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Catch quality of Northeast Atlantic cod *(Gadus morhua)* caught by bottom trawl and gillnet – Effects of changes in gear design and fishing practices

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CONTENTS

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II. Summary

Cod caught with bottom trawls and gillnets have often been associated with poor and variable quality, and little is known about how changes in gear design and fishing practices may influence the quality of fish caught by these two fishing gears. It is difficult, if not impossible, to improve catch quality if fish are damaged during the capture process. Therefore, preventing the deterioration of the catch during the capture process is of utmost importance in improving the quality of caught cod. This thesis studied the effects of changes in gear design and practice in bottom trawl and gillnet fisheries on the catch quality of Northeast Atlantic cod *(Gadus morhua)*.

Paper I evaluated the improvement in catch quality of cod caught using a dual sequential codend compared with a conventional codend by evaluating residual blood levels in cod fillets as measured by hemoglobin concentration. No significant differences were found in the residual blood levels of fish caught by the two different codends. Whether the use of a dual sequential codend mitigated the effect of postponed bleeding compared with a conventional codend was also investigated. It was found that postponed bleeding influenced the residual blood levels in caught cod, and that this effect was similar whether the fish were caught using the conventional or sequential codends.

Another solution that potentially could improve catch quality is to turn the direction of the codend netting 90 degrees (T90) perpendicular to the towing direction. Paper II compared the amount and severity of external catch-related damage and the residual blood levels in muscle between cod caught using a conventional codend configuration (a sorting grid followed by a diamond-mesh (T0) codend) and a T90-codend without a grid. No significant differences were found between fish caught by the two different trawl configurations.

Paper III compared the color and amounts of residual blood in cod loin captured by trawling both with and without buffer towing. Further investigation looked at whether buffer

towing affected the shelf life of fish, measured as total volatile basic nitrogen (TVB-N) levels of thawed cod. The results showed that cod exposed to buffer towing had slightly, but non-significant increased redness and hemoglobin concentrations in the loin. No significant differences in TVB-N levels during chilled storage were found.

In Paper IV, an experimental gillnet study was conducted to investigate the effect of soaking time on fish survival and residual blood levels, measured as muscle hemoglobin concentration. The results showed that longer soaking times led to lower survival rates and increased fillet redness.

Previous information on the blood distribution in cod fillets is scarce. This issue was therefore addressed in both Papers I and IV, which clearly demonstrated that belly had significantly higher levels of residual blood than the loin and tail.

III. Abbreviations

ATP	Adenosine triphosphate
CDI	Catch damage index
Hb	Hemoglobin
HSI	Hyperspectral Imaging
ICES	International Council for the Exploration of the Sea
JNRFC	Joint Norwegian-Russian Fisheries Commission
NEA-cod	Northeast Atlantic cod
TAC	Total allowable catch
TVB-N	Total Volatile Basic Nitrogen

IV. List of papers

Paper I

Jensen, T. K., Tobiassen, T., Heia, K., Møllersen, K., Larsen, R. B. & Esaiassen, M. 2022. Effect of codend design and postponed bleeding on hemoglobin in cod fillets caught by bottom trawl in the Barents Sea demersal fishery. *Journal of Aquatic Food Product Technology*. Accepted.

Paper II

Jensen, T. K., Brinkhof, J., Lindberg, S. K., Tobiassen, T., Heia, K., Olsen, S. H., Larsen, R. B. & Esaiassen, M. 2022. Effect of the T90-codend on the catch quality of cod *(Gadus morhua)* compared to the conventional codend configuration in the Barents Sea bottom trawl fishery. *Fisheries Research*, *250*, 106277.

Paper III

Esaiassen, M., Jensen, T. K., Eilertsen, V. T., Larsen, R. B., Olsen, S. H. & Tobiassen, T. The effect of buffer towing on quality aspects of frozen and thawed Atlantic cod *(Gadus morhua). Journal of Aquatic Food Product Technology.* Under revision.

Paper IV

Svalheim, R. A., Hustad, A. & Jensen, T. K. Experimental gillnet fishery: Effect of soaking time on survival, blood physiology and muscle heamoglobin. Manuscript.

1. INTRODUCTION

Price and applicability of wild-caught fish will depend on the quality of the fish landed, which is influenced by several factors, including type of fishing gear being used and fishing practices. In the Norwegian fisheries, one of the most important species is the Northeast Atlantic (NEA) cod (*Gadus morhua*). This thesis is based on two important fishing gears used in the Norwegian NEA-cod fishery, bottom trawls and gillnets, and investigates how changes in gear design and fishing practice of these two gear types affects the catch quality of NEA-cod.

1.1. Northeast Atlantic cod fishery

1.1.1. Ethical and economical aspects of the bottom trawl and gillnet NEA-cod fisheries

The NEA-cod is the most important species in the Barents Sea fishery, both in terms of catch volume and economic yield (Nedreaas et al., 2011; Yaragina et al., 2011), and are predominantly caught using bottom trawls (ICES, 2021a, 2021b; Nedreaas et al., 2011; Yaragina et al., 2011). In Norway, 53% of the total allowable catch (TAC) was caught with bottom trawls and gillnets in 2021, of which 30% was with bottom trawls and 23% with gillnets (Fisheries Directorate, 2022). The total catch of NEA-cod landed in Norway in 2021 was 376,109 metric tonnes (Fisheries Directorate, 2022).

The use of bottom trawls is important for global food security, landing about 18 million tonnes of fish and invertebrates annually (Amoroso et al., 2018). The same holds true for gillnets, which are one of the most important fishing gears for harvesting fish in the sea (He, 2006). However, both bottom trawls and gillnets share the major problem of poor and variable catch quality. This challenge is frequently encountered in Norway, especially in the gadoid fishery. It has been shown that cod caught using bottom trawls have a poorer overall quality compared with those caught by longlines (Rotabakk et al., 2011), which command premium prices 18–24.6% higher in the UK grocery retail market compared with cod caught using other fishing gears (Sogn-Grundvåg et al., 2013; 2014). Sogn-Grundvåg et al. (2020) conducted a hedonic price analysis of the value chain in the Norwegian groundfish fishery at the ex-vessel level and reported that cod caught with longlines obtained a price premium of 15% compared with those caught by bottom trawling, while accounting for variables such as fish size, lot size and season. Cod caught by gillnets are of poorer quality than those caught using other gears such as demersal seines, longlines and handlines (Joensen et al., 2021; Sogn-Grundvåg et al., 2022).

Poor catch quality has negative economic consequences because it reduces the usability of fish raw material and limits the types of products in which they can be used (Sogn-Grundvåg et al., 2020). Muscle discoloration decreases fish suitability for use in high quality products that require a white fillet, such as loin and clipfish. Furthermore, poor quality can also lead to less of the fish raw material being utilized. For instance, severe blood related damage in cod fillets must be trimmed and this is both a direct loss for the producer and a food waste problem. In some cases (e.g., when fish have died in the fishing gear) the whole fish may be discarded. Poor catch quality can also increase the risk of illegal discard of fish and 'high-grading' (discarding fish of low value which allows the fishers to land more valuable fish) (Batsleer et al., 2015). The global demand for food is increasing and the FAO has asked nations to take better care of scarce marine resources and utilize fish stocks in a sustainable way (FAO, 2020). Therefore, improving the quality of the large quantity of cod landed will increase the percentage of caught fish raw material used, and contribute to more sustainable fishing, optimal use of limited fish stocks, and better exploitation of marine resources. Furthermore, improving the quality of caught fish may result in higher sale prices and increase the value added to the industry (Sogn-Grundvåg et al., 2020; 2021). Improving catch quality with more gentle gears would also probably improve fish welfare in capture fisheries, an issue that has been of increasing research interest in recent years (Veldhuizen et al., 2018). Taken overall, improving the quality of caught fish will have a positive impact on the economic, environmental, and ethical aspects of the fishing industry.

1.1.2. *Management of the NEA-cod fishery in the Barents Sea ecoregion*

The Barents Sea ecoregion includes part of the Norwegian Sea, as well as the Barents Sea (Figure 1). It borders the Norwegian and Russian coast to the south and connects with the Norwegian Sea to the west, the Arctic Ocean to the north, and the Kara Sea to the east (Fuglestad et al., 2020; ICES, 2019). The region is one of the most intensively fished areas in the world, with NEA-cod, haddock *(Melanogrammus aeglefinus)*, saithe *(Pollachius virens)*, herring *(Clupea harengus)*, and capelin *(Mallotus villosus)* being the most commercially important fish species (Fuglestad et al., 2020). Of these five species, NEA-cod is the most commercially important, and the Barents Sea region currently has the largest cod stock globally (Fuglestad et al., 2020; Nedreaas et al., 2011; Yaragine et al., 2011).

The two main nations targeting NEA-cod in the Barents Sea ecoregion are Norway and Russia, and the stock is managed by these two countries through the Joint Norwegian-Russian Fisheries Commission (JNRFC) (Eide et al., 2013; Shamray & Sunnaå, 2011; Shevelev et al., 2011). Annual quota negations are held between Norway and Russia, and the commission determines the TAC based on annual recommendations from the International Council for the Exploration of the Sea (ICES), which develops science and advice to support sustainable use of the oceans. The TAC of NEA-cod set by the JNRFC is divided equally between Russia and Norway (Shamray & Sunnaå, 2011), after setting aside around 15% of the quota for allocation to other countries (Fuglestad et al., 2020).

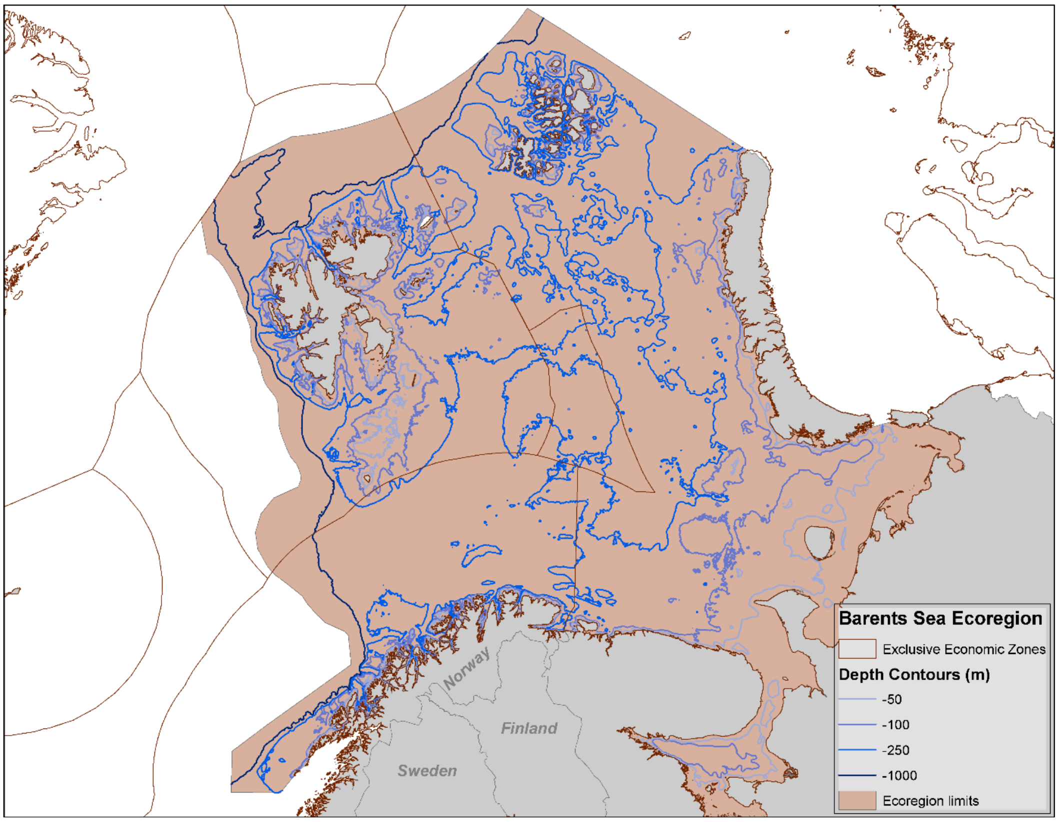

Figure 1: The Barents Sea ecoregion. Retrieved from ICES (2019).

