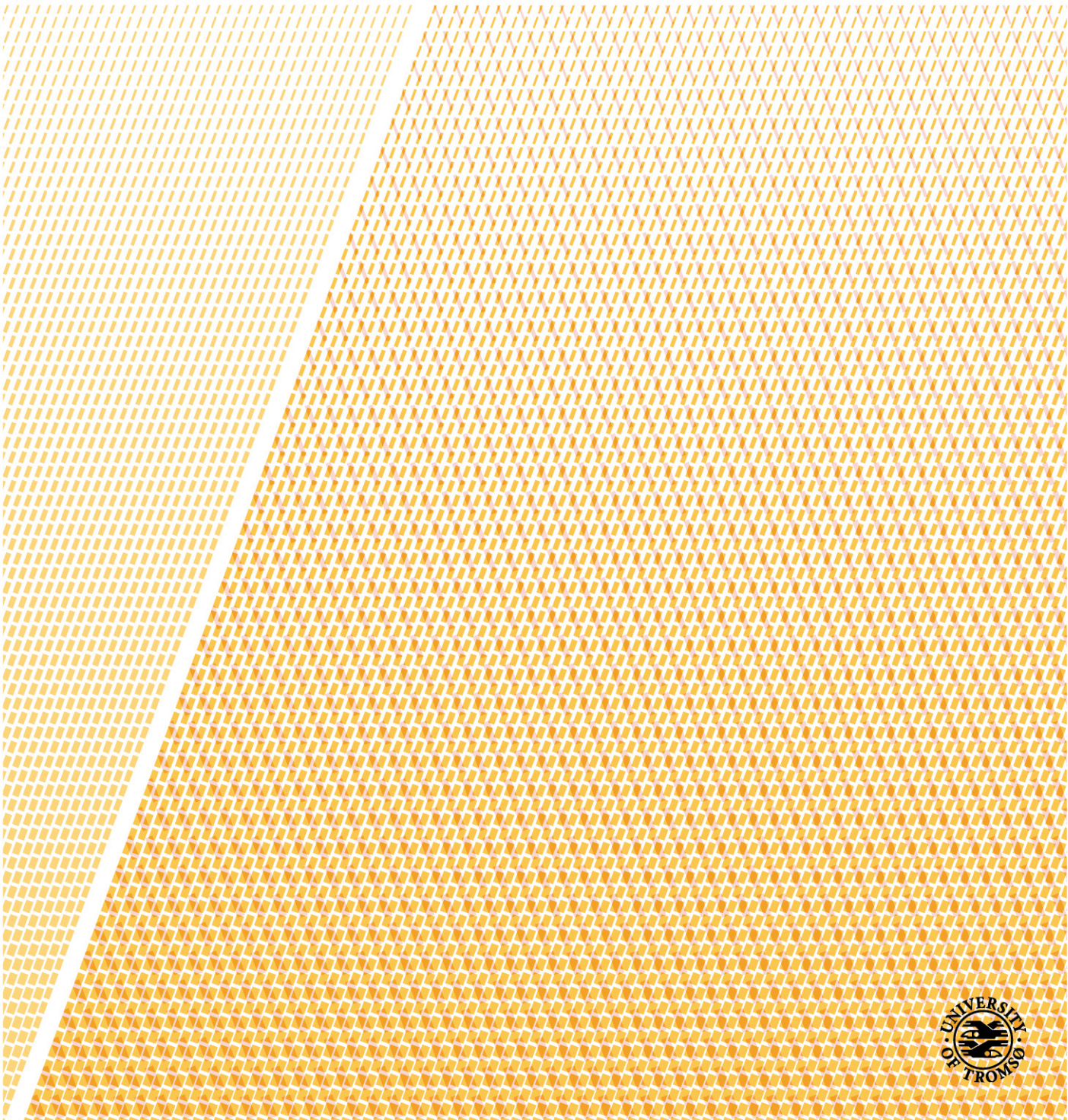


Catch quality and size selectivity in the Barents Sea bottom trawl fishery: effect of codend design and trawling practice

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A dissertation for the degree of Philosophiae Doctor – November 2018



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Summary

This study focused on two important issues on the Barents Sea bottom trawl fishery for Northeast Arctic cod (*Gadus morhua* L.); catch quality (i.e., the quality of the fish caught) and size selectivity. The high abundance of cod encountered in recent years in the Barents Sea, leading to subsequent large annual quotas, has led to increased interest in improving the quality of fish caught by trawls. This increasing interest in improving the quality of fish caught by trawls has also been driven by the increasing demands from the industry, retailers, and consumers for traceable high-quality products, as well as fish welfare. Although catch efficiency and size selectivity have been the major aspects of the bottom trawl fishery for decades, the focus on catch quality and how the quality of the catch is affected by the fishing process has remained limited. To ensure a sustainable fishery, in terms of ecological, societal, and economical sustainability, both catch quality and size selectivity are the two important factors that must be considered. In many cases, these two factors are interlinked, as a given change in a trawling procedure or trawl gear component with the aim of improving catch quality might simultaneously influence size selectivity. Therefore, in this thesis, I investigate the effect of a trawling practice (Paper I and II) and trawl codend design (Paper III and IV) on catch quality (Paper I and III) and size selectivity (Paper II and IV).

The first part of my thesis (Paper I and II) presents a trawling practice, called buffer towing. It is claimed that this practice has a negative effect on both catch quality and size selectivity. Trawlers commonly re-deploy (“shoot”) the trawl directly after hauling a catch onboard. However, the approximate desired amount of fish is often caught before the catch from the previous haul has been processed. This issue frequently results in buffer towing, which entails lifting the trawl from the seabed and towing the catch midwater at low velocity until the onboard processing capacity is restored. Applying a new method for analyzing data derived from the assessment of catch quality demonstrated that buffer towing had a significant negative impact on the quality of the catch (Paper I). Furthermore, by applying a structural catch comparison method, Paper II demonstrated that, in addition to having a negative impact on catch quality, buffer towing negatively impacts size selectivity.

The first part of this thesis presents the effect of a trawl operation, while the second part presents the effect of gear design on the quality of the catch and size selectivity. This part presents a new codend concept, termed “dual sequential codend”. This codend was designed to improve the quality of cod and was specifically investigated in Paper III. However, due to the design of the codend, there were concerns that it would compromise size selectivity, which was

investigated in Paper IV. The results demonstrated that the new codend concept significantly improved the quality of cod (i.e., reduced the damages incurred during the catch process compared to a conventional codend). Specifically, five times more flawless cod (i.e., no damage incurred during capture) was obtained using the new codend compared to the conventional codend. Investigation of size selectivity (Paper IV) indicated that the new codend concept led to a minor increase in the retention of small cod. The benefit of improved catch quality by applying the sequential codend concept should be regarded as more important than the minor increase in the retention of small cod, both from the industry and management perspectives.

Abbreviations

CA	Correspondence analysis
CCA	Canonical correlation analysis
CDI	Catch damage index
CI	Confidence interval
CPUE	Catch per unit effort
ICES	International Council for the Exploration of the Sea
JNRFC	Joint Norwegian-Russian Fisheries Commission
L ₅₀	Length of fish at 50% probability of retention
MCRS	Minimum conservation reference size
NEA-cod	Northeast Arctic cod
PA	Polyamide
PE	Polyethylene
PCA	Principal component analysis
ROV	Remote operated vehicles
SP	Split value
SR	Selection range
TAC	Total allowable catch

List of papers

- Paper I** Brinkhof, J., Larsen, R.B., Herrmann, B., Olsen, S.H., 2018. Assessing the impact of buffer towing on the quality of Northeast Atlantic cod (*Gadus morhua*) caught with a bottom trawl. Fisheries Research, 206: 209-219, <https://doi.org/10.1016/j.fishres.2018.05.021>
- Paper II** Brinkhof, J., Herrmann, B., Larsen, R.B., Sistiaga, M., 2017. Escape rate for cod (*Gadus morhua*) from the codend during buffer towing. ICES Journal of Marine Science, 75(2): 805-813, <https://doi.org/10.1093/icesjms/fsx200>
- Paper III** Brinkhof, J., Olsen, S.H., Ingólfsson, Ó., Herrmann, B., Larsen R.B., 2018. Sequential codend improves quality of trawl-caught cod. PLoS ONE 13(10): e0204328, <https://doi.org/10.1371/journal>
- Paper IV** Brinkhof, J., Herrmann, B., Larsen, R.B., Veiga-Malta, T., 2018. Effect of a quality-improving codend on size selectivity and catch patterns of cod in bottom trawl fishery. Submitted to Canadian Journal of Fisheries and Aquatic Sciences (under review)

1. Introduction

This thesis investigates how catch quality (i.e., the quality of the fish caught) and size selectivity can be influenced by both trawl gear design and trawling practice in the Barents Sea bottom trawl fishery for gadoids. The thesis focuses on the main target species in this gadoid bottom trawl fishery, the Northeast Arctic cod (*Gadus morhua* L.). This species currently is the largest cod stock in the world, and is the most important fishery in the Barents Sea (Yaragina et al., 2010). Although size selectivity has been the main focus in the bottom trawl fishery for decades, information on catch quality and how the quality of the catch affects the fishing process has been limited. To ensure a fully sustainable fishery (i.e., ecological, societal, and economical), both catch quality and size selectivity are of vital importance.

The synopsis contains five main sections that introduce and discuss the four papers included in this thesis in a common context. The first section of the synopsis describes the basic principles of bottom trawling. The second section presents the Barents Sea bottom trawl fishery for Northeast Arctic cod (NEA-cod) and the current status and challenges of the fishery. This information is preceded by a description of the current status and challenges regarding catch quality and size selectivity. This part leads to the third section, in which the overall objectives of this thesis are presented in a common framework. The fourth section presents a case of trawling practice that is believed to have an impact on both catch quality (Paper I) and size selectivity (Paper II). The fifth section presents a case of trawl gear design, investigating whether it is possible to improve the quality of the catch (Paper II) without compromising size selectivity (Paper IV). The sixth section presents the main conclusions of the studies, discussing how the various studies presented here contribute to improving the bottom trawl fishery, as well as the science of fishing gear technology. Finally, future recommendations are identified, followed by the presentation of the four papers included in this thesis.

1.1 Basic principles of bottom trawling

Bottom trawling is a common fishing method practiced globally for the capture of demersal fish species and crustaceans (Graham, 2010; Winger et al., 2010). Trawling is an active fishing method, as it requires active mobilization of the gear to catch fish. In general, trawls are divided into three main categories: beam trawls, bottom trawls, and pelagic trawls. The main difference between beam trawls and bottom and pelagic trawls is the mechanism that maintains the vertical and horizontal opening of the net. The net of beam trawls is kept open by

a rigid frame or beam, whereas the net of bottom and pelagic trawls is kept open horizontally by a pair of otter boards and vertically by weights and floats (Sainsbury, 1996; Gabriel et al., 2005). Furthermore, pelagic trawls are towed in the water column to capture pelagic fish species, while bottom trawls are towed on the seabed to capture demersal fish species and crustaceans.

The design and rigging of bottom trawls varies greatly, depending on the fishery, vessel size, and target species (Sainsbury, 1996; Winger et al., 2010). In some fisheries, multiple trawls are towed simultaneously (double or triple trawls), or one trawl is towed by two vessels, i.e., paired trawling (Sainsbury, 1996; Gabriel et al., 2005). However, the basic principles is similar for all bottom trawls. The trawls are towed by a vessel with wires, also called towing cables, which are connected to a set of otter boards (Figure 1a). Depending on the fishery, the size, weight, and shape of the otter boards varies greatly, ranging from 1 m², weighing 100–200 kg, up to 7–10 m², weighing 5000–6000 kg (Gabriel et al., 2005). In the Barents Sea bottom trawl fishery, the most commonly applied otter boards weigh between 3000 and 5000 kg, covering an area of 7–10 m². Bottom trawls applied by the Norwegian fleet in this region are commonly towed in a twin-trawl configuration, requiring a center weight (roller clump) of 3000–7000 kg between the two trawls. The purpose of the otter boards is to maintain the horizontal spread of the trawl net. In addition, the otter boards are the first part of the trawls that fish encounter, resulting in fish either being herded towards the trawl mouth guided by the sound clouds swirled up behind the otter boards, or escaping on the outside of the otter boards (Wardle 1993; Winger et al., 2010; Sistiaga et al., 2015). The otter boards are followed by the ground sweeps. The length of the sweeps varies depending on the target species. For instance, shrimp trawls usually have short sweeps, while trawls targeting demersal fish usually have long sweeps. These long sweeps are typically 70–150 m in the gadoid bottom trawl fishery of the Barents Sea, which increases the swept area, i.e., the zone in which fish are herded towards the trawl mouth.

The sweeps, which take over the herding effect after the otter boards, are connected to the ground gear (Sistiaga et al., 2015). The purpose of the ground gear is to ensure contact with the seabed for the efficient capture of fish, and to protect the trawl netting from excessive abrasion. Hence, there is great variation in the design, weight, and size of the ground gear depending on the topographical structures and target species (Engås and Godø, 1989; Hannah and Jones, 2000; Ingólfsson and Jørgensen, 2006; Brinkhof et al., 2017). Small, light weighted ground-gear, which is often composed of chains, or ‘cookies’ (rubber discs), are mostly applied in areas with soft seabed and/or onboard smaller vessels (Sainsbury, 1996; He and Winger,

2010). Areas where the seabed is rough and uneven with rocks and boulders, like in the Barents Sea, often require larger and heavier ground-gear. Such ground-gear often has two side-gears consisting of bobbins made of steel or rubber (Figure 1b), with a center gear, which is attached to the fishing line of the trawl. The most commonly applied center ground-gear in large trawls, including those used in the Barents Sea bottom trawl fishery, is the rockhopper gear (Figure 1c), which is composed of Ø35–66 cm equally spaced rubber discs (Ingólfsson and Jørgensen, 2006; Brinkhof et al., 2017).

Prior to the 1960s, the netting of trawls was mostly built from natural fibers, such as cotton, hemp, and sisal. However, contemporary trawls are mainly built from different combinations of plastics, with polyethylene (PE) being the most widespread, followed by polyamide (PA) (Sainsbury 1996; Gabriel et al., 2005). The main parts of the trawl netting are composed of the wings on both sides, followed by the trawl body, which narrows down through an extension piece and ends in a codend, where the fish are retained (Figure 1e) (He and Winger, 2010). However, in many trawl fisheries, the extension piece inserted between the trawl body and the codend is equipped with a size and/or species-selective sorting device (Figure 1f) (e.g. Larsen and Isaksen, 1993; Krag et al., 2009; Graham et al., 2010; He and Balzano, 2012; Larsen et al., 2017).

