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Assessing the impact of buffer towing on the quality of Northeast Atlantic cod (*Gadus morhua*) caught with a bottom trawl

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Abstract

The dense aggregations of Northeast Atlantic cod (*Gadus morhua*) in the Barents Sea have led to a new fishing practice termed "buffer towing." In this fishery, many trawlers redeploy the trawl directly after taking the catch onboard in an attempt to secure a continuous supply of fish and avoid any unnecessary stops during processing. If the approximate desired amount of fish is caught or exceeded before the catch from the previous haul is processed, the trawl is lifted off the seabed and towed at a given depth at low speed, usually ~1–2 knots, until the production capacity of the onboard factory is restored. Both researchers and fishermen onboard trawlers believe that buffer towing has a negative impact on fish quality, as indicated by increased frequency of gear marks and dead fish, poorer exsanguination, ecchymosis, skin abrasion, fillet gaping, and fillet redness. However, the effect that buffer towing has on fish quality has not been scientifically evaluated. The aim of this study was to document the effects of buffer towing on fish quality. The quality was assessed using two different indexes, one for whole cod and one for cod fillets. The results proved that buffer towing has a negative impact on fish quality. Specifically, cod subjected to buffer towing, in contrast to direct haul-back, had an increased relative probability of 371% for poor exsanguination and an increased relative probability of 209% for fillet redness. Furthermore, combining scores of the different quality categories within the indexes (e.g., gear marks, ecchymosis, poor exsanguination, and skin abrasion) proved a significant reduction in the quality of cod subjected to buffer towing.

Keywords: Buffer towing; cod; fish quality; bottom trawl

1. Introduction

The current stock of Northeast Atlantic cod (*Gadus morhua*) is the largest cod stock in the world, and it is the most important fishery in the Barents Sea (Yaragina et al., 2011). About

70% of the annual Northeast Atlantic cod quota is caught with bottom trawls (ICES, 2015). The high abundances and dense aggregations of cod frequently lead to large catches (20–30 metric tons) during short towing times (10–20 min). Although the use of catch sensors can provide an estimate of the approximate amount of catch in the codend, the time from haul-back initiation to when the trawl physically is lifted off the seabed takes several minutes, and during this time fish are continuously herded into the trawl mouth. In addition, large numbers of fish can already be inside the front part of the trawl when the catch sensors on the codend are activated. During periods of high fish entry rates, trawlers have reported problems with fish blocking the grid section, and thus entering the codend too slowly for effective catch control (Grimaldo et al., 2014). The grid section, which purpose is to release undersized fish, comprise of a grid with 55 mm bars spacing, according to the legislations (Sistiaga et al., 2016).

These high and dense abundances of cod in the Barents Sea have led to a widespread practice among Norwegian trawlers called “buffer towing,” which is believed to negatively affect the quality of the catch (Norwegian Directorate of Fisheries, 2013; Brinkhof et al., 2017a). Buffer towing is also known as “short-wiring” in the Alaska pollock trawl fishery (Dietrich and Melvin, 2007). In this fishery, many trawlers choose to redeploy the trawl directly after taking the catch onboard in order to secure a continuous supply of fish and avoid unnecessary stops during processing in the factory. However, the approximate desired amount of fish is often caught before the catch from the previous haul has been processed. To avoid excessively large catches, the trawl is lifted from the seabed and towed at a given depth at low speed, usually ~1–2 knots, until the production capacity onboard is restored (Fig. 1). However, both researchers and fishermen onboard trawlers claim that this practice has a negative impact on the quality of the catch in the form of increased presence of gear marks and dead fish, poorer exsanguination, ecchymosis, skin abrasion, fillet gaping, and fillet redness. Previous studies have documented a significant reduction in fish quality with increasing towing time (Olsen et al., 2013), exhaustive swimming (Svalheim et al., 2017), and catch size and crowding (Suuronen et al., 2005; Margeirsson et al., 2007; Olsen et al., 2008; Rotabakk et al., 2011; Digre et al., 2017). All of these factors are present during buffer towing. Because cod have a physoclist swim bladder, the rapid decompression that occurs when lifting the trawl off the seabed causes the swim bladder to expand and eventually burst when the reduction in ambient water pressure exceeds ~70% of the original depth (Midling et al., 2012; Humborstad and

Mangor-Jensen, 2013). Thus, the depth at which the trawl is positioned during buffer towing could be of major importance for the final quality of the fish.

FIG. 1

From an industry point of view, poor fish quality results in reduced price and thus reduced revenue. It also limits the ability to use the fish in various products. From a management point of view, poor fish quality is believed to increase the risk of illegal dumping and high-grading (Batsleer et al., 2015), subsequently contributing to mortality that is not accounted for in catch records. Hence, poor fish quality is not in accordance with sustainable resource exploitation. Furthermore, Brinkhof et al. (2017a) reported a high escape rate of cod up to at least 42 cm long from the codend during buffer towing. The survival rate of these escaping cod is unknown, but it is likely lower than the survival rates reported for cod escaping at the seabed (Soldal et al., 1993; Suuronen et al., 1995; Ingólfsson et al., 2007) due to barotrauma related injuries, elevated stress, suffocation, and subsequent increased risk of predation or disease susceptibility (DeAlteris and Reifsteck, 1993; Chopin and Arimoto, 1995; Davis, 2002; Ryer et al., 2004; Humborstad and Mangor-Jensen, 2013; Brinkhof et al., 2017a; Rankin et al., 2017).

This study was conducted to assess the impact of buffer towing on fish quality by investigating the following research questions:

- Is there any difference in quality of whole fish from buffer towed hauls and hauls that are taken directly onboard?
- Is there any difference in fillet quality of fish from buffer towed hauls and hauls that are taken directly onboard?

2. Materials and methods

2.1 Study area and trawl configuration

The fishing trials were conducted during November 2016 onboard the R/V "Helmer Hanssen" (63.8 m, 4080 HP) in the central part of the Barents Sea (N 74°59'–N 75°26'; E 30°54'–E31°17'). The configuration of the trawl was similar to the setup used in commercial fisheries. A set of Injector otter boards for bottom trawl (3100 kg and 8 m^2) with backstraps were followed by 60 m long sweeps that were 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 on both sides of a 14 m long chain equipped with three steel bobbins (Ø53 cm) and an 18.9 m long rock-hopper gear in the center composed of Ø53 cm rubber discs. The trawl used was a two-panel Alfredo 3 fish trawl built from polyethylene with a 150 mm nominal mesh size. A size sorting grid with a 55 mm bar spacing was inserted between the codend and the trawl belly, which is compulsory in the trawl fishery in the Northeast Atlantic (Sistiaga et al., 2016). A four-panel codend (mesh size 132.1 ± 2.6 mm (mean ± standard deviation)) with a 2- to 4-transition section was mounted after the grid section.

Catch size is known to affect fish quality. To reduce the variation in catch size between hauls, the amount of fish allowed in the codend was set to approximately 2 metric tons. This was achieved by inserting an excessive fish excluder device (i.e., a release mechanism in the anterior part of the codend) (Grimaldo et al., 2014; Brinkhof et al., 2017a). The excessive fish excluder device comprise of a fish lock with two escape openings in the front. When the codend is filled up to the fish lock, all excessive fish will be released through the escape openings in front of the fish lock (Grimaldo et al., 2014; Brinkhof et al., 2017a).

The trawl was monitored with a set of door sensors, a height sensor, and a catch sensor from Scanmar. In addition, a Scanmar trawl eye was used to control the buffer towing depth.

2.2 Data sampling

Directly after taking the catch onboard, 30 cod were randomly sampled from the codend. These fish were immediately killed and exsanguinated in running seawater (ca. 50 l/min) for 30 min. Afterwards the water was drained from the tank and the fish were gutted and decapitated before being frozen at –30 °C for further analysis on land. On land, the fish were thawed in tanks containing 1000 l of chilled water (1 °C) for 24 h and then further thawed on ice for an additional 24 h at 0–1 °C. Once the fish were thawed, they were evaluated for catch-related defects incurred during the catching process using a catch damage index (Table 1) (Rotabakk et al., 2011; Esaiassen et al., 2013; Olsen et al., 2013). The fish were then filleted manually and the black lining (peritoneum) was removed to enable evaluation of the belly flap. Both fillets from each fish were assessed for defects using a fillet index (Table 2) (Olsen et al., 2013, 2014; Svalheim et al., 2017). The assessment fish quality applying the two indexes were done consecutively, i.e. the samples are not traceable between the two indexes. In addition to the fillet index, the number of severe bleedings in the posterior dorsal side muscle of the abdominal cavity caused by the rupture of the swim bladder during the ascent was counted. The assessment of catch damage and fillet quality was performed as a blinded experiment, i.e. the evaluators were unaware if the fish came from a regular tow or a buffer tow. The evaluation was conducted by four persons that were professionally trained to assess catch damage and fillet index.

