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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

I.   Acknowledgements

This PhD would not have been possible without the support of many people, and I am truly thankful to all of you who have contributed in any way during my five years as a PhD student.

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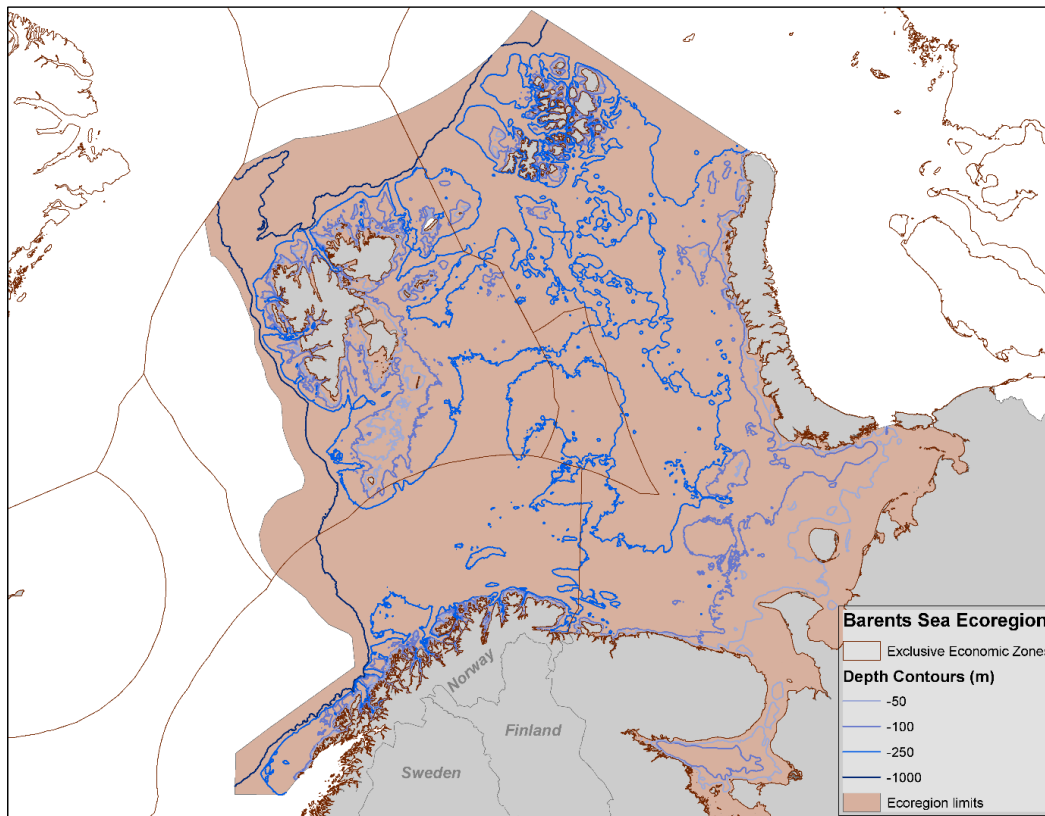
Figure 1: The Barents Sea ecoregion. Retrieved from ICES (2019).

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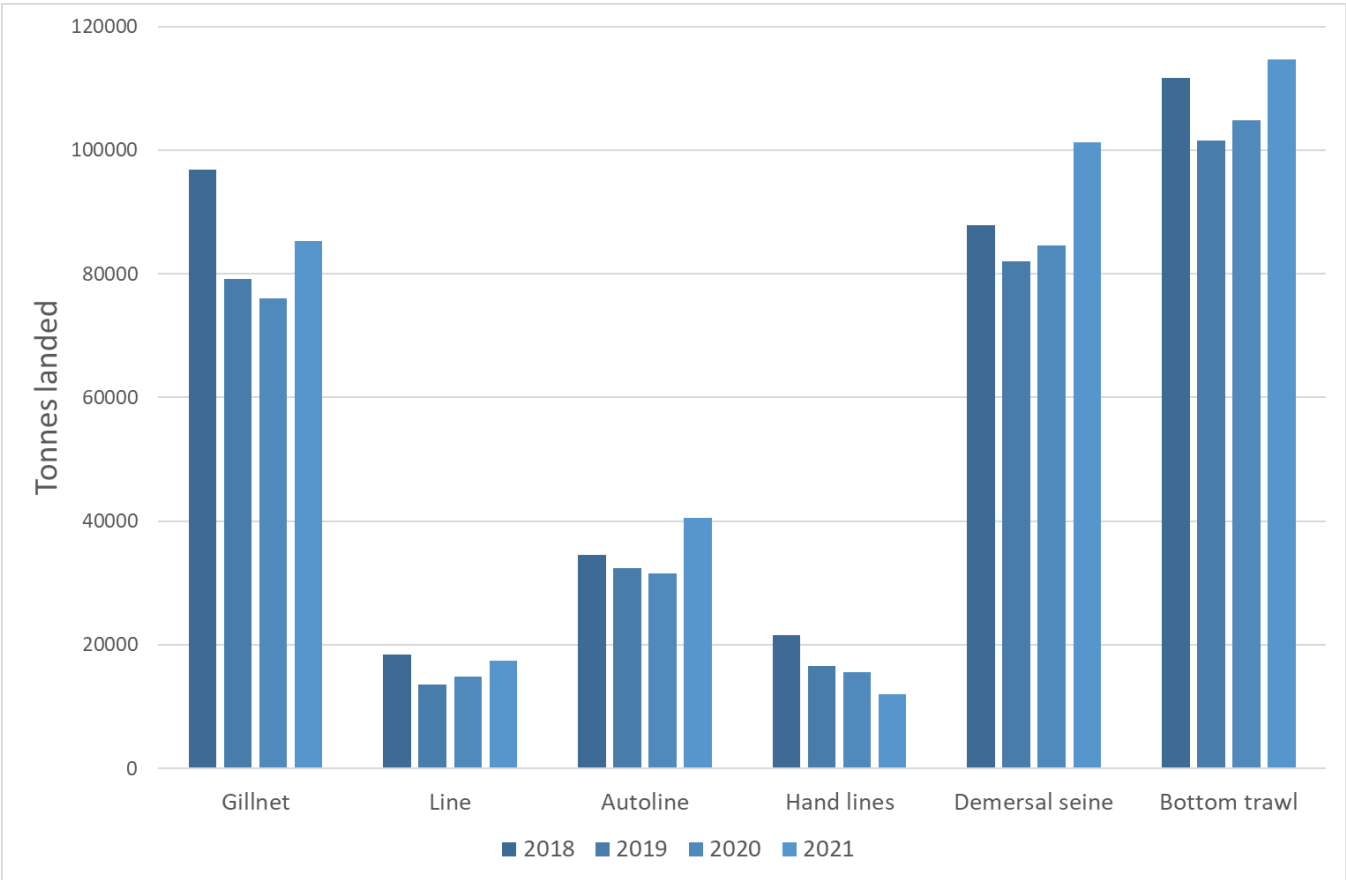
Figure 2: Metric tonnes landed NEA-cod in Norway by fishing gear (Fisheries Directorate, 2022).