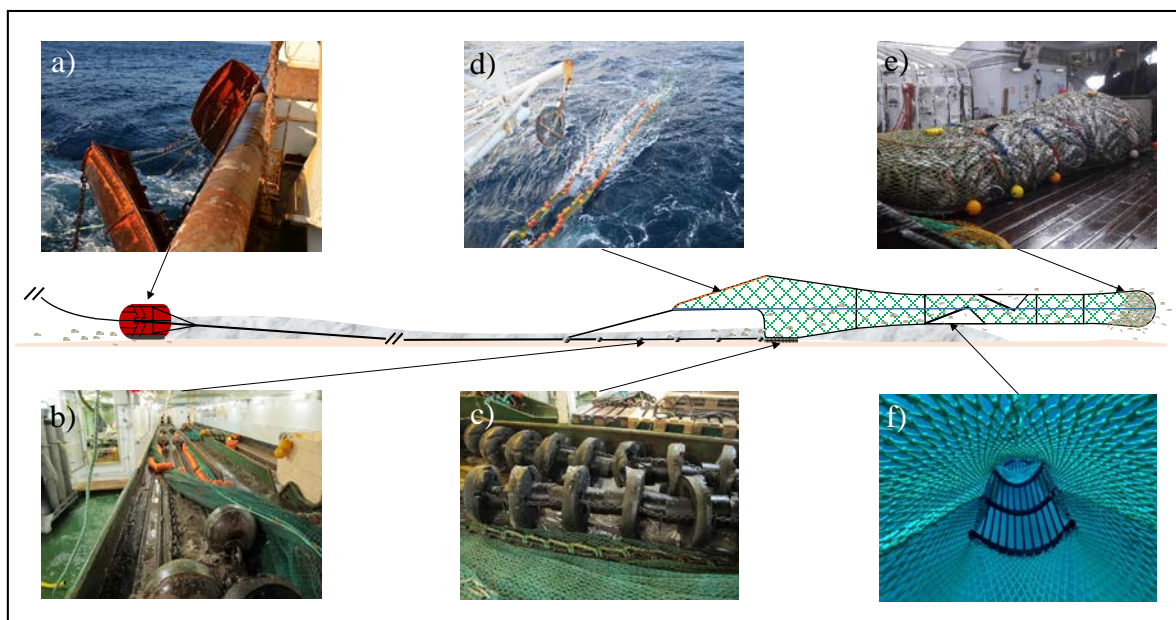


Figure 1. A typical configuration of a bottom trawl fishing for gadoids in the Barents Sea. Images show: a) otter boards, b) side ground-gear, c) headline with floats, d) Ø53 cm rockhopper ground-gear, e) selective sorting grid (Flexigrid), and f) the codend.

Trawls are flexible systems that are influenced by various factors, such as bottom topography and substrate, towing depth and speed, water current at the seabed, and vessel movement, which, in turn, are affected by surface currents and sea-state (Weinberg and Kotwicki, 2008). All components of a trawl, as well as the trawling practice implemented, influence the total catch efficiency and catch composition; thus, these parameters may be modified to achieve desired goals.

1.2 Gadoid bottom trawl fishery in the Barents Sea

The NEA-cod stock (*Gadus morhua*) is currently the largest cod stock globally (Yaragina et al., 2011). Annually, the total allowable catch (TAC) is determined by the Joint Norwegian-Russian Fisheries Commission (JNRFC) based on annual recommendations from the International Council for the Exploration of the Sea (ICES), and is equally divided between Russia and Norway, which are the two main nations targeting NEA-cod (Shamray and Sunnanå, 2011). After a historical peak in 2013, with a TAC of 1 million metric tons, the annual catches have declined slightly (Figure 2). The JNRFC agreed on a TAC of 894 000 t in 2016, which declined to 890 000 t in 2017 (Bakketeig et al., 2017; ICES, 2017). Furthermore, according to advice from ICES, the TAC for 2018 and 2019 should not exceed 712 000 t and 674 678 t, respectively (ICES, 2018).

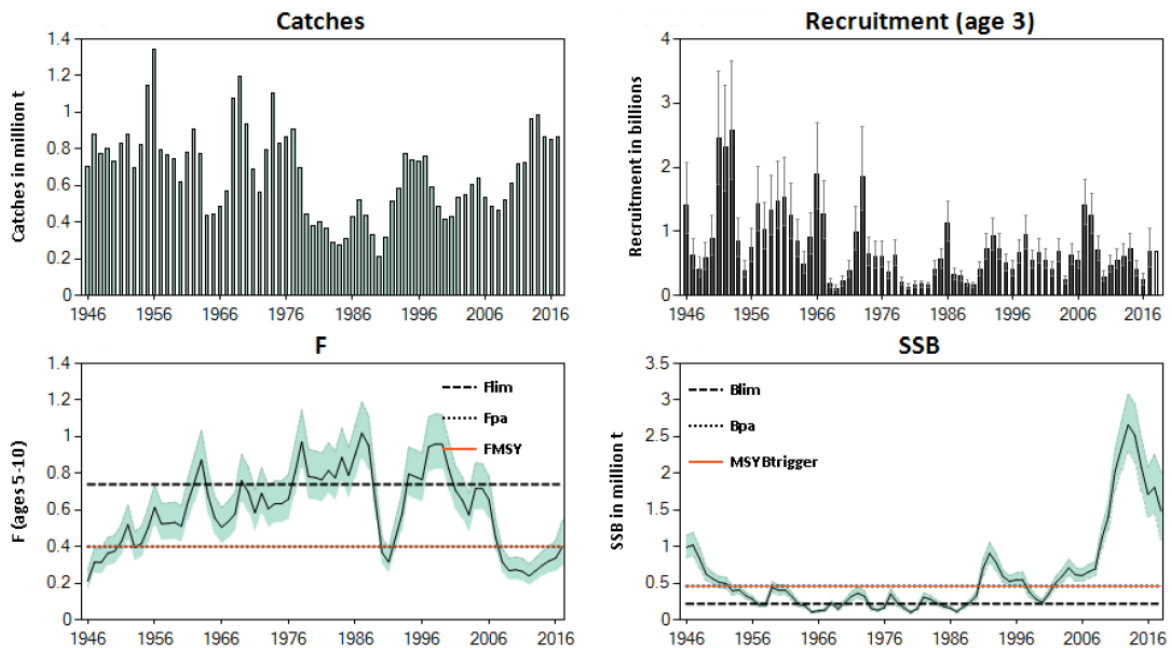


Figure 2. Cod in subareas 1 and 2 (Northeast Arctic). Catch, recruitment, F, and SSB. Recruitment, F, and SSB have confidence intervals (95%) in the plot. (Source: ICES, 2018)

The NEA-cod is the most important fishery in the Barents Sea, both in terms of catch volume and economic yield (Yaragina et al., 2011). Most of the fish and shrimp in the Barents Sea are caught using bottom trawls (Pavlenko and Isaksen, 2011). About 70% of the annual NEA-cod TAC is caught with bottom trawls. Of the annual Russian TAC, about 95% is caught with bottom trawls. Due to the widespread use of other fishing methods, in addition to bottom trawls (such as demersal seine, long line, and gillnets), approximately 35% of the annual Norwegian TAC for NEA-cod is caught by bottom trawls (ICES, 2014). However, this phenomenon exists because NEA-cod migrates towards the Norwegian coast during the spawning season, increasing its likelihood of being captured in other fishing gears besides bottom trawls, which is the most applied fishing gear in the Barents Sea throughout the rest of the year.

In addition to the annual TAC, the NEA-cod fishery is regulated through minimum conservation reference sizes (MCRS), limits on the intervention of undersized fish, and the by-catch of other species, landing obligation, and technical regulations, amongst other parameters. Currently, the MCRS for NEA-cod caught above 62°N, is 44 cm. In general, the catch of fish below the MCRS size must not exceed 15% in terms of numbers, whereas the catch of other by-catch species (i.e., species that a vessel does not have a quota for) must not exceed 10% by weight (Norwegian Directorate of Fisheries, 2018). The purpose of the technical regulations is to mitigate the catch of unwanted species, as well as the capture of fish below the MCRS. To ensure the release of fish below the MCRS, a minimum mesh size of 130 mm is enforced in the trawl fisheries (Norwegian Directorate of Fisheries, 2018). Furthermore, size selective sorting grids, with a minimum bar spacing of 55 mm have been mandatory in the fishery since 1997 (Yaragina et al., 2011; Norwegian Directorate of Fisheries, 2017). Currently, three different types of size-selective sorting grids are allowed in the fishery (Pavlenko and Isaksen, 2011); namely, the Sort-X grid (Larsen and Isaksen, 1993), the Sort-V (Jørgensen et al., 2006), and the Flexi-grid, which is the most frequently applied grid system (Sistiaga et al., 2016).

2. Current status and challenges in the Barents Sea bottom trawl fishery

Bottom trawling is often criticized because of its negative impacts, including high fuel consumption, sea bed disturbance, by-catch, mortality of escapees, and varying catch quality. The Norwegian management system and research on by-catch reduction in the Norwegian bottom trawl fishery has led to the introduction of size selective sorting grids, which have

substantially reduced the capture of undersized fish and other by-catch species (Pavlenko and Isaksen, 2011; Yaragina et al., 2011). The high abundance of cod in the Barents Sea contributes to a high catch per unit effort (CPUE), leading to increased focus on catch quality. Improving catch quality has the potential of increasing economic revenue, as well as improving animal welfare, which is also gaining increased attention. Owing to the high catch efficiency of the present commercial factory trawlers, catch quality has gained increasing interest as a way to increase yield. The increasing interest for catch quality has also been driven by the increasing demand from consumers for traceable high-quality products, as well as fish welfare. Therefore, catch quality should be considered when evaluating the quality of the fishery itself, i.e., sustainable fishing practices. Furthermore, seasonal and spatial variability in the NEA-cod fishery, reinforced by the fishers attempt to maximize CPUE has led to uneven landings of cod that deviates from the demands on land (Hermansen et al., 2012). Subsequently, this issue has led to the increased interest of keeping cod catches alive in capture-based aquaculture (Dreyer et al., 2008; Isaksen and Midling, 2010; Humborstad et al., 2013; Humborstad et al., 2016). However, this approach requires improved survivability, which is interlinked with improved catch quality, i.e., reduced catch damages and improved fish welfare.

2.1 Importance of catch quality

A catch that is considered to be of good quality contains fish with negligible physical injuries and low levels of stress related agents. However, bottom trawl caught fish is often deemed to be of poor quality, especially in comparison with other, more lenient, fishing methods, such as longline (Digre et al., 2010; Rotabakk et al., 2011). Fish caught with bottom trawl often have visually detectable scrape marks, scale loss, internal and external ecchymosis, and reduced ability of sufficient bleeding, with all of these factors contributing to reduce overall quality (Esaiassen et al., 2004; Ingólfsson and Jørgensen 2006; Digre et al., 2010; Rotabakk et al., 2011; Olsen et al., 2013; Olsen et al., 2014). Blood and tissue samples from trawl caught often contain elevated levels of lactate, cortisol, and glucose, along with lower pH, which reduce overall quality (Digre et al., 2010; Rotabakk et al., 2011). From the management perspective, poor catch quality increases the risk for illegally discarding and high-grading (discard of unwanted species, sizes or quality for the benefit of better payed catch) of fish, leading to unaccounted mortality (Batsleer, 2015). From the fisheries perspective, poor catch quality leads to a decline in its use for various products, reduced value, and, thus, revenue, which reduces its sustainability to compensate for poor catch quality. Catch quality determines

how fish is used for various products, including their shelf life (Cole et al., 2003; Bonilla et al., 2007). Therefore, improving the quality of catch landed with trawls could increase its value, and contribute to a more sustainable fishery.

Although fish quality is of prime importance, limited number of studies have been conducted on this subject. However, the focus on catch quality and fish welfare has intensified over the last decade. Several studies have documented the effect of post-catch handling onboard bottom trawlers (Botta et al., 1986; Borderías and Sánchez-Alonso, 2011; Olsen et al., 2013 and 2014; Erikson et al., 2016); however, relatively few studies have investigated the effect of various trawl components and trawling procedures on catch quality. It is difficult, if not impossible, to improve catch quality based on existing processing methods onboard factory trawlers once it has deteriorated during the catch process. Hence, preventing the deterioration of the catch during the catching process is key to improving fish quality and enhancing revenue.

2.1.1 Factors that potentially influence catch quality

Besides the obvious factors related to trawl design and operation, many different factors potentially affect catch quality (and size selectivity), including water temperature, fishing depth, and other spatial and seasonal differences (Sartoris et al., 2003; Mello and Rose, 2004; Suuronen et al., 2005; Margeirsson et al., 2007). Other factors that influence catch quality include catch size, towing time (Olsen et al., 2008, 2013), and towing speed, which is associated with endurance (Svalheim et al., 2017). NEA-cod start migrating towards the Norwegian coast in fall (October–November), arriving at spawning areas in February–March, and migrating northwards after the end of the spawning season (Yaragina et al., 2010). Since spawning migration causes fish to aggregate, resulting in increased densities, combined with the fact that the cod are located in the vicinity of the coast, a large part of the annual cod quota is caught during this season. However, the spawning season, including the migration period, might affect the quality of cod caught by trawlers (Mello and Rose 2004; Margeirsson et al., 2005). According to fishers, the quality of cod caught is at its best during fall and until the fish start to migrate. Migrating cod often feed on capelin (*Mallotus villosus*), which is claimed to negatively impact the quality of the catch, as the cod fillets become softer and easily disintegrate (Love, 1975; Ang and Haard, 1985). After spawning the cod is deprived of energy, which also has a negative impact on catch quality.

Besides the spatial and seasonal factors, the process of catching fish likely affects the catch quality. The effect of this process begins when fish first react to the approaching otter boards by swimming into or out of the catching zone. The fish that enter the catching zone are herded into the trawl opening by the sweeps. The metabolic rate of fish might increase due to increased swimming speed, depending on the length of the sweeps and the angle of attack, as well as towing speed and the body length of fish (Winger et al., 2010). When located in front of the trawl opening, fish usually alter the swimming direction and try to maintain a constant position towards the approaching trawl, which requires the least energy consumption (Wardle, 1993). The fish often swim until they become exhausted, which forces them to shift from aerobic to anaerobic metabolism, which is identified by the transition from an optomotor response to an erratic response (Wardle, 1993; Kim and Wardle, 2003). Exhaustive swimming might negatively affect the quality of cod (Svalheim et al., 2018). Furthermore, cod tend to seek an escape route downwards, resulting in a substantial number of cod being run over by the ground gear, leading to ground gear related injuries (Ingolfsson and Jørgensen et al., 2006; Brinkhof et al., 2017). When fish drop into the narrowing trawl belly, they enter the sorting grid, which some fishers claim to have a negative impact on catch quality. However, this issue has yet to be objectively investigated. After fish pass through the sorting grid, they enter the extension piece followed by the codend.