The NEA-cod stock in the Barents Sea ecoregion is considered to be healthy and in good condition (ICES, 2021b), which is believed to be mainly due to the successful co-management regime between Norway and Russia (Fuglestad et al., 2020). The JNRFC set the 2022 NEA-cod quotas in the Barents Sea at a total of 708,480 tonnes (ICES, 2021a). This is about 20% lower than in 2021, but the quotas are still at historically high levels. Between 2010–2020, the average annual catches of NEA-cod in ICES Subareas I and II were 796,085 metric tonnes (ICES, 2021a). During these 10 years, about 87% of the catch was harvested by Norwegian and Russian vessels, the rest being caught by vessels from Iceland, Greenland, and other European countries (ICES, 2021a). In the Barents Sea region, larger coastal and ocean-going vessels land the largest quantity of cod, the dominant fishing gear being the bottom trawl (Shevelev et al., 2011) and in 2020, 74% of the annual catch of NEA-cod in subareas I and II was caught in this way (ICES, 2021a). About 95% of the Russian annual catch of NEA-cod is caught using bottom trawls, and the rest by mechanized longlining (autoline) (ICES, 2021b, Nedreaas et al., 2011).

The Norwegian cod fishery, however, is much more diverse, ranging from many quite small and medium-sized coastal inshore vessels to a smaller number of deep-sea bottom trawlers and mechanized longline vessels (Figure 2). Mature NEA-cod migrate towards the Norwegian coast during the spawning season (January-April), and most of these fish are caught using fishing methods other than bottoms trawls. Around 30% of the annual Norwegian catch of NEA-cod was caught using bottom trawls in 2021, and most of this was caught by large ocean-going vessels which freeze the fish raw material on board (Fisheries Directorate, 2022; Nedreaas et al., 2011). The rest of the NEA-cod landed in Norway is mostly caught by the costal fleet which lands fresh fish raw material. These vessels mainly use gillnets, longlines, demersal seines, and handlines (Figure 2). In 2021, gillnets accounted for 23% of the Norwegian part of the TAC of NEA-cod (Fisheries Directorate, 2022).

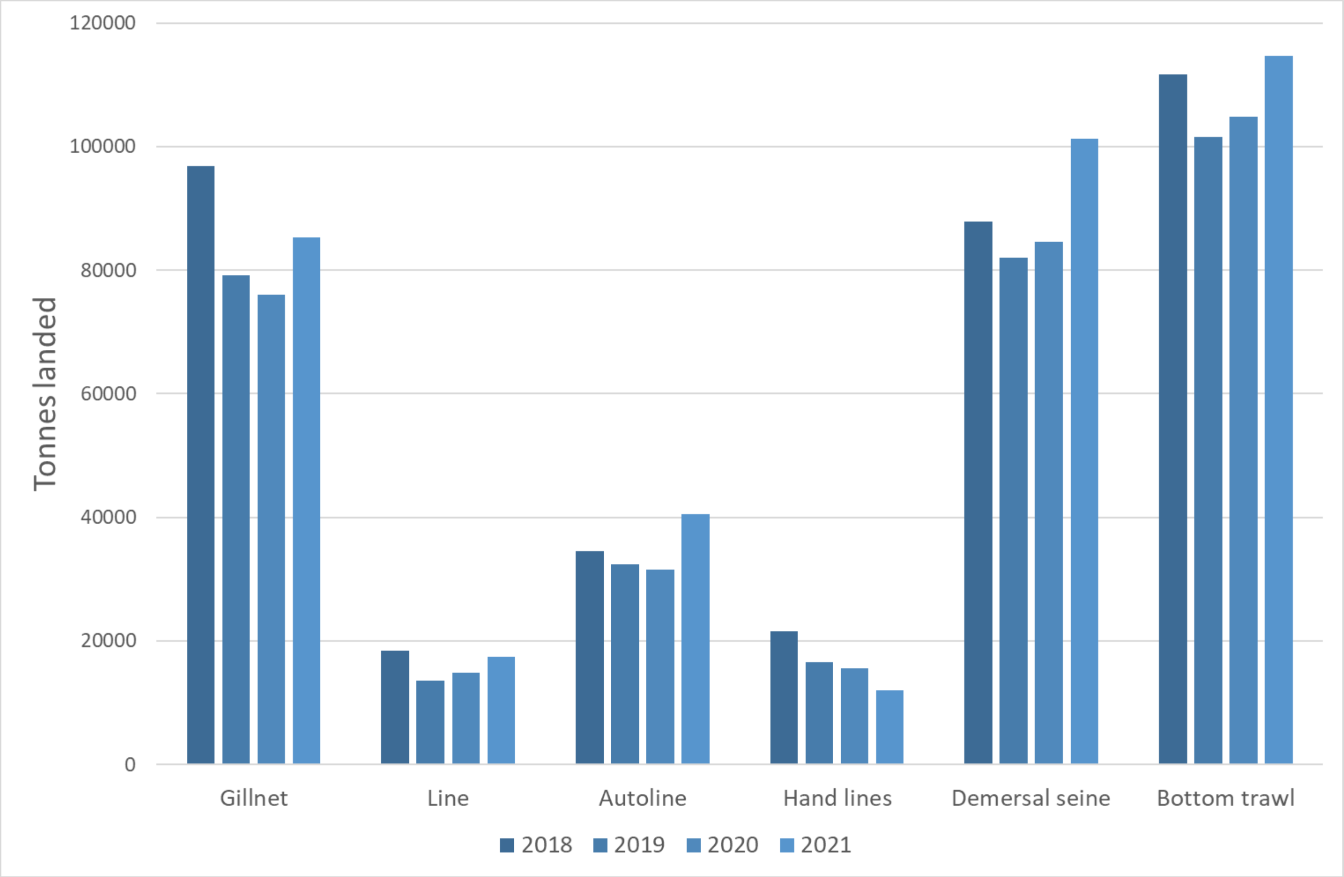

Figure 2: Metric tonnes landed NEA-cod in Norway by fishing gear (Fisheries Directorate, 2022).

1.2. Fishing gears

The fishing gear design and use of modern bottom trawls and gillnets have not changed drastically during the last 70 years. During the second half of the 20th century, fishing operations underwent a dramatic improvement in catch efficiency through technological improvements, allowing the capture of fish to grow (Valdemarsen, 2001). In the 1960s and early 1970s, powerful new fleets were built which could operate far from land. The introduction of synthetic fibers in fishing gear around 1950 (Valdemarsen, 2001) also contributed to an improvement in the efficiency of fishing operations. Synthetic fibers have many advantages which allow the manufacture of more effective fishing gear. Among their most useful properties are their high resistance to rotting, high breaking strength and resilience, favorable tenacity, low visibility in water and thin fibers which create low hydrodynamic drag when operated. Moreover, various synthesized materials (PA: polyamide, PES: polyester, PE: polyethylene, PP: polypropylene) are chosen according to the needs of different fishing methods. For instance, netting for bottom trawl is typically built from PE and to some extent PP, while the web in gillnets is built from PA due to the favorable tensile strength and elasticity of nylon filaments.

1.2.1. Bottom trawls

1.2.1.1. Basic principles and practices

There are many variations in design, rigging, and towing methods of bottom trawls, depending on the fishery, vessel size, and target species (Gabriel et al., 2005; Sainsbury, 1996; Winger et al., 2010). One trawl can be towed by one or two vessels, or multiple trawls can be towed simultaneously. However, the basic principle is similar for all bottom trawls, in which a fishing net is towed along the seabed, catching demersal fish species and crustaceans. In Norway, the otter trawl for capturing NEA-cod is most used, in a single or double trawl configuration. Modern otter trawlers were developed by an Irish fisher between 1860 and 1870 (Valdermasen, 2001). Trawl gear has gone through several stages of development since then, and the introduction of synthetic fibers in trawls in the 1950s and 1960s was a major step towards increasing their size and efficiency (Valdemarsen, 2001).

Bottom trawls consist of a large cone shaped net which is wide at the front (wings and square from the mouth), leading to the body of the net which then narrows down through an extension piece and into a closed bag termed the codend, in which the fish eventually become trapped (Figure 3). In the Barents Sea gadoid fishery, sorting grid systems are located in the extension piece, inserted between the trawl body and the codend. Sorting grids are mandatory to allow the release of the smaller, juvenile fish (i.e., fish below minimum landing size) (Ministry of Trade, Industry and Fisheries, 2022; Yaragina et al., 2011).

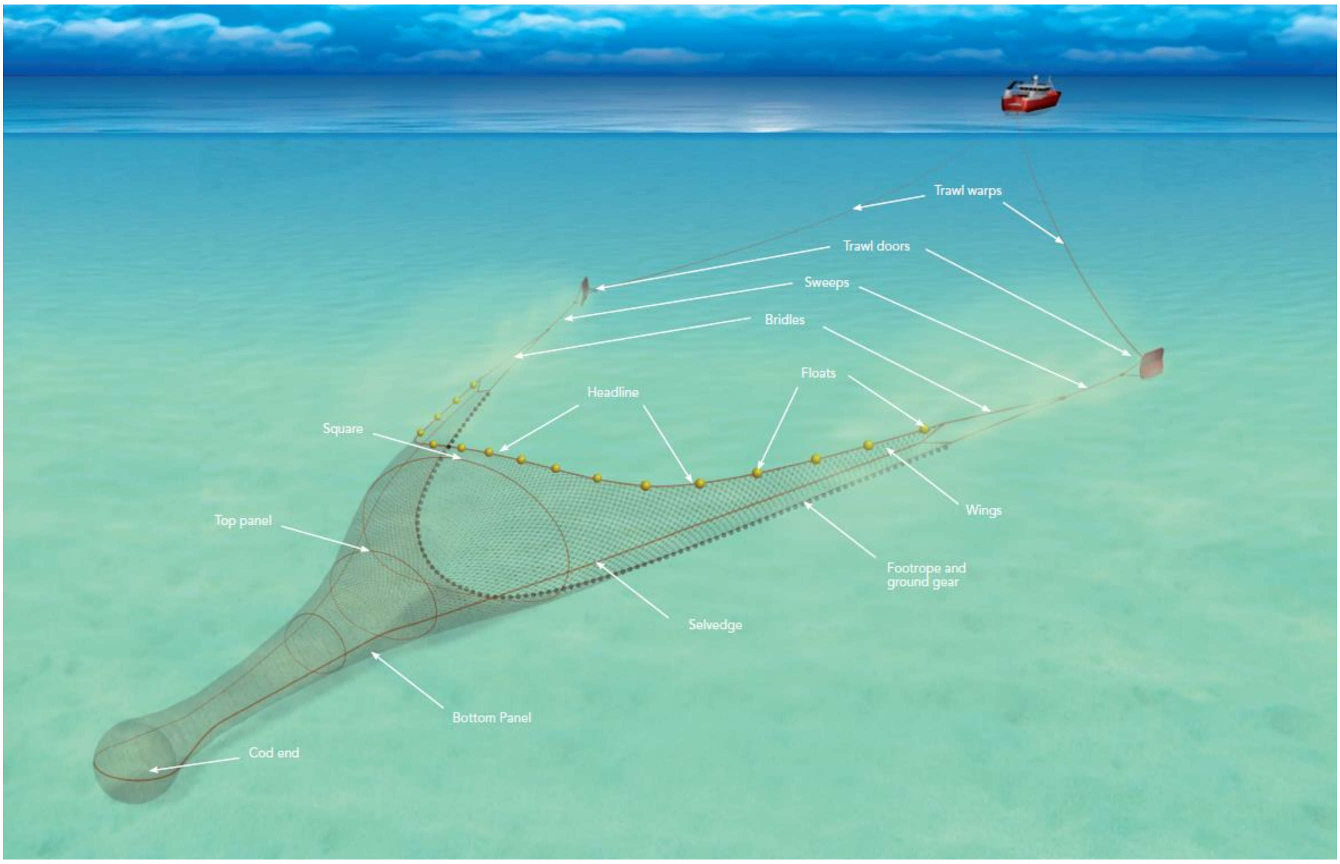

Figure 3: Overview of a bottom trawl with basic components of trawl gear. Retrieved from Seafish.