TABLE 1

TABLE 2

2.3 Data analysis

We wanted to determine if there was any difference in the probability between the hauls with and without buffer towing for cod to obtain a specific catch damage score and fillet quality score. For each index the score on a specific category was either 0, 1, 2, or 3 (Tables 1 and 2). A high score indicates severe damage (i.e., low fish quality). Analyses of the obtained scores from the catch damage index and fillet index were carried out separately, following the procedure described below.

For buffer towing and regular towing (i.e., direct haul-back) separately, the expected average value $\widehat{p_{as}}$ for the probability for the score *s* on category *a* is:

$$\widehat{p_{as}} = \frac{\sum_{j=1}^{m}\left\{\frac{1}{n_j}\sum_{t=1}^{n_j} equal(s, k_{ajt})\right\}}{m} \quad (1)$$
$$with$$
$$equal(s,k) = \begin{cases} 1 \ \forall \ k = s \\ 0 \ \forall \ k \neq s \end{cases}$$

where *m* is the number of hauls conducted with either buffer towing or regular towing with direct haul-back; n_j is the number of fish given a score in haul *j*; k_{ajt} is the score given in category *a* to fish or fillet number *t* evaluated in haul *j*.

Equation (1) was used to estimate the probability of obtaining a given score *s* in category *a* according to the catch damage index and the fillet index for the two different towing types separately. We also estimated the probability $\widehat{pm_{as}}$ for obtaining a score that did not exceed *s* on category *a* (i.e., the probability of obtaining a given score or lower):

$$\widehat{pm_{as}} = \frac{\sum_{j=1}^{m}\left\{\frac{1}{n_j}\sum_{t=1}^{n_j} lequal(s, k_{ajt})\right\}}{m} \quad (2)$$
$$with$$
$$lequal(s,k) = \begin{cases} 1 \ \forall \ k \leq s \\ 0 \ \forall \ k > s \end{cases}$$

Equations (1) and (2) provide an evaluation of each category separately. However, we also investigated the probability for a fish to score s or maximum s on two or more of the categories simultaneously. To estimate such probabilities we extended (1) and (2) as follows:

$$\widehat{p_{as}p_{bs}} = \frac{\sum_{j=1}^{m}\left\{\frac{1}{n_j}\sum_{t=1}^{n_j} equal(s,k_{ajt})\times equal(s,k_{bjt})\right\}}{m}$$
$$p_{as}\widehat{p_{bs}}p_{cs} = \frac{\sum_{j=1}^{m}\left\{\frac{1}{n_j}\sum_{t=1}^{n_j} equal(s,k_{ajt})\times equal(s,k_{bjt})\times equal(s,k_{cjt})\right\}}{m} \quad (3)$$
$$p_{as}p_{bs}\widehat{p_{cs}}p_{ds} = \frac{\sum_{j=1}^{m}\left\{\frac{1}{n_j}\sum_{t=1}^{n_j} equal(s,k_{ajt})\times equal(s,k_{bjt})\times equal(s,k_{cjt})\times equal(s,k_{djt})\right\}}{m}$$

and

$$\widehat{pm_{as}pm_{bs}} = \frac{\sum_{j=1}^{m}\left\{\frac{1}{n_j}\sum_{t=1}^{n_j} lequal(s,k_{ajt})\times lequal(s,k_{bjt})\right\}}{m}$$
$$pm_{as}\widehat{pm_{bs}}pm_{cs} = \frac{\sum_{j=1}^{m}\left\{\frac{1}{n_j}\sum_{t=1}^{n_j} lequal(s,k_{ajt})\times lequal(s,k_{bjt})\times lequal(s,k_{cjt})\right\}}{m} \quad (4)$$
$$pm_{as}pm_{bs}\widehat{pm_{cs}}pm_{ds} = \frac{\sum_{j=1}^{m}\left\{\frac{1}{n_j}\sum_{t=1}^{n_j} lequal(s,k_{ajt})\times lequal(s,k_{bjt})\times lequal(s,k_{cjt})\times lequal(s,k_{djt})\right\}}{m}$$

Equations (3) and (4) were applied for all possible combinations of the categories.

Estimation of the uncertainties in the expected values for the probability parameters calculated based on (1)-(4) required consideration of several aspects: i) the average score may vary between hauls with the same type of fishing process (regular or buffer tow) due to uncontrolled effects in the fishing process; ii) the average score for the individual hauls is subjected to within-haul variability because a limited sample of fish is evaluated in each haul; iii) there may be correlation between the probability for the scores between categories, which complicates the estimations of uncertainties for the combined probabilities (3) and (4).

To account correctly for these uncertainties in the estimations, a double bootstrap method was adapted that is well established for evaluating fishing gear selectivity and catch efficiency for trawl fisheries that are known to be subjected to a similar structure of uncertainty (Wienbeck et al., 2014; Brinkhof et al., 2017ab). The procedure accounted for between-haul variation in the obtained scores by selecting *m* hauls with replacement from the pool of hauls of the specific haul type (i.e., regular or buffer tow) during each bootstrap repetition. Within-haul uncertainty in the obtained scores was accounted for by randomly selecting fish or fillets with replacement from the selected haul. The number of fish or fillets selected from each haul was the same as the number of fish or fillets evaluated for that haul (n_j). The resulting data for each bootstrap were then used to estimate the expected category probabilities based on equations (1)-(4). We performed 1000 bootstrap repetitions and calculated the Efron 95% percentile confidence limits (Efron, 1982) for the estimated probabilities.

The difference in fish quality between regular hauls with direct haul-back and those with buffer towing could in principle be inferred by pairwise comparison of 95% confidence intervals (CIs) for the category probabilities (1)-(4) that are estimated for the two types of towing separately. In cases for which the CIs did not overlap it could be concluded that buffer towing would have a significant effect on the parameter(s) compared. However, we also can consider the situation as a two-sample problem (Moore et al., 2003) with two independent samples, for which the results for the regular hauls represent one of the samples and the results for the buffer towing hauls the other. Based on this we can use the 1000 bootstrap results for an arbitrary parameter r (one based on (1) to (4)) for regular hauling r_{base} and buffer towing r_{buffer} to obtain a bootstrap population with 1000 results for the difference:

$$\Delta r_i = r_{buffer_i} - r_{base_i} \quad i \in [1 \dots 1000] \quad (5)$$

where i denotes the bootstrap repetition index. Because sampling was random and independent for the two groups of results (regular and buffer tows), it is valid to generate the bootstrap population of results for the difference based on (5) using the two independent generated bootstrap files (Moore et al., 2003). Based on the bootstrap population we can obtain Efron 95% percentile confidence limits for Δr as described above. If the CI for Δr does not contain 0.0, we can conclude that buffer towing has a significant effect on the value of parameter r. In general, the CI for Δr cannot exceed what is spanned by r_{base} and r_{buffer} together and will often be smaller (Moore et al., 2003). Therefore, using this approach will increase the power of inference of the effect of buffer towing compared to the simple strategy based on the search for non-overlapping CIs for the separate parameter values. Following the strategy for Δr we can also obtain a bootstrap population for the relative percentage effect of buffer towing by:

$$relr_i = \frac{r_{buffer_i} - r_{base_i}}{r_{base_i}} \times 100 \quad i \in [1 \dots 1000] \qquad (6)$$

We used (6) to obtain Efron 95% percentile confidence limits for the relative differences in the parameter values between regular towing and buffer towing.

The estimation procedures described above were implemented in the analysis tool SELNET (Herrmann et al., 2012). The results were exported for graphical presentation in R (R Core Team, 2013).

3. Results

During the cruise 20 hauls were conducted alternating between regular haul-back and buffer towing (Table 3). From each tow 30 cod were randomly sampled from the codend on deck directly after the catch was hauled onboard. This resulted in 600 cod for the assessment of catch quality, 300 cod subjected to buffer towing, and 300 cod haul-back directly. The towing time was restricted to a maximum of 2 h at the seabed and 1 h of buffer towing. The catch restriction device ensured that each haul contained approximately 2 tons of cod. The towing depth during buffer towing was controlled by the trawl eye to ensure that the trawl was kept at a depth that was approximately 40% of the fishing depth (Table 3, Fig. 1).