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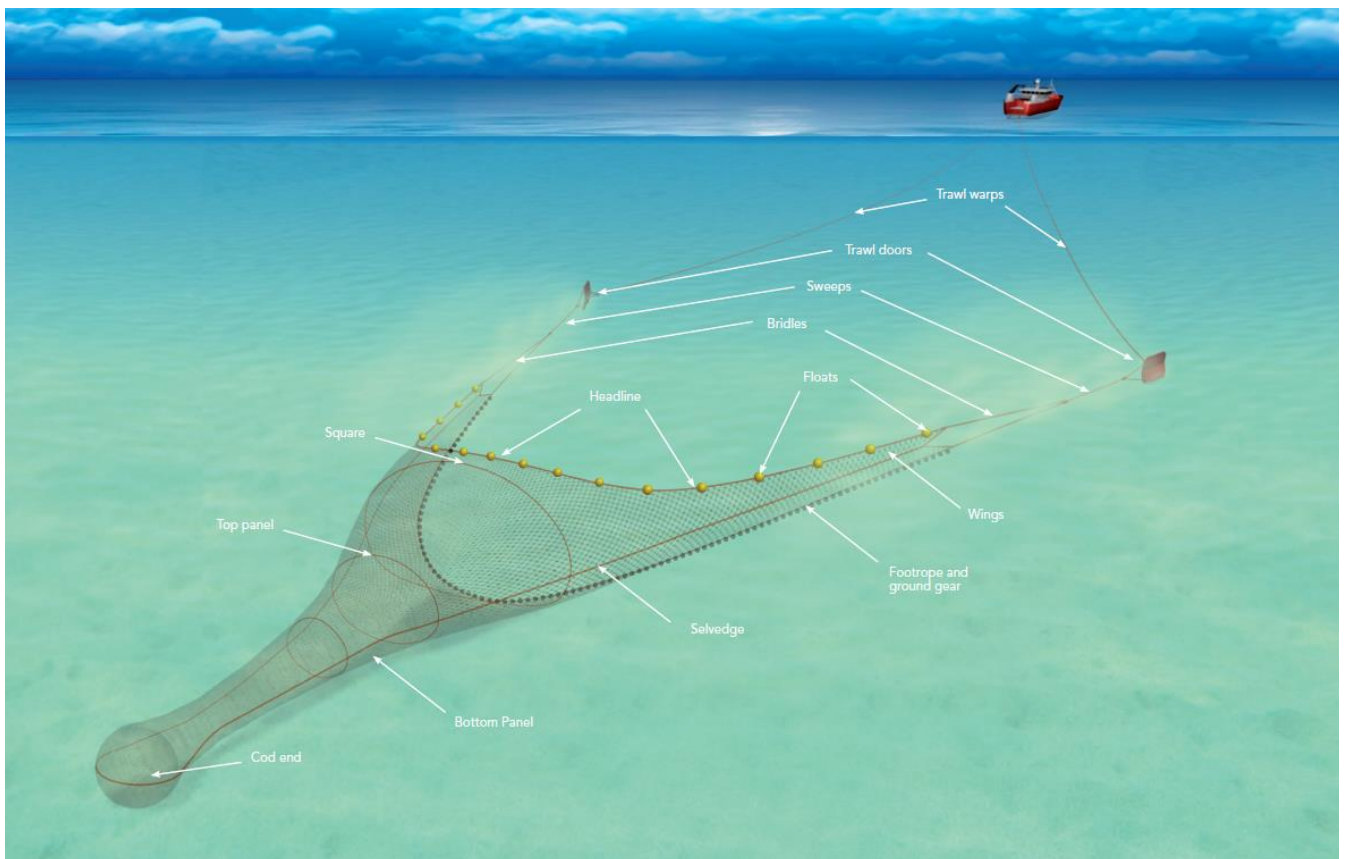
Figure 3: Overview of a bottom trawl with basic components of trawl gear. Retrieved from Seafish.

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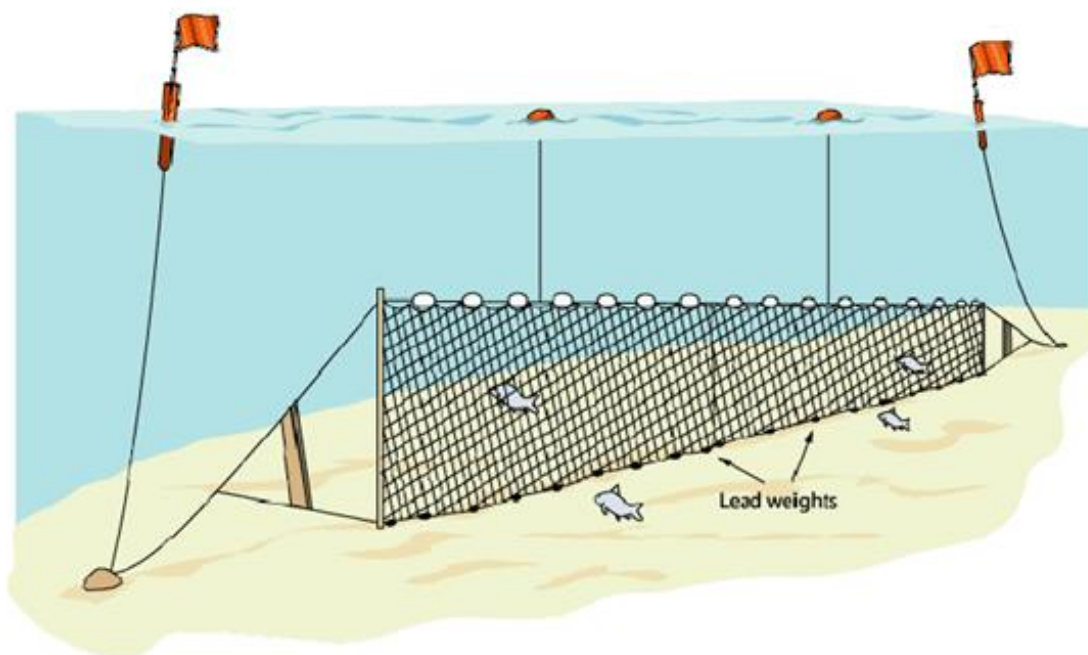
Figure 4: Principle rigging of a bottom-set gillnet. Retrieved from Michigan Sea Grant.

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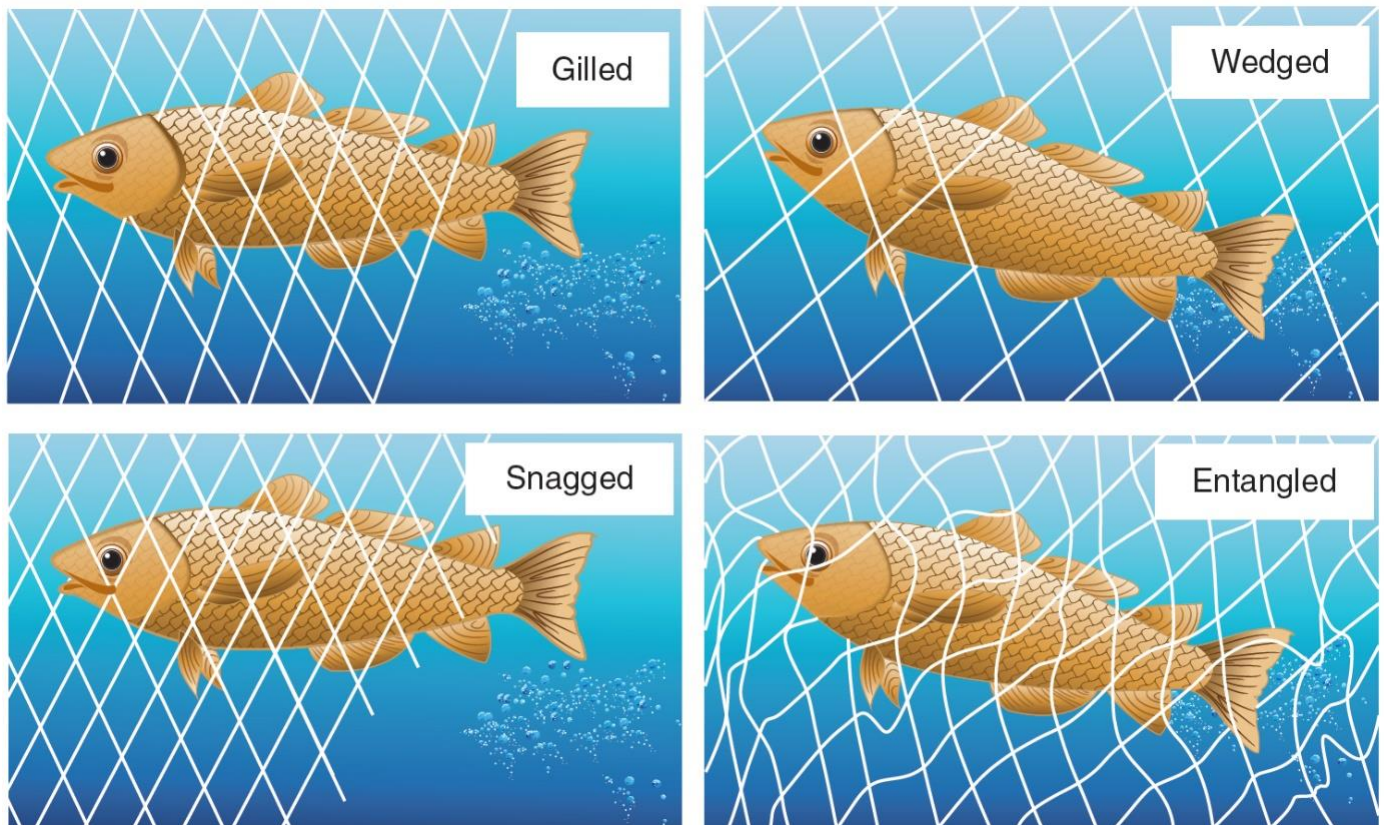
Figure 5: Fish capture by gillnets, illustrating the four modes of capture: gilling, wedging, snagging, and entangling. Modified from He and Pol, 2010.