The entire trawl is towed by a vessel using wires (towing cables), which are connected to a set of otter boards (trawl doors) (Figure 3). The doors are set at an angle to provide the outward force necessary to spread the wings and mouth of the trawl net horizontally. In addition, the otter boards disturb the sea bottom which generates noise and creates mud clouds along the seabed which leads the fish towards the trawl (Winger et al., 2010). The otter boards are attached to long cables called sweeps which increase the swept area and help to herd fish towards the trawl mouth (Winger et al., 2010). The sweeps are connected to the fishing line and ground gear (groundropes/footropes) which are weighted to ensure contact with the seabed. The size, weight, and shape of the otter boards and the ground gear, and the length of the sweeps, are dependent on the fishery. However, in the Barents Sea bottom trawl fishery, the most commonly used otter boards have an area of 8-12 m^2 and weigh between 3–5000 kg, while the sweeps are usually 60–120 m long, and the most commonly used ground gear is the rockhopper style. The headline (headrope, floatline) runs around the upper edge of the trawl mouth (square) and is equipped with floats. The combined effects of the weighted ground gear and the floats keep the trawl mouth open vertically (Sainsbury, 1996). To ensure that fish do not escape upwards, the headline and top of the mouth (the square) overhang the ground gear. In addition, the mouth of the netting has wings ahead of each side. In this way, fish are herded into the trawl mouth, instead of escaping upwards or to the sides.

1.2.1.2. Fish behavior and responses during the capture process

Fish trying to escape an approaching trawl, maintain a sustained swimming speed until they cease swimming in the trawl mouth and fall back into the codend. A change in fish gait from steady to unsteady swimming (burst and glide) is often observed and may be a sign of metabolic exhaustion (Winger et al., 2010). How long the fish are able to swim away from the trawl mouth is dependent on the towing speed. The endurance of cod and how long they can swim away from the net opening decreases as towing speed increases (Winger et al., 2010). Normal towing speed for trawls targeting cod is 3.5 knots, which exceeds the sustained swimming speed of cod so that the fish will eventually fall back into the codend where they are trapped. However, exactly how long a fish is able to swim in front of the trawl mouth before drifting into the codend depends on its physical and physiological condition (Winger et al., 2010).

1.2.2. Gillnets

1.2.2.1. Basic principles and practices

In contrast to bottom trawls, which are classified as an active fishing gear (i.e., the fishing gear chases the fish), gillnets are passive gears (i.e., the gear is stationary) and fish swim into the gear themselves (Gabriel et al., 2005; Sainsbury, 1996). Gillnets do not require bait to catch fish and are therefore a simple and versatile fishing gear (He & Pol, 2010). However, the construction of gillnets is complex because even small details may affect the species caught and size selectivity, so there are many different methods of constructing and operating them (He & Pol, 2010; Sainsbury, 1996).

As with bottom trawls, the introduction of synthetic fibers was very beneficial in improving the capture efficiency of gillnets. Gillnets made of transparent polyamide (nylon) monofilaments have low visibility in water and catch more fish compared to other materials, for instance cotton. In addition, the gillnets last longer because synthetic fibers are highly resistant to rotting compared with natural fibers (Gabriel et al., 2005). Synthetic fibers are also much stronger than the previously used natural fibers, and commercial scale gillnet operation are mechanized using hydraulic hauling equipment (Valdermarsen, 2001).

In general terms, a gillnet is a large wall of netting that hangs in the water column and is kept vertical by floats on the upper line and weights on the ground line (Gabriel et al., 2005;

He & Pol, 2010; Sainsbury, 1996) (Figure 4). Gillnets are usually not used as single nets, but several are linked together in fleets and set as straight walls, or in a bow-shaped pattern (Gabriel et al., 2005). If the proper mesh size and netting materials are used, gillnets generally catch larger fish and have a more even catch size distribution than other gears (He & Pol, 2010).

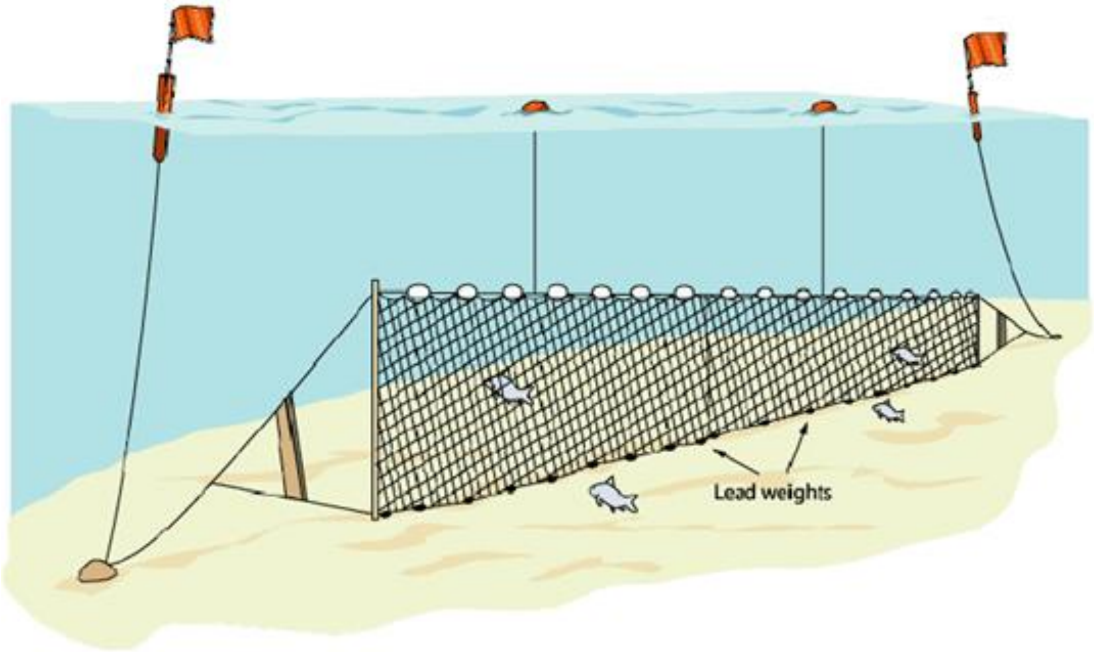

Figure 4: Principle rigging of a bottom-set gillnet. Retrieved from Michigan Sea Grant.

1.2.2.2. Fish behavior and responses during the capture process

When fish try to swim through a gillnet mesh that is a little smaller than the largest circumference of their body, they can be caught in various ways. As shown in Figure 5, He and Pol (2010) described four basic modes of fish capture by gillnets: gilling, wedging, snagging, and entangling. These modes are length dependent, and fish can be caught by more than one in the same gillnet. Gilling happens when a fish swims through the mesh, then tries to back out of it, and the net twine gets hooked behind the gills. The fish can then go neither forward nor backward (Gabriel et al., 2005). The fish will struggle and try to get out, which only leads to it becoming more stuck in the gillnet. When a fish is caught by wedging, the largest part of its body is caught in the mesh. Snagging is when a fish is caught by the mouth or other part of its head. Entangling occurs when the spine, fins, or other parts of the body get stuck as the fish struggles (He & Pol, 2010).

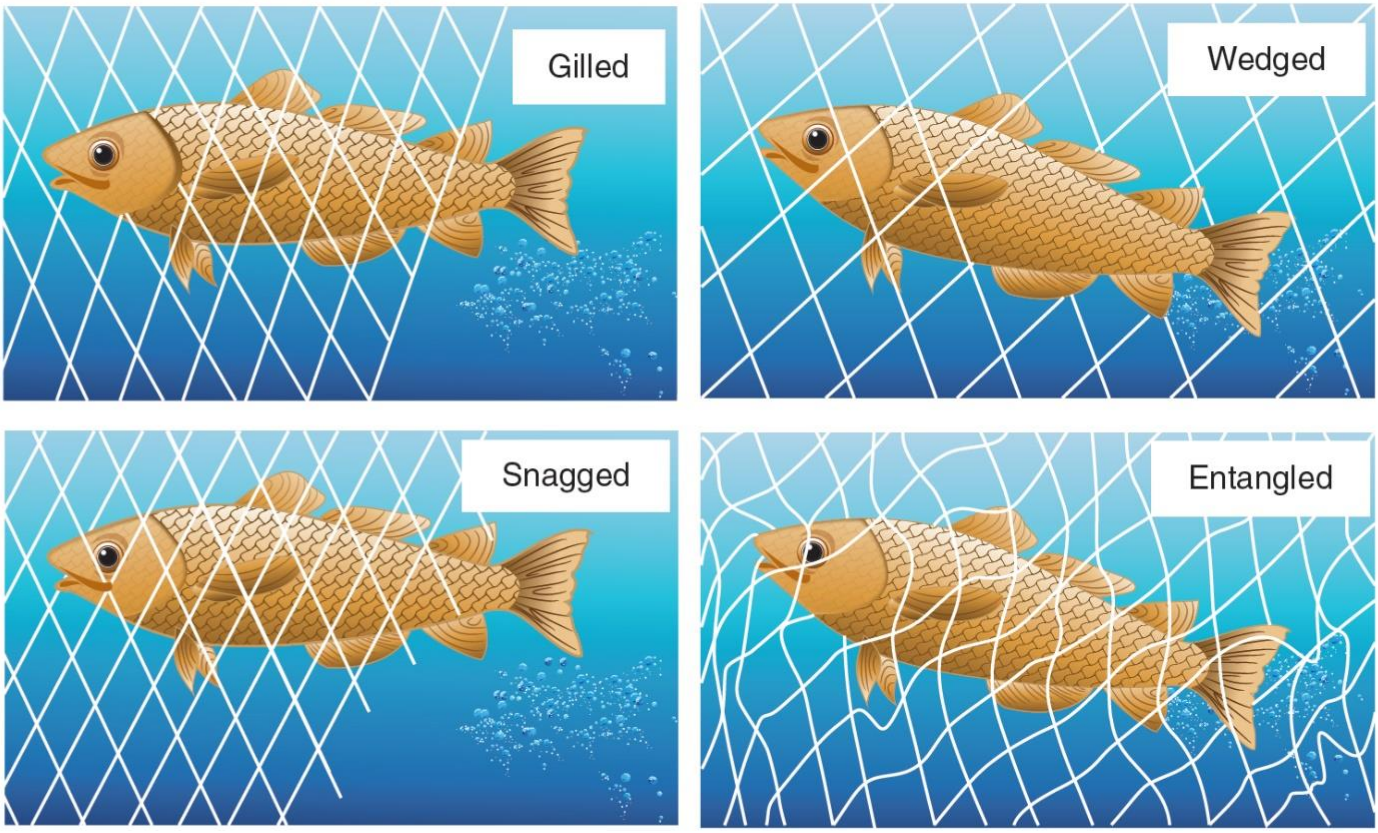

Figure 5: Fish capture by gillnets, illustrating the four modes of capture: gilling, wedging, snagging, and entangling. Modified from He and Pol, 2010.

Underwater observations of fish behavior near gillnets are scarce, but laboratory tank observation of Atlantic salmon *(Salmo salar)* captured by gillnets reported that they initially struggled powerfully for less than 30 seconds (Potter & Pawson, 1991). Even though salmon and cod have shown different behavior and responses to different factors, there is reason to believe that cod also struggle for only a short period of time after being caught in a gillnet.

1.3. Fish quality

1.3.1. *Anatomical and physiological features to quality*

The skeletal muscles of fish are segmented and myotomal. The myotomes are a series of blocks of muscle tissue shaped like a sideways W, and separated by connective tissue, the myoseptum (Nelson, 2011). Fish swim using two types of skeletal muscle, red and white muscle, typically comprising about 10% and 90% of the skeletal muscle, respectively (Nelson, 2011). Red muscle is located parallel to the length of a fish, just under the skin, and are rich in mitochondria and myoglobin which gives the characteristic red appearance, in addition to high levels of glycogen and fat. The main purpose of the myoglobin is to store and supply oxygen to the muscle cells. In contrast, white muscle contains low levels of mitochondria, myoglobin, fat, and glycogen, giving it its lighter color (Nelson, 2011).