TABLE 3

Figure 2 shows the frequency of the different scores for the catch damage index for the hauls with regular haul-back, and Figure 3 shows the frequency of the scores for the hauls that were buffer towed.

FIG. 2

FIG. 3

Figure 4 shows the frequency of the different scores for the fillet index for the hauls with regular haul-back, and Figure 5 shows the frequency of the scores for the hauls that were buffer towed.

FIG. 4

FIG. 5

Figures 6–9 show the probability for cod that were either buffer towed or hauled-back directly to obtain a score from 0 to 3. A high probability of obtaining a score of 0 or 1 indicates good quality and thus little damage. In contrast, a high probability of obtaining a score of 2 or 3 indicates poor quality and a high degree of damage. Nearly all estimated probabilities show a reduction in the quality of cod exposed to buffer towing. However, differences in fish quality are only deemed significant in cases where the CIs from the relative difference in probabilities calculated by applying the two sample bootstrapping method described in section 2.3 do not contain the value 0.0.

Figure 6 compares results for quality assessed by applying the catch damage index for each single category between the regular tows and the hauls that were buffer towed. Cod that were buffer towed had a significantly higher probability of obtaining a score of 2 for the category “poor exsanguination”, whereas the probability of getting a score of 0 and ≤ 1 was significantly higher for cod that were hauled back directly (i.e., good exsanguination) (Fig. 6, Table 4). Table 4 presents all estimated probabilities with 95% CI that exhibited a significant difference in the probability of obtaining a given score between regular towing and buffer towing. Applying two sample bootstrapping enabled the calculation of the relative differences in probability. A negative relative probability value indicates a significant reduction in the probability of obtaining a given score when buffer towing and vice versa. Thus, a negative relative probability value for score 0 or ≤ 1 means a reduction in the probability of obtaining these scores for fish subjected to buffer towing, whereas a positive relative probability value for score 2 means increased probability of obtaining this score for fish subjected to buffer towing. Because scores of 0 and 1 are equivalent to “flawless” and “slightly” and scores of 2 and 3 are equivalent to “moderate” and “severe”, all results in Table 4 prove a significant reduction in the quality of fish subjected to buffer towing. Specifically, the probability of achieving a score of 2 for regular haul-back was 2% compared to 11% for buffer towing, which resulted in a 371% increase in the relative probability of poor exsanguination (Table. 4).

FIG. 6

Comparing the results from the catch damage index for all categories combined proved significantly better quality for cod for the regular hauls with direct haul-back compared to buffer towed hauls, i.e. increased probability of obtaining a score of 0 and ≤ 1 (Fig. 7). Moreover, comparing the results for all possible combinations of two categories proved a significant reduction in the quality of buffer towed cod for the following category combinations: “ecchymosis and exsanguination”, “exsanguination and skin abrasion”, “ecchymosis and gear marks”, and “exsanguination and gear marks” (Fig. 7, Table 4).

FIG. 7

For the following combinations of three categories, (“ecchymosis, gear marks, and exsanguination”, “exsanguination, ecchymosis, and skin abrasion”, “ecchymosis, gear marks, and skin abrasion”, and “ecchymosis, exsanguination, and skin abrasion”), the estimated probabilities proved a significant reduction in the quality of cod that were buffer towed (Fig. 8, Table 4).

FIG. 8

Figure 9 shows the estimated probabilities for obtaining a given score according to the fillet index for the regular tows and the hauls that were buffer towed. Cod that were buffer towed had a significantly higher probability of obtaining a score of 2 for the category “discoloration”, whereas the probability of obtaining a score of 0 and ≤ 1 was significantly higher for cod that were hauled-back regularly (Fig. 9, Table 4). Specifically, the probability of achieving a score of 2 for regular haul-back was 4% compared to 13% for buffer towing, which resulted in a 209% increase in the relative probability of obtaining a high score, i.e. high degree of fillet redness (Table 4). Furthermore, the probability of achieving score of 0 for regular haul-back was 34% compared to 17% for buffer towing, which resulted in a 52% decrease in the relative probability of achieving a score 0 for the degree of fillet whiteness (Table 4). Also, for the score ≤ 1, buffer towing proved a significant reduction in the quality, i.e. increased fillet redness (Fig. 9, Table 4). The two fillets shown in the left panel of Figure 10a represent a typical example of score 0 for the category “discoloration”, whereas the two fillets on the right were given a score of 2. Figure 10b shows a typical example of fillet gaping.

FIG. 9

FIG. 10

TABLE 4

The significant differences in the category “discoloration” from the fillet index for the hauls that were buffer towed (i.e., increased fillet redness) (Fig. 9, Table 4) are corroborated by the results from the catch damage index that proved a significantly poorer exsanguination for cod that were buffer towed (Fig. 6, Table 4).

4. Discussion

Results of this study proves that buffer towing negatively affects the quality of cod. Cod subjected to buffer towing exhibited a significantly increased probability of poor exsanguination, which was further reflected in the increased redness of the fillets. Specifically, the results demonstrated a 371% increased relative probability of poor exsanguination and a 209% increase in relative probability of fillet redness for cod subjected to buffer towing. In addition, considering the combined impact of two or three categories simultaneously within the catch damage index, proved a significant reduction in quality for buffer towed cod for scores within 10 out of 12 possible combinations. Investigating the probability of obtaining a given score for all categories simultaneously also proved a significant probability that buffer towed cod would obtain a higher score (i.e., reduced quality). For the scores from the fillet index, only the category “discoloration” was significantly poorer, (i.e. increased redness) for cod subjected to buffer towing compared to direct haul-back. The results for the categories “surface consistency” and “fillet texture” were approximately equal between buffer towed cod and cod hauled-back directly, which was expected because these two categories are mainly affected by storage of fish.

The results presented in this study are likely to be conservative due to small catch size (2 tons) and short towing time. In the commercial fishery catch sizes often exceed 10 tons, and towing times can be up to 7 hours. Skippers usually delay the decision to buffer tow, and combined with the difficulty of judging the density of the fish entering the trawl according to the echogram and the catch sensors on the codend, buffer towing entails additional time in the water as well as large catches. Previous studies have reported that increased catch size and towing time negatively affect fish quality (Olsen et al., 2013; Digre et al., 2017; Svalheim et al., 2017), and Olsen et al. (2008) reported that crowding of fish in the codend has a negative effect on fish quality, especially the degree of exsanguination and fillet discoloration. Besides, the time from catch to processing has a significant impact on the final quality of fish (Margeirsson et al., 2007). Since buffer towing entails prolonged time from catch to processing under conditions which are known to negatively affect catch quality, it is highly likely that the duration of buffer towing has an impact on the fish quality. Furthermore, previous studies report that the bursting of swim bladder results in the evacuation of gas through an intraperitoneal path to the anal area (Midling et al., 2012; Humborstad and Magnor-Jensen, 2013). However, underwater video recordings have shown that the dense packing of cod in the codend prohibits cod from turning belly up when the swim bladder is overinflated, which results in the gas remaining trapped within the dorsal side of the abdominal cavity when the swim bladder ruptures near the pin bones during buffer towing, causing severe bleeding. Thus, we speculate that in addition to buffer towing duration, also the depth to where the trawl is lifted during buffer towing could impact the quality of fish catches. Furthermore, fishermen frequently claim increased amounts of dead fish in catches subjected to buffer towing, especially for long buffer towing with large catches. This is likely caused by the dense packing of fish in the codend, which prohibits the fish from moving their operculum, resulting in suffocation; it also reduces fish quality due to insufficient exsanguination (Olsen et al., 2014).

This study presents a method for analyzing scores based on the catch damage index and fillet index. It provides results with a specific probability with 95% confidence limits. This method also provides conservative estimates of the probability, as it takes into account uncontrolled effects between each measurement within each haul as well as the variation between hauls.

All categories within the catch damage index and the fillet index are indicative of the quality of the catch. Although many studies document the importance of correct processing procedures of caught fish, it is impossible to improve fish quality if it is already reduced during the catching process, as is the case with buffer towing. The consequences of poor fish quality include reduced revenue and limited applicability of the fish for various products. High end markets demand good quality fish. Moreover, poor fish quality is thought to increase the risk of dumping and high-grading (Batsleer et al., 2015). Another negative consequence of buffer towing is the high escape rate of cod during that towing phase, where the probability of survival of escaped fish is believed to be reduced (Brinkhof et al., 2017a). Based on the results presented in this study, which proves a significant reduction in the quality of cod subjected to buffer towing, as well as the documented escape rate from the codend (Brinkhof et al., 2017a), buffer towing should be avoided.