Although few, most of the studies on the quality of trawl caught fish have focused on the codend. Previous studies claim that changing the mesh design from a standard diamond mesh to T90 (turning the meshes 90° from the conventional N-direction) significantly improves the quality of haddock in terms of reduced external injuries; however, similar results were not obtained for cod (Digre et al., 2010). Furthermore, the effect of towing time and catch size has been investigated. Increasing towing time (>5 h) and catch size (>10 t) lead to significantly elevated levels of lactate, increased mortality in the trawl, and reduced levels of muscle- and blood pH (Olsen et al., 2013). In addition, several studies have investigated how various abiotic factors (such as water temperature, season, and fishing depth) and biotic factors (such as the species, weight, size, and condition of fish) affect the quality and vitality of fish (Davis, 2002; Mello and Rose, 2004; Midling et al., 2012; Esaiassen et al., 2013 Humborstad and Mangor-Jensen 2013; Rankin et al., 2017).

2.1.2 Current methods used to investigate and quantify catch quality

Currently, three main methods are used to quantify catch quality: i) measurements of stress parameters, such as pH, lactate, and glucose, ii) visual evaluation of catch defects by applying indices (Rotabakk et al., 2011, Esaiassen et al., 2013; Olsen et al., 2013; Svalheim et al., 2017), and iii) diffuse reflectance hyperspectral imaging (Skjelvareid et al., 2017).

Stress parameters are good indicators of the state of fish and/or quality over time. However, to determine how these parameters change over time, fish must be kept alive and sampled at standardized intervals over time. Commercial factory trawlers used for the gadoid bottom trawl fishery in the Barents Sea produce directly headed and gutted fish that are usually frozen into blocks, with a few exceptions where fresh fish and/or fillets are produced. Hence, measuring the discrepancy in various stress agents over time to determine catch quality is not feasible at present in this fishery. Diffuse reflectance hyperspectral imaging represents a promising tool that is under development, which provides objective quantification of the residual blood in fish (Skjelvareid et al., 2017). Therefore, currently, catch quality is primarily determined by the visual assessment of damage inflicted during the catching or processing phase onboard fishing vessels or by fish dealers. The factors that are used to distinguish good versus poor quality are standardized into a catch damage index (Table 1, and Figure 3) and fillet index (Table 2, and Figure 4). Both indices are used in the fishing industry and by various studies investigating catch quality (Rotabakk et al., 2011, Esaiassen et al., 2013; Olsen et al., 2013; Svalheim et al., 2017).

Table 1. Catch damage index applied in Paper I and III to assess catch inflicted damage.

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 caused by gear contact
Pressure injuries	0	1	2	3	Injuries caused by crushing
Skin abrasion	0	1	2	3	Loss off scales

Table 2. Fillet index used in Paper I to assess fillet quality.

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



Figure 3. Example of poor-quality cod (top) that would score 2 on ‘gear marks’, 3 on ‘ecchymosis’, and 1 on ‘skin abrasion’. Example of a good-quality cod (bottom) that would score 0 for all five categories within the catch damage index. (Paper III).



Figure 4. (a) The two fillets on the left represent a typical example that would score 0 for the category “discoloration,” whereas the two fillets on the right represent a typical example that would score 2. (b) Example of fillet gaping (arrows). (Paper I)

Currently, few studies have documented fish quality, especially in relation to fishing gear. The catch damage and fillet indices have been developed to standardize the assessment of catch quality, both for scientists and the fishing industry. However, at present, scores of quality for both indices tend to be pooled and analyzed using statistical significance tests, resulting in a p-value, sometimes in combination with multivariate statistical tools, such as principal component analysis (PCA), correspondence analysis (CA), and canonical correlation analysis (CCA). There are multiple issues with using such significance tests (e.g. Yoccoz, 1991; Stephens et al., 2007; Goodman, 2008; Nuzzo, 2014; Baker, 2016; Wasserstein and Lazar, 2016). Amongst others, such hypothesis tests provide no measure of the effect size, and can be biological insignificant although proving statistical significance. Furthermore, pooling the data from all hauls does not account for between haul variance and uncertainties that exist in such data. Therefore, reliable and robust methods must be developed to analyze data derived from the assessment of catch quality.

Both from a scientific and fisheries industry perspective, it is of interest to quantify how changing certain parameters, such as the codend design or a trawling practice, might affect catch quality. From a production perspective, knowing the probability of obtaining a fish without any catch damage is crucial. In addition, knowing the probability and severity of damage to catch is important. Furthermore, knowing the probability of obtaining a given combination of catch damage and not exceeding a given score (severity) could be useful. Methods used to analyze such data derived from the assessment of catch quality should account for both between and within haul variance.

2.2 Importance of size selectivity

Components of a trawl, including trawling practices, contribute to total catch efficiency and catch composition, including catch quality; thus, these components and practices could be modified to achieve the desired goals. However, changing a specific trawling practice, or a given trawl component, to improve catch quality might simultaneously affect other properties, such as size selectivity. Therefore, when changing an established trawling practice or a trawl component, it is important to document both its effect on catch quality and its potential effect on size selectivity.

Size selectivity in fishing gear, particularly trawls, represents the main area of research focus over the last decades (Walsh et al., 2002; Jørgensen et al., 2006; Sistiaga et al., 2008;

Graham, 2010). Species selectivity refers to the species composition in the catch that differs from the species available to the fishing gear, whereas size selectivity refers to the length distribution of the retained fish that differs from the length distribution of fish available in fishing area, given that it entered the trawl. This phenomenon is quantified by measuring the discrepancy in fish length between the fish that have been retained and the fish that have escaped. Although some selective processes are unintended (Ingolfsson and Jørgensen, 2006; Brinkhof et al., 2017), others aim to deliberately adjust the species (Engås et al., 1998; Krag et al., 2010) and size (Sistiaga et al., 2010, 2016) composition in the codend catch. By adjusting the size and species composition of the catch, it is possible to mitigate the bycatch of unwanted species and/or juvenile fish below the MRCS. In the Barents Sea bottom trawl fishery for cod, the MRCS of 44 cm is regulated by codend configuration, which includes a minimum mesh size of 130 mm (Norwegian Directorate of Fisheries, 2018). In addition, a sorting grid with a minimum bar-spacing of 55 mm is compulsory (Norwegian Directorate of Fisheries, 2018). Due its low weight and small size, the Flexigrid is currently by far the most used grid system in the fishery.

2.2.1 Basic theory of size selectivity in trawls

A size selective process occurs when there is a discrepancy in the length distribution of the fish retained and the size distribution of the population being fished. This discrepancy may be quantified by: i) directly calculating the difference between the fish retained in the codend and the fish that escaped, which are retained in a cover, i.e., covered codend method; ii) alternating between a non-selective control trawl and a trawl with an experimental setup, i.e., paired-gear method; or iii) comparing the length distribution between two catches, i.e., catch comparison. To model the discrepancy, the total length of the fish from all compartments (codend(s) and/or cover(s)) must be measured. Size selectivity is commonly modeled by applying a logistic cumulative distribution function (Equation. 1), resulting in a sigmoid curve (Figure 3):

$$\text{logit}(l) = \frac{\exp(a+bl)}{1+\exp(a+bl)} \quad (1)$$

where l denotes the length of the fish, and a and b the parameters of the model. L_{50} represents the fish length at which there is 50% probability of retention (Figure 3):

$$L_{50} = -\frac{a}{b} \quad (2)$$

and SR (Selection Range) represents the length range of fish with the probability of retention between L_{25} and L_{75} (Figure 3),

$$SR = \frac{2 \times \ln(3)}{b} = \frac{\ln(9)}{b} \quad (3)$$

Equation (1) may be rewritten as:

$$r_{logit}(l, L_{50}, SR) = \frac{\exp\left(\frac{\ln(9)}{SR} \times (l - L_{50})\right)}{1 + \exp\left(\frac{\ln(9)}{SR} \times (l - L_{50})\right)} \quad (4)$$

The lower the SR , the steeper the selection curve, i.e., fewer fish below the MCRS are retained, and fewer fish above the MCRS escape. Figure 3 shows that, when considering an MCRS of 44 cm (as is the case for Northeast Arctic cod), few fish below the MCRS are likely to be retained, while a substantial fraction of fish size groups above the MCRS manage to escape in this specific example.

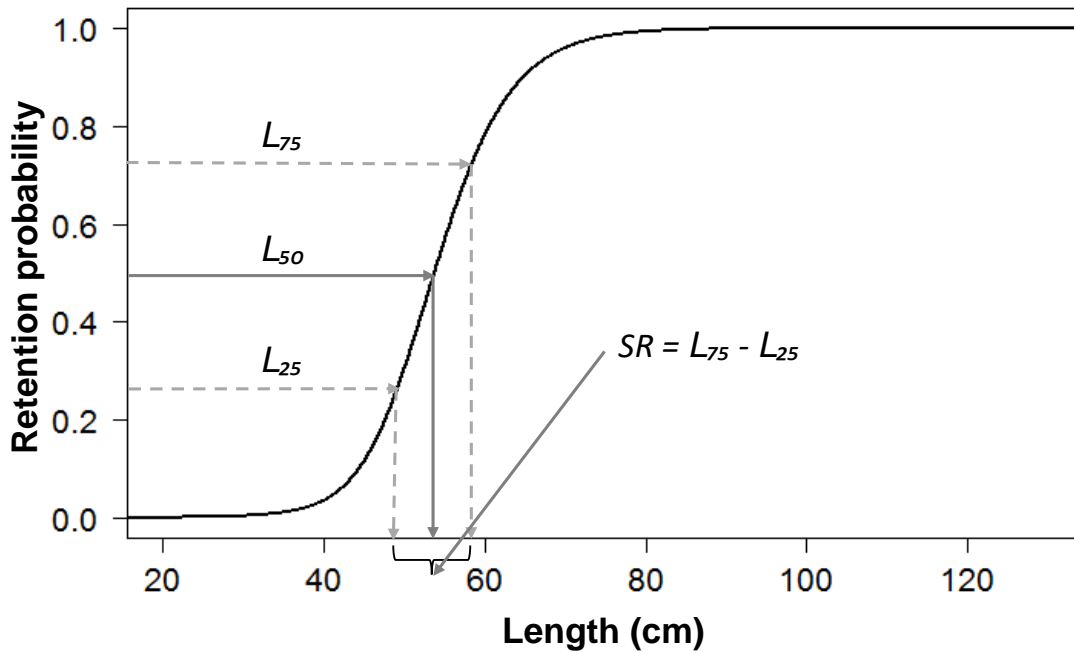


Figure 3. A typical selection curve for cod in the Barents Sea bottom trawl fishery, demonstrating the L_{50} (length with 50% probability of retention) and SR (Selection Range, $SR = L_{75} - L_{25}$).

Depending on the nature of the data, different models may be used to calculate size selectivity. Due to the complex trawl setups that are used (such as in the Barents Sea bottom

trawl fishery), the original Logit model, presented in Wileman et al. (1996), has been developed into extended models that account for dual selectivity systems (grid combined with mesh selectivity) and contact parameters (Sistiaga et al., 2010 and 2016; Grimaldo et al., 2016). In all instances, these are estimations of size selectivity. Because size selection is influenced by many factors, both biotic and abiotic, variation within and between hauls exists. These variations are commonly accounted for by using bootstrapping methods, including the estimation of Efron's percentiles (Efron, 1982).

2.2.2 Factors influencing size selectivity in trawls

Making relatively small adjustments to trawl components that have size selective properties might have a significant effect on size selectivity. The most commonly manipulated factors that influence size selectivity are mesh size and sorting grids (Jørgensen et al., 2006; Grimaldo et al., 2008; Sistiaga et al., 2008; Graham, 2010; Grimaldo et al., 2016). However, several studies have demonstrated that codends of equal mesh size with different twine thicknesses, twine numbers, and mesh orientation affect size selectivity properties (Herrmann and O'Neill, 2006; Sala et al., 2007; Wienbeck et al., 2011; Herrmann et al., 2013). In addition to affecting size selectivity, many fishers and researchers claim that different codend designs affect catch quality. For instance, codends build from T90-meshes had significantly improved size selectivity compared to codends with regular meshes (Wienbeck et al., 2011). Digre et al. (2010) investigated the quality of cod and haddock retained with T90 codends in comparison to fish from regular codends, and concluded that fish retained with T90 codends had less catch related damages. Some fishers and researchers claim that codends built of knotless Ultracross (PE based twines) improve catch quality by reducing the amount of blood spots often seen in fish fillets, which are caused by the coarse knots in regular codends (pers. obs. and comm.). Thus, codend design might affect both the size selectivity and quality of catch. However, aside from size selectivity being affected by the design of the various trawl components, it is also be affected by various operational procedures, such as the height of the fishing line above the seabed and ground-gear configuration (Main and Sangster, 1981; Engås and Godø, 1989; Ingolfsson, and Jørgensen, 2006; Krag et al., 2010; Brinkhof et al., 2017), haul-back procedures (Madsen et al., 2008; Grimaldo et al., 2009; Herrmann et al., 2013), and various environmental factors (Engås and Ona, 1990; Ona and Godø, 1990; Petrakis et al., 2001). Such trawling procedures might influence both size selectivity and catch quality.

3. Objectives and justification

Based on the current challenges in the Barents Sea bottom trawl fishery for cod, the objectives of this thesis were to investigate two aspects that are believed to affect the quality of trawl caught fish. Many factors that potentially affect both catch quality and size selectivity (such as water temperature, fishing depth, and other spatial and seasonal differences) are difficult to control (Sartoris et al., 2003; Mello and Rose, 2004; Suuronen et al., 2005; Margeirsson et al., 2007). However, several other factors that also are believed to have a direct impact on both catch quality and size selection may be controlled to some degree. For instance, factors such as catch size and towing time influence the quality of the catch (Olsen et al., 2008, 2013) and size selectivity (Herrmann, 2005). In addition, towing time and speed, which are interlinked with exhaustive swimming, also influence the quality of the catch (Svalheim et al., 2017) and size selectivity (Dahm et al., 2002). However, these and other factors, such as haul-back speed and buffer towing, need to be investigated to understand how they affect both catch quality and size selectivity. The practice of buffer towing has increased due to the high abundancies of cod in the Barents Sea. The practice might negatively impact the catch quality, along with the risk of releasing fish at a depth that may be lethal (to fish). Hence, the primary objectives of Papers I and II were:

- i) To investigate and quantify the effect of buffer towing on the quality of the catch (Paper I)
- ii) To investigate whether size selectivity occurs during buffer towing (Paper II)

Buffer towing is an example of a trawling practice that might influence both catch quality and size selectivity, whereas the design of the trawl and its components might also have a substantial effect on both catch quality and size selectivity. In particular, the codend materials and design might have a major effect on catch quality and size selectivity. Although many studies have documented size selectivity in various codend designs (Herrmann and O'Neill, 2006; Jørgensen et al., 2006; Sala et al., 2007; Grimaldo et al., 2010; Wienbeck et al., 2011; Herrmann et al., 2012; Herrmann et al., 2013), few studies have investigated the effect of codend design on catch quality (Digre et al., 2010). Therefore, a new codend concept was designed with the aim of improving catch quality without compromising size selectivity. Hence, the primary objectives of Papers III and IV, respectively, were to investigate:

- i) The quality of the catch retained in the new codend concept (Paper III)
- ii) Whether the new codend concept compromises size selectivity (Paper IV)

4. Effect of buffer towing on catch quality and size selectivity

Buffer towing, also known as ‘short-wiring’ in the Alaska Pollock fishery (Dietrich and Melvin, 2007), is a trawling practice that has been increasingly conducted over the current decade when fishing densities are high (Norwegian Directorate of Fisheries, 2013). It involves lifting the trawl up in the water column where it is towed for an extended time until the fish storage bins containing the catch from the previous haul are emptied, and the production capacity onboard is restored (Figure 5). The rationale for this practice is to avoid stopping the onboard the trawler processing factory unnecessarily by redeploying the trawl immediately after taking a catch onboard, with the aim of securing a continuous supply of fish. However, if the approximate desired amount of fish is caught before the catch from the previous haul is processed, the trawlers choose to buffer tow to avoid excessively large catches.