Red muscle metabolism is aerobic and is used for slow to moderate sustained swimming, while white muscle is used during high-speed burst swimming and is metabolically anaerobic. Anerobic metabolism occurs when energy in the form of adenosine triphosphate (ATP) is produced without oxygen, while aerobic metabolism occurs when energy is produced using oxygen. Energy conversion in fish occurs in the cytoplasm by anaerobic glycolysis and continues in the mitochondria by aerobic turnover in the citric acid cycle. Glucose is burned and the energy is passed on in the form of energy-rich ATP molecules. ATP-production by anaerobic metabolism is about twice as fast as in aerobic metabolism, and anaerobic metabolism is favored over aerobic metabolism in situations where high ATP generation rates are required to support intense muscle activity (i.e., during intensive swimming) (Wang & Richards, 2011).

The cardiovascular system of fish includes the heart, blood, and blood vessels. The heart pumps blood around the circulatory system, and has four chambers: atrium, ventricle, sinus venosus and the bulbus arteriosus (Farrell & Pieperhoff, 2011). Blood has three major components: red blood cells, white blood cells, and plasma. The most important role of red blood cells is to transport oxygen via the blood flow through the circulatory system. Red blood cells contain hemoglobin (Hb), a protein molecule which carries oxygen from the respiratory organs (gills in fish) to the rest of the body. Hemoglobin occurs in large amounts in the red blood cells and gives the blood its red color. There are three types of blood vessels: arteries which carry blood away from the heart, veins which carry blood back to the heart, and capillaries (the smallest blood vessels,) which connect the arteries and veins. The major systemic arteries and veins are shown in Figure 6. The circulatory system of fish forms a single circuit, with blood flowing from the heart to the gills and then to the rest of the body. As well as oxygen, the blood carries nutrients and hormones to the cells, and removes waste products, such as carbon dioxide (Olson 2011a; 2011b).

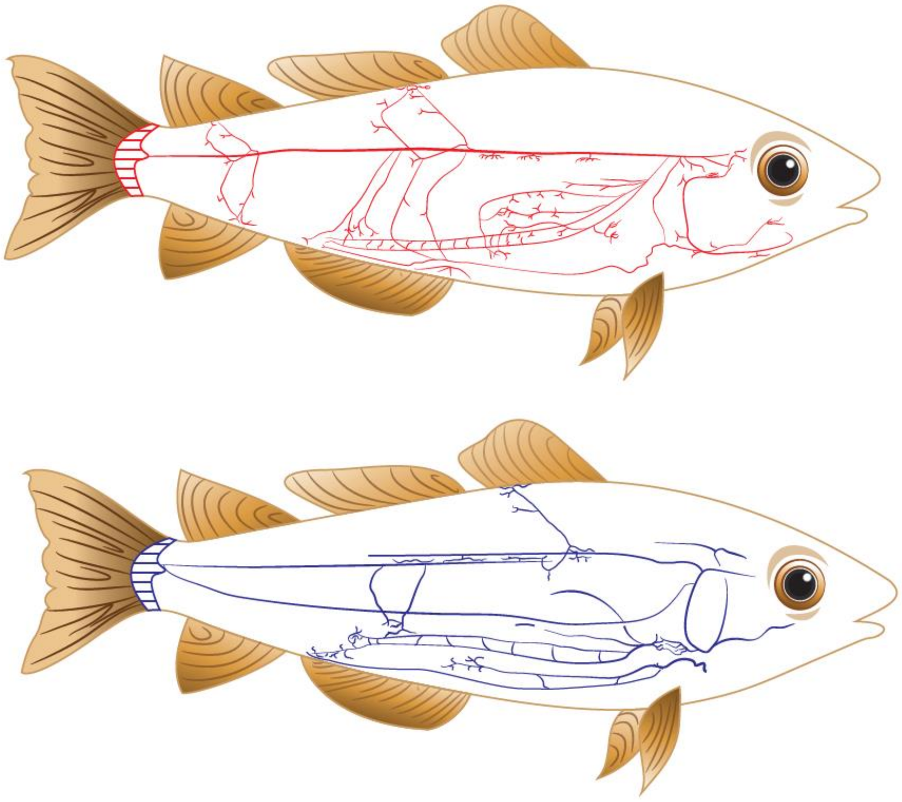

Figure 6: The major systemic arteries (top) and veins (bottom). Modified from Olson 2011a.

During capture by both active (e.g., trawls and demersal seines) and passive (e.g., gillnets, longlines) fishing gear, fish muscle activity and energy consumption increase. It has been shown that blood flow to both white and red muscles increases after muscular activity (Neumann et al., 1983). When fish try to free themselves from a gillnet or swim away from an approaching trawl, the fish engages in explosive exercise and exhaustive swimming in which white muscles are used. When the white muscles are primarily used, anaerobic metabolism occurs, leading to a rise in lactate levels (Sopinka et al., 2016). Lactate levels are frequently used as stress indicators in fish. Other metabolic stress parameters include cortisol, glucose, pH, and the osmolality of specific ions (Moon, 2011; Sopinka et al., 2016).

The capture process in trawls and gillnets involves fish in exhaustive swimming, struggling in the gillnet, crowding in the codend and contact with species with hard body parts such as Atlantic redfish (*Sebastes norvegicus)*, followed by air-exposure after the fish are landed. These physical factors all have the potential to induce stress in fish and may have a negative effect on catch quality.

1.3.2. ***Factors influencing fish quality***

The quality of fish is a very complex concept which has not been clearly defined (Bremner, 2000; Haard, 1992; Nielsen et al., 2002). Botta (1995) listed 15 different definitions of quality, showing that it is important to keep in mind that the definition of quality may be specific to any particular context. Good quality is subjective; fish are judged based on the desired attributes relevant to the specific case. There are many factors which determine the quality of fish including nutritional properties, price/value ratio, consistency, availability, and so on (Olafsdóttir et al., 1997). However, the quality of fish is often associated with freshness, sensory attributes such as visual appearance, texture, odor and taste, or degree of spoilage (Cheng et al., 2015; Olafsdóttir et al., 1997). Freshness and shelf life are essential factors and make major contributions to the quality of fish (Bonilla et al., 2007; Olafsdóttir et al., 1997). Several well-established traditional methods are available for the evaluation of fish freshness, including sensory evaluation, chemical methods, lipid oxidation levels, and microbial inspection (Bonilla et al., 2007; Cheng et al., 2015; Olafsdóttir et al., 1997; Warm et al., 1998).

In general, the quality of wild fish is influenced by several factors, including: 1) natural factors (e.g., water temperature, season, feeding status, stock size, and fish size) (Ang & Haard, 1985; Botta et al., 1987a; 1987b; Love, 1975; Margeirsson et al., 2007; Mello & Rose, 2005; Suuronen et al., 2005); 2) capture method and handling on board (e.g., catch location, gear type, capture depth, fishing duration, catch size, and slaughter method) (Botta et al., 1986; 1987a; 1987b; Esaiassen et al., 2004; 2013; Margeirsson et al., 2007; Olsen et al., 2013; 2014; Rotabakk et al., 2011; Savina et al., 2016; Veldhuizen et al., 2018); 3) packaging method and storage conditions (Bøknes et al., 2000; Cyprian et al., 2013; Duun & Ruustad, 2007; Lauzon et al., 2009; Lorentzen et al., 2020; Wang et al., 2008); and 4) fish freezing (Boknes et al., 2001; Burgaard & Jørgensen, 2010) and thawing protocols (Erikson et al., 2021b; Stormo & Skåra, 2021).

Most studies to date have investigated factors influencing quality during handling, processing, and storage, while studies investigating the prevention of quality deterioration during the capture process are few. It is difficult, if not impossible, to improve catch quality if damage occurs during the capture process. Therefore, studies aimed at preventing the deterioration of the catch during capture are of utmost importance in improving the quality of caught fish. There has been increasing research attention paid to trawl-caught fish (Brinkhof et al., 2018a, 2018b, 2019, 2021; Digre et al., 2010; Svalheim et al., 2017, 2019, 2020; Tveit et al., 2019), the main focus being on how different codend designs affect catch-related fish damage. However, ways of improving the quality of fish caught by gillnets and reducing fish damage during the capture process has received little attention and are limited to a few studies (Santos et al., 2002; Savina et al., 2016; Toledo-Guedes et al., 2016).

1.3.3. *Blood related quality defects in white fish*

Regarding white fish such as cod, the common consensus is that blood related damage is a major quality issue, because people expect white fish to be white and without blood stains. The catch damage index (CDI) which is commonly used to assess the quality of caught fish, includes an assessment of blood related damage (Esaiassen et al., 2013). In addition to being an aesthetic problem, residual blood in fish fillets can also accelerate lipid oxidation and microbial growth, causing an unpleasant odor and reducing shelf life (Maqsood & Benjakul, 2011a; 2011b; Richards & Hultin, 2002). A report published by The Norwegian Institute of Food, Fisheries and Aquaculture Research (NOFIMA) described how the Norwegian seafood industry considers gaping, insufficient exsanguination, and bruises as the most severe quality defects in white fish, the latter two of which lead to muscle discoloration and blood stains in the final product (Heide & Henriksen, 2013).

The time from capture until the fish are bled is of the utmost importance in achieving adequate exsanguination and minimizing muscle discoloration (Borderías & Sánchez-Alonso 2011; Botta et al., 1986; Margeirsson et al., 2007; Olsen et al., 2014).

Fish that die in the fishing gear before being brought on board are very difficult to bleed out properly (Olsen et al., 2014), and muscle discoloration can be so severe that the fish are unsuitable for human consumption and must be discarded by law (Ministry of Trade, Industry and Fisheries, 2022). Both long gillnet soaking times (the period for which the net is deployed to capture fish) and long towing times for trawls with large catch volumes can increase the risk of mortality during fish capture (Joensen et al., 2021; Suuronen et al., 2005). To avoid downgrading due to the presence of blood and discoloration of the fillet, it is mandatory to routinely bleed cod and other whitefish on board fishing vessels after capture (Ministry of Trade, Industry and Fisheries, 2022). However, this task can be quite challenging on vessels such as trawlers where the entire catch is brought on board at the same time, unless the catch are transferred to onboard holding tanks from which live fish are consecutively processed (Digre et al., 2017; Erikson et al., 2019; Olsen et al., 2013). In comparison, this task is much easier for fish caught using longlines and handlines, where fish can be bled one after another as they are hauled on board.

Capture-related stress may also influence muscle discoloration. Stress causes increased blood flow to the capillaries in the muscles, making proper bleeding more difficult (Olsen et al., 2008; 2014), increasing the amount of residual blood in the fillet (Farrell et al., 2001; Svalheim et al., 2019; Svalheim et al., 2020). Svalheim et al. (2019) showed that stress both from crowding and air-exposure resulted in increased levels of residual blood in cod fillets. Figure 7 shows an example of a fish with gear marks and bruises compared with a fish without such catch-related damage. Figure 8 shows a fish that has been properly exsanguinated (left) compared with one that has been insufficiently bled (right).

Figure 7: Example of a trawl-caught cod with gear marks and bruises (top) and one of good quality (bottom). Photo by Jesse Brinkhof.

Figure 8: Example of a cod that is properly exsanguinated (left) and one that has been insufficiently exsanguinated which consequently lead to muscle discoloration (right). Photo by Sjúrður Joensen, Nofima.

1.3.4. *Quality challenges using bottom trawls*

A study comparing trawling and longlining found that 60% of the cod caught by trawl were poorly bled and 80% had bruises (Rotabakk et al., 2011). In comparison, 11% of the cod caught with longlines were poorly bled and no bruising damage was observed. Rotabakk et al. (2011) reported that for trawl-caught cod, the main catch-related damages were bruises observed as blood extravasations and red discoloration of the skin. They concluded that the bruises were most likely caused by the high pressures applied to fish in the trawl during hauling, and that poor exsanguination was probably due to the large catch sizes which make it difficult to cut and bleed the fish immediately after capture. According to Olsen et al. (2013), it is not unusual for large hauls of fish caught using bottom trawls to be kept in storage bins for hours before bleeding and gutting.

In addition to factors that influence the quality of caught fish in general, it has also been shown that the quality of trawl-caught fish is affected by trawl gear design and trawling procedures (Brinkhof et al., 2018a, 2018b, 2021; Digre et al., 2010; Sistiaga et al., 2020; Tveit et al., 2019). The most common quality defects reported in trawl-caught fish are gear marks, skin abrasion, pressure injuries, and internal and external bruises (Brinkhof et al, 2021; Digre et al., 2010; Olsen et al., 2013; Rotabakk et al., 2011; Tveit et al., 2019), several of which may lead to blood related damage (examples are illustrated in Figure 9).