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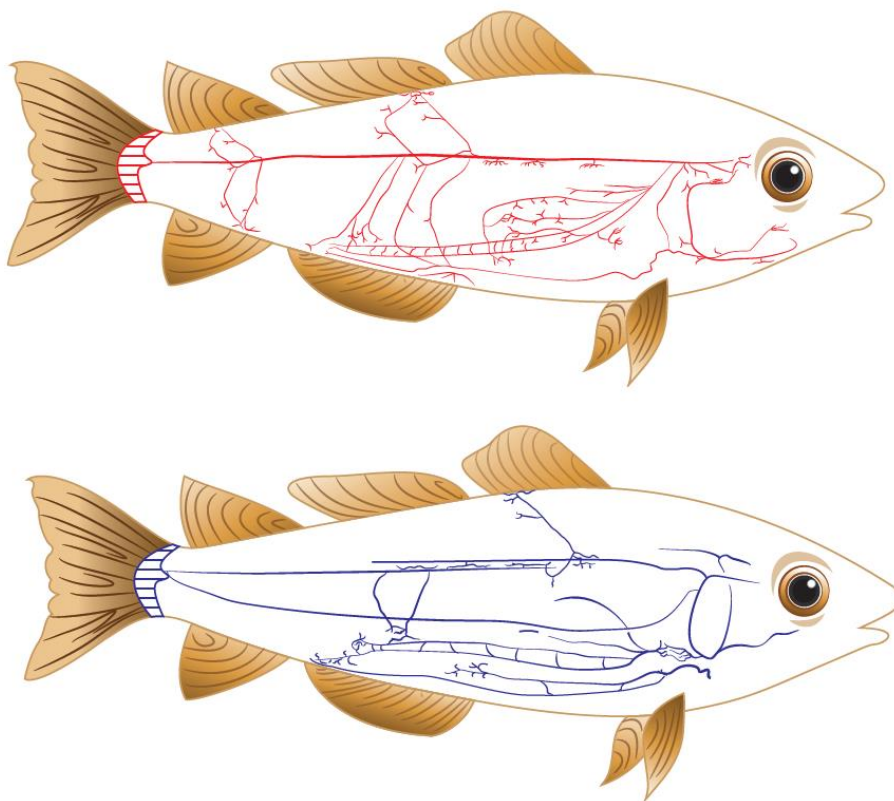
Figure 6: The major systemic arteries (top) and veins (bottom). Modified from Olson 2011a.

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.
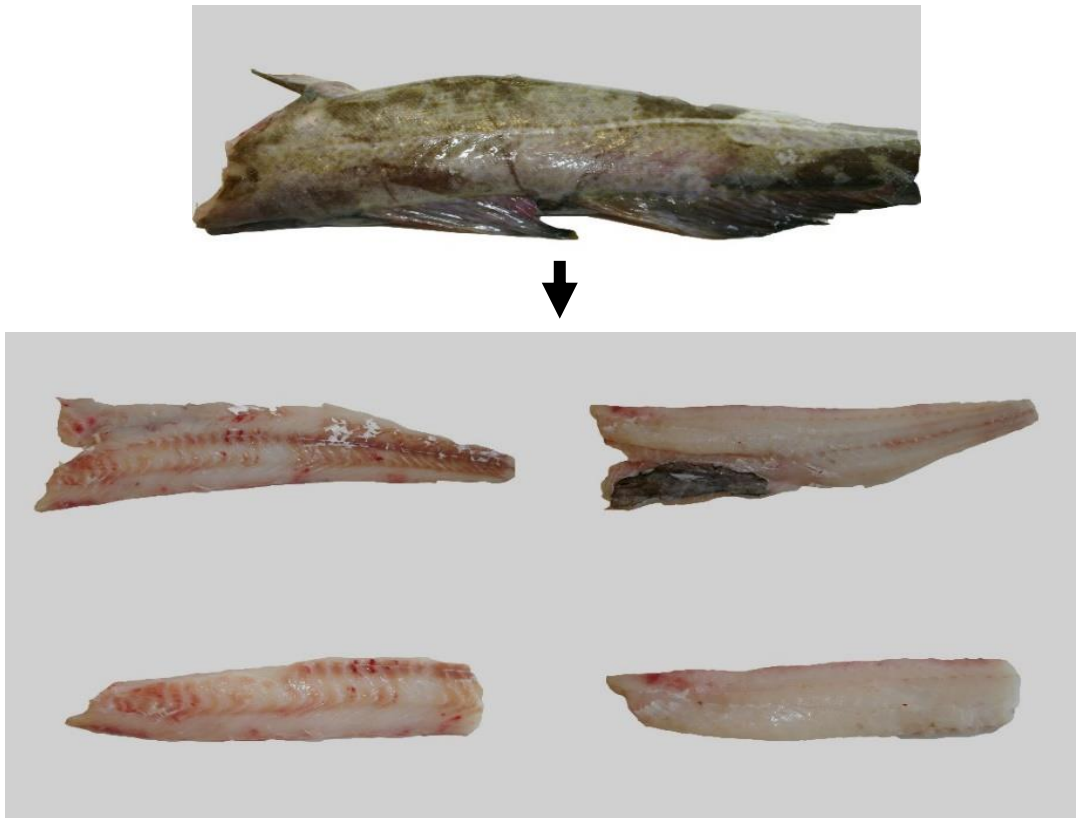
Figure 9: Example of trawl-caught cod fillets with blood related damage including blood stains and red muscle discoloration. Photo by Sjúrður Joensen, Nofima.
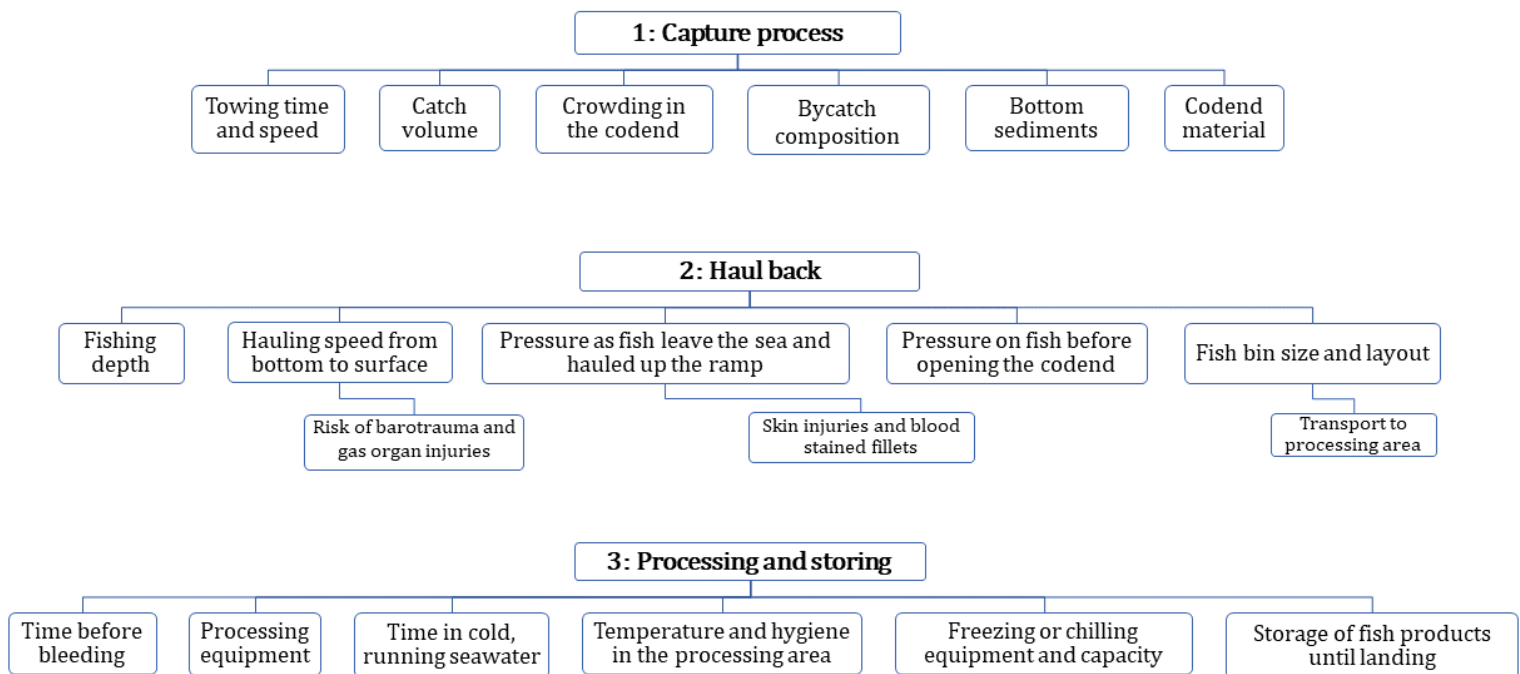
Figure 10. Possible factors affecting the catch quality of fish captured by bottom trawls, at each stage of the capture and onboard handling processes.