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Table 1. The catch damage index used to assess the quality of the fish caught.

Table 2. The fillet index used to assess the quality of the fillets.

Table 3. Overview of the hauls conducted showing the towing start time and towing time, haul type, depth, average buffer towing depth with the standard deviation in parenthesis, and the percentage depth reduction during buffer towing.

Table 4. The probability estimation with 95% CI in parenthesis for the scores according to the different categories that proved a significant difference in terms of catch damage between regular towing and buffer towing. The relative differences in the probability for a given score presented in the right column were calculated by applying the two sample bootstrapping method implemented in SELNET.

Table 1

Catch damage	Score				Description
	Flawless	Slightly	Moderate	Severe	
Poor exsanguination	0	1	2	3	Improper bleeding, blood in veins
Ecchymosis	0	1	2	3	Discoloration on the skin, bruises
Gear marks	0	1	2	3	Marks on the skin caused by gear contact
Skin abrasion	0	1	2	3	Loss of scales

Table 2

Fillet quality	Score				Description
	Flawless	Slightly	Moderate	Severe	
Gaping	0	1	2	3	Gaping of fillet, disintegration
Discoloration	0	1	2	3	Fillet redness from white, pinkish, to reddish
Texture	0	1	2	3	Disintegration of fillet surface
Consistency	0	1	2	3	Fillet softness, firmness

Table 3

Haul no.	Time start (UTC)	Towing time (min)	Buffer towing	Depth (m)	Mean buffer towing depth (m)	Depth reduction (%)
1	16:48	130	No	365.5	-	-
2	00:53	196	Yes	374.1	216.9 (4.0)	42.0
3	04:54	108	No	367.4	-	-
4	07:29	193	Yes	372.8	208.9 (3.3)	44.0
5	12:00	120	No	362.7	-	-
6	15:00	145	Yes	372.0	212.8 (4.0)	42.8
7	20:46	114	No	372.7	-	-
8	00:43	193	Yes	360.4	225.2 (6.5)	37.5
9	04:49	120	No	368.3	-	-
10	12:53	192	Yes	368.6	210.4 (5.4)	42.9
11	17:00	90	No	365.5	-	-
12	19:29	168	Yes	361.7	209.2 (5.8)	42.2
13	23:01	100	No	359.3	-	-
14	01:26	175	Yes	358.8	217.7 (4.4)	39.3
15	08:12	133	No	341.8	-	-
16	13:31	192	Yes	335.1	195.1 (5.1)	41.8
17	17:09	120	No	347.9	-	-
18	20:06	195	Yes	341.9	205.1 (5.9)	40.0
19	00:00	120	No	351.1	-	-
20	03:13	199	Yes	354.3	192.0 (3.8)	45.8

Table 4

Catch damage index	**Score**	**Probability for score in regular tow**	**Probability for score in buffer tow**	**Differences in score probability**	**Relative differences in score probability (%)**
Poor exsanguination	**= 0**	0.46 (0.33-0.58)	0.30 (0.21-0.39)	−0.16 (−0.32-−0.004)	−35.22 (−61.71-−2.89)
	= 2	0.02 (0.00-0.04)	0.11(0.06-0.17)	0.09 (0.03-0.15)	371.43 (60.48-2082.92)
	≤ 1	0.98 (0.96-1.00)	0.89 (0.83-0.94)	−0.09 (−0.15-−0.03)	−9.19 (−16.84-−4.67)
All categories combined	**= 0**	0.21 (0.09-0.33)	0.07 (0.03-0.12)	−0.13 (−0.26-−0.02)	−65.48 (−86.44-−16.16)
	≤ 1	0.88 (0.82-0.94)	0.73 (0.65-0.81)	−0.15 (0.26-−0.05)	−17.08 (−29.67-−6.44)
Ecchymosis & poor exsanguination	**≤ 1**	0.90 (0.84-0.95)	0.76 (0.68-0.83)	−0.13 (−0.23-−0.05)	−15.24 (−25.35-−6.67)
Poor exsanguination & skin abrasion	**≤ 1**	0.96 (0.92-0.99)	0.87 (0.81-0.92)	−0.09 (−0.16-−0.03)	−10.69 (−16.00-−3.28)
Ecchymosis & gear marks	**= 0**	0.41 (0.28-0.54)	0.21 (0.15-0.27)	−0.20 (−0.33-−0.07)	−48.03 (−68.56-−22.73)
	≤ 1	0.90 (0.84-0.95)	0.80 (0.72-0.86)	−0.10 (−0.19-−0.02)	−12.97 (−21.59-−2.05)
Poor exsanguination & gear marks	**= 0**	0.34 (0.25-0.45)	0.17 (0.10-0.23)	−0.18 (−0.29-−0.60)	−52.54 (−72.40-−24.72)
	≤ 1	0.96 (0.93-0.99)	0.85 (0.78-0.92)	−0.11 (−0.20-−0.04)	−12.66 (−21.54-−4.18)
Poor exsanguination, ecchymosis, & gear marks	**= 0**	0.25 (0.15-0.36)	0.09 (0.05-0.14)	−0.16 (−0.29-−0.05)	−64.84 (−83.58-−30.37)
	≤ 1	0.89 (0.84-0.94)	0.74 (0.66-0.82)	−0.15 (−0.25-−0.06)	−17.27 (−28.76-−7.39)
Poor exsanguination, gear marks, & skin abrasion	**= 0**	0.27 (0.17-0.38)	0.12 (0.06-0.17)	−0.16 (−0.28-−0.04)	−58.68 (−82.75-−23.19)
	≤ 1	0.95 (0.91-0.99)	0.84 (0.76-0.91)	−0.11 (−0.19-−0.03)	−12.81 (−21.72-−3.10)
Ecchymosis, gear marks, & skin abrasion	**= 0**	0.31 (0.19-0.45)	0.16 (0.11-0.20)	−0.16 (−0.29-−0.03)	−50.00 (−69.28-−14.44)
	≤ 1	0.89 (0.83-0.94)	0.79 (0.72-0.86)	−0.10 (−0.19-−0.01)	−12.85 (−21-49-−2.40)
Ecchymosis, poor exsanguination, & skin abrasion	**≤ 1**	0.89 (0.82-0.95)	0.75 (0.67-0.82)	−0.14 (0.23-−0.04)	−16.70 (−26.73-−5.37)
Fillet index					
Discoloration	**= 0**	0.34 (0.27-0.43)	0.17 (0.11-0.22)	−0.17 (−0.28-−0.07)	−52.08 (−72.48-−26.02)
	= 2	0.04 (0.02-0.08)	0.13 (0.08-0.18)	0.09 (0.03-0.16)	208.72 (41.57-805.96)
	≤ 1	0.96 (0.92-0.98)	0.86 (0.81-0.91)	−0.09 (−0.16-−0.03)	−11.27 (−20.18-−4.91)

Figure 1. Schematic showing a regular tow with direct haul-back (a) and a buffer tow (b).

Figure 2. Frequency of scores from the catch damage index for all cod caught with regular haul-back.

Figure 3. Frequency of scores from the catch damage index for all cod that were buffer towed.

Figure 4. Frequency of scores from the fillet index for cod that were hauled-back directly.

Figure 5. Frequency of scores from the fillet index for cod that were buffer towed.

Figure 6. Results from the catch damage index showing the probability for cod to obtain a score ranging from 0 to 3 for the four categories investigated. The bars represent 95% CIs. RT denotes regular tows and BT denotes buffer tows. The scores that proved a significant difference in fish quality between RT and BT are highlighted in bold and black.

Figure 7. Results from the catch damage index showing the probability for cod to obtain a score ranging from 0 to 3 for the four categories investigated for all categories combined as well as for all possible combinations of two categories. The bars represent 95% CIs. RT denotes regular tows and BT denotes buffer tows. The scores that proved a significant difference in fish quality between RT and BT are highlighted in bold and black.

Figure 8. Results from the catch damage index showing the probability for cod to obtain a score ranging from 0 to 3 for the four categories investigated for all possible combinations of three categories. The bars represent 95% CIs. RT denotes regular tows and BT denotes buffer tows. The scores that proved a significant difference in fish quality between RT and BT are highlighted in bold and black.

Figure 9. Results from the fillet index showing the probability for cod to obtain a score ranging from 0 to 3 for the four categories investigated. The bars represent 95% CIs. RT denotes regular tows and BT denotes buffer tows. The scores that proved a significant difference in fish quality between RT and BT are highlighted in bold and black.