In addition to catch-related damage, discoloration of fillets due to poor exsanguination is a major quality issue in trawl-caught cod. To avoid downgrading the entire catch due to the presence of blood and muscle discoloration, fish should be bled as soon as possible after capture to achieve adequate exsanguination and minimize residual blood content (Borderías & Sánchez-Alonso, 2011; Botta et al., 1986; Margeirsson et al., 2007; Olsen et al., 2014). Olsen et al. (2014) recommended that cod should be bled within 30 minutes of capture. However, their study was conducted on unstressed fish, and this recommendation is likely to be less relevant in commercial trawl fisheries where fish are exposed to severe capture stress. Trawl-caught fish were shown to have elevated levels of several products of stress responses such as lactate, cortisol, and glucose, and have a lower pH (Digre et al., 2010; Erikson et al., 2019; Rotabakk et al., 2011; Olsen et al., 2013).

During capture in trawls, fish are exposed to stress and mechanical strain due to prolonged swimming, interactions with fishing gear, crowding in the codend and exposure to other species such as Atlantic redfish, barotrauma, light and temperature changes, and air-exposure. The individual steps of the capture process and possible factors affecting fish quality in each are shown in Figure 10.

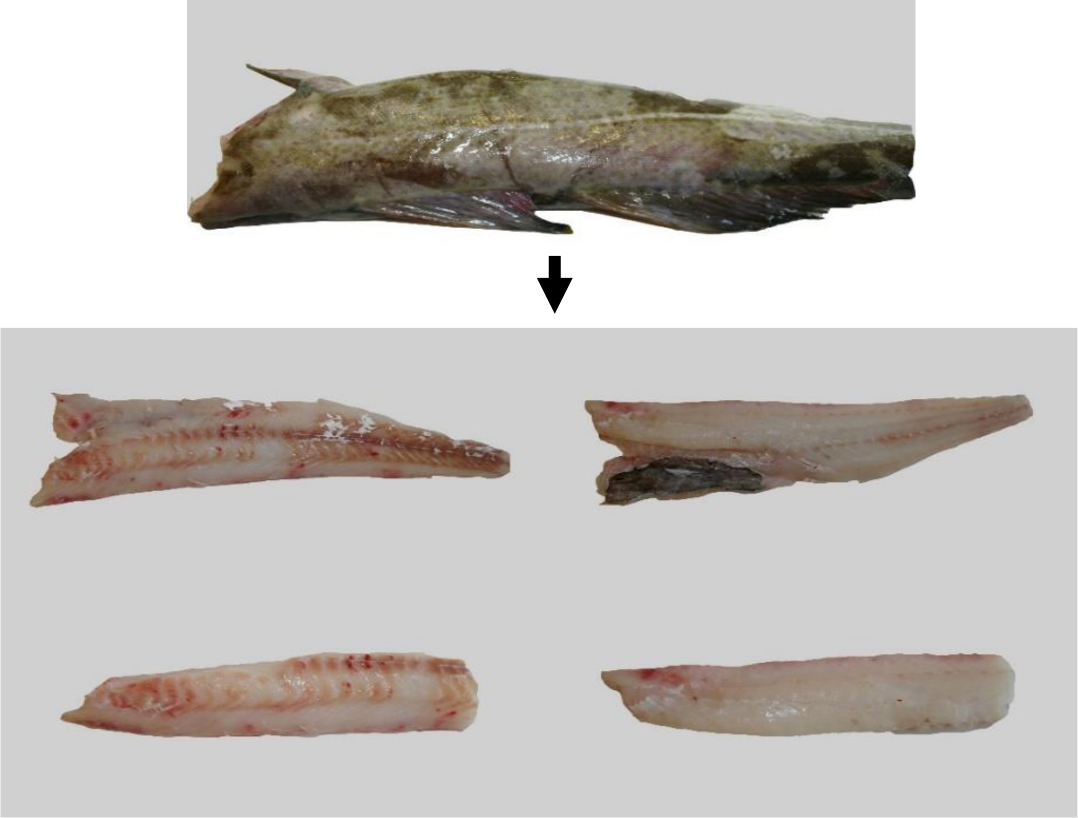

Figure 9: Example of trawl-caught cod fillets with blood related damage including blood stains and red muscle discoloration. Photo by Sjúrður Joensen, Nofima.

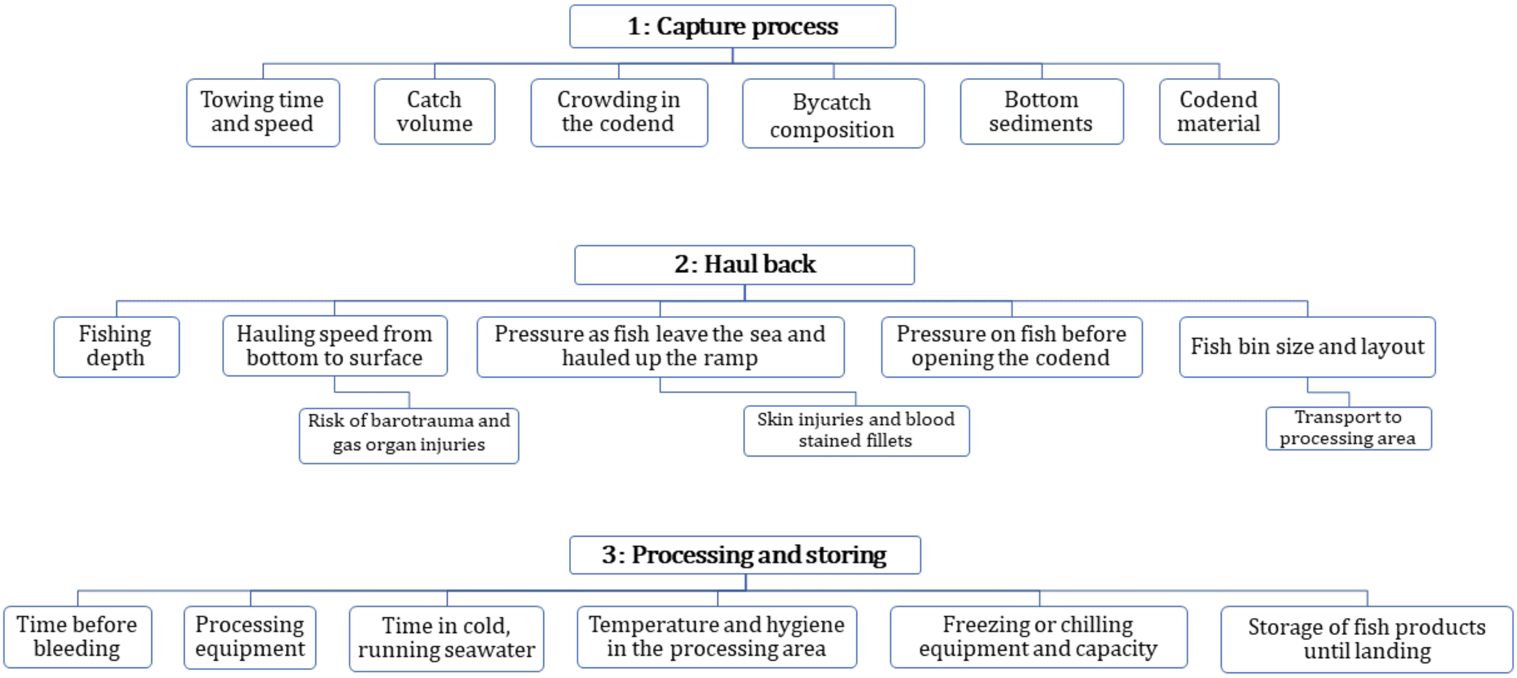

Figure 10. Possible factors affecting the catch quality of fish captured by bottom trawls, at each stage of the capture and onboard handling processes.

There is reason to believe that final quality is not determined during the initial part of the capture process, when the fish are swimming near the trawl mouth trying to avoid the approaching trawl, as the stress related to swimming to exhaustion has not been found to reduce quality (Svalheim et al., 2017). Crowding pressure in the codend increases during the capture process, as more and more fish accumulate, and crowding is influenced by factors such as water flow rate and catch size. The water flow depends on the codend material and towing speed, but also on the number of fish in the codend (Winger et al., 2010). Large catches of fish (> 10 tonnes) may cause severe crowding pressure in the codend, especially during haul-back. The swim bladder of cod is physoclistous, meaning that the secretion and reabsorption of gas inside the swim bladder are slow processes (Midling et al., 2012). During the first step of haul-back, when the trawl is lifted from the seabed to the surface, the ambient water pressure reduces quickly, and fish are not able to remove the gas in a natural manner, causing the swim bladder, and hence the whole fish, to expand, increasing the total volume in the codend. The crowding pressure therefore increases drastically during haul-back.

Svalheim et al. (2020) showed that swimming to exhaustion followed by extreme crowding (700–800 kg/m^3) reduced the quality of cod fillets, as measured by fillet redness and muscle pH. Therefore, severe crowding in the codend during haul-back can impact catch quality. In the worst case, fish will die during the capture process due to impaired opercular movement leading to insufficient ventilation because of the high density of fish inside the codend. This is not optimal, from both catch quality and welfare perspectives. In addition, rapid decompression when lifting the trawl from the seabed makes the swim bladder expand so much that it can eventually burst, which may cause internal blood stains in the part of the fillet nearest to the swim bladder (Midling et al., 2012).

The next important step during haul-back which may affect fish quality occurs when the trawl is lifted from the sea and hauled up the ramp. During this process, fish that are closest to the codend netting will be squeezed against the netting and dense crowding and pressure may result in skin abrasion, pressure injuries, and bruises (Figure 11).

Figure 11: Illustration of a crowded codend. Photo by Jesse Brinkhof.

The next step after the fish have been hauled on board is to open the codend and transfer the fish to a dry bin below deck. Emptying the catch from the codend into the holding bins may cause bruising. Another quality impact is related to air-exposure immediately after fish are lifted from the sea. It has been reported that death by air-exposure negatively effects fillet quality, especially if the fish have been exposed to extreme crowding prior to air-exposure (Svalheim et al., 2019).

As seen in Figure 10 the final step is processing and storing before bleeding and the time spent at this stage greatly affects catch quality. The fish should be bled as fast as possible after capture (Botta et al., 1986; Borderías & Sánchez-Alonso, 2011; Olsen et al., 2014) and preferably before air-exposure (Svalheim et al., 2019), to achieve proper bleeding and avoid muscle discoloration. Naturally, the bigger the catch size, the longer the time from capture until bleeding. This is not necessarily a problem if the processing capacity on board is high enough (i.e., the catch size does not exceed the processing capacity). However, if the catch size exceeds the processing capacity, some of the catch can be stored for hours in the dry bin before bleeding (Erikson et al., 2021a; Olsen et al., 2013), or be towed at low speed (usually ~1–2 knots) behind the vessel, a procedure termed buffer towing (Brinkhof et al., 2018a).

1.3.5. *Quality challenges using gillnets*

The general data collected on catch-related damage registrations over the years 2014–2020 conducted by NOFIMA, show that cod caught using gillnets have a higher incidence of gear marks, bruising, and discolored fillets compared to those caught by other gears than bottom trawls, such as demersal seines, longlines and handlines (Joensen et al., 2021; Sogn-Grundvåg et al., 2022). Özyurt et al. (2007) reported that the freshness of captured pike perch *(Sander lucioperca)* was affected by the capture method, with an acceptable shelf life of 15 days for pike perch caught by gillnets, compared with 22 days for longlines and harpoons. Esaiassen et al. (2004) showed that cod caught using gillnets had a lower pH and higher condition (Fulton's K-factor) compared with those caught by longlines. Botta et al. (1987a, 1987b) found that cod caught by gillnets had more discoloration and bruising compared those caught by longlines. It is however important to mention that the soaking time for gillnets was longer than for the longlines in this study.

Catch quality depends on how the gillnets are operated and many gillnet vessels deliver cod of excellent quality. Possible factors affecting the catch quality of fish captured by gillnets are shown in Figure 11.