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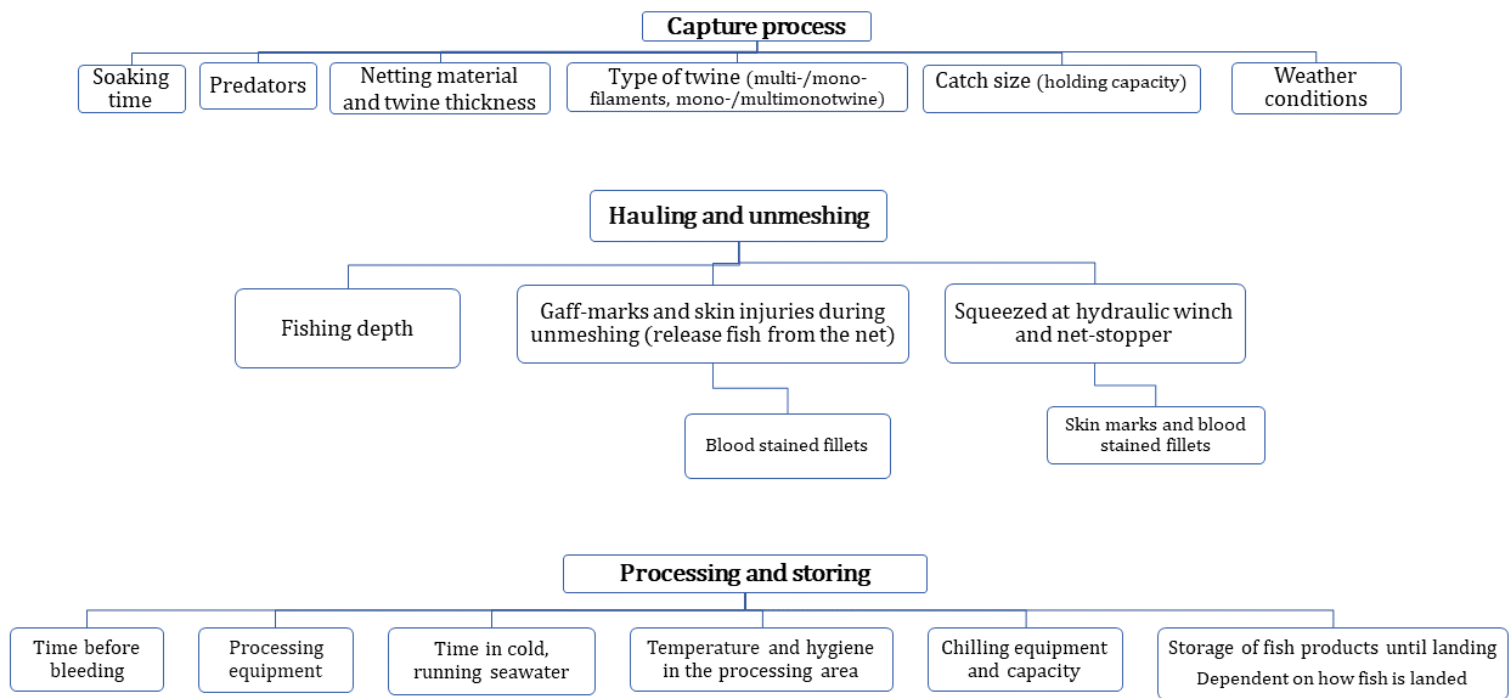
Figure 11: Possible factors affecting the catch quality of fish captured by gillnets

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).
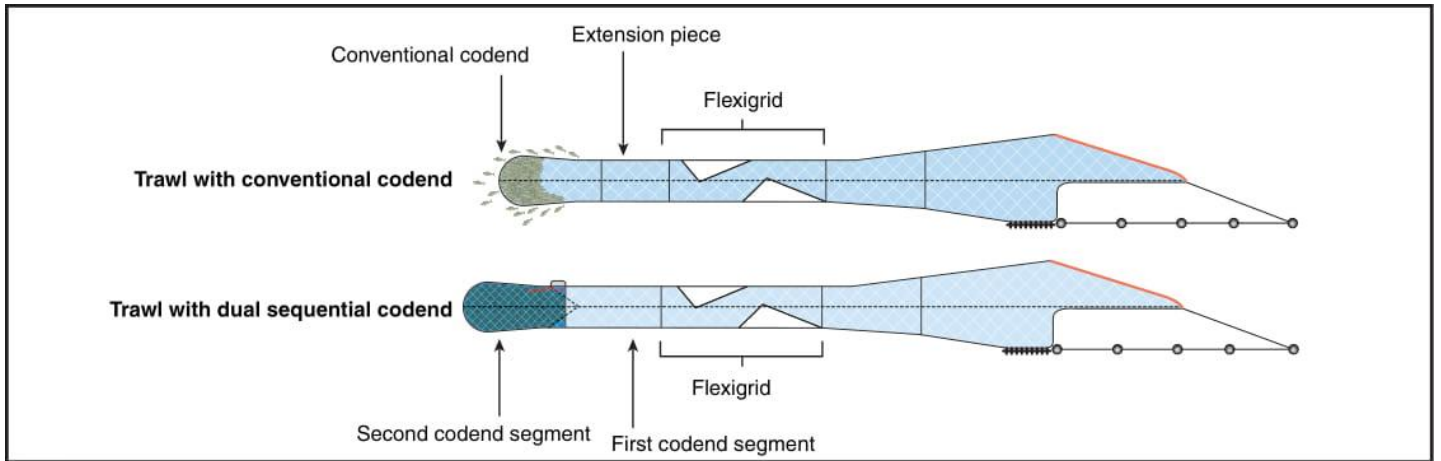
Figure 13: Diagrammatic representations of trawls with a conventional codend and a dual sequential codend, seen from the side.
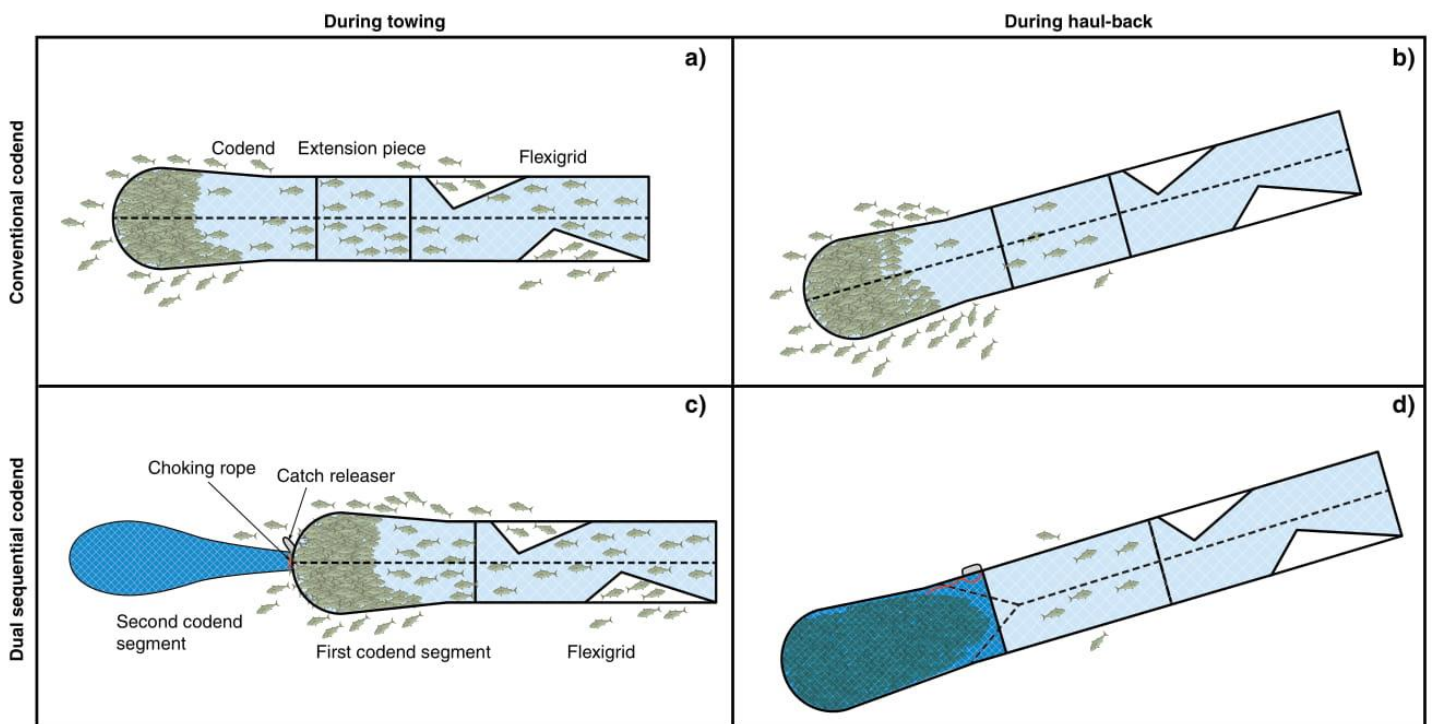
Figure 14: Side-views of a conventional codend during a) towing and b) haul-back. In contract, the dual sequential codend consists of two codend segments: the first codend segment with size-selective properties as legislated, in which the fish are retained during c) trawling, and a second codend segment 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.
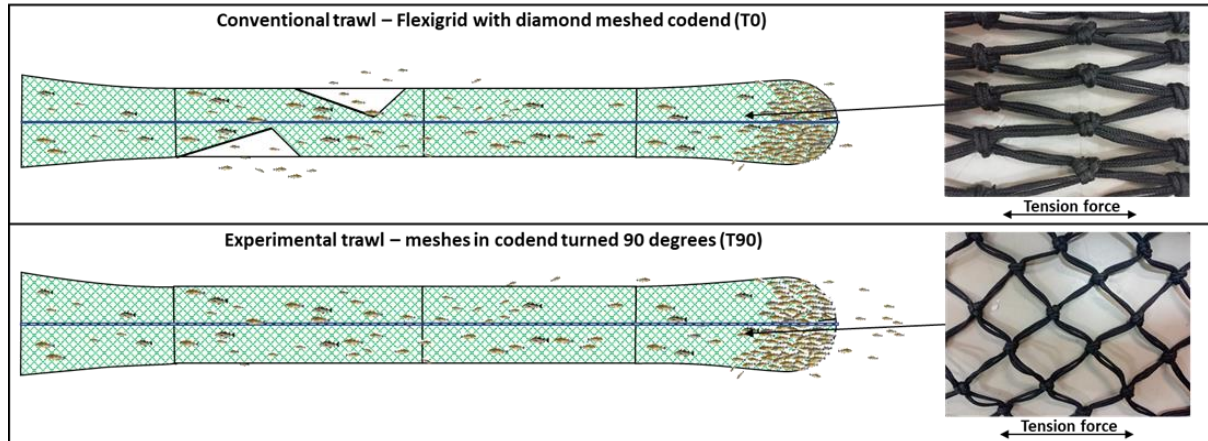
Figure 15: Setup of the two trawl configurations: the conventional trawl configuration (flexigrid with diamond-mesh codend) and the experimental trawl configuration (meshes in the codend turned 90 degrees)