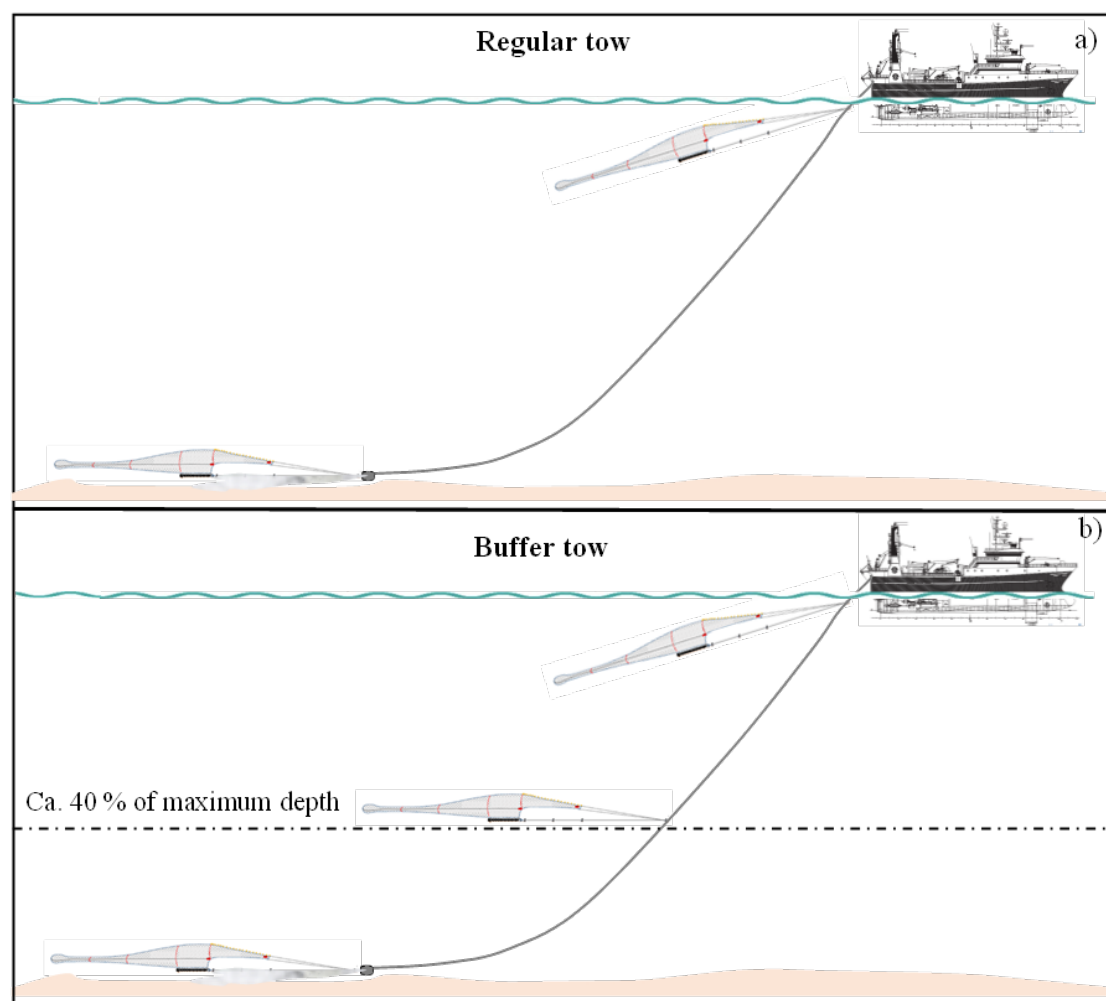


Figure 5. Schematic showing a regular tow with direct haul-back (a) and a buffer tow (b). (Paper I)

Fish catches subjected to buffer towing might contain an increased frequency and severity of fish with gear marks, skin abrasion, fillet gaping and redness, poor exsanguination, and dead fish; thus, this practice might have a negative impact on catch quality. This suggestion is corroborated by previous studies that have documented the negative effect of various factors that are present during buffer towing on catch quality, such as exhaustive swimming by fish (Svalheim et al., 2017), increased towing time (Olsen et al., 2013), increased catch size, and increased crowding (Suuronen et al., 2005; Margeirsson et al., 2007; Olsen et al., 2008, Rotabakk et al., 2011; Digre et al., 2017). Furthermore, rapid decompression when lifting the trawl off the seabed might have a negative effect on catch quality, as the swim bladder of cod, which is physoclistous, expands and eventually bursts when ambient water pressure drops below ~70% of the capture depth (Midling et al., 2012; Humborstad and Mangor-Jensen, 2013).

Buffer towing might also lead to the mortality of escaping cod for two main reasons. First, the Norwegian coast guard has documented fish floating on the surface behind trawlers engaged in buffer towing. Fish floating at the surface are positively buoyant, due to an overinflated swimbladder and rarely survive (Midling et al., 2012). Second, buffer towed catches contain suspiciously fewer undersized fish, indicating the presence of a size selective process during buffer towing (Norwegian Directorate of Fisheries, 2013). This observation supports that of previous studies, which documented a continuous size selective process in the codend during haul-back and at the surface (Isaksen and Løkkeborg, 1993; Madsen et al., 2008; Grimaldo et al., 2009; Herrmann et al., 2013). Although several studies have documented high survivability of cod escaping from trawl codends at the seabed (Soldal et al., 1993; Suuronen et al., 1996; Ingólfsson et al., 2007), few studies that have investigated the likelihood of survivability of fish escaping during haul-back and at the surface indicated higher mortality rates (Breen et al., 2007). Furthermore, the mortality rates of fish escaping during haul-back and at the surface might be even higher when considering long-term factors known to affect survivability, such as stress, behavioral impairment, barotrauma, osmotic disturbances due to scale loss, and other types of injuries. These factors increase the risk of predation and disease susceptibility (DeAlteris and Reifsteck, 1993; Soldal et al., 1993; Chopin and Arimoto, 1995; Suuronen et al., 1996, 2005; Davis, 2002; Ryer, 2002; Ryer et al., 2004; Nichol and Chilton, 2006; Humborstad and Mangor-Jensen, 2013; Rankin et al., 2017). Hence, in addition to documenting the effect of buffer towing on catch quality (Paper I), it was also of interest to document any potential size selection, which is addressed in the second study (Paper II). Therefore, the specific objectives of Paper I were to answer the following research question:

- 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?

Followed by the specific objectives for Paper II, which aimed to answer the following research questions:

- Does size selection occur during buffer towing?
- If size selectivity does occur during buffer towing, then what are the sizes of the cod that escape and what is their escape rate?

4.1 Investigating the effect of buffer towing on catch quality (Paper I)

Methods used to document catch quality have been limited to measurements of stress parameters (such as pH, lactate, and glucose) and visual evaluations of catch defects by applying indices (Rotabakk et al., 2011, Esaiassen et al., 2013; Olsen et al., 2013; Svalheim et al., 2017). Stress parameters provide a good indicator of the state of the fish and/or quality over time. However, fish must be kept alive to obtain measurements at standardized intervals over a period of time. In addition, stress may directly impact catch defects, and vice versa, with these parameters being regarded as interlinked (Olsen et al., 2008). Moreover, commercial factory trawlers in the Barents Sea gadoid bottom trawl fishery produce directly headed and gutted fish, which are mostly frozen into blocks, with some fresh fish and/or fillets being produced. Thus, measurements of stress parameters are not possible, desirable, or representative when the aim is to document the effect of a given gear component or trawling procedure on catch quality. Visual assessment of catch defects by applying standardized catch damage indices and fillet indices are the current methods used to evaluate catch quality, both scientifically and in the fishing industry. Therefore, this method was used for assessing the effect of buffer towing on catch quality in the present study.

Both from a scientific and fishery industry perspective, it is important to determine how large the effect of a given change in the codend or trawling procedure might have on catch quality. Statistical significance tests do not provide any measure of the effect size, and may be biologically insignificant although proving statistical significance ($p < 0.05$) (Yoccoz, 1991; Goodman, 2008; Baker, 2016). For instance, the magnitude might be so minor that it has no or little influence on total catch quality. Therefore, in Paper I, a new statistical method for

estimating the effect of scores derived from catch damage indices and fillet indices is presented. This method estimates the probability of obtaining a given score. It also estimates the probability of obtaining a given score for a given combination of catch damage categories, as well as the probability for not exceeding a given score (the probability of obtaining a given score or lower). Similar to the methods commonly applied in selectivity studies, the present study also incorporates between haul variations by estimating uncertainties in the form of confidence intervals through applying bootstrap methodology. Estimating the probability of obtaining a given score for a given category (catch damage) for cod hauled-back directly and cod subjected to buffer towing provides an applicable measurement of catch quality. Estimating the confidence limits by applying bootstrapping methods provides reliable limits for the estimated score probabilities, i.e., quality levels. By providing bootstrap based estimates for the difference in the estimated quality scores, this method allows the direct comparison of catch quality between cod subjected to buffer towing and cod hauled-back. In addition, this method allowed the relative difference in the probability of obtaining a given score to be obtained, and thus a magnitude of the improvement or reduction in catch quality. Furthermore, this method allows the probability for obtaining a given score for a combination of categories to be estimated. Knowing the probability of obtaining a given score for a combination of categories provides valuable information for production managers in the industry when deciding which product the fish are suitable according to the type of catch-inflicted defects. For instance, gear marks and/or skin abrasion, depending on the severity, are not necessarily critical for fillet production, whereas ecchymosis and poor exsanguination are.

By applying this method on the scores derived from the quality assessment of cod subjected to buffer towing, it was possible to demonstrate that buffer towing had a significant negative effect on the quality of the catch compared to cod haul-back directly. The relative probability of poor exsanguination increased by 371%, while fillet redness increased by 209% (amongst other parameters). The study confirms that the negative impact of buffer towing is severe, and should be avoided. Hence, the results presented in this study corroborate claims from the trawler industry that buffer towing causes a reduction in catch quality. Due to the statistical methods applied, this study allowed the magnitude of the negative effect to be quantified, instead of only demonstrating that there is a difference, as would be the case when providing a p-value from a statistical significance test. Furthermore, it provides the first probabilities for obtaining a given level of catch quality, and thus quantifying the amount of a given catch that could be expected to achieve a specific quality level. Both for scientific and

fishing industry purposes, knowing the magnitude of negative effects from buffer towing is crucial for future decision making. The results of the current study demonstrate that buffer towing with the aim of securing a continuous supply of fish to the factory onboard trawler, and thus ensuring maximum production efficiency, is not necessarily the most profitable way of fishing. However, this interpretation depends on the price differentiation between good and poor catch quality, and requires an associated economical assessment for each specific fishery. However, besides the economic implications of reduced catch quality of fish subjected to buffer towing, buffer towing might contribute to increased (unaccounted) fishing mortality for two reasons. First, poor catch quality might increase the risk of high-grading (Batsleer et al., 2015). Second, the catch defects fish incur when subjected to buffer towing might be lethal. Since management authorities claim that fish escape from the codend during buffer towing (Norwegian Directorate of Fisheries, 2013), likelihood of escaping fish surviving is questionable and might contribute to unaccounted fishing mortality. Therefore, the purpose of Paper II was to investigate the release of fish during buffer towing.

4.2 Investigating potential size selectivity during buffer towing (Paper II)

The most common method for quantifying size selectivity requires the retention of the escapee. This method is commonly achieved by mounting a small-meshed cover over the selective device (i.e., sorting grid or codend). This direct estimation of size selectivity allows the computation of selectivity parameters. However, in the case of documenting size selectivity during buffer towing, applying the covered-codend method was not possible, due to several limitations. First, a cover would collect all the escapes throughout the entire towing period, not just those during buffer-towing. Second, a cover might lead to biased estimates, as it might affect the escape possibilities of fish out of the codend, as well as the possibility of fish re-entering the codend (Madsen and Holst, 2002). Therefore, to investigate the effect of buffer towing on size selectivity, this type of direct estimation was not possible. Thus, an indirect method (i.e., catch comparison) was required. This indirect method constitutes of hauling back the trawl alternating between direct haul-back and buffer towing, allowing catch comparison. A benefit of applying this type of indirect method is that it requires no modification of the trawl, and is easy to use onboard commercial trawlers, where there is usually no time for delay, as it would delay the fishing efficiency. Because no additional equipment is needed, this method also increases sampling efficiency.

Commonly, catch comparisons use empirical models. However, a major drawback with empirical models is the lack of providing selectivity parameters. In addition, empirical models assume equal entry rates of fish between two sampling gears, which is often not the case, as demonstrated by the split value (SP), which is implemented in structural models, and accounts for variation in the entry rates of fish. Therefore, the present study applies a catch comparison with structural models, allowing the estimation of selectivity parameters and selection curves for the additional selection process during buffer towing. Another benefit of applying structural models is the robustness of extrapolations outside the range of length classes that are measured (Santos et al., 2016).

Using this indirect method, 20 hauls were conducted onboard the R/V “Helmer Hanssen” to collect experimental data, alternating between direct haul-back and buffer towing. Applying the structural catch comparison model demonstrated that a significant number of cod up to 42 cm long escaped during buffer towing. Specifically, during buffer towing, cod of 20, 30, and 40 cm, had escape probabilities of at least 60, 53, and 45%, respectively. It is possible that cod above 42 cm in length manage to escape during buffer towing; however, it was not possible to prove this in the present study due to the wide CI. For instance, the results indicate that buffer towing causes the loss of cod above the MCRS. Thus, these results corroborate the observations from the Norwegian Directorate of Fisheries and the Norwegian coast guard, who claim that catches subjected to buffer towing contain fewer fish below the MCRS than catches hauled-back directly (Norwegian Directorate of Fisheries, 2013). The results of the present study also corroborate previous findings, which documented a size selective process in the codend of trawls and demersal seines during haul-back, and at the surface (Isaksen and Løkkeborg, 1993; Madsen et al., 2008; Grimaldo et al., 2009; Herrmann et al., 2013).