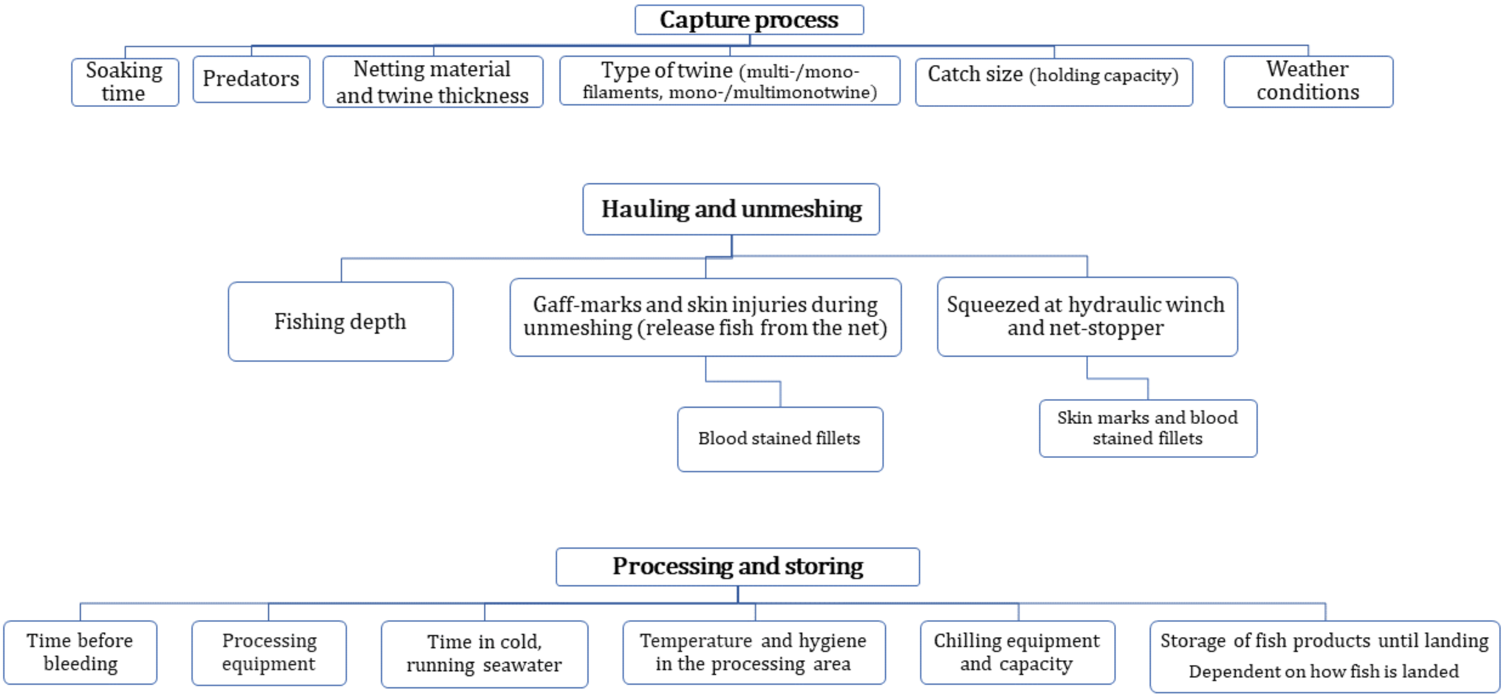

Figure 11: Possible factors affecting the catch quality of fish captured by gillnets

Savina et al. (2016) investigated the effect of soak time on catch damage in plaice *(Pleuronectes platessa)* and found that catch damage was more likely for longer soaking times. Joensen et al. (2021) reported that soaking time was the most important single factor affecting the quality of fish caught using gillnets. Short soaking times may increase fish survival compared with soaking times > 12 h, and result in better catch quality (decreases in catch-related damage, muscle discoloration, and bruises). However, catch efficiency is highly dependent on soaking time, and too short soaking times may not be realistic as the catch efficiency will be too low (Sogn-Grundvåg et al., 2022).

As mentioned in section 1.3.2., fish become trapped in a gillnet by gilling, wedging, snagging, and entangling. When fish are caught by gilling, the mesh tightens around the gills, usually behind the operculum (Gabriel et al., 2005). This makes ventilation difficult, and the fish will eventually die by asphyxiation. Fish that die trapped in the fishing gear before being taken on board are very hard to bleed properly, and this may occur to varying degrees if the soaking time is too long (Joensen et al., 2021). When a fish is caught in a gillnet it will attempt to free itself and struggle for a period which may cause gear marks and consequently lead to severe blood stains (Figure 12). After the fish is taken on board, several factors may affect quality, including time before bleeding, slaughter practices, and storage conditions (see also Figure 11).

Figure 12: Example of a fish caught using a gillnet with severe gear marks, which consequently led to blood related damages to the fillet, such as blood stains. Photo by Sjúrður Joensen, Nofima.

2. AIMS OF THE STUDY

Cod caught by bottom trawls and gillnets are often associated with poor and variable quality in terms of catch-related damage including pressure injuries, gear marks, bruises, and insufficient exsanguination, which may lead to blood related damage such as blood stains and muscle discoloration in the fillets (Rotabakk et al., 2011; Sogn-Grundvåg et al., 2022). However, there is little understanding of how new gear designs or practices could help improve these quality issues. The overall aim of this thesis is to study the effects of changing gear design or fishing practices in the trawl and gillnet fishery on the quality of NEA-cod. This was done by testing two different codend designs (Papers I and II), studying the consequences of buffer towing (Paper III), and finally performing an experimental study on gillnet soaking time to better understand fish mortality, stress, and quality during gillnet fishing (Paper IV).

3. METHODS USED TO EVALUATE CATCH RELATED DAMAGES AND MUSCLE DISCOLORATION

In this thesis, fish quality was defined by catch-related damage and muscle discoloration. Catch-related damage was assessed using the catch-damage-index (CDI) developed by Esaiassen et al. (2013), and color in fillets was measured using a colorimeter. The main factor responsible for muscle discoloration in white fish is residual blood in the fillets (Olsen et al., 2008). Hemoglobin occurs in large amounts in the red blood cells and colors the blood red. The Hb concentration in fish muscle was evaluated using two different methods: chemical analyses and hyperspectral imaging (HSI).

3.1. Catch damage index

The catch damage index (CDI) was developed and published by Esaiassen et al. (2013) to assess the quality of cod at landing. It determines fish quality by visual assessment of catch-related damage, standardized into a repeatable index. The original CDI included eight different types of catch-related damage: dead in gear, gear-related damage, bruises, gaffing damage, poorly bled, skin abrasion, pressure injuries, and biting injuries (Esaiassen et al., 2013). In this thesis dead in gear, gaffing damage, and biting injuries were omitted as they are not common in trawl-caught fish. The CDI-index was not used in the experimental gillnet study.

All catch-related damage was registered according to the categories described in Table 1. Fish were examined by trained personnel and scored for each type of damage according to its severity: 0 (flawless), 1 (moderate), or 2 (severe). The scores are based on the extent to which the value of the final product was compromised (e.g., score 2 is given when the value of the end product was compromised) (Esaiassen et al., 2013).

Table 1

The catch damage index used to evaluate damage to the cod included in this thesis.

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

3.2. Color measurement

Muscle color was measured using the CIE L*, a*, b* system, using a Minolta chromameter (Wu & Sun, 2013).

3.3. Chemical analyses of hemoglobin

Several classical methods have been widely used to quantify Hb levels in muscle tissue (Brown, 1961; Drabkin, 1950; Hornsey, 1956; Karlsson & Lundström, 1991). However, the recovery of Hb from fish muscle using these methods is believed to be limited by poor extraction levels (Chaijan & Undeland, 2015). Therefore, a new haemoprotein determination method for fish muscle was developed by Chaijan & Underland (2015), which was shown to recover more haemoprotein than the classical methods. The principle is to homogenize and heat samples in an SDS-containing phosphate buffer to dissolve the fish muscle and convert haemoproteins to hemichrome. Then, by measuring the light absorbance of the samples at 535 nm and, comparing it with a standard curve based on bovine Hb, the total haemoprotein concentration can be quantified.

3.4. Hyperspectral imaging

Blood detection in fish muscle using HSI was described by Skjelvareid et al. (2017). The principle is based on the diffuse reflectance mode in the visible/near infra-red (VIS/NIR) range. Skjelvareid et al. (2017) developed a model that can be used to translate any blood abundance value to a Hb concentration. Blood detection using HSI can also be used on whole fish with the skin on, but since this method is new and under development, no conversions of blood abundance to Hb concentration are currently available. Although blood detection using HSI is a new method, some studies using it have been published recently (Svalheim et al., 2019; 2020).

4. GENERAL RESULTS AND DISCUSSION

4.1. Effects of changes in bottom trawl codend design

There have been several studies aimed at improving the quality of trawl-caught fish (Brinkhof et al., 2018a, 2018b, 2021; Digre et al., 2010; Svalheim et al., 2019, 2020; Tveit et al., 2019), with the main focus being on codend design. The general goal is to prevent deterioration of catch quality during the capture process. If damage occurs during fish capture, it is difficult, if not impossible, to improve overall catch quality. Hence, preventing deterioration of the catch during capture is important in improving the quality of trawl-caught cod. Two different trawl configurations aimed at improving the quality of trawl-caught cod were studied. The dual sequential codend study is described in Paper I, while Paper II describes the T90-codend study.

4.1.1. Sequential codend

In the Barents Sea gadoid fishery, sorting grid systems are mandatory to ensure the escape of juvenile fish (Ministry of Trade, Industry and Fisheries, 2022; Yaragina et al., 2011), followed by a diamond-mesh codend with a minimum mesh size of 130 mm (Ministry of Trade, Industry and Fisheries, 2022). The dual sequential codend is a concept aimed at improving the quality of trawl-caught fish, where the first codend segment has size-selective properties as required by law, while the sequential codend segment is designed to reduce the strain on the fish (Figures 13 and 14).

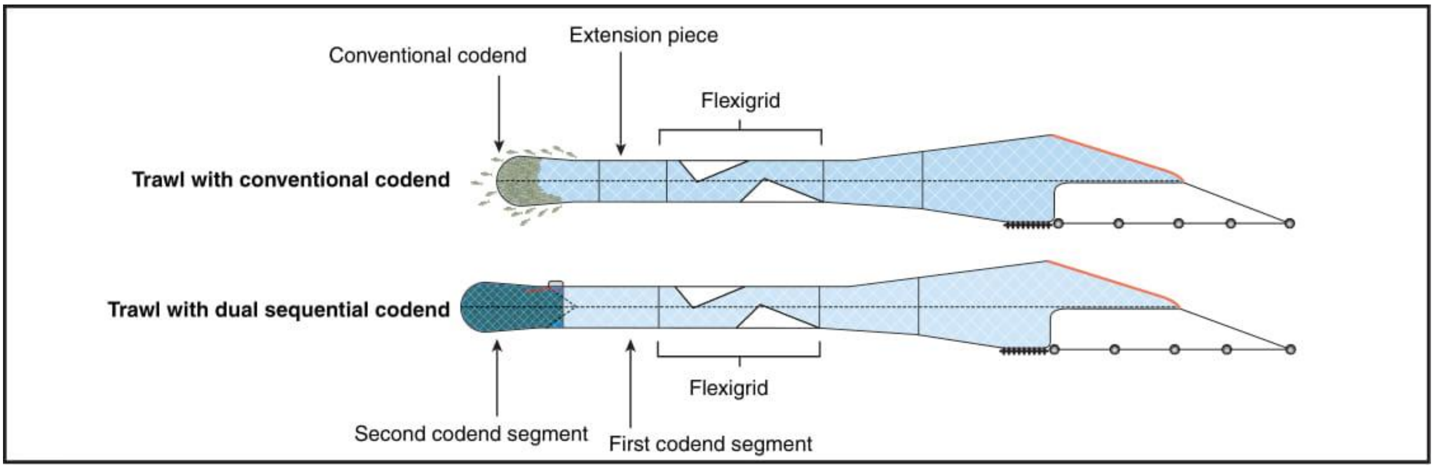

Figure 13: Diagrammatic representations of trawls with a conventional codend and a dual sequential codend, seen from the side.