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 °C 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.

6. REFERENCES

Amoroso, R. O., Pitcher, C. R., Rijnsdorp, A. D., McConnaughey, R. A., Parma, A. M., Suuronen, P., Eigaard, O. R., Bastardie, F., Hintzen, N. T., Althaus, F., Baird, S. J., Black, J., Buhl-Mortensen, L., Campbell, A. B., Catarino, R., Collie, J., Cowan Jr. J. H., Durholtz, D., Engstrom, N., … & Jennings, S. (2018). Bottom trawl fishing footprints on the world's continental shelves. *Proceedings of the National Academy of Sciences*, *115*(43), E10275–E10282.

Ang, J. F., & Haard, N. F. (1985). Chemical composition and postmortem changes in soft textured muscle from intensely feeding Atlantic cod (*Gadius morhua,* L). *Journal of Food Biochemistry, 9*(1), 49–64.

Batsleer, J., Hamon, K. G., van Overzee, H. M., Rijnsdorp, A. D., & Poos, J. J. (2015). High-grading and over-quota discarding in mixed fisheries. *Reviews in Fish Biology and Fisheries*, *25*(4), 715–736.

Boknes, N., Guldager, H. S., Sterberg, C., & Nielsen, J. (2001). Production of high quality frozen cod (Gadus morhua) fillets and portions on a freezer trawler. *Journal of Aquatic Food Product Technology*, *10*(1), 33–47.

Bonilla, A. C., Sveinsdottir, K., & Martinsdottir, E. (2007). Development of Quality Index Method (QIM) scheme for fresh cod (Gadus morhua) fillets and application in shelf life study. *Food control*, *18*(4), 352–358.

Borderías, A. J., & Sánchez-Alonso, I. (2011). First processing steps and the quality of wild and farmed fish. *Journal of Food Science*, *76*(1), R1–R5.

Botta, J. R. (1995). *Evaluation of seafood freshness quality*. John Wiley & Sons.

Botta, J. R., Squires, B. E., & Johnson, J. (1986). Effect of bleeding/gutting procedures on the sensory quality of fresh raw Atlantic cod (Gadus morhua). *Canadian Institute of Food Science and Technology Journal*, *19*(4), 186–190.

Botta, J., Bonnell, G., & Squires, B. (1987a). Effect of method of catching and time of season on sensory quality of fresh raw Atlantic cod (*Gadus morhua*). *Journal of Food Science*, *52*(4), 928–931.

Botta, J. R., Kennedy, K., & Squires, B. E. (1987b). Effect of method of catching and time of season on the composition of Atlantic cod (Gadus morhua). *Journal of Food Science*, *52*(4), 922–924.

Bremner, H. A. (2000). Toward practical definitions of quality for food science. *Critical Reviews in Food Science and Nutrition*, *40*(1), 83–90.

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.

Brinkhof, J., Larsen, R. B., Herrmann, B., & Olsen, S. H. (2018a). 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.

Brinkhof, J., Olsen, S. H., Ingólfsson, Ó. A., Herrmann, B., & Larsen, R. B. (2018b). Sequential codend improves quality of trawl-caught cod. *PloS One*, *13*(10), e0204328.

Brinkhof, J., Herrmann, B., Larsen, R. B., & Veiga-Malta, T. (2019). Effect of a quality improving cod end on size selectivity and catch patterns of cod in bottom trawl fishery. *Canadian Journal of Fisheries and Aquatic Sciences*, *76*(11), 2110–2120.

Brinkhof, J., Herrmann, B., Sistiaga, M., Larsen, R. B., Jacques, N., & Gjøsund, S. H. (2021). Effect of gear design on catch damage on cod *(Gadus morhua)* in the Barents Sea demersal trawl fishery. *Food Control*, *120*, Article e107562.

Brinkhof J., Larsen, R. B., & Herrmann, B. (2022). Make it simpler and better: T90 codend improves size selectivity and catch efficiency compared with the grid-and-diamond mesh

codend in the Northeast Atlantic bottom trawl fishery for gadoids. *Ocean & Coastal Management*, *217*, Article e106002.

Brown, W. D. (1961). Chromatography of myoglobin on diethylaminoethyl cellulose columns. *Journal of Biological Chemistry*, *236*(8), 2238–2240.

Burgaard, M. G., & Jørgensen, B. M. (2010). Effect of temperature on quality-related changes in cod (Gadus morhua) during short-and long-term frozen storage. *Journal of Aquatic Food Product Technology*, *19*(3-4), 249–263.

Bøknæs, N., Østerberg, C., Nielsen, J., & Dalgaard, P. (2000). Influence of freshness and frozen storage temperature on quality of thawed cod fillets stored in modified atmosphere packaging. *LWT-Food Science and Technology*, *33*(3), 244–248.

Chaijan, M., & Undeland, I. (2015). Development of a new method for determination of total haem protein in fish muscle. *Food Chemistry*, *173*, 1133-1141.

Cheng, J. H., Sun, D. W., Zeng, X. A., & Liu, D. (2015). Recent advances in methods and techniques for freshness quality determination and evaluation of fish and fish fillets: A review. *Critical Reviews in Food Science and Nutrition*, *55*(7), 1012–1225.

Cyprian, O., Lauzon, H. L., Jóhannsson, R., Sveinsdóttir, K., Arason, S., & Martinsdóttir, E. (2013). Shelf life of air and modified atmosphere-packaged fresh tilapia (O reochromis niloticus) fillets stored under chilled and superchilled conditions. *Food Science & Nutrition*, *1*(2), 130–140.

Digre, H., Hansen, U. J., & Erikson, U. (2010). Effect of trawling with traditional and 'T90'trawl codends on fish size and on different quality parameters of cod *Gadus morhua* and haddock *Melanogrammus aeglefinus*. *Fisheries Science*, *76*(4), 549–559.

Digre, H., Rosten, C., Erikson, U., Mathiassen, J. R., & Aursand, I. G. (2017). The on-board live storage of Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) caught by trawl: fish behaviour, stress and fillet quality. *Fisheries Research, 189*, 42–54.

Drabkin, D. L. (1950). The distribution of the chromoproteins, hemoglobin, myoglobin, and cytochrome c, in the tissues of different species, and the relationship of the total content of each chromoprotein to body mass. *Journal of Biological Chemistry*, *182*(1), 317–333.

Duun, A. S., & Rustad, T. (2007). Quality changes during superchilled storage of cod (Gadus morhua) fillets. *Food Chemistry*, *105*(3), 1067–1075.

Eide, A., Heen, K., Armstrong, C., Flaaten, O., & Vasiliev, A. (2013). Challenges and successes in the management of a shared fish stock–the case of the Russian–Norwegian Barents Sea cod fishery. *Acta Borealia*, *30*(1), 1–20.

Erikson, U., Tveit, G. M., Bondø, M., & Digre, H. (2019). On-board live storage of Atlantic cod (Gadus morhua): effects of capture stress, recovery, delayed processing, and frozen storage on fillet color characteristics. *Journal of Aquatic Food Product Technology*, *28*(10), 1076–1091.