The impact of buffer towing may be two folded. First, from a fishing industry perspective, buffer towing leads to the loss of marketable catch, reducing the catch per unit effort, in addition to reducing the quality of the catch, as described in Paper I. Second, although the industry concerns regard the loss of marketable catch, the concerns of the management authorities are related to the release of fish below the MCRS. The reduced retention probability of cod below the MCRS could, at first sight, be regarded as a positive improvement of the overall trawl selectivity. However, this interpretation depends on the fate of cod that escape. Previous studies have documented high survival rates of cod that escape during towing at the seabed (Soldal et al, 1993; Suuronen et al., 1996; Ingólfsson et al., 2007). However, it is possible that mortality increases when fish escape during haul-back and at the surface (Breen et al.,

2007). A number of long term factors also affect fish survival, thus the risk of a lethal outcome for cod escaping during buffer towing might be even higher (DeAlteris and Reifsteck, 1993; Soldal et al., 1993; Chopin and Arimoto, 1995; Suuronen et al., 1996, 2005; Davis, 2002; Ryer, 2002; Ryer et al., 2004; Nichol and Chilton, 2006; Suuronen and Erickson, 2010; Humborstad and Mangor-Jensen, 2013; Rankin et al., 2017).

Hence, buffer towing should be avoided both from a management and fishing industry perspective when considering the documented escape of cod above and below the MCRS and the reduced catch quality of cod subjected to buffer towing compared to direct haul-back.

5. Effect of codend design on catch quality: Is it possible to improve catch quality without compromising size selectivity?

The first two studies document the effect of a trawling practice on catch quality (Paper I) and size selection (Paper II), while the third study (Paper III) investigates a new codend concept with the aim of improving catch quality. Defects in fish quality (such as gear marks, skin abrasion, pressure injuries, internal and external ecchymosis, and insufficient exsanguination) are the most common type of visually detectable defects (Margeirsson et al., 2007; Rotabakk et al., 2011; Olsen et al., 2013; Digre et al., 2017). Conventional codends that are currently used in the demersal trawl fishery are built with large meshes (minimum 130 mm) and knots, and are made of coarse and stiff materials (e.g., PE from Euronet, Polar Gold). These codends are believed to cause skin abrasions, gear marks, and ecchymosis on fish. In particular, large knots are often perceived as red spots on the skin and/or fillets on fish that were pressed against the codend netting. Furthermore, conventional codends often become densely packed with fish when the catch aggregates, especially during haul-back (Figure 6). Such dense crowding of fish in the codend might prevent fish from freely moving their operculum, leading to hypoxic and anoxic conditions, due to inhibited water flow over the gill arches. This again, may result in increased levels of stress and suffocation which results in poor exsanguination. Another factor that might contribute to catch defects is the hauling of the codend with the catch over the stern. When hauling large catches over the stern, fish are exposed to the pressure of the surrounding catch, especially fish located at the aft of the codend.



Figure 6. Typical dense packing of fish in a trawl codend (left), resulting in visually detectable damage to catch (right).

Thus, a new codend was designed with the aim of improving catch quality by reducing damage to catch caused by the codend (Paper III). The attributes of such a codend should include a reduction of the mechanical strain on the catch, by avoiding dense crowding and coarse materials. Consequently, the codend was made of thick-twined knotless small-sized meshes. Designing a codend with small meshes with little opening for water flow, due to the thick twine, was believed to reduce the dense packing of fish inside the codend. Thus, the codend was believed to reduce both the mechanical strain caused by the conventional codend materials, as well as reducing water flow inside the codend, allowing fish to swim calmly and move their operculum. In addition, the codend was supposed to retain water inside the codend while the catch is pulled up the slip, further reducing the mechanical strain of the fish, due to the presence of the surrounding catch.

However, the bottom trawl fishery in the Barents Sea is regulated, amongst others, with a minimum codend mesh size of 130 mm (Norwegian Directorate of Fisheries, 2018), to ensure the release of fish below the MCRS. Although the compulsory sorting grid is supposed to release most of the fish below the MCRS, studies have demonstrated that the release efficiency in the most applied sorting grid is insufficient (Sistiaga et al., 2016), and that a minimum codend mesh size is important to ensure sufficient release of undersized fish. Hence the new codend concept had a dual sequential codend, with the aim of improving catch quality (Paper III), while maintaining equal release opportunities of undersized fish, as in a conventional codend, during the fishing process (Paper IV). The concept was that the first codend segment in the dual sequential codend fulfills the minimum mesh size, as required. During fishing the fish are retained in the first codend segment (Figure 7a). The entrance of the second codend segment is kept closed during towing, and is only opened during haul-back, resulting in the catch falling back into the second codend segment that has quality improving attributes (Figure 7b). However, because the entrance of the second codend segment opens during haul-back, any

potential release of undersized fish ceases. As several studies have documented a size selective process during haul-back and at the surface (Isaksen and Løkkeborg, 1993; Madsen et al., 2008; Grimaldo et al., 2009; Herrmann et al., 2013), this approach might alter the size distribution in the catch compared to a catch from a conventional codend. Hence, the aim of Paper IV was to investigate whether the size selectivity in the dual sequential codend differed to that in a conventional codend.

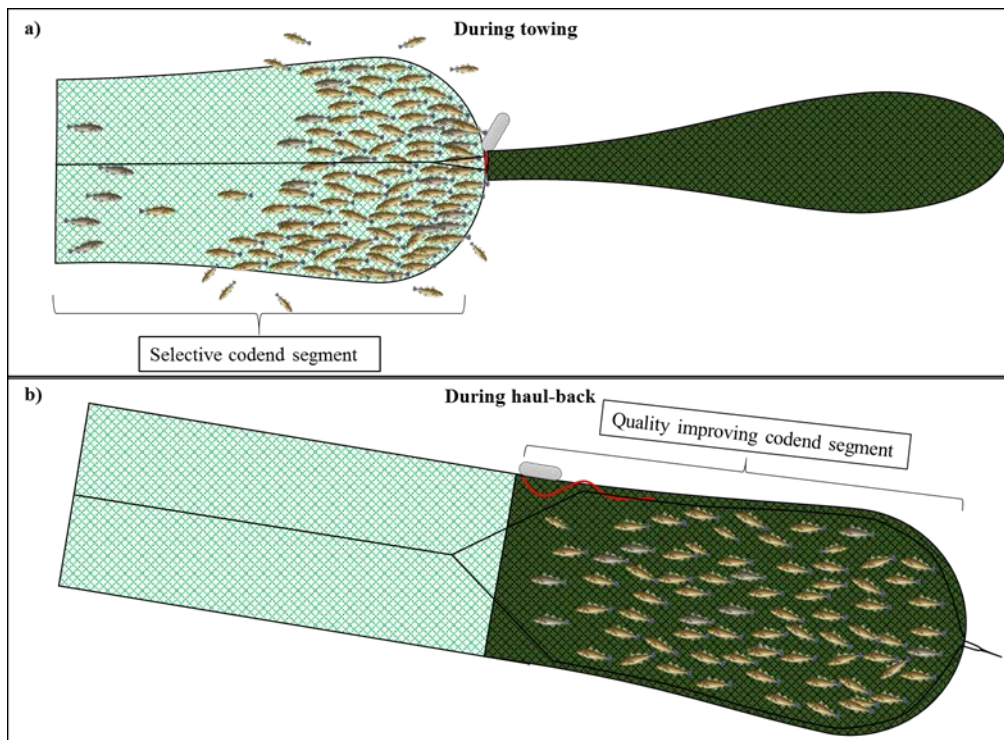


Figure 7. Dual sequential codend concept showing the first codend segment (a), where the fish are retained during towing, with the selective properties as legislated, followed by the quality-improving codend segment (b), where the catch falls back into during haul-back. The grey cylinder represents the catch reloader with the choking rope (red). (Paper III)

Thus, the specific objectives of Paper III were to:

- Investigate damage to cod caught with the conventional codend versus the sequential codend, and to compare the amount and severity of catch damage between the two codends.
- Document the functionality of the new sequential codend concept.

Paper IV addressed the following research questions:

- Is there any difference in the size selectivity between the trawl equipped with the conventional codend to that with equipped with the dual sequential codend?
- Is there any effect on the length-dependent catch patterns between the two codends?
- Will the retention risk for small cod be sufficiently low when using the sequential codend?

5.1 Improving catch quality by reducing catch damage through implementing a dual sequential codend concept (Paper III)

Defects in the quality of fish (such as gear marks, skin abrasion, pressure injuries, internal and external ecchymosis, and insufficient exsanguination) are the most common type of visually detectable defects in trawl caught fish (Margeirsson et al., 2007; Rotabakk et al., 2011; Olsen et al., 2013; Digre et al., 2017). Although several studies have documented the effect of various processing techniques on catch quality (Botta et al., 1986; Borderías and Sánchez-Alonso, 2011; Olsen et al., 2013 and 2014; Erikson et al., 2016), few studies have focused on how to prevent the quality of catch deteriorating during the catching process. Consequently, there has been a recent focus on improving the quality of trawl caught fish, with several ideas being developed and/or tested. Examples include direct pumping from the codend, transportation of fish from the trawl at the seabed to the surface with ROVs (Remote Operated Vehicles). All of these ideas are expensive, require the major development of new technology, and major intervention and reconstruction of the current ways of designing trawlers. Therefore, the idea of the current study was to develop a codend that improved the quality of trawl caught fish compared to current codends, without compromising the size selective properties required by law. The design of the codend was supposed to reduce the packing of fish inside the codend, reduce water flow, and retain water inside the codend, especially when the codend is pulled up the slip. These attributes were believed to reduce the mechanical strain and stress on catch and, thus, reduce the frequency and severity of damage to catch, leading to improved quality. To achieve such codend attributes, the codend should be built entirely of soft materials with little or no mesh opening. However, this contradicts the codend attributes required to attain sufficient size selectivity, which necessitates a large mesh size.

Therefore, the codend concept was designed to be dual sequential, where the first codend segment fulfills the size selective properties required by law, and the second codend

segment contains the quality improving attributes. During towing the entrance of the posterior codend segment is kept closed with a choking rope, which is released at a preset depth during haul-back by an inverse hydrostatic release mechanism, termed the catch releaser. Thus, during towing, the fish aggregate in the anterior codend segment, which allows fish to be released below the MCRS. During haul-back, the entry of the posterior codend is opened by the catch releaser, and the catch falls back into the quality improving codend segment. The anterior codend segment is built from regular codend material (i.e., hotmelt; Ø 8 mm), with a mesh size of 130 mm, which is in accordance with the minimum mesh size regulations. The posterior codend segment is a 4-panel codend built entirely out of knotless thick twine, with a mesh size of 6 mm, and is strengthened with an outer codend of knotless UltraCross, with a mesh size of 112 mm.

The sequential codend concept was trialed onboard the commercial trawler MTr “J. Bergvoll” by applying a double trawl, where one trawl was equipped with a conventional codend and the other trawl was equipped with the dual sequential codend. The same methods for assessing the quality of the catch was applied as in Paper I (i.e., applying the catch damage index). In addition, the same methods for analyzing the data from the quality assessment as in Paper I were applied. However, the method was further developed to make full use of the experimental design with the two codends being fished simultaneously, which allowed a paired comparison that removes some of the contribution from between haul variations in the estimated difference in catch quality scores. Applying this paired method increased the power of the analysis by narrowing the confidence bands for the estimated difference in score probability. Comparison of the quality of cod retained in the conventional codend with cod from the sequential codend confirmed a significant improvement in the quality for the latter codend. Cod retained in the sequential codend had a significant lower probability of incurring gear marks, poor exsanguination, skin abrasions, and ecchymosis. Estimating the probability for cod to obtain no catch damages at all (score 0, flawless) demonstrated that only 3.6% of cod retained in the conventional codend had no catch damage. In comparison, cod retained in the sequential codend had an 18% probability of obtaining no catch damage (Table 3). The probability of not exceeding score 1 (≤ 1 , slightly) demonstrated a significant improved probability for cod retained in the sequential codend (86%) compared to cod retained in the conventional codend (62%) (Table 3).

Table 3. Mean score probability with 95% CI for all catch damage categories combined for the conventional and sequential codends. The improvement in the score probability is presented in the far-right column.

Codend type	Score	Mean score probability (95% CI)	Improvement in score probability (95% CI)
Conventional	0	0.036 (0.008–0.072)	0.14 (0.06–0.24)
Sequential	0	0.18 (0.11–0.26)	
Conventional	≤1	0.62 (0.48–0.75)	0.24 (0.12–0.35)
Sequential	≤1	0.86 (0.79–0.92)	
Conventional	≤2	0.95 (0.89–0.99)	0.04 (-0.01–0.1)
Sequential	≤2	0.99 (0.97–1.00)	

From a fishing industry perspective, a more than five-folded increase in good quality cod (flawless) is substantial. In addition to the increased probability of obtaining flawless cod, there was a significant reduction in the severity for all catch damage categories within the catch damage index for cod retained in the sequential codend. In addition to the improved quality, which improves the potential of using the fish for various products and extends shelf life, the improved quality also reflects improved welfare. In particular, high catch quality and good fish welfare are becoming a prerequisite for capture-based aquaculture (Dreyer et al., 2008; Isaksen and Midling, 2010; Humborstad et al., 2013; Humborstad et al., 2016). Although fish kept in capture-based aquaculture are currently caught by demersal seines, the dual sequential codend design presented in this study facilitates the landing of live cod from trawlers. Furthermore, the sequential codend could be easily be applied to demersal seines. Because poor catch quality might increase the risk of illegal dumping and high-grading (Baatsleer et al., 2017), the risk for trawlers to high-grade their catch might be reduced when implementing the sequential codend.

5.2 Effect of using a quality improving codend on size selectivity and catch patterns of cod in the Barents Sea bottom trawl fishery (Paper IV)

Since the sequential codend significantly improved the quality of cod (Paper III), the next step was to investigate whether the new codend had any effect on size selectivity compared to the size selectivity of conventional codends. The fish are located in the anterior codend segment during towing, which has the same mesh size as the conventional codend. Therefore, it is reasonable to assume that, during towing, the size selective properties in the sequential codend are similar to that of conventional codends. However, it is possible that when the catch

releaser opens the entry of the posterior quality improving codend segment during haul-back that a difference in size selectivity arises. Several studies have documented that there is an ongoing size selective process during haul-back and at the surface (Isaksen and Løkkeborg, 1993; Madsen et al., 2008; Grimaldo et al., 2009; Herrmann et al., 2013).