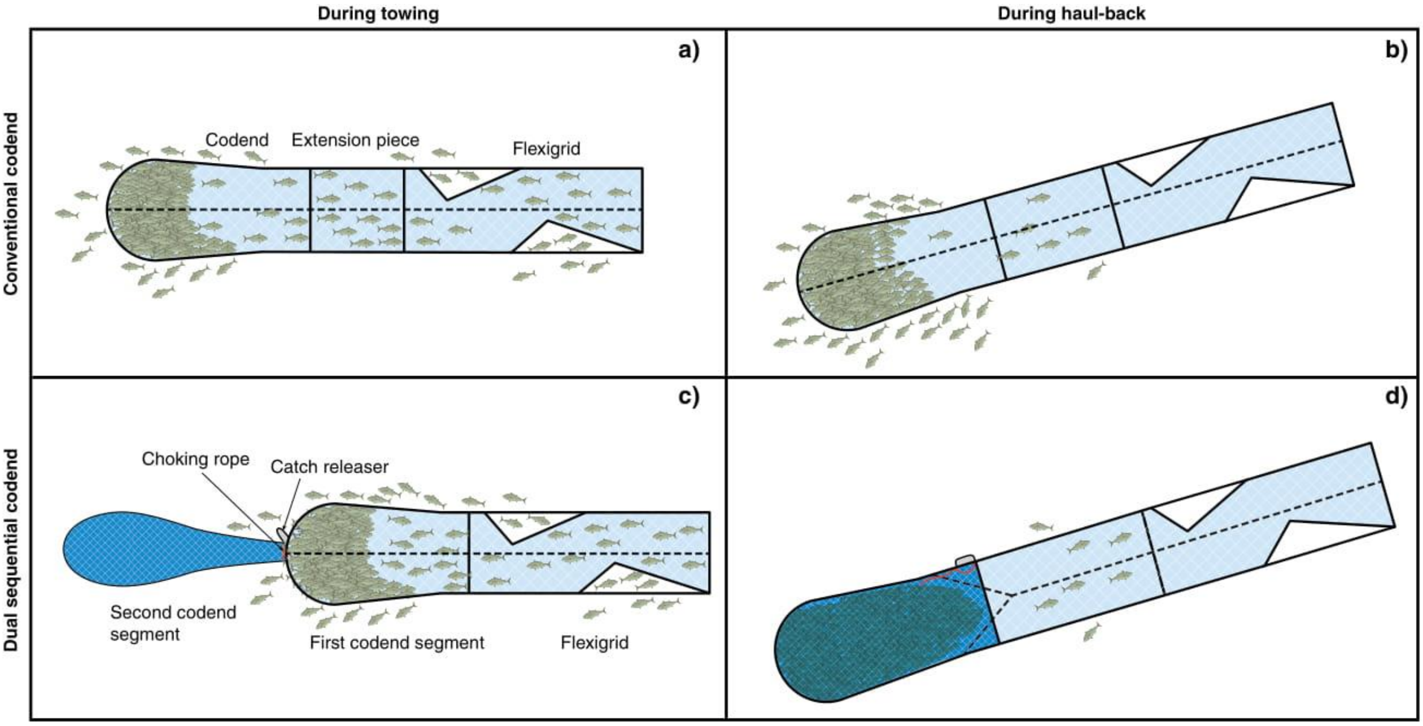

Figure 14: Side-views of a conventional codend during a) towing and b) haul-back. In contract, the dual sequential codend consists of two codend segments: the first codend segment with size-selective properties as legislated, in which the fish are retained during c) trawling, and a second codend segment with expected quality-improvement properties, into which the fish fall during d) haul-back.

The large mesh sizes required by law are believed to contribute to catch defects such as gear marks, bruises, and skin abrasion (Brinkhof et al., 2018b). The sequential codend segment is therefore designed with a knotless small-sized mesh (i.e., 6 mm mesh size), which retains water inside the codend during hauling. The idea is that the fish will be kept in a water bath when the codend is lifted from the sea onto the trawl deck, preventing them from being squeezed against the codend netting. In this way, gear marks and bruises should be reduced. Brinkhof et al. (2018b) reported that compared with cod caught with a conventional codend, those caught using a sequential codend had a 14% (confidence interval (CI): 6–24%) higher probability of catching cod without any external catch-related damage, as evaluated by the CDI (Esaiassen et al. 2013). In addition to catch-related damage, residual blood present in fish fillets is also a very important quality parameter but this is not included in the CDI, which assesses headed and gutted fish (Esaiassen et al., 2013). Therefore, Paper I investigated whether the dual sequential codend affected residual blood in cod fillets, as measured by Hb concentration determined by HSI.

No significant differences in Hb content between fish caught by the sequential codend and those caught by the conventional codend were discovered. Brinkhof et al. (2018a, 2018b) used the CDI to assess the quality of caught cod, while the study presented in Paper I investigated residual blood in cod *fillets* by measuring Hb levels in the muscle. It is therefore possible that the dual sequential codend improves fish quality in terms of catch-related external damages as evaluated by the CDI, but not quality defects related to red muscle discoloration/residual blood in the fillets.

An important factor that might have influenced the results is catch sizes during the experiments. There were consistently larger catches in hauls using the sequential codend compared with those using the conventional codend. Knowing that increased catch size reduces fish quality (Digre et al., 2017; Margeirsson et al., 2007; Olsen et al., 2013; Rotabakk et al., 2011; Veldhuizen et al., 2018), it is not possible to separate the influence of various codends from that of catch size. Furthermore, the catch sizes in Paper I was very low compared with those found in commercial fisheries, where catches easily exceed 10 tonnes. It is therefore also possible that the small catch sizes and short towing times studied may have concealed any effects of codend type on the amount of residual blood in the fish. Therefore, it is not possible to draw a definite conclusion about the effects of the different codends on residual blood in cod fillets in this case.

Either way, Brinkhof et al. (2018a, 2018b) demonstrated improved quality of fish caught with the dual sequential codend. Implementing this codend in the bottom trawl fishery could therefore potentially improve the quality of trawl-caught fish. On the other hand, the dual sequential codend is expensive and difficult to handle, and the extra costs spent on improving fish quality by using it may exceed any additional revenue earned from improving the quality of the catch. Therefore, the optimal solution would be to find a way to improve catch quality without investing in new equipment. One simple solution that could potentially deliver this would be to turn the direction of the codend netting 90 degrees (T90) perpendicular to the towing direction, and this codend modification was studied in Paper II.

4.1.2. T90-codend

The T90-codend is one where the mesh direction in the codend panels is turned 90 degrees (Figure 15). Anecdotal information provided by fishers suggests that T90-codends provide better catch quality. Digre et al. (2010) investigated the effect of a partial T90-codend on the catch quality of cod and haddock (*Melanogrammus aeglefinus*). However, their experimental trawl setup included a sorting grid and diamond knotless meshes in the last four meters of the codend, which makes it difficult to assess the potential effect of the T90-codend on catch quality specifically. Other than this, we know of no studies investigating the effect of the T90-codend on catch quality.

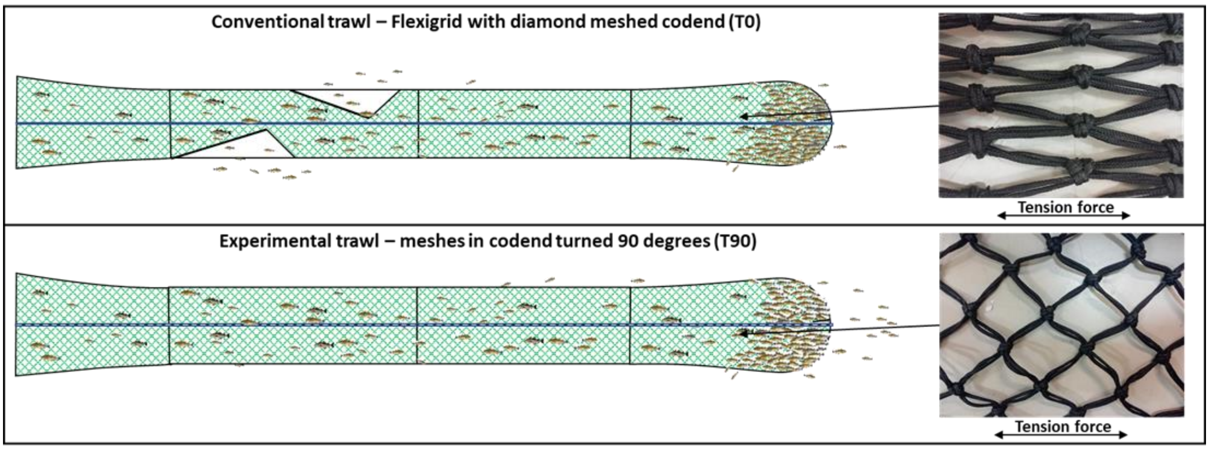

Figure 15: Setup of the two trawl configurations: the conventional trawl configuration (flexigrid with diamond-mesh codend) and the experimental trawl configuration (meshes in the codend turned 90 degrees)

Some fishers claim that the use of a sorting grid, which is compulsory in the bottom trawl fishery in the Barents Sea (Brinkhof et al., 2021; Sistiaga et al., 2016), negatively affects catch quality. Therefore, in Paper II, the catch quality of NEA-cod in the Barents Sea bottom trawl fishery caught using the conventional configuration (a sorting grid followed by a diamond-mesh (T0) codend) was compared with that of a T90-codend without a grid. The catch quality was assessed using the CDI, and HSI to estimate the residual blood levels in fish muscle.

The results showed that cod caught using the T90-codend had the same amount and severity of catch-related damage as those caught by the conventional trawl configuration. The results also showed no significant differences between the residual blood levels of cod caught with the two different trawl configurations. Paper II therefore showed that removing the compulsory sorting grid and replacing the regular diamond-mesh codend with a T90-codend did not compromise catch quality. Another important issue in the bottom trawl fishery is size selectivity, and Brinkhof et al. (2022) demonstrated that using the same T90-codend configuration as studied in Paper II improved release of juvenile cod while simultaneously increasing catch efficiency of fish larger than minimum landing size in the Barents Sea. Since the T90-codend does not alter the catch quality of trawl-caught cod and improves size selection (Brinkhof et al., 2022), the use of the T90-codend without a sorting grid could be beneficial for the trawl industry, as this codend design is much easier to handle and addresses the concerns of fishers about sorting grid related fish damage.

4.2. Effects of changes in practice for bottom trawls and gillnets

4.2.1. Buffer towing

A fishing practice known as buffer towing is common among many trawlers in the Barents Sea (Brinkhof et al., 2018a), and is used to secure a continuous supply of fish. The trawl is redeployed immediately after taking the catch on board, and if the processing of the previous haul has not been completed when the desired amount of fish has been caught, the trawl is lifted from the seabed and towed at low speed (1–2 knots). Buffer towing is continued until the processing capacity has been restored. Brinkhof et al. (2018a) reported that cod subjected to buffer towing suffered increased probability of poor exsanguination and increased fillet redness compared with those captured by regular haul-back (i.e., without buffer towing) as evaluated by the CDI and a fillet quality index.

In Paper III, the color and amounts of residual blood in cod loin were compared after trawling with and without buffer towing. The results showed no significantly increased redness (a*) or Hb concentration in loin from cod exposed to buffer towing compared with those caught by regular haul-back. The posterior part of the loin had higher levels of Hb, indicating ecchymosis in the loin caused by rupture of the swim bladder.

We also investigated whether buffer towing affected the shelf life of thawed cod as evaluated by the total volatile basic nitrogen (TVB-N) levels. No significant differences were found in TVB-N levels during chill storage of cod at 0 and 4 ºC between those caught by regular haul-back and buffer towing.

Brinkhof et al. (2018a) proved that buffer towing significantly reduced the quality of caught cod. They showed that cod subjected to buffer towing had an increased relative probability of fillet redness of 209% compared with those subjected to regular (direct) haul-back, as assessed by sensory evaluation. In contrast, in the present work, only slightly higher and non-significant redness (a*) and Hb concentration were found in loins from cod exposed to buffer towing compared with regular haul-back. However, in the study by Brinkhof et al. (2018a), discoloration was assessed using a “Fillet index”, in which the visual appearance of the whole fillets was evaluated. Olsen et al. (2008) and have shown that cod loins contain significantly less residual blood than the belly in both unstressed and stressed fish. This is also demonstrated in Paper I and IV. It is therefore possible that redness and residual blood in the whole fillet are influenced by buffer towing, as demonstrated by Brinkhof et al (2018a), while the loin part of the fillet is less affected.