Erikson, U., Grimsmo, L., & Digre, H. (2021a). Establishing a method for electrical immobilization of whitefish on board fishing vessels. *Journal of Aquatic Food Product Technology*, *30*(6), 694–705.

Erikson, U., Uglem, S., & Greiff, K. (2021b). Freeze-chilling of whitefish: effects of capture, on-board processing, freezing, frozen storage, thawing, and subsequent chilled storage—a review. *Foods*, *10*(11), 2661.

Esaiassen, M., Nilsen, H., Joensen, S., Skjerdal, T., Carlehög, M., Eilertsen, G., & Elvevoll, E. O. (2004). Effects of catching methods on quality changes during storage of cod (*Gadus morhua*). *LWT - Food Science and Technology, 37*(6), 643–648.

Esaiassen, M., Akse, L., & Joensen, S. (2013). Development of a catch-damage-index to assess the quality of cod at landing. *Food Control*, *29*(1), 231–235.

FAO. (2020). *The State of World Fisheries and Aquaculture 2020*. *Sustainability in action*. Rome. https://doi.org/10.4060/ca9229en. [Accessed: 7 June 2022].

Farrell, A. P., & Pieperhoff, D. (2011) Design and physiology of the heart. In A. P. Farrel (Ed.), *Encyclopedia of Fish Physiology - From genome to Environment, Vol. 2 (Academic Press* (pp. 998–1005). London, UK.

Farrell, A. P., Thorarensen, H., Axelsson, M., Crocker, C. E., Gamperl, A. K., & Cech Jr, J. J. (2001). Gut blood flow in fish during exercise and severe hypercapnia. *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology*, *128*(3), 549–561.

Fisheries Directorate. (2022). Fishermen, vessels and permits. https://www.fiskeridir.no/Yrkesfiske/Tall-og-analyse/Fangst-og-kvoter/Fangst/Fangst-fordelt-paa-redskap. [Accessed: 9 April 2022].

Flaaten, O., & Heen, K. (2004). Fishing vessel profitability and local economic link obligations—the case of Norwegian trawlers. *Marine Policy*, *28*(6), 451-457.

Fuglestad, J. L., Benestad, R., Ivanov, V., Jørgensen, L. L., Kovacs, K. M., Nilssen, F., Skjoldal H. R., & Tchernova, J. (2020). Ecosystems of the barents sea region. In O. R. Young, P. A. Berkman, & A. N. Vylegzhanin (Eds.), *Governing arctic seas: regional lessons from the bering strait and barents sea*, Vol. 1 *(*pp. 119–142)*. Springer.

Gabriel, O., Lange, K., Dahm, E., & Wendt, T (Eds.). (2005). *Fishing Catching Methods of the World* (4th ed.). Blackwell Publishing.

Haard, N. F. (1992). Control of chemical composition and food quality attributes of cultured fish. *Food Research International*, *25*(4), 289–307.

He, P. (2006). Gillnets: gear design, fishing performance and conservation challenges. *Marine Technology Society Journal*, *40*(3), 12–19.

He, P., & Pol, M. (2010). Fish Behaviour near Gillnets: Capture Process and Influencing Factors. In P. He (Ed.), *Behavior of Marine Fishes: Capture Processes and Conservation Challenges* (pp. 315–337)*. WileyBlackwell, Ames Iowa.

Heide, M., & Henriksen, E. (2013). Variable quality in the value chain - How does quality affect profitability? Nofima Report 3/2013. ISBN 978-82-8296-049-6. (In Norwegian).

Hornsey, H. C. (1956). The colour of cooked cured pork. I. Estimation of the Nitric oxide-Haem Pigments. *Journal of the Science of Food and Agriculture*, *7*(8), 534–540.

Huse, I., Løkkeborg, S., & Soldal, A. V. (2000). Relative selectivity in trawl, longline and gillnet fisheries for cod and haddock. *ICES Journal of Marine Science*, *57*(4), 1271–1282.

ICES (2019). Barents Sea Ecoregion – Ecosystem overview. In Report of the ICES Advisory Committee (2019). ICES Advice 2019, Section 5.1. https://doi.org/10.17895/ices.advice.5747. [Accessed: 9 April 2022]

ICES (2021a). ICES Advice on fishing opportunities, catch, and effort Arctic Ocean, Barents Sea, Faroes, Greenland Sea, Icelandic Waters, and Norwegian Sea ecoregions – Cod (*Gadus morhua*) in subareas 1 and 2 (Northeast Arctic). ICES, June, 2021. https://www.ices.dk/sites/pub/Publication%20Reports/Advice/2021/2021/cod.27.1-2.pdf [Accessed: 22 February 2022]

ICES (2021b). Arctic Fisheries Working Group (AFWG). ICES Scientific Reports. 3:58. 817. https://doi.org/10.17895/ices.pub.8196. [Accessed: 22 February 2022]

Joensen, S., Bendiksen, B. I., Martinsen, G., Tobiassen, T., & Nilsen, H. (2021). Catch damage registration 2014–2020 – Assessment of the quality inspection by Norges Råfisklag. Nofima Report 6/2021. ISBN 978-82-8296-670-2. (In Norwegian).

Karlsson, A., & Lundström, K. (1991). Meat pigment determination by a simple and non-toxic alkaline haematin method—(an alternative to the Hornsey and the cyanometmyoglobin methods). *Meat Science*, *29*(1), 17–24.

Lauzon, H. L., Magnússon, H., Sveinsdóttir, K., Gudjónsdóttir, M., & Martinsdóttir, E. (2009). Effect of brining, modified atmosphere packaging, and superchilling on the shelf life of cod (Gadus morhua) loins. *Journal of Food Science*, *74*(6), M258–M267.

Lambooij, E., H. Digre, H. G. M. Reimert, I. G. Aursand, L. Grimsmo and J. W. van de Vis (2012). Effects of on-board storage and electrical stunning of wild cod *(Gadus morhua)* and haddock *(Melanogrammus aeglefinus)* on brain and heart activity. *Fisheries Research 127-128,* 1-8.

Lorentzen, G., Ageeva, T. N., Heide, M., & Esaiassen, M. (2020). Temperature fluctuations in processing and distribution: effect on the shelf life of fresh cod fillets (*Gadus morhua* L.). *Food Control*, *112*, 107102.

Love, R. M. (1975). Variability in Atlantic cod (Gadus morhua) from the Northeast Atlantic: a review of seasonal and environmental influences on various attributes of the flesh. *Journal of the Fisheries Board of Canada*, *32*(12), 2333–2342.

Maqsood, S., & Benjakul, S. (2011a). Effect of bleeding on lipid oxidation and quality changes of Asian seabass (Lates calcarifer) muscle during iced storage. *Food Chemistry*, *124*(2), 459–467.

Maqsood, S., & Benjakul, S. (2011b). Comparative studies on molecular changes and pro oxidative activity of haemoglobin from different fish species as influenced by pH. *Food Chemistry*, *124*(3), 875–883.

Margeirsson, S., Jonsson, G. R., Arason, S., & Thorkelsson, G. (2007). Influencing factors on yield, gaping, bruises and nematodes in cod (*Gadus morhua*) fillets. *Journal of Food Engineering*, *80*(2), 503–508.

Mello, L. G. S., & Rose, G. A. (2005). Seasonal cycles in weight and condition in Atlantic cod (Gadus morhua L.) in relation to fisheries. *ICES Journal of Marine Science*, *62*(5), 1006–1015.

Midling, K. Ø., Koren, C., Humborstad, O. B., & Sæther, B. S. (2012). Swimbladder healing in Atlantic cod *(Gadus morhua)*, after decompression and rupture in capture-based aquaculture. *Marine Biology Research*, *8*(4), 373-379.

Ministry of Trade, Industry and Fisheries. (2022). Act on the Management of Wild Marine Resources (Marine Resources Act).

https://lovdata.no/dokument/LTI/lov/2008-06-06-37. [Accessed: 12 March 2022]

Moon, T. W. (2011). Stress effect on growth and metabolism. In A. P. Farrel (Ed), *Encyclopedia of fish physiology - from genome to environment*, Vol. 2 (pp. 1534–1540) Academic Press, London

Nedreaas, K. H., Drevetnyak, K. V., Shamray, E. A. (2011). Commercial data. In T. Jakobsen & V. K. Ozhigin (Eds.), *The barents sea: ecosystem, resources, management: half a century of russian-norwegian cooperation* (pp. 609–620). Tapir Academic Press, Trondheim, Norway

Nelson, J. A. (2011). General Energy Metabolism. In A. P. Farrell (Ed) *Encyclopedia of fish physiology – from genome to environment*, Vol. 3 (pp. 1566–1572). Academic Press, London.