Figure 10. (a) The fillets on the left represent a typical example of score 0 for the category “discoloration”, whereas the two fillets on the right are a typical example of a score of 2. (b) shows an example of fillet gaping (arrows).

FIG. 1

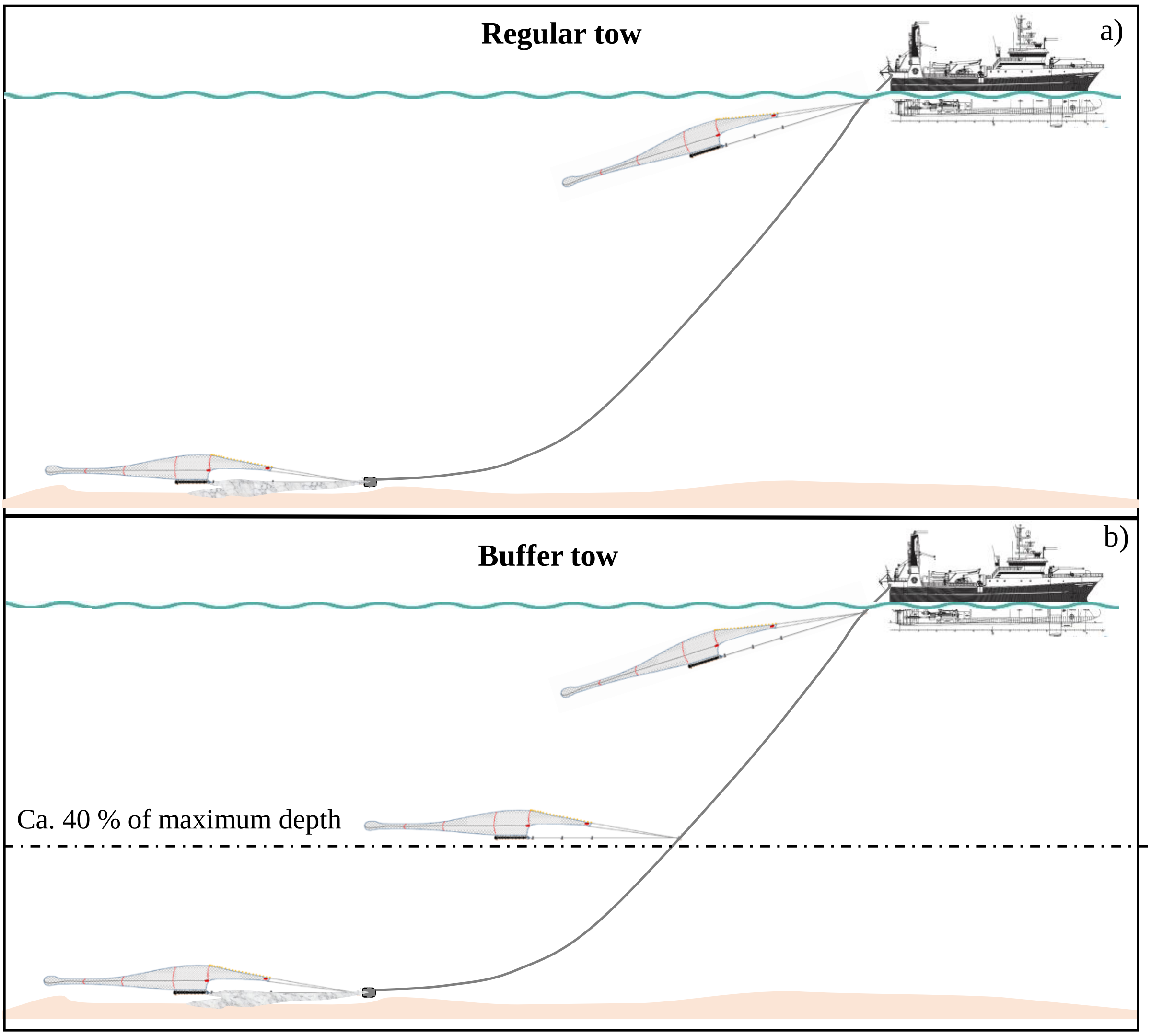
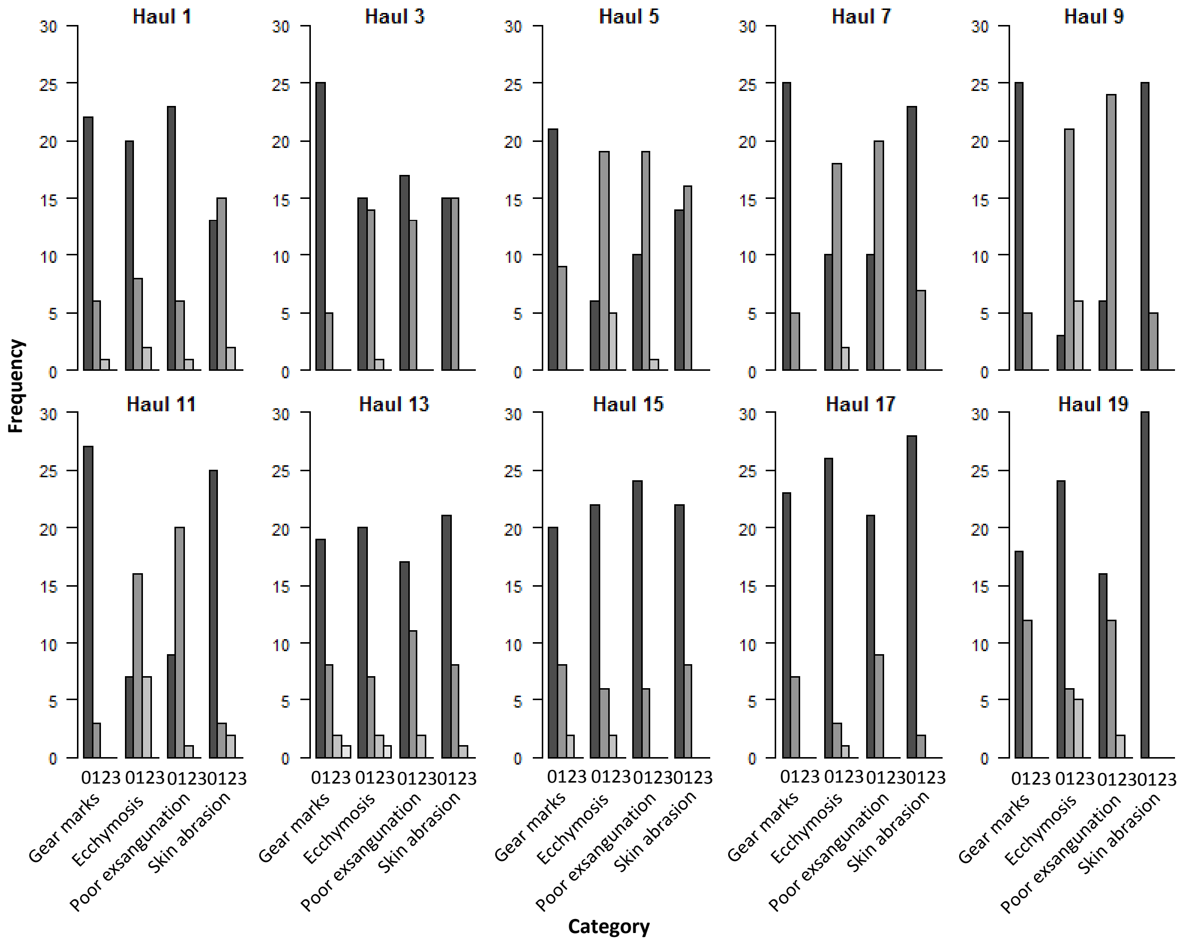


FIG. 2



Haul 1
Haul 3
Haul 5
Haul 7
Haul 9
Haul 11
Haul 13
Haul 15
Haul 17
Haul 19
Frequency
0123
Gear marks
Ecchymosis
Poor exsangunation
Skin abrasion
Category