4.2.2. Quicker killing and bleeding of fish

It is well established that time from the catch being brought on board until bleeding is of the utmost importance in achieving sufficient exsanguination and reducing red muscle discoloration (Borderías & Sánchez-Alonso, 2011; Botta et al., 1986; Margeirsson et al., 2007; Olsen et al., 2014). In addition, capture-related stress has been shown to influence residual blood levels in cod fillets (Svalheim et al., 2019; 2020). Since it was expected that fish caught with the dual sequential codend would be treated more gently compared with those caught with a conventional codend, we investigated whether the dual sequential codend mitigates the effect of postponed bleeding. In other words, whether fish caught using the sequential codend were more resilient to postponed bleeding compared with those caught with a conventional codend.

Postponed bleeding had a statistically significant effect on the amount of residual blood in cod fillets for both the dual sequential codend and the conventional codend, indicating that postponed bleeding led to higher amounts of residual blood in the fish regardless of the codend used. For both fish caught with the dual sequential codend and the conventional codend, it was concluded that cod bled 40 minutes after capture (i.e., after the fish were taken from the dry bin) had significantly higher levels of Hb than those bled immediately after capture. Olsen et al. (2014) reported that cod should be bled within 30 minutes after being hauled on board. However, this recommendation was based on results from unstressed fish and is likely to be less relevant in commercial fisheries, where fish are exposed to several stressors. In Paper I, the postponed bleeding experiment was conducted on live-caught fish that had been exposed to several capture-related stress factors. Although we hypothesized that fish bled after 20 minutes would have higher amounts of residual blood compared with those bled immediately after capture, no significant differences were found. However, due to fish welfare considerations, the fish in Paper I were stunned with a blow to the head prior to air-exposure and postponed bleeding. Svalheim et al. (2019) showed that crowding and air-exposure were associated with increased metabolic stress, resulting in increased amounts of residual blood in the muscle after bleeding. It is therefore possible that the effects of postponed bleeding may have been higher if the fish had been kept conscious in air prior to bleeding, instead of being stunned.

4.2.3. Shorter soaking times for gillnets

In Paper IV, an experimental study on gillnet soaking time was conducted to better understand fish mortality and quality during gillnet fishing. The results showed that mortality was significantly affected by soaking time, with longer soaking time causing higher mortality. As seen in Figure 16, fish that died in the gillnet had the net wrapped around the operculum probably making it difficult for the fish to ventilate, and so eventually leading to death by asphyxiation. Fish survival was higher for those only caught in the gillnet for 2 h, compared with 12 and 24 h, but even when soaking time was short (i.e., 2 h), dead fish were registered with the gillnet wrapped around the operculum. Fish caught in the net by snagging or wedging (Figures 17 and 18) were able to move the operculum, allowing them to survive the capture process. Clearly, the way in which fish are caught in the gillnet (i.e., gilling, wedging, snagging, or entangling) affects the survival of the catch. This may have further consequences for catch quality because fish that die in the fishing gear are very hard to bleed out properly, consequently leading to red muscle discoloration.

Chemical analyses of Hb in the loin and belly was conducted. No significant effect of soaking time on the Hb levels in belly were found. However, soaking time significantly affected the amount of Hb in the loin for the fish that survived, but not for the fish that died in the gillnet during the experiment. This is somewhat in accordance with Savina et al. (2016) who investigated the effect of soaking time on catch damage in plaice *(Pleuronectes platessa)* and found that catch damage was more likely for longer soaking times.

Figure 16: Example of two different fish from the experimental gillnet study that died in the gillnet after 2 h (top) and 24 h (bottom) soaking time. The gear marks show that the gillnet had become wrapped around the operculum. The red circle indicates visible skin abrasion caused by the gillnet

Figure 17: Example of a fish from the experimental gillnet study after 12 h soaking time. The gear marks show that this fish had been caught by both gilling and wedging.

Figure 18: Example of a fish from the experimental gillnet study after 12 h soaking time. The gear marks show that this fish had been caught by snagging.

4.3. Differences in muscle discoloration between loin, belly and tail and the economic implications of these differences

The results regarding the distribution of residual blood in the various fillets provide new and interesting information. For cod caught by both bottom trawls and gillnets, it was found that the belly had significantly higher levels of residual blood compared with the loin and tail. Since loin is paid higher than other cuts of the fillet (Svorken et al., 2015), discoloration and residual blood in the loin entails a greater potential economic loss than if the blood has accumulated in other parts of the fillet.

4.4. Use of the catch damage index and hemoglobin as quality indicators

The benefit of blood detection using HSI is that it provides an objective quantification of the residual blood in fish, without compromising the quality of the fish/fillets. HSI can be used to assess several other quality parameters in addition to estimating residual blood content, including detection of nematodes (Sivertsen et al., 2012) and estimations of fillet freshness (Sivertsen et al., 2011), water content of clipfish (Wold, 2006), ice fraction (Ottestad et al., 2009), and fat content in salmon fillets (Segtnan et al., 2009).

The CDI covers some catch-related damage that cannot be detected using HSI, such as skin abrasion and gear marks. However, analyzing fish one by one using the CDI is time consuming and requires trained personnel, while estimating residual blood using HSI meets industrial speed requirements by assessing one fish/fillet per second. Furthermore, the CDI does not register flaws such as soft muscle, fillet gaping, or the condition factor of the fish. Cod caught by gillnets are usually larger and in better condition than those caught by longlines (Esaiassen et al., 2004; Huse et al., 2000; Ovegård et al., 2012), which are also important quality parameters for the production of saltfish and clipfish.

Chemical analysis is a reliable method of quantifying Hb in fish muscle (Olsen et al., 2008; 2013; 2014). However, it is time consuming and requires laboratory facilities and chemicals. In addition, the fish is destroyed during analysis so this method cannot be used on an industrial scale. Blood detection by HSI is therefore a much easier and faster method of estimating Hb levels in fish muscle.

4.5. Difference between bottom trawls and gillnets

There are two main differences between the use of bottom trawls and gillnets, besides the fact that bottom trawlers are active fishing gears, while gillnets are passive fishing gears.

Firstly, the bottom trawl fleet consist of large ocean-going vessels with powerful engines that are able to cover vast and distant areas of ocean. This makes it possible for the trawlers to take longer trips compared to smaller gillnet operating vessels, which follow the spawning aggregation of NEA-cod and mainly operate in coastal areas during specific times of the year. The large industrial trawlers, however, can operate far from land and have thus the opportunity to spread landings over the course of a year and profit from fluctuations in market price and availability of cod outside the seasonality of the coastal fishery.

Secondly, most of the trawlers is equipped with onboard freezing facilities, and trawlers primarily deliver frozen products (Flaaten & Heen, 2004; Standal & Hersoug, 2015). The availability of modern freezing facilities onboard trawlers provides and advantage in the market as they are not compelled to sell the fish immediately, unlike gillnetters that land fresh cod.

In terms of catch related quality challenges, both gears share the common factor that catch efficiency affects the quality. For bottom trawls high catch size and long towing times consequently lead to increased mortality, and decreased catch quality (Digre et al., 2017; Margeirsson et al., 2007; Olsen et al., 2013; Rotabakk et al., 2011; Veldhuizen et al., 2018). The high frequency of bruises and muscle discoloration observed in trawl-caught cod is most likely caused by the high pressures applied to fish in the trawl during hauling, and large catch sizes which make it difficult to cut and bleed the fish immediately after capture. For gillnets it has been shown that soaking time affects the quality of fish (Savina et al., 2016). This is further supported by the experimental gillnet study in Paper IV, which concluded that longer soaking times led to lower survival rates and increased fillet redness. However, soaking time also affect catch efficiency, and too short soaking times may not be realistic in commercial scale as the catch efficiency will be too low. Therefore, both bottom trawlers and gillnets share the common issues related to catch quality and catch efficiency. If the catch size is too high, this negatively affects the catch quality, but is the catch size is too low, this will consequently lead to negative economic consequences since less fish is landed, and/or the vessel needs to invest more time and effort in catching the same amount of fish over a longer period of time.

5. CONCLUSIONS, FINAL REMARKS AND FUTURE PERSPECTIVE

This thesis did not find any significant effects by changing gear design on catch-related damage and muscle discoloration in cod caught by bottom trawls. On the other hand, it did show that the T90-codend does not compromise catch quality compared with the conventional trawl configuration in terms of catch-related damage and amount of residual blood. Because the T90-codend does not alter the catch quality of trawl-caught cod, its use without a sorting grid could be beneficial for the trawl industry, because this codend design is easier to handle for the fishers. When investigating the effect on quality of changes in trawling practice, it was concluded that reducing bleeding time was important to achieve sufficient exsanguination and avoid muscle discoloration. Regarding cod caught by gillnets, it was shown that long soaking times negatively affected fish survival and quality through increased levels of Hb in the loin.

There are two important factors regarding improvement of catch quality of trawl-caught cod: 1) In order to reduce external catch related damages such as gear marks, pressure injuries and bruises which consequently lead to blood stains the fish should be captured as gentle as possible, and 2) to achieve sufficient exsanguination and avoid muscle discoloration, it is of utmost importance to bleed caught fish as quickly as possible after brought onboard and exposed to air. To achieve this for trawl-caught fish, catch size is the key. Crowding in the codend increases with increasing catch sizes. During haul-back of a codend with high density of fish, the fish are crushed against the codend netting. This may result in various pressure injuries, including skin abrasion, gear marks, and bruises. Furthermore, the bigger the catch, the harder it becomes to bleed out all the fish soon enough to ensure proper exsanguination. The optimum catch size should not exceed the processing capacity of the vessel. Even though good onboard handling practices can help to achieve good catch quality, it is quite challenging to improve catch quality if the damage has already occurred during the capture process and preventing deterioration of the catch during the capture process is highly important in improving the quality of trawl-caught fish. Therefore, studies should be conducted both to investigate new gear designs, which can reduce the strains on fish, as well as into improvements that will ensure that the fish are bled as fast as possible after capture.

Furthermore, it has been shown that stress through air-exposure has a negative effect on fillet quality in cod (Svalheim et al., 2019). Therefore, studies should be conducted to investigate how to bleed the fish in as short a time as possible (within 30 minutes after capture, according to Olsen et al., 2014), and preferably without air-exposure. Increased focus on killing fish as quickly as possible is also desirable to improve fish welfare. Lambooij et al. (2012) have reported that cod and haddock show brain activity for up to two hours after being taken on board and placed in dry bins. Keeping the fish alive in dry bins for a long period of time must be considered unacceptable in terms of animal welfare (Van De Vis et al., 2003). A possible solution could be to transfer the catch to onboard holding tanks from which live fish are consecutively processed (Digre et al., 2017; Erikson et al., 2019; Olsen et al., 2013), which has been shown to improve their final quality (Olsen, 2013).

Regarding cod caught by gillnets, catch quality depends on how the gillnets are operated. Savina et al. (2016) reported that catch damage in plaice was more likely for longer soaking times. When gillnets are hauled, fish are immediately released from the meshes one by one, bled, exsanguinated in running seawater, and usually stored in containers with ice-chilled seawater until landing. If the fish is alive when hauled onboard, this procedure can result in cod of excellent quality. If the fish is dead, however, there is little to be gained from good onboard handling. Short soaking times may increase fish survival compared with soaking times > 12 h, and result in better catch quality (decreases in catch-related damage, muscle discoloration, and bruises). However, catch efficiency is highly dependent on soaking time. Shorter soaking times may increase quality but reduce catch efficiency and increase fishing costs. The case is similar for cod caught using bottom trawl (i.e., reduced catch size might increase quality, but reduces catch efficiency).

Reducing catch size for bottom trawls and reducing soaking time for gillnets, and/or implementing new gear and other expensive equipment (i.e., storage tanks and stunning machines) increase fishing costs. Therefore, it will prove challenging to implement possible measures to improve catch quality on commercial vessels. Overall, it will be of benefit to continue studies into ways of improving the quality of caught fish without compromising catch efficiency.

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