Neumann, P., Holeton, G.F. & Heisler, N. (1983) Cardiac Output and Regional Blood Flow in Gills and Muscles after Exhaustive Exercise in Rainbow Trout (*Salmo Gairdneri*). *Journal of Experimental Biology*, *105*(1), 1-14.

Nielsen, J., Hyldig, G., & Larsen, E. (2002). 'Eating Quality'of fish-a review. *Journal of Aquatic Food Product Technology*,*11*(3-4), 125–141.

Olafsdóttir, G., Martinsdóttir, E., Oehlenschläger, J., Dalgaard, P., Jensen, B., Undeland, I., Mackie, I. M., Henehan, G., Nielsen, J., & Nilsen, H. (1997). Methods to evaluate fish freshness in research and industry. *Trends in Food Science & Technology, 8*(8), 258–265. http://dx.doi.org/10.1016/S0924-2244(97)01049-2

Olsen, S. H., Sørensen, N. K., Larsen, R., Elvevoll, E. O., & Nilsen, H. (2008). Impact of pre-slaughter stress on residual blood in fillet portions of farmed Atlantic cod (Gadus morhua)—Measured chemically and by Visible and Near-infrared spectroscopy. *Aquaculture*, *284*(1-4), 90–97.

Olsen, S. H., Tobiassen, T., Akse, L., Evensen, T. H., & Midling, K. O. (2013). Capture induced stress and live storage of Atlantic cod (*Gadus morhua*) caught by trawl: consequences for the flesh quality. *Fisheries Research*, 147, 446–453.

Olsen, S. H., Joensen, S., Tobiassen, T., Heia, K., Akse, L., & Nilsen, H. (2014). Quality consequences of bleeding fish after capture. *Fisheries Research*, 153, 103–107.

Olson, K. R. (2011a). Circulation - design and phyiology of arteries and veins. In A. P. Farrell (Ed.) *Encycopedia of fish physiology - from genome to environment*, Vol. 1 (pp. 1085–1094). Academic Press, London.

Olson, K. R. (2011b). Physiology of resistance vessels. In A. P. Farrell (Ed), *Encycopedia of fish physiology from genome to environment*, Vol. 2 (pp. 1104–1110). Academic Press, London

Ottestad, S., Høy, M., Stevik, A., & Wold, J. P. (2009). Prediction of ice fraction and fat content in super-chilled salmon by non-contact interactance near infrared imaging. *Journal of Near Infrared Spectroscopy*, *17*(2), 77–87.

Ovegård, M., Berndt, K., & Lunneryd, S. G. (2012). Condition indices of Atlantic cod (Gadus morhua) biased by capturing method. *ICES Journal of Marine Science*, *69*(10), 1781–1788.

Potter, E. C. E., & Pawson, M. G. (1991). *Gill netting*. Ministry of Agriculture, Fisheries and Food, Directorate of Fisheries Research.

Richards, M. P., & Hultin, H. O. (2002). Contributions of blood and blood components to lipid oxidation in fish muscle. *Journal of Agricultural and Food Chemistry*, *50*(3), 555–564.

Rotabakk, B. T., Skipnes, D., Akse, L., & Birkeland, S. (2011). Quality assessment of Atlantic cod (*Gadus morhua*) caught by longlining and trawling at the same time and location. *Fisheries Research*, *112*(1), 44–51.

Santos, M. N., Gaspar, M. B., Monteiro, C. C., & Vasconcelos, P. (2002). Gill net and long-line catch comparisons in a hake fishery: the case of southern Portugal. *Scientia Marina*, *66*(4), 433–441.

Savina, E., Karlsen, J. D., Frandsen, R. P., Krag, L. A., Kristensen, K, & Madsen, N. (2016). Testing the effect of soak time on catch damage in a coastal gillnetter and the consequences on processed fish quality. *Food Control*, *70*(1), 310–317.

Sainsbury, J. C. (1996). *Commercial fishing methods – an introduction to vessels and gear* (3rd ed.). Fishing News Books.

Segtnan, V. H., Høy, M., Lundby, F., Narum, B., & Wold, J. P. (2009). Fat distribution analysis in salmon fillets using non-contact near infrared interactance imaging: a sampling and calibration strategy. *Journal of Near Infrared Spectroscopy*, *17*(5), 247–253.

Shamray, E. A., & Sunnanå, K. (2011). Development of management strategies. In T. Jakobsen & V. K. Ozhigin (Eds.), *The barents sea: Ecosystem, resources, management : Half a century of Russian-Norwegian Cooperation* (pp. 532–540). Tapir Academic Press, Trondheim, Norway.

Shevelev, M. S., Sunnanå, K., & Gusev, E. V. (2011). History of fisheries and hunting. In T. Jakobsen & V. K. Ozhigin (Eds.), *The barents sea: Ecosystem, resources, management : Half a century of Russian-Norwegian Cooperation* (pp. 495–514). Tapir Academic Press, Trondheim, Norway.

Sistiaga, M., Brinkhof, J., Herrmann, B., Grimaldo, E., Langård, L., & Lilleng, D. (2016). Size selective performance of two flexible sorting grid designs in the Northeast Arctic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) fishery. *Fisheries Research*, *183*, 340–351.

Sistiaga, M., Herrmann, B., Brinkhof, J., Larsen, R. B., Jacques, N., Santos, J., & Gjøsund, S. H. (2020). Quantification of gear inflicted damages on trawl-caught haddock in the Northeast Atlantic fishery. *Marine Pollution Bulletin*, *157*, 111366.

Sivertsen, A. H., Kimiya, T., & Heia, K. (2011). Automatic freshness assessment of cod (Gadus morhua) fillets by Vis/Nir spectroscopy. *Journal of Food Engineering*, *103*(3), 317-323.

Sivertsen, A. H., Heia, K., Hindberg, K., & Godtliebsen, F. (2012). Automatic nematode detection in cod fillets (*Gadus morhua L.*) by hyperspectral imaging. *Journal of Food Engineering*, *111*(4), 675–681.

Skjelvareid, M. H., Heia, K., Olsen, S. H., Stormo, S. K. (2017). Detection of blood in fish muscle by constrained spectral unmixing of hyperspectral images. *Journal of Food Engineering*, *212*, 252–261.

Sogn-Grundvåg, G., Larsen, T. A., & Young, J. A. (2013). The value of line-caught and other attributes: An exploration of price premiums for chilled fish in UK supermarkets. *Marine Policy, 38,* 41–44.

Sogn-Grundvåg, G., Larsen, T. A., & Young, J. A. (2014). Product differentiation with credence attributes and private labels: The case of whitefish in UK supermarkets. *Journal of Agricultural Economics*, *65*(2), 368-382.

Sogn-Grundvåg, G., Zhang, D., & Dreyer, B. (2020). Fishing methods for Atlantic cod and haddock: Quality and price versus costs. *Fisheries Research, 230*, 105672.

Sogn-Grundvåg, G., Zhang, D., Henriksen, E., Bendiksen, B. I., & Hermansen, Ø. (2021). Fish quality and market performance: the case of the coastal fishery for Atlantic cod in Norway. *Marine Policy*, *127*, e104449.

Sogn-Grundvåg, G., Zhang, D., Henriksen, E., Joensen, S., Bendiksen, B. I., & Hermansen, Ø. (2022). Fishing tactics and fish quality: The case of the coastal fishery for Atlantic cod in Norway. *Fisheries Research*, *246*, 106167.

Sopinka, N. M., Donaldson, M. R., O'Connor, C. M., Suski, C. D., & Cooke, S. J. (2016). Stress indicators in fish. In *Fish physiology* (Vol. 35, pp. 405–462). Academic Press.

Standal, D., & Hersoug, B. (2015). Shaping technology, building society; the industrialization of the Norwegian cod fisheries. *Marine Policy*, *51*, 66-74.

Stormo, S. K., & Skåra, T. (2021). Liquid loss in thawed cod—Deconvoluting the effects of freezing-rate, freezing cycles, frozen storage time, and thawing-rate through a full factorial design. *Journal of Food Process Engineering*, *44*(6), e13691.

Suuronen, P., Lehtonen, E., & Jounela, P. (2005). Escape mortality of trawl caught Baltic cod *(Gadus morhua)*—the effect of water temperature, fish size and codend catch. *Fisheries Research*, *71*(2), 151–163.

Svalheim, R. A., Karlsson-Drangsholt, A., Olsen, S. H., Johnsen, H. K., & Aas-Hansen, Ø. (2017). Effects of exhaustive swimming and subsequent recuperation on flesh quality in unstressed Atlantic cod *(Gadus morhua). Fisheries Research*, *193*, 158–163.

Svalheim, R. A., Burgerhout, E., Heia, K., Joensen, S., Olsen, S. H., Nilsen, H., Tobiassen, T. (2019). Differential response to air-exposure in crowded and uncrowded Atlantic cod *(Gadus morhua)*: consequences for fillet quality. *Food Bioscience*, *28*, 15–19.