FIG. 3

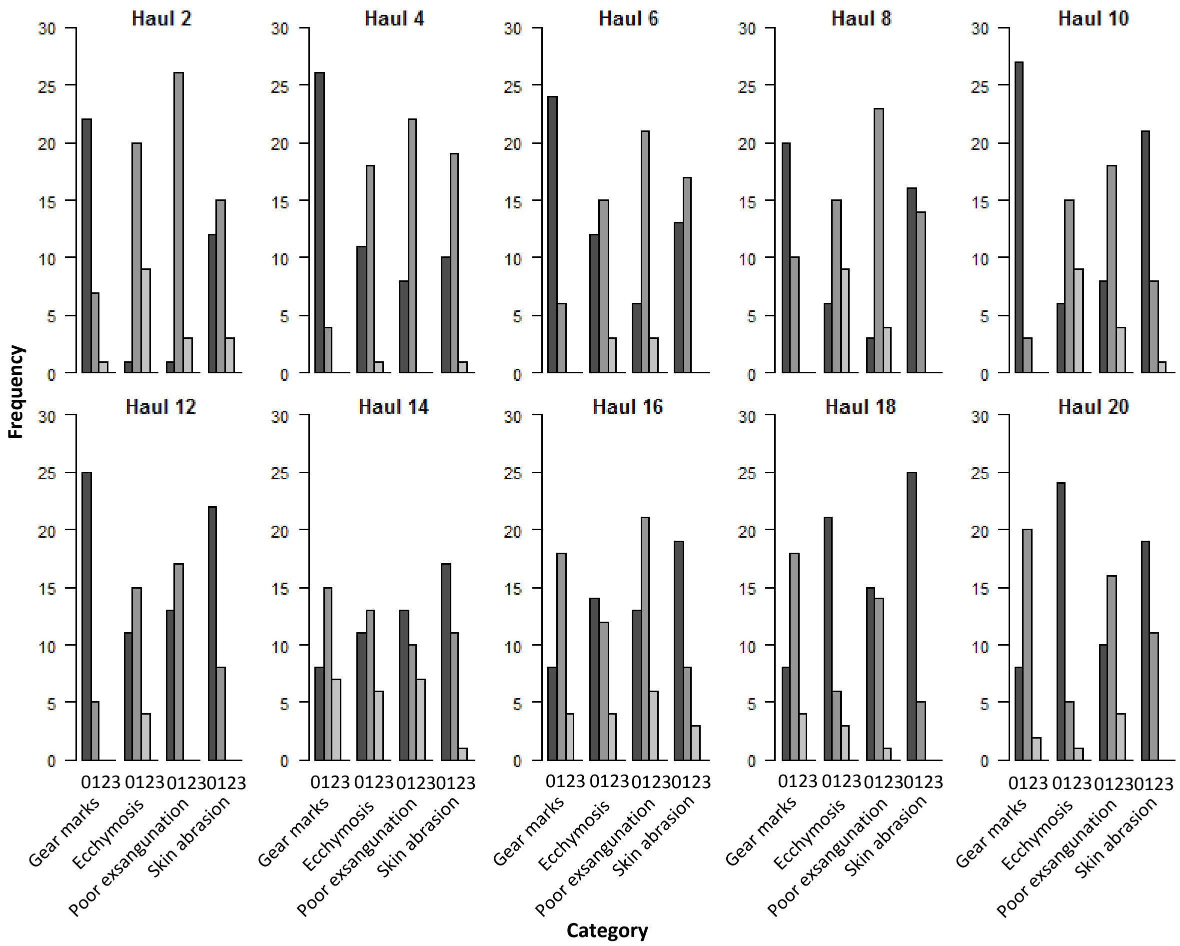

Haul 2
Haul 4
Haul 6
Haul 8
Haul 10
Haul 12
Haul 14
Haul 16
Haul 18
Haul 20
Frequency
0
5
10
15
20
25
30
0123
Gear marks
Ecchymosis
Poor exsangunation
Skin abrasion
Category

FIG. 4

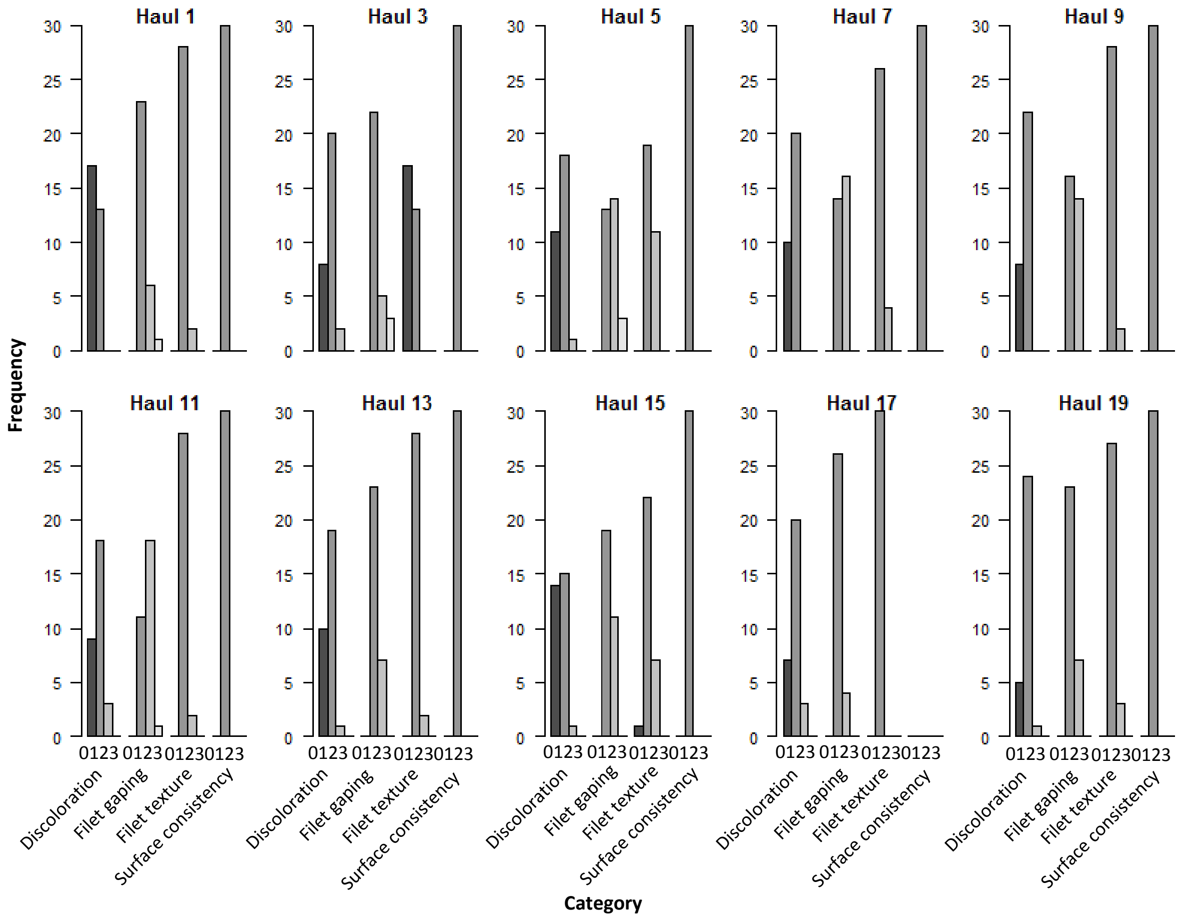

Haul 1
Haul 3
Haul 5
Haul 7
Haul 9
Haul 11
Haul 13
Haul 15
Haul 17
Haul 19
Frequency
0123 0123 0123 0123
Discoloration
Filet gaping
Filet texture
Surface consistency
Category