Experimental fishing and data collection for this study were conducted onboard the R/V “Helmer Hanssen.” Similar to the issues when investigating size selectivity during buffer towing (paper II), it was not convenient to apply the covered-codend method in this study. Therefore, the same indirect catch comparison methods as those applied in Paper II were applied during the first part of the cruise, alternating between two trawls, one equipped with a conventional codend, and the other equipped with the sequential codend. During the last part of the cruise, covers were mounted over the grids and the codend of one of the trawls to retain all cod entering the trawl.

The data retrieved from the first part of the cruise were analyzed by applying the same procedures as in Paper II. In addition, a structural model was applied, allowing size selective parameters and the curve for the missing size selectivity in the sequential codend to be calculated. This model also benefitted from the robustness for extrapolations outside the range of available data (Santos et al., 2016), and allowed variation in the rates of fish entering the trawl (SP) to be accounted for. The results demonstrated that, compared to the conventional codend, the quality improving sequential codend had a significantly lower relative size selectivity for cod up to 47 cm in length. However, comparison of the catch patterns of the two codends demonstrated no significant differences. Notably, catch patterns are case specific, with two possible explanations as to why no difference in the catch patterns was detected. First, there were no small cod present in the area during experimental fishing. Second, all small cod entering the trawl were released before reaching the codend, i.e., through the flexigrid. The hauls conducted during the last part of the cruise, where all escapees were retained, demonstrated that small cod were present in the trawl; however, they managed to escape before haul-back. Furthermore, knowing the abundance of cod of all length groups entering the trawl allowed the absolute size selectivity for the entire process to be estimated. Estimation of the absolute size selectivity for the two trawls with the two different codends indicated that the trawl with the sequential codend had a slightly lower size selectivity for small cod compared to the trawl with the conventional codend; however, this difference was minor. The L_{50} of 64.33 cm (CI: 56.87–69.81) for the conventional codend and 62.90 cm (CI: 57.69–69.68) for the

sequential codend, although slightly lower for the latter codend, was not significantly different. Furthermore, both L_{50} values were far above the MCRS for cod of 44 cm body length.

Thus, a minor increase in the retention of small cod, should, arguably, be of less importance than improved catch quality, which, as demonstrated by Paper III, the application of the sequential codend facilitates. From a management perspective, the increased retention of undersized fish is not desirable, and the size selective properties of the conventional and dual sequential codend should be equal through all fishing phases. However, this approach requires survival of the escaping fish. Several studies have documented that the mortality of cod escaping at the seabed is negligible (Soldal et al., 1993; Suuronen et al., 1996; Ingólfsson et al., 2007). However, few studies have investigated the survival rates of cod escaping during haul-back or at the surface (Breen et al., 2007; Madsen et al., 2008). Many studies have documented that trawl caught fish frequently sustain injuries related to exhaustion, stress, and behavioral impairment, as well as barotrauma (DeAlteris and Reifsteck, 1993; Soldal et al., 1993; Chopin and Arimoto, 1995; Suuronen et al., 1996, 2005; Suuronen and Erickson, 2010; Midling et al., 2012; Rankin et al., 2017). Although injuries (such as scale damage, hemorrhages, stress and behavioral impairment, barotrauma, and other types of injuries) are not necessarily immediately lethal, they may cause delayed mortality over the long-term, due to elevated susceptibility to diseases and an increased risk of predation (Chopin and Arimoto, 1995; Davis, 2002; Ryer, 2002, 2004; Ryer et al., 2004; Suuronen and Erickson, 2010; Midling et al., 2012). Current knowledge on fish survival suggests that the escape of fish during haul-back and at the surface should be mitigated. Therefore, reducing unaccounted fishing mortality is important for precise stock assessment; thus, the potential increased retention of undersized fish in the dual sequential codend should be regarded as beneficial from a management perspective. This interpretation is particularly pertinent when considering both the uncertainty of the fate of escapees combined with the knowledge that poor catch quality increases the risk of illegal dumping and high-grading (Baatsleer et al., 2017). By significantly improving the catch quality of trawl caught fish, any increased retention of fish above the MCRS in the dual sequential codend would contribute to increased catch efficiency.

6. Conclusions, final remarks, and future recommendations

This thesis demonstrates the importance of trawl gear design and trawling practices on catch quality. Moreover, this thesis also demonstrates the importance of documenting size

selectivity when changing codend design or trawling procedure. Papers I and II documented the effect of a trawling procedure, i.e., buffer towing, on catch quality and size selectivity. It was concluded that buffer towing has a significant negative effect on catch quality (Paper I), with a significant number of cod of at least 42 cm escaping (Paper II). Papers III and IV documented the effect of a trawling gear component, presenting a new codend concept, which was designed to improve the quality of the catch. Paper III demonstrates that the new codend concept, termed sequential codend, worked as intended and improved catch quality significantly. However, due to its design, concerns were raised regarding its size selective properties, which were investigated in Paper IV. The study concluded that the sequential codend causes a minor increase in the retention of cod below the MCRS. However, as argued in Paper IV, the benefits of the improved quality when using the sequential codend overcome the minor increase in the retention of undersized cod.

Papers I and III present a novel method for analyzing data obtained from the visual assessment of catch quality when applying catch damage indices. The method estimates the probability of obtaining a given catch damage score. This method allows probability of obtaining a given score to be estimated for a given combination of catch damage, such as gear marks and poor exsanguination, or gear marks and ecchymosis. Furthermore, this method allowed the probability of not exceeding a given score to be estimated (the probability of obtaining a given score or lower). Double bootstrapping, which is commonly applied in size selectivity studies, enabled the confidence intervals to be estimated while accounting for uncertainties both within and between each haul. In general, studies investigating catch quality have applied the hypothesis test, resulting in a p-value that is often presented in combination with principal component analysis or the calculation of the average scores derived from the quality indices. There are certain risk in applying such hypothesis tests, as p-values do not present any magnitude of the effect; thus, such results do not provide meaningful information in terms of the probabilities for obtaining quality score, and could be statistically significant but biologically insignificant (Yoccoz, 1991; Stephens et al., 2007; Goodman, 2008; Nuzzo, 2014; Baker, 2016; Wasserstein and Lazar, 2016). From both a scientific and fishing industry perspective, results presented with a p-value are often difficult to interpret. Thus, the methods presented in Papers I and III provide the reader with an informative value that represents the probability of obtaining a given score according to catch damage indices. This approach is beneficial both from a scientific and fishing industry perspective, whereby knowledge of the probability of obtaining a given catch damage is essential to determine catch quality.

Papers II and IV investigated size selectivity, modifying the commonly applied catch comparison, which does not require any modification of the trawl. This indirect method is beneficial, especially when conducting research onboard commercial vessels where the time and possibilities for modifying fishing equipment are limited or out of question. In addition, instead of an empirical catch comparison, the studies applied a structural catch comparison that allowed size selectivity to be estimated, as well as being robust for extrapolation outside the range of available experimental data and taking into account the variation in the rates of fish entering the trawl. A disadvantage of this indirect catch comparison method is the need for robust data to achieve narrow confidence intervals. However, this issue may be compensated for by increasing the number of hauls.

Since the quality and vitality of fish caught is highly affected by biotic and abiotic factors depending on spatial and/or seasonal variation (Davis, 2002; Mello and Rose, 2004; Midling et al., 2012; Esaiassen et al., 2013 Humborstad and Mangor-Jensen 2013; Rankin et al., 2017), it is important to emphasize that the results from Papers I and III are case specific, and that the demonstrated differences in catch quality, as such, should be regarded as relative differences. Even size selectivity might be affected by spatial and seasonal variation. For instance, the circumference of a fish (which is related to the condition factor) is affected, amongst other factors, by the availability of food, and thus affects the possibility of a fish to pass through a mesh or grid-bar. However, the effect on seasonal and spatial variation on size selectivity needs investigation.

This thesis investigated the effect of buffer towing and codend design on the quality of catch and size selectivity. However, catch quality and size selectivity are influenced by many other factors, both in terms of how bottom trawls are operated and how trawls are designed; thus, further investigation is required. In terms of trawl operation, future studies should investigate the effect of a range of factors, including haul-back speed (ascend speed), depth during buffer towing, steepness of the stern ramp on the trawlers, catch size, towing speed and towing time. To the best of my knowledge, the effects of these factors as well as the effects of various trawl gear components have not yet been investigated. Future studies should investigate codend design, including material, mesh opening, 4-panel versus 2-panel, and codend circumference. In general, fishers have a clear idea of what possibly affects catch quality and size selectivity. Although many of the stated factors are believed to influence both catch quality and size selectivity, supporting scientific research and evidences are required.

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Paper I

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



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.

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

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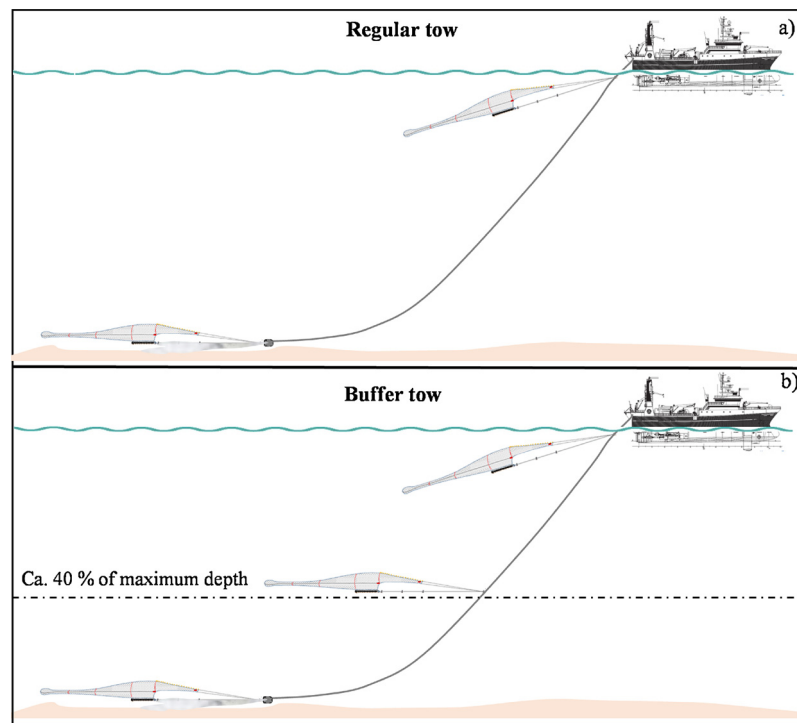


Fig. 1. Schematic showing a regular tow with direct haul-back (a) and a buffer tow (b).

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.

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 m²) 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 mt. 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

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

Catch damage	Score				Description
	Flawless	Slightly	Moderate	Severe	
Poor exsanguination	0	1	2	3	Improper bleeding, blood in veins
Echymosis	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
The fillet index used to assess the quality of the fillets.

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

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 $-30\text{ }^{\circ}\text{C}$ for further analysis on land. On land, the fish were thawed in tanks containing 1000 l of chilled water ($1\text{ }^{\circ}\text{C}$) for 24 h and then further thawed on ice for an additional 24 h at $0\text{--}1\text{ }^{\circ}\text{C}$. 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

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.

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

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.

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 \hat{p}_{as} for the probability for the score s on category a is:

$$\hat{p}_{as} = \frac{\sum_{j=1}^m \left\{ \frac{1}{n_j} \sum_{t=1}^{n_j} equal(s, k_{ajt}) \right\}}{m}$$

with

$$equal(s, k) = \begin{cases} 1 & \forall k = s \\ 0 & \forall k \neq s \end{cases} \tag{1}$$

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 .

Eq. (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 $pr\hat{m}_{as}$ for obtaining a score that did not exceed s on category a (i.e., the probability of obtaining a given score or lower):

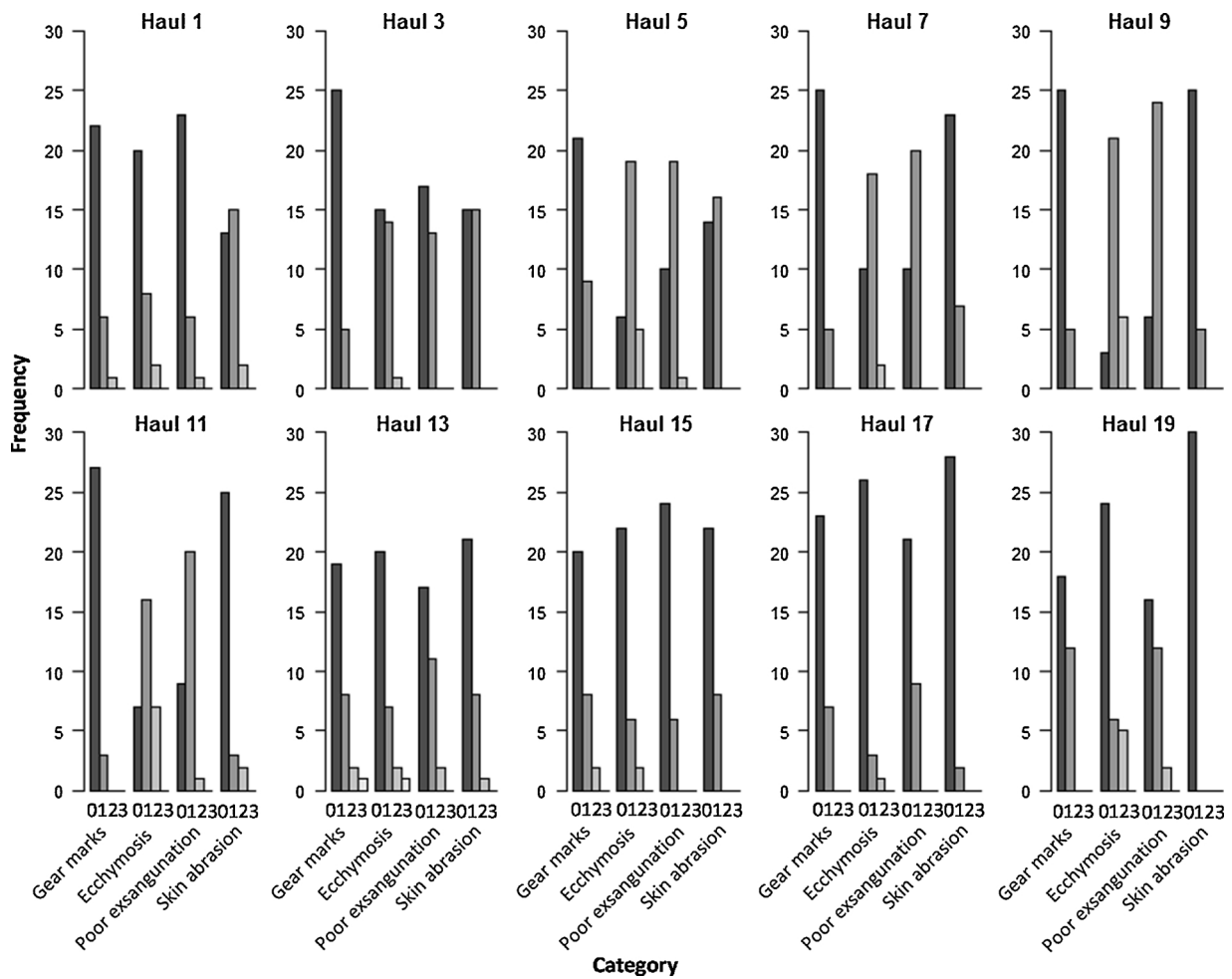


Fig. 2. Frequency of scores from the catch damage index for all cod caught with regular haul-back.

