− 0.33% (−1.68 to 0.00%)	− 0.69% (−3.35 to 2.33%)
Poorly, Bruises, Gear & Press	− 1.86% (−11.45 to 7.77%)	0.34% (−1.68 to 2.70%)	− 0.33% (−1.68 to 0.00%)	− 2.07% (−7.60 to 4.36%)
Poorly, Bruises, Gear & Skin	− 2.20% (−11.74 to 7.77%)	− 1.00% (−3.38 to 0.67%)	− 0.33% (−1.35 to 0.00%)	− 1.73% (−7.73 to 40%)
Poorly, Bruises, Press & Skin	− 2.51% (−12.13 to 6.53%)	− 0.33% (−1.67 to 0.00%)	− 0.33% (−1.67 to 0.00%)	− 1.05% (−6.71 to 4.25%)
Poorly, Gear, Press & Skin	− 1.11% (−13.22 to 10.83%)	− 0.33% (−1.68 to 0.00%)	− 0.33% (−1.68 to 0.00%)	− 0.02% (−3.68 to 3.29%)
Bruises, Gear, Press & Skin	0.57% (−11.37 to 13.22%)	− 0.33% (−1.36 to 0.00%)	− 0.33% (−1.36 to 0.00%)	− 2.74% (−8.48 to 2.68%)

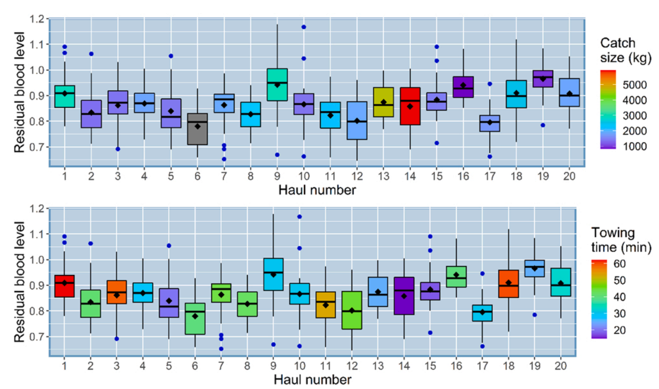

Fig. 4. Box plots showing blood abundance (in arbitrary unit) in the cod in the different hauls, coloured according to catch size and towing time. The conventional configuration was used for hauls 1–10, and the T90-codend was used for hauls 11–20. The catch size was not recorded for haul number 6, hence the box is coloured grey.

Several studies conducted in recent years have quantified the level of gear-inflicted damage on fish in the Barents Sea bottom trawl fishery, and all of them used the same conventional trawl rigging and analysis method used in our study (Brinkhof et al., 2018a, 2018b, 2021; Sistiaga et al., 2020; Tveit et al., 2019). Brinkhof et al. (2018a), (2021) reported that cod caught by the conventional trawl configuration had a probability of obtaining no catch damage of 21% (CI: 9–33%) and 5.38% (CI: 2.6–8.7%), respectively.

Previous studies of how to improve the catch quality of trawl-caught cod have focused on the trawl configurations (e.g., the codend). Tveit et al. (2019) investigated the effect of substituting conventional knotted codends with knotless netting, and they further tested the effect of changing the codend construction from a 2-panel to a 4-panel codend. They found that the probability of obtaining fish with no catch damage was 9.4% (4.7–15.8%) for the 2-panel knotted codend, 11.6% (5.9–18.6%) for the 2-panel knotless codend, and 11.3% (6.7–17.4%) for the 4-panel knotless codend. However, those codend designs did not significantly decrease the catch damage compared to the conventional

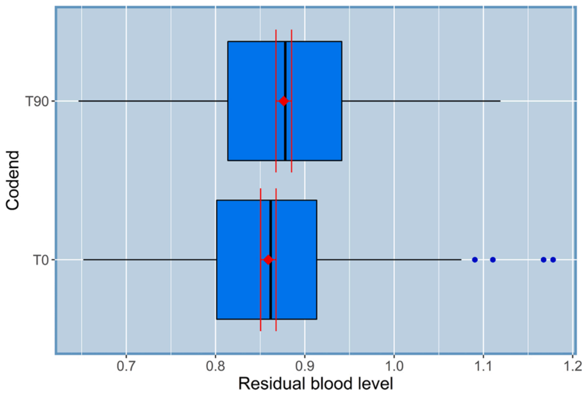

Fig. 5. Overall average blood abundance (in arb. unit) for cod caught with the T0 and T90 trawl configurations. The red diamond marks the mean and the vertical red lines shows the 95% CIs for the mean. The length of the whiskers was set to a maximum of 1.5 times the interquartile range.