FIG. 5

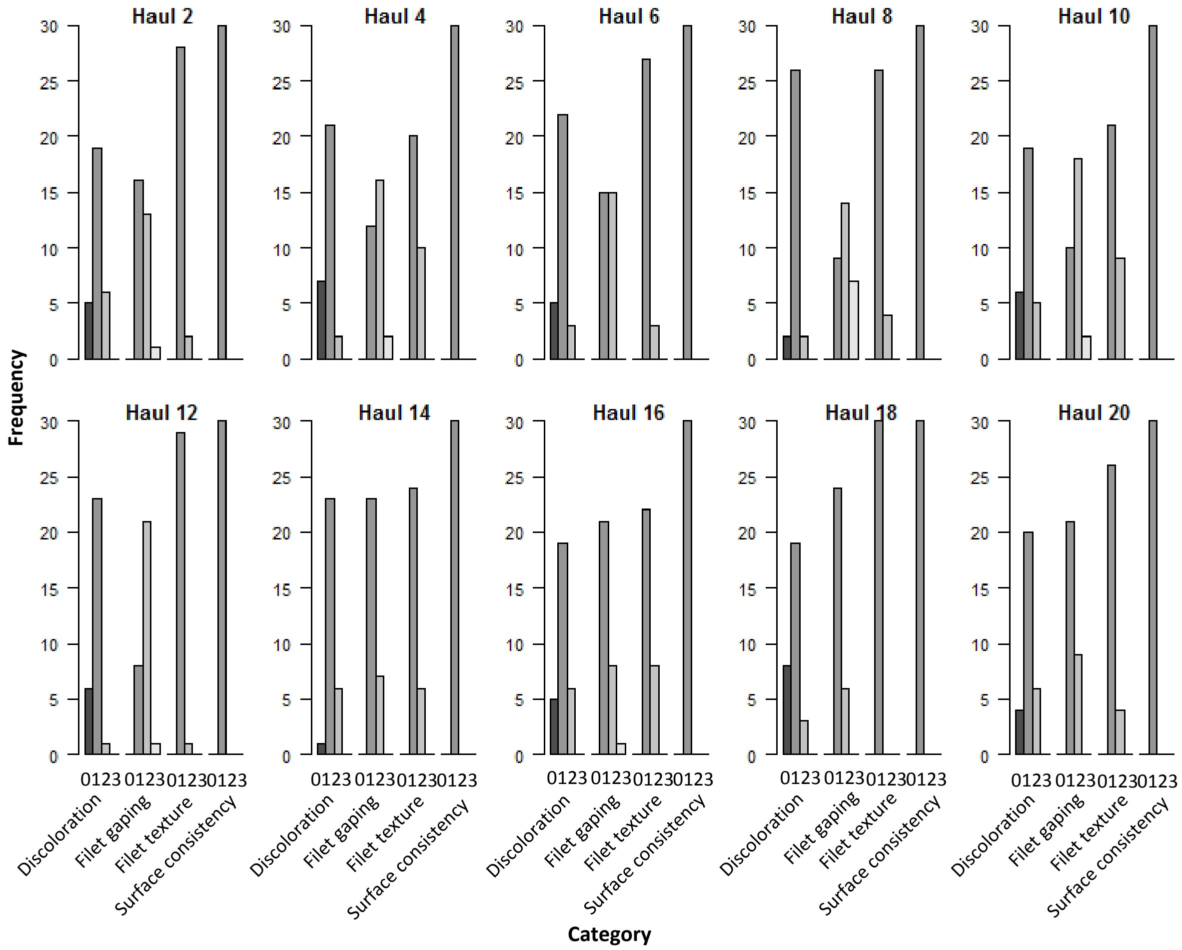
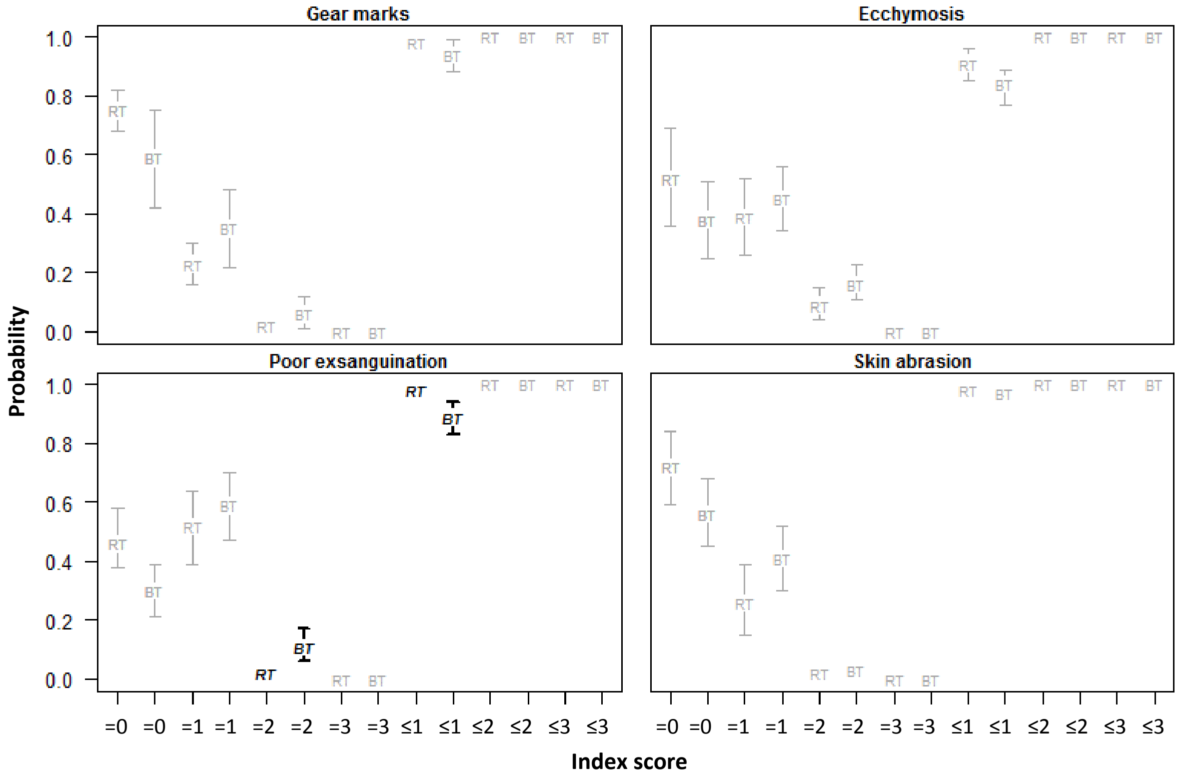
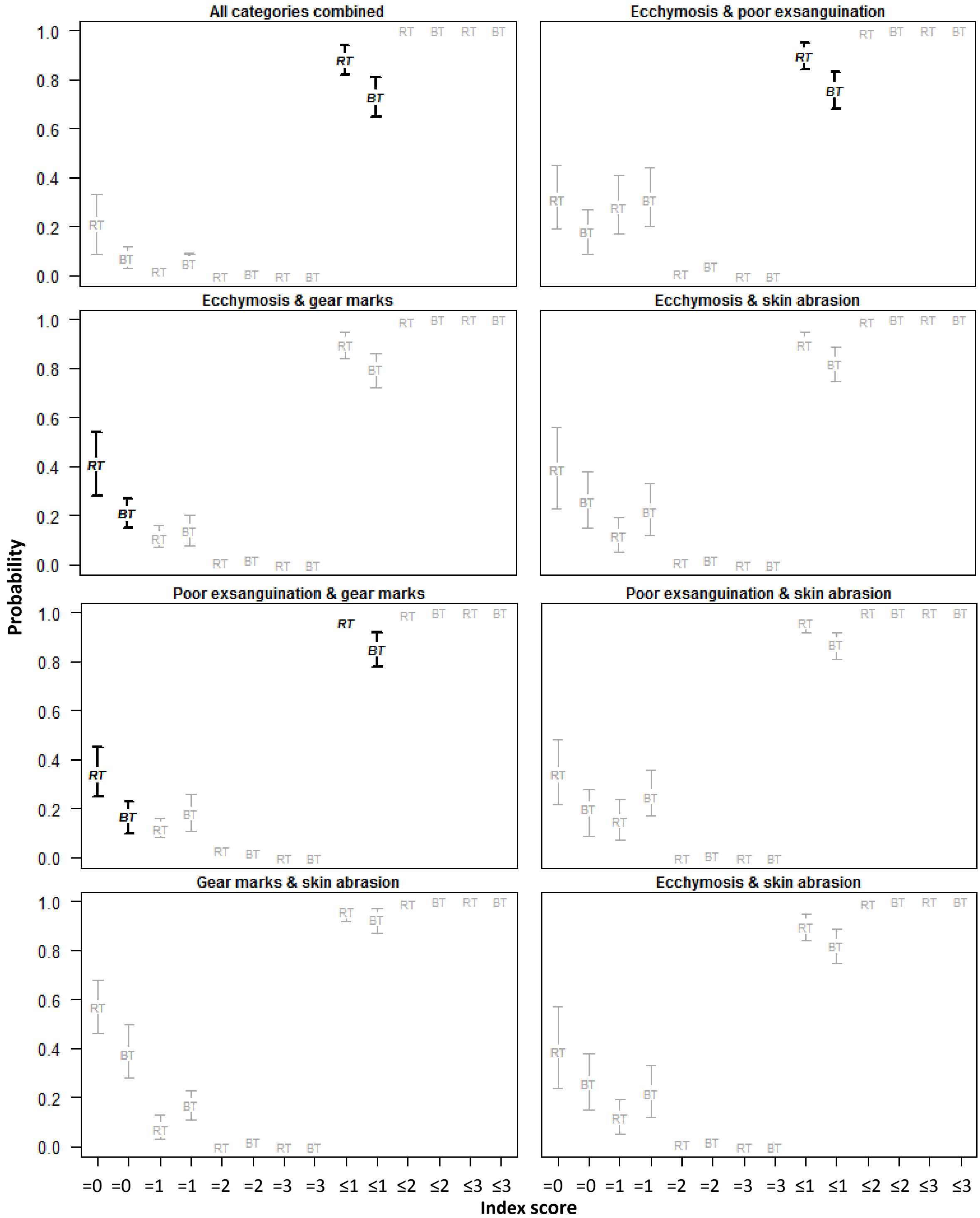