$$\hat{p}m_{as} = \frac{\sum_{j=1}^m \left\{ \frac{1}{n_j} \sum_{t=1}^{n_j} \text{lequal}(s, k_{ajt}) \right\}}{m}$$

with

$$\text{lequal}(s, k) = \begin{cases} 1 & \forall k \leq s \\ 0 & \forall k > s \end{cases}$$

Eqs. (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:

$$\hat{p}_{as} \hat{p}_{bs} = \frac{\sum_{j=1}^m \left\{ \frac{1}{n_j} \sum_{t=1}^{n_j} \text{equal}(s, k_{ajt}) \times \text{equal}(s, k_{bjt}) \right\}}{m}$$

$$\hat{p}_{as} \hat{p}_{bs} \hat{p}_{cs} = \frac{\sum_{j=1}^m \left\{ \frac{1}{n_j} \sum_{t=1}^{n_j} \text{equal}(s, k_{ajt}) \times \text{equal}(s, k_{bjt}) \times \text{equal}(s, k_{cjt}) \right\}}{m}$$

$$\hat{p}_{as} \hat{p}_{bs} \hat{p}_{cs} \hat{p}_{ds} = \frac{\sum_{j=1}^m \left\{ \frac{1}{n_j} \sum_{t=1}^{n_j} \text{equal}(s, k_{ajt}) \times \text{equal}(s, k_{bjt}) \times \text{equal}(s, k_{cjt}) \times \text{equal}(s, k_{djt}) \right\}}{m}$$

and

$$\hat{p}m_{as} \hat{p}m_{bs} = \frac{\sum_{j=1}^m \left\{ \frac{1}{n_j} \sum_{t=1}^{n_j} \text{lequal}(s, k_{ajt}) \times \text{lequal}(s, k_{bjt}) \right\}}{m}$$

$$\hat{p}m_{as} \hat{p}m_{bs} \hat{p}m_{cs} = \frac{\sum_{j=1}^m \left\{ \frac{1}{n_j} \sum_{t=1}^{n_j} \text{lequal}(s, k_{ajt}) \times \text{lequal}(s, k_{bjt}) \times \text{lequal}(s, k_{cjt}) \right\}}{m}$$

$$\hat{p}m_{as} \hat{p}m_{bs} \hat{p}m_{cs} \hat{p}m_{ds} = \frac{\sum_{j=1}^m \left\{ \frac{1}{n_j} \sum_{t=1}^{n_j} \text{lequal}(s, k_{ajt}) \times \text{lequal}(s, k_{bjt}) \times \text{lequal}(s, k_{cjt}) \times \text{lequal}(s, k_{djt}) \right\}}{m}$$

Eqs. (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

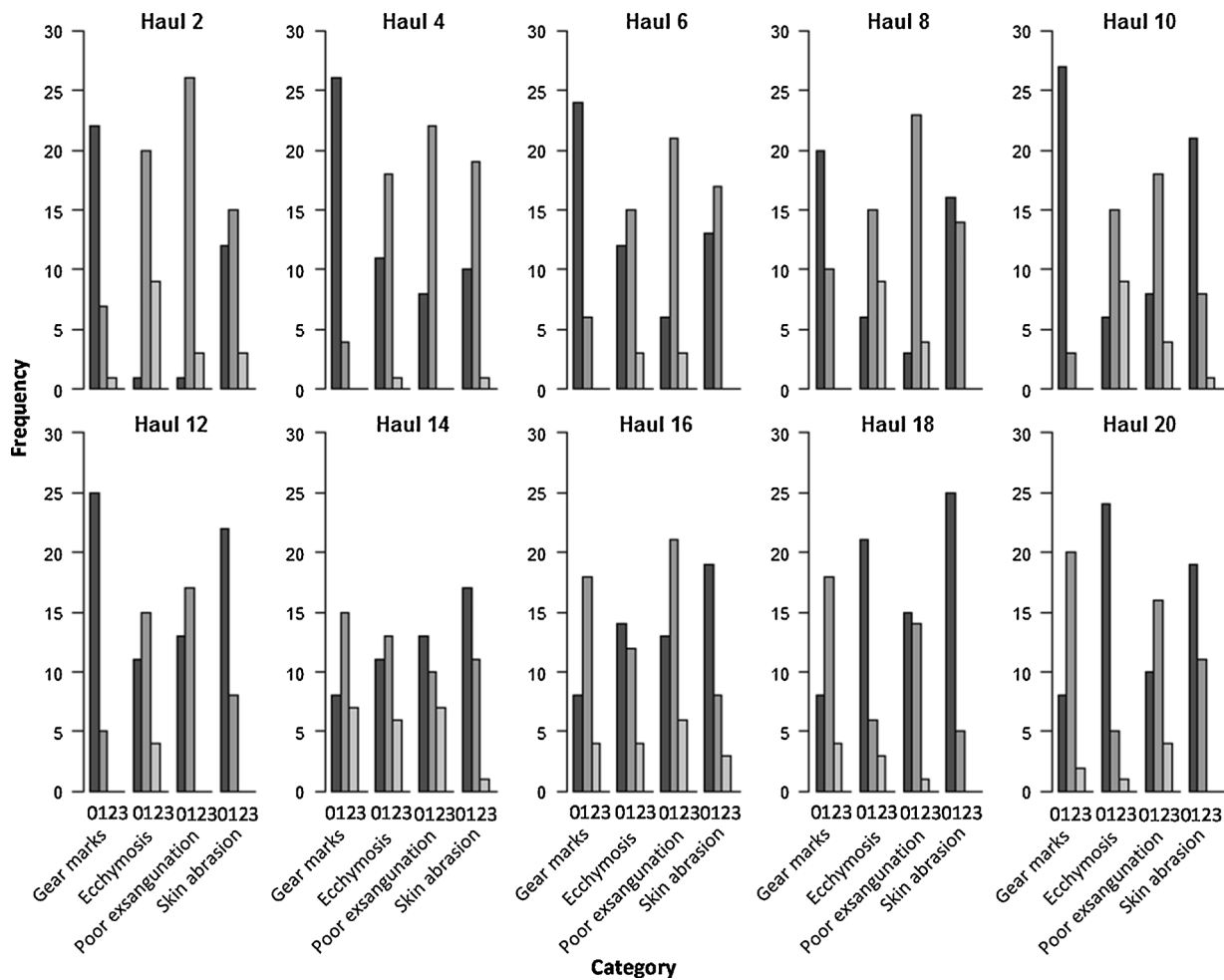


Fig. 3. Frequency of scores from the catch damage index for all cod that were buffer towed.

(Wienbeck et al., 2014; Brinkhof et al., 2017a,b). 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_i). The resulting data for each bootstrap were then used to estimate the expected category probabilities based on Eqs. (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:

$$\Delta r_i = r_{buffer}^i - r_{base}^i \quad i \in [1...1000] \quad (5)$$

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:

$$relr_i = \frac{r_{buffer}^i - r_{base}^i}{r_{base}^i} \times 100 \quad i \in [1...1000] \quad (6)$$

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

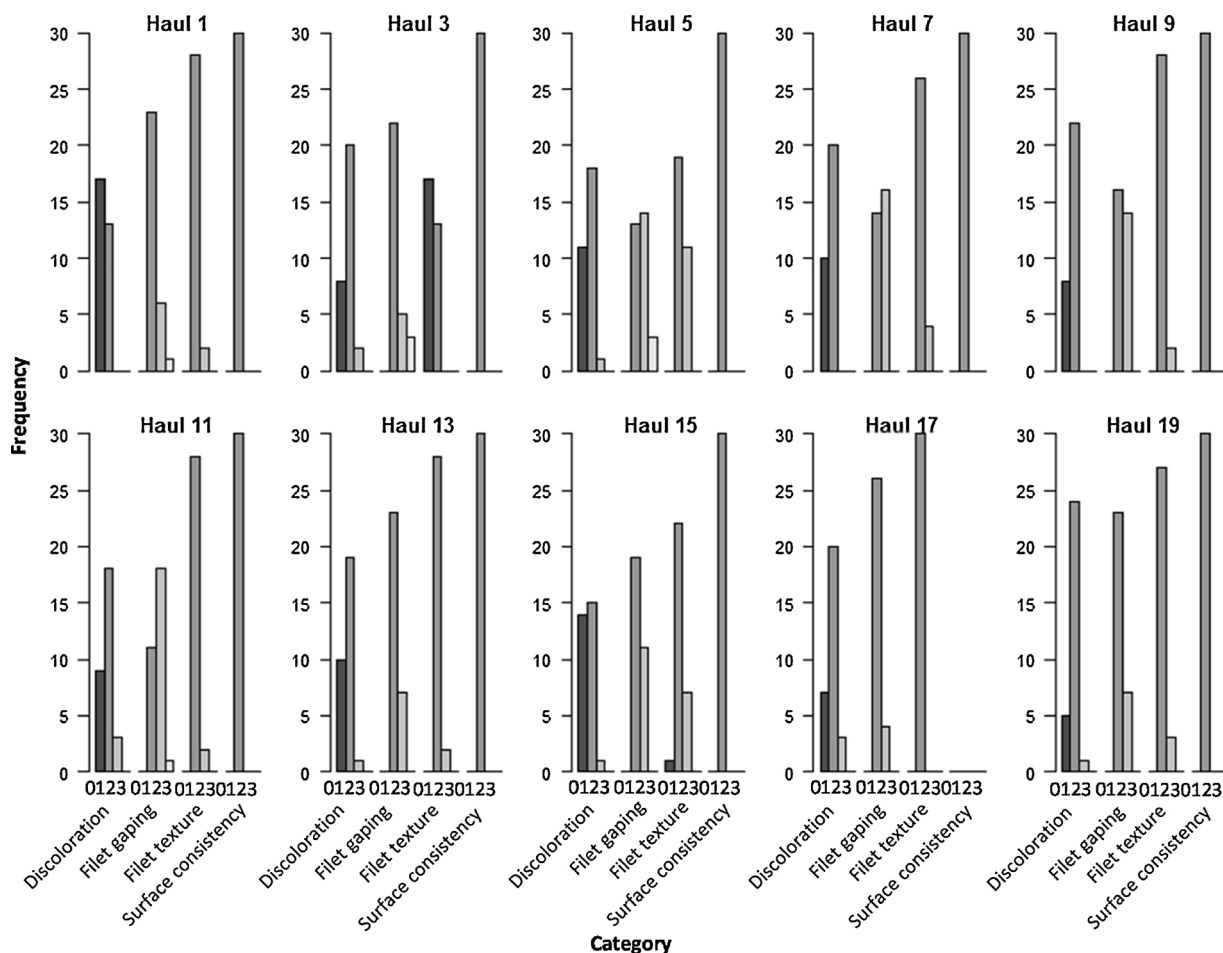


Fig. 4. Frequency of scores from the fillet index for cod that were hauled-back directly.

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).

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

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

Figs. 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.

Fig. 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).

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

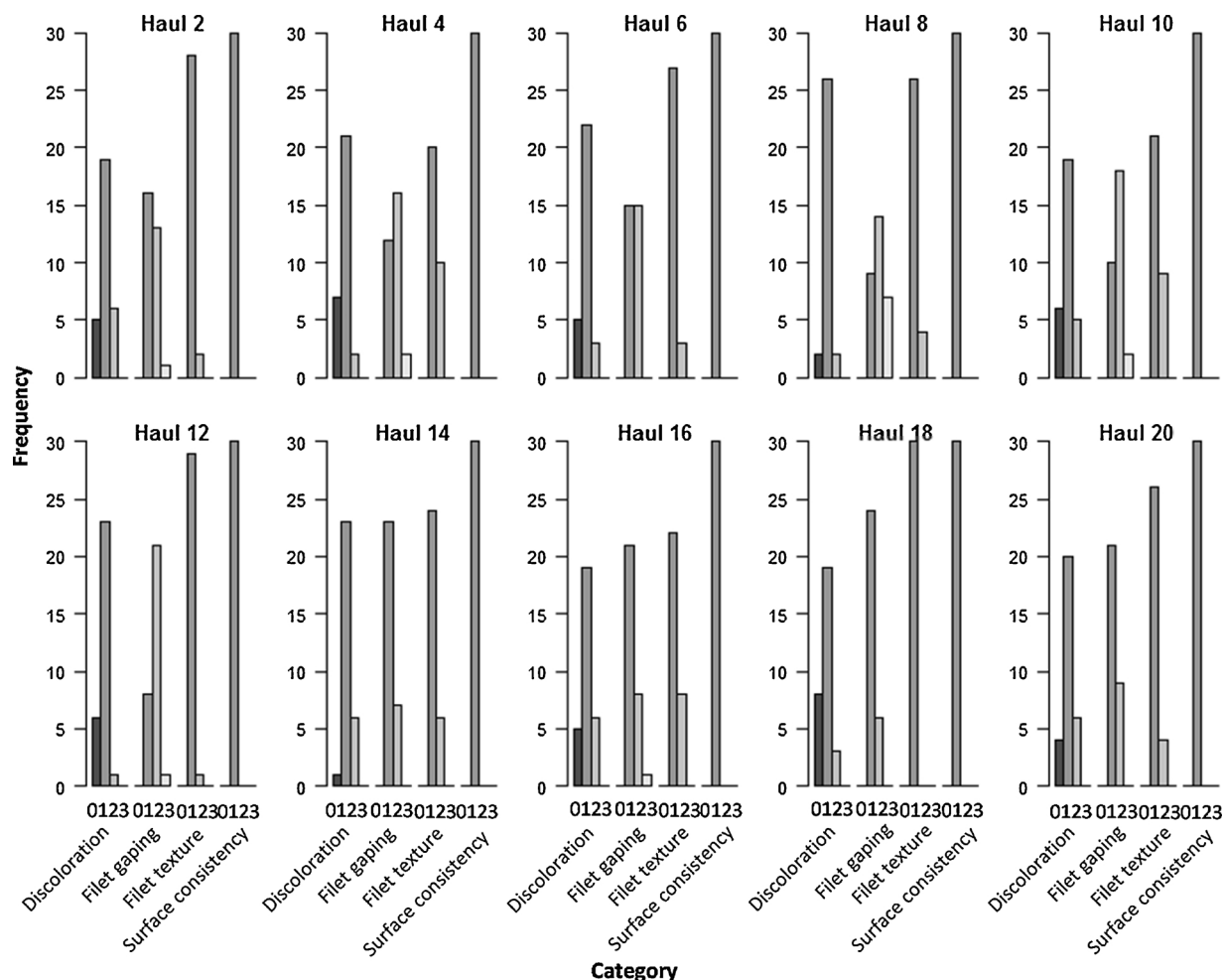


Fig. 5. Frequency of scores from the filet index for cod that were buffer towed.