trawl configuration. Brinkhof et al. (2021) recently tested whether removing the compulsory sorting grid and replacing the conventional codend with a dual sequential codend with expected quality-improving properties could reduce catch damage to trawl-caught cod. For cod captured with the dual sequential codend without the sorting grid, the probability of capturing cod with no damage was reported to be 11.4% (CI: 7.2–16.1%). Furthermore, Brinkhof et al. (2021) demonstrated that the quality-improving codend configuration without the sorting grid significantly improved the catch quality of cod by 6.0% (CI: 0.6–11.4%) compared to the conventional trawl configuration with a sorting grid and regular codend.

When discussing the catch quality in the Barents Sea bottom trawl fishery, it is important to keep in mind that catch quality is influenced by a number of factors, such as natural variations (season, weather, catch location, stock, size of fish), catching procedure (towing time, catch size), and trawl gear design. For instance, previous studies reported reduction in fish quality with increasing catch size and towing time (Digre et al., 2017; Margeirsson et al., 2007; Olsen et al., 2013; Rotabakk et al., 2011). This is also important to keep in mind when comparing the catch damage for cod caught by the conventional configuration and the T90-codend. Changing from a conventional configuration to a T90-codend without a sorting grid was estimated to decrease the probability of obtaining cod with no damage by 2.2% (CI: –11.0–7.8%). However, this decrease was not statistically significant. Several factors other than mesh direction in the codend may affect fish quality in a bottom trawl fishery, including twine thickness and stiffness in the codend panels, knotted or knotless netting, type of net material, circumference and length of the codend, and amount of fish captured. During trials on board our research vessel, we mimicked the commercial trawl fishery in many ways, but we could not exceed hauls > 4–5 tons of fish. This is a limitation of our study, as commercial trawlers in the Barents Sea can catch > 10 tons of fish in each haul.

Residual blood in fish also influences fish quality (Botta et al., 1987; Digre et al., 2017; Esaiassen et al., 2004; Margeirsson et al., 2007; Olsen et al., 2013, 2014; Svalheim et al., 2019, 2020). Fillet colour is an important quality parameter for whitefish. Thus, capture-induced internal damage (bruises and red discolouration) was measured as residual blood level in headed and gutted cod. We did not find significant differences between cod caught by the conventional configuration compared to the T90-codend in terms of residual blood. Thus, our objective hyperspectral imaging estimates of the residual blood in the fish agree with our subjective external catch-related damage index results.

The catch damage evaluation is subjective, whereas the residual blood level measurements are objective. The two methods yielded the same statistical results, which strengthens our premise that the catch quality did not differ between cod caught by the two different trawl configurations. Furthermore, the "poorly bled" catch damage category results provided by experienced personnel corresponded with the results of the hyperspectral imaging assessment of residual blood.

This study demonstrates that the T90-codend does not compromise catch quality compared to the conventional trawl configuration in terms of catch-related damage and amount of residual blood. Because the T90-codend does not alter the catch quality of trawl-caught cod and improves size selection (Brinkhof et al., 2021, in prep), the use of the T90-codend without a sorting grid could be beneficial for the trawl industry, as this codend design is much easier to handle. However, while we found that the T90-codend did not negatively affect catch quality, it did not improve catch quality. Therefore, new strategies for improving quality and minimizing catch damage to fish during the trawling process need to be developed.

CRediT authorship contribution statement

Tonje K. Jensen: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Writing – review & editing. **Jesse Brinkhof:** Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Writing – review & editing. **Stein-Kato Lindberg:** Formal analysis, Writing – review & editing. **Torbjørn Tobiassen:** Conceptualization, Methodology, Investigation, Writing – review & editing. **Karsten Heia:** Conceptualization, Methodology, Software, Investigation, Writing – review & editing. **Stein Harris Olsen:** Investigation, Writing – review & editing. **Roger B. Larsen:** Conceptualization, Methodology, Investigation, Writing – review & editing. **Margrethe Esaiassen:** Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

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

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