Haul 2
Haul 4
Haul 6
Haul 8
Haul 10
Haul 12
Haul 14
Haul 16
Haul 18
Haul 20
Frequency
0123 0123 0123 0123
Discoloration
Filet gaping
Filet texture
Surface consistency
Category

FIG. 6



Gear marks
Ecchymosis
Poor exsanguination
Skin abrasion
Probability
1.0
0.8
0.6
0.4
0.2
0.0
RT
BT
=0 =0 =1 =1 =2 =2 =3 =3 ≤1 ≤1 ≤2 ≤2 ≤3 ≤3
Index score

FIG. 7



All categories combined
Ecchymosis & poor exsanguination
Ecchymosis & gear marks
Ecchymosis & skin abrasion
Poor exsanguination & gear marks
Poor exsanguination & skin abrasion
Gear marks & skin abrasion
Ecchymosis & skin abrasion
Probability
Index score
=0 =0 =1 =1 =2 =2 =3 =3 ≤1 ≤1 ≤2 ≤2 ≤3 ≤3
RT
BT

FIG. 8

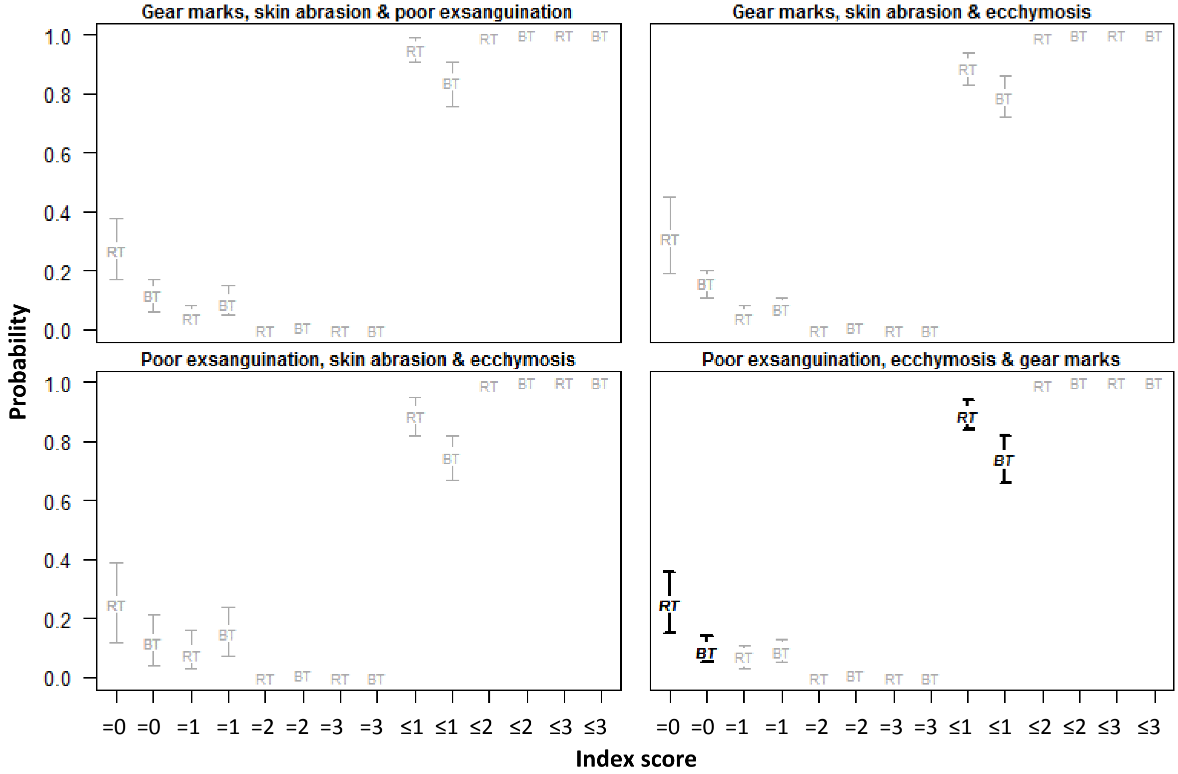

Gear marks, skin abrasion & poor exsanguination
Gear marks, skin abrasion & ecchymosis
Poor exsanguination, skin abrasion & ecchymosis
Poor exsanguination, ecchymosis & gear marks
Probability
1.0
0.8
0.6
0.4
0.2
0.0
=0 =0 =1 =1 =2 =2 =3 =3 ≤1 ≤1 ≤2 ≤2 ≤3 ≤3
Index score
RT
BT

FIG. 9

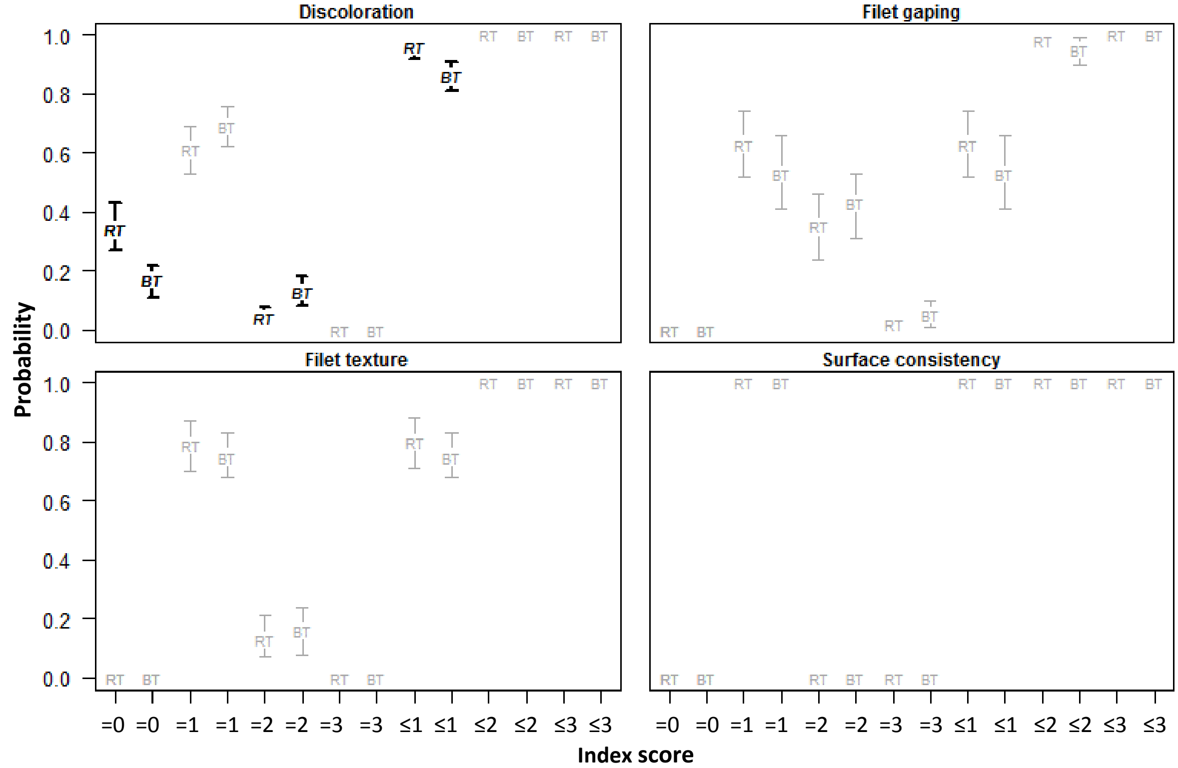

Discoloration
Filet gaping
Filet texture
Surface consistency
Probability
1.0
0.8
0.6
0.4
0.2
0.0
=0 =0 =1 =1 =2 =2 =3 =3 ≤1 ≤1 ≤2 ≤2 ≤3 ≤3
Index score
RT
BT

FIG. 10