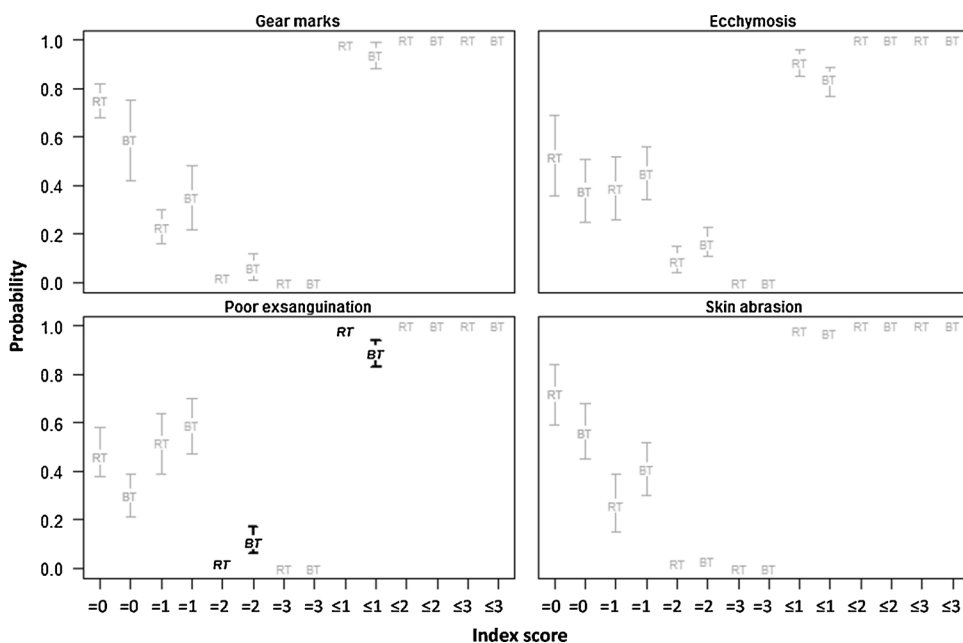


Fig. 6. Results from the catch damage index showing the probability for cod to obtain a score ranging from 0 to 3 for the four categories investigated. The bars represent 95% CIs. RT denotes regular tows and BT denotes buffer tows. The scores that proved a significant difference in fish quality between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

gear marks”, and “exsanguination and gear marks” (Fig. 7, Table 4).

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. 9 shows the estimated probabilities for obtaining a given score

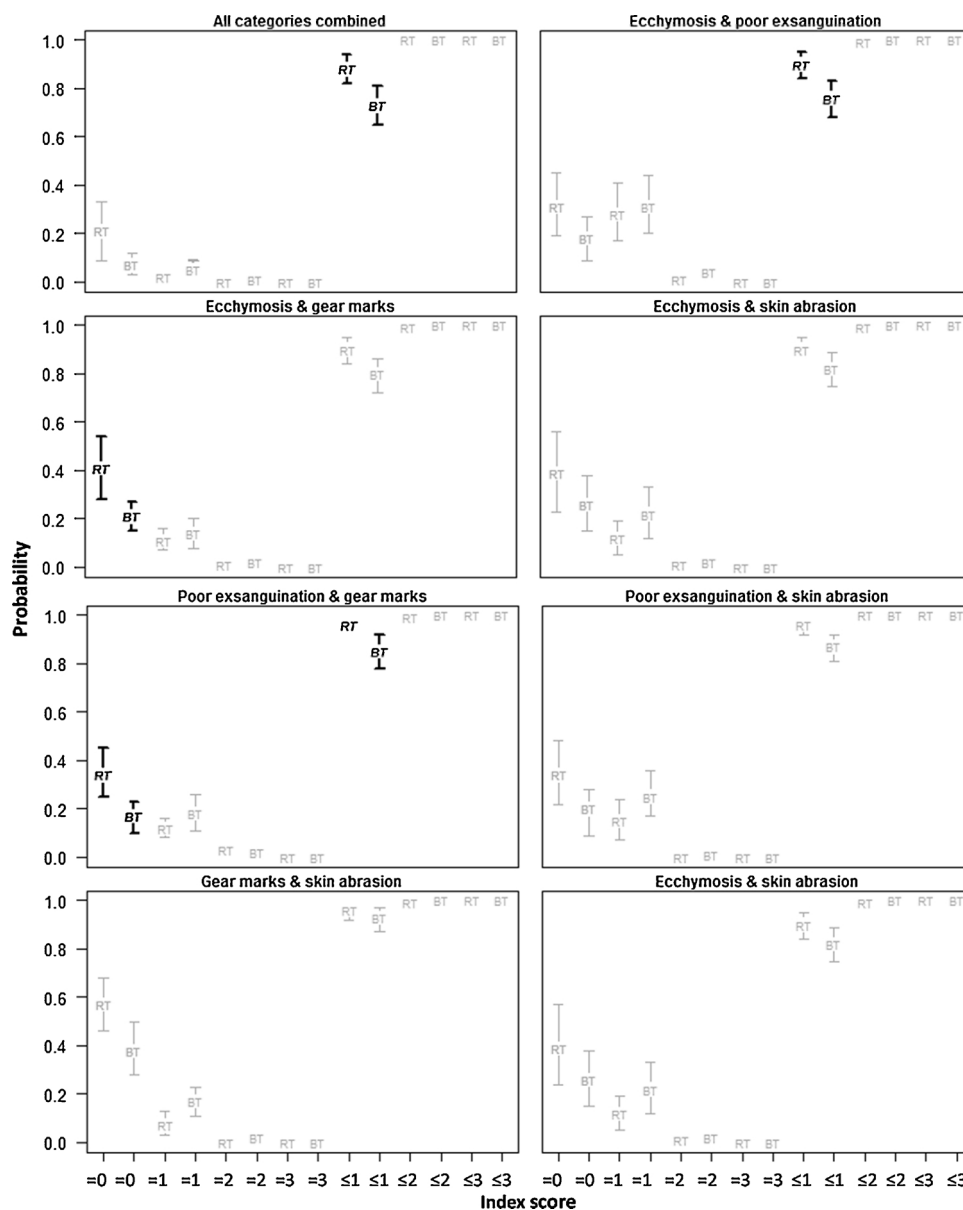


Fig. 7. Results from the catch damage index showing the probability for cod to obtain a score ranging from 0 to 3 for the four categories investigated for all categories combined as well as for all possible combinations of two categories. The bars represent 95% CIs. RT denotes regular tows and BT denotes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

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 Fig. 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. Fig. 10b shows a typical example of fillet gapping.

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.

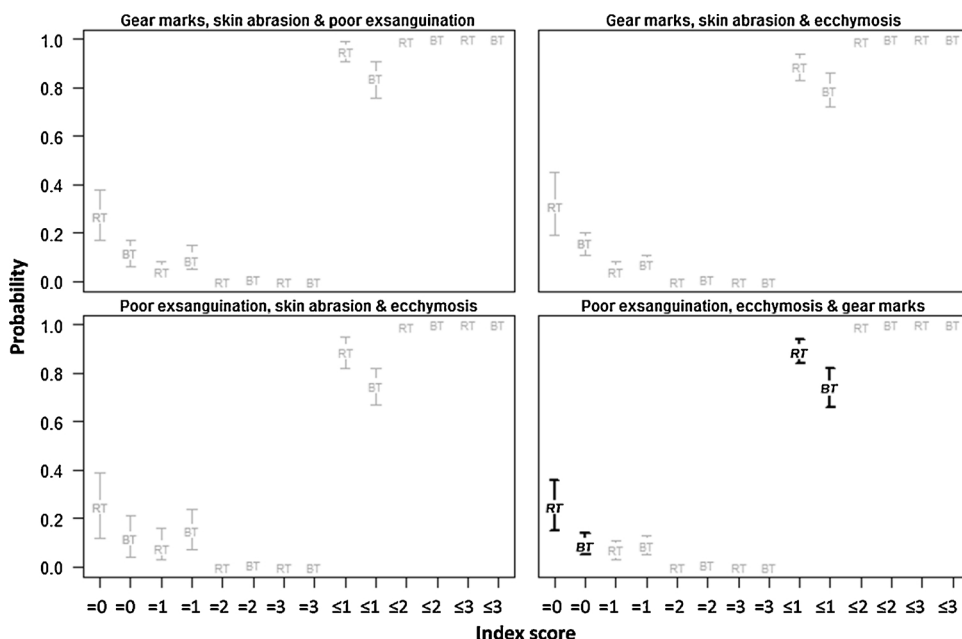


Fig. 8. Results from the catch damage index showing the probability for cod to obtain a score ranging from 0 to 3 for the four categories investigated for all possible combinations of three categories. The bars represent 95% CIs. RT denotes regular tows and BT denotes buffer tows. The scores that proved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

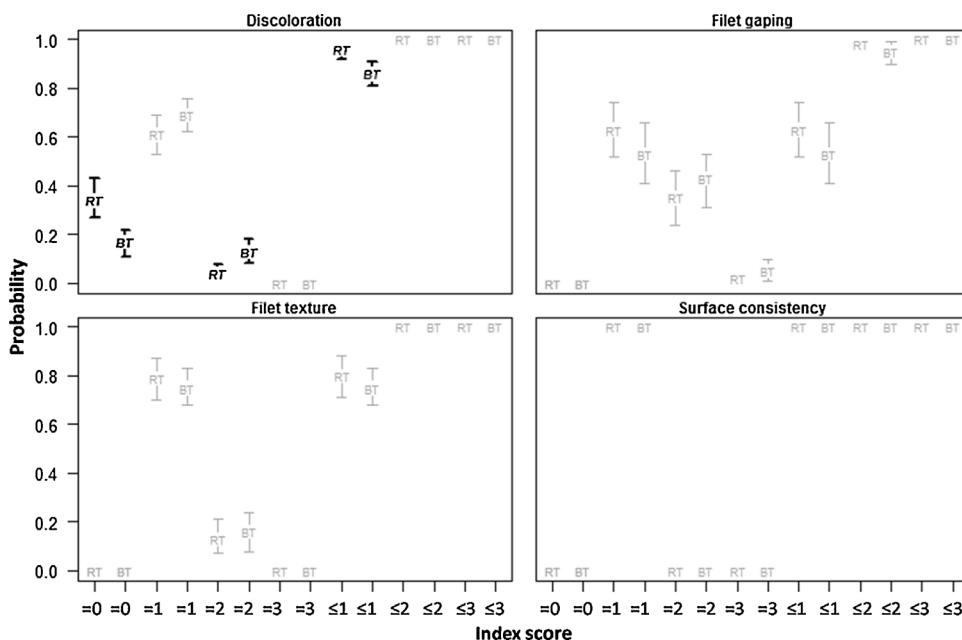


Fig. 9. Results from the fillet index showing the probability for cod to obtain a score ranging from 0 to 3 for the four categories investigated. The bars represent 95% CIs. RT denotes regular tows and BT denotes buffer tows. The scores that proved a significant difference in fish quality between RT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

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 h. 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 over-inflated, 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

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.

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 to -0.004)	-35.22 (-61.71 to -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 to -0.03)	-9.19 (-16.84 to -4.67)	
	All categories combined	= 0	0.21 (0.09–0.33)	0.07 (0.03–0.12)	-0.13 (-0.26 to -0.02)	-65.48 (-86.44 to -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 to -6.44)
		≤ 1	0.90 (0.84–0.95)	0.76 (0.68–0.83)	-0.13 (-0.23 to -0.05)	-15.24 (-25.35 to -6.67)
	Poor exsanguination & skin abrasion	≤ 1	0.96 (0.92–0.99)	0.87 (0.81–0.92)	-0.09 (-0.16 to -0.03)	-10.69 (-16.00 to -3.28)
		= 0	0.41 (0.28–0.54)	0.21 (0.15–0.27)	-0.20 (-0.33 to -0.07)	-48.03 (-68.56 to -22.73)
	Poor exsanguination & gear marks	≤ 1	0.90 (0.84–0.95)	0.80 (0.72–0.86)	-0.10 (-0.19 to -0.02)	-12.97 (-21.59 to -2.05)
		= 0	0.34 (0.25–0.45)	0.17 (0.10–0.23)	-0.18 (-0.29 to 0.60)	-52.54 (-72.40 to -24.72)
Poor exsanguination, ecchymosis, & gear marks	≤ 1	0.96 (0.93–0.99)	0.85 (0.78–0.92)	-0.11 (-0.20 to -0.04)	-12.66 (-21.54 to -4.18)	
	= 0	0.25 (0.15–0.36)	0.09 (0.05–0.14)	-0.16 (-0.29 to -0.05)	-64.84 (-83.58 to -30.37)	
Poor exsanguination, gear marks, & skin abrasion	≤ 1	0.89 (0.84–0.94)	0.74 (0.66–0.82)	-0.15 (-0.25 to -0.06)	-17.27 (-28.76 to -7.39)	
	= 0	0.27 (0.17–0.38)	0.12 (0.06–0.17)	-0.16 (-0.28 to -0.04)	-58.68 (-82.75 to -23.19)	
Ecchymosis, gear marks, & skin abrasion	≤ 1	0.95 (0.91–0.99)	0.84 (0.76–0.91)	-0.11 (-0.19 to -0.03)	-12.81 (-21.72 to -3.10)	
	= 0	0.31 (0.19–0.45)	0.16 (0.11–0.20)	-0.16 (-0.29 to -0.03)	-50.00 (-69.28 to -14.44)	
Ecchymosis, poor exsanguination, & skin abrasion	≤ 1	0.89 (0.83–0.94)	0.79 (0.72–0.86)	-0.10 (-0.19 to -0.01)	-12.85 (-21.49 to -2.40)	
	≤ 1	0.89 (0.82–0.95)	0.75 (0.67–0.82)	-0.14 (0.23–0.04)	-16.70 (-26.73 to -5.37)	
Fillet index						
	Discoloration					
	= 0	0.34 (0.27–0.43)	0.17 (0.11–0.22)	-0.17 (-0.28 to -0.07)	-52.08 (-72.48 to -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 to -0.03)	-11.27 (-20.18 to -4.91)		



Fig. 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).

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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Paper II

**‘Escape rate for cod (*Gadus morhua*) from the
codend during buffer towing’**

Paper III

**‘Sequential codend improves quality of trawl-caught
cod’**

Paper IV

‘Effect of a quality-improving codend on size selectivity and catch patterns of cod in bottom trawl fishery’