Svalheim, R. A., Aas-Hansen, Ø., Heia, K., Karlsson-Drangsholt, A., Olsen, S. H., & Johnsen, H. K. (2020). Simulated trawling: exhaustive swimming followed by extreme

crowding as contributing reasons to variable fillet quality in trawl-caught Atlantic cod (*Gadus morhua*). *PLoS One*, *15*(6), e0234059.

Svorken, M., Hermansen, Ø., & Karlsen, K. M. (2015). Raw material quality and sales value - Estimated loss for cod in 2013. Nofima Report 4/2015. ISBN 978-82-8296-242-1. (In Norwegian)

Toledo-Guedes, K., Ulvan, E. M., & Uglem, I. (2016). Commercial gillnetting is more stressful for saithe (Pollachius virens L.) than jigging: but is fillet quality affected? *Aquatic Living Resources*, *29*(2), 203.

Tveit, G. M., Sistiaga, M., Herrmann, B., & Brinkhof, J. (2019). External damage to trawl-caught northeast arctic cod (*Gadus morhua*): effect of codend design. *Fisheries Research*, *214*, 136–147.

Valdemarsen, J. W. (2001). Technological trends in capture fisheries. *Ocean & Coastal Management*, *44*(9-10), 635–651.

Veldhuizen, L. J. L., Berentsen, P. B. M., De Boer, I. J. M., Van De Vis, J. W., & Bokkers, E. A. M. (2018). Fish welfare in capture fisheries: a review of injuries and mortality. *Fisheries Research*, *204*, 41–48.

Wang, Y., & Richards, J. G. (2011). Anaberobic Metabolism in Fish. In A. P. Farrell (Ed.), *Encycopedia of fish physiology - from genome to environment, Vol. 1* (pp. 1757–1763). Academic Press, London.

Wang, T., Sveinsdóttir, K., Magnússon, H., & Martinsdóttir, E. (2008). Combined application of modified atmosphere packaging and superchilled storage to extend the shelf life of fresh cod (Gadus morhua) loins. *Journal of Food Science*, *73*(1), S11–S19.

Warm, K., Boknass, N., & Nielsen, J. (1998). Development of quality index methods for evaluation of frozen cod (Gadus morhua) and cod fillets. *Journal of Aquatic Food Product Technology*, *7*(1), 45–59.

Winger, P. D., Eayrs, S. & Glass, C. W. (2010). Fish behaviour near bottom trawls. In P. He. (Ed.), *Behavior of Marine Fishes: Capture Processes and Conservation Challenges (*pp. 67–103). WileyBlackwell, Ames Iowa.

Wold, J. P., Johansen, I. R., Haugholt, K. H., Tschudi, J., Thielemann, J., Segtnan, V. H., Narum, B., & Wold, E. (2006). Non-contact transflectance near infrared imaging for representative on-line sampling of dried salted coalfish (bacalao). *Journal of Near Infrared Spectroscopy*, *14*(1), 59–66.

Wu, D., & Sun, D. W. (2013). Colour measurements by computer vision for food quality control–A review. *Trends in Food Science & Technology*, *29*(1), 5–20.

Yaragina, N. A., Aglen, A., & Sokolov, K. M. (2011). Cod In T. Jakobsen & V. K. Ozhigin (Eds.), *The Barents Sea: Ecosystem, Resources, Management : Half a Century of Russian Norwegian Cooperation* (pp. 225–270). Tapir Academic Press, Trondheim, Norway.

Paper I

Effect of codend design and postponed bleeding on hemoglobin in cod fillets caught by bottom trawl in the Barents Sea demersal fishery

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Effect of codend design and postponed bleeding on hemoglobin in cod fillets caught by bottom trawl in the Barents Sea demersal fishery

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Effect of codend design and postponed bleeding on hemoglobin in cod fillets caught by bottom trawl in the Barents Sea demersal fishery

Previous studies reported that cod caught using a newly developed dual sequential codend showed significant reduction in external catch-related damage compared to cod caught by a conventional codend. In this study, it was investigated whether this new codend affects residual blood in cod fillets, and/or mitigates the effect of postponed bleeding. Residual blood was assessed by measuring hemoglobin using VIS/NIR hyperspectral imaging. No significant differences in hemoglobin content between fish caught by the two different codends were proven, and this was true for whole fillets and fillet compartments (loin, belly, and tail). However, a significant effect of postponed bleeding on the hemoglobin concentration in cod was demonstrated, and this effect was similar whether the fish was caught using the conventional or the sequential codend. Fish bled 40 minutes after catch had significant higher levels of hemoglobin compared to fish bled immediately after catch. When comparing the hemoglobin content in the different fillet sections, significant higher levels of hemoglobin were found in the belly compared to the loin and tail.

Introduction

Atlantic cod (*Gadus morhua*) is the dominant species in the demersal fishery in the Barents Sea (Nedreaas et al. 2011; Yaragina et al. 2011). During the last five years, the average annual catch of Atlantic cod in the Northeast Arctic (ICES Subareas I and II) has been 810,664 metric tonnes (ICES 2020). The two main nations targeting Atlantic cod are Norway and Russia (Shamray and Sunnanå 2011), and about 70% of the annual quota is caught using bottom trawls (ICES 2018; Yaragina et al. 2011).

Trawl-caught cod have often been associated with reduced quality (Digre et al. 2010; Olsen et al. 2013; Rotabakk et al. 2011), and the most common quality defects in trawl-caught white fish are gear marks, skin abrasion, pressure injuries, internal and external ecchymosis, and insufficient exsanguination (Digre et al. 2017; Olsen et al. 2013; Rotabakk et al. 2011). Such quality defects may lead to a downgrading of the fish and economic loss for the producer, and a negative correlation between the amounts of catch defects and proportions of high value products has been found (Margeirsson et al. 2006; Sogn-Grundvåg et al. 2021).

Quality defects in trawl-caught fish can be related to the design of the gear itself and to trawling procedures. Several studies have investigated the effect of various trawling procedures and trawl configurations on catch quality (Brinkhof et al. 2018a; Brinkhof et al. 2018b; Brinkhof et al. 2021; Sistiaga et al. 2020; Tveit et al. 2019). The large mesh size (i.e., minimum 130 mm codend mesh size) that is required by law is believed to contribute to catch defects (Brinkhof et al. 2018b), and a new codend concept aimed at improving the quality of trawl-caught fish has been tested (Brinkhof et al. 2018b). The new concept consists of a dual sequential codend: the first codend segment has size-selective properties as required by law, and the sequential codend segment is designed to reduce the strain on the fish. The sequential codend segment, which opens at a predefined depth during haul-back, consists of knotless

small-sized meshes (i.e., 6 mm mesh size) that retain water inside the codend during haul-back, and it should reduce gear marks, bruises, and stress due to crowding. Brinkhof et al. (2018b) showed that compared to cod caught with a conventional codend, the fish caught using the sequential codend had significantly reduced external catch-related damage, as evaluated by the catch damage index (CDI; Esaiassen et al. 2013).

The amounts and types of external catch damage registered by the CDI directly impact the use of caught fish in various fish products. Residual blood present in fish fillets also influences fish quality (Botta et al. 1987; Digre et al. 2017; Esaiassen et al. 2004; Margeirsson et al. 2007; Olsen et al. 2013; Olsen et al. 2014; Svalheim et al. 2019; Svalheim et al. 2020), but it is not included in the CDI. Therefore, in this study it was investigated whether the dual sequential codend, compared to a conventional codend, could reduce the amount of residual blood in cod fillets as measured by the hemoglobin levels in the fillets.

Time from catch to bleeding is of utmost importance in achieving adequate exsanguination and minimizing residual blood (Borderías and Sánchez-Alonso 2011; Botta et al. 1986; Digre et al. 2011; Margeirsson et al. 2007; Olsen et al. 2014). According to Olsen et al. (2013), it is not unusual for large hauls of fish caught by bottom trawls to be kept in storage bins for hours before bleeding and gutting. Poor exsanguination decreases fillet whiteness and thus its applicability to high quality products that require a white fillet, such as fillet loins and clipfish. Hence, improving the quality of trawl-caught fish (e.g., minimizing residual blood by avoiding postponed bleeding) could increase its value and possibly expand the bottom trawl fishery market.

The aim of this study was to investigate the effect of codend type and postponed bleeding on the residual blood levels in cod fillets measured as hemoglobin concentration. In addition, hemoglobin content in different fillet sections (loin, belly, and tail) of trawl-caught cod was compared.

Materials and methods

Study area and trawl configuration

Atlantic cod were caught by the research trawler R/V *Helmer Hanssen* (63.8 m, 4080 HP) between 27 February and 5 March 2018. The fishing area was located along the coast of Northern Norway in the southern Barents Sea (N 71°21′ E 23°43′–N 71°21′ E 24°24′). The towing speed (over ground) varied between 3.0 and 3.5 knots (average 3.3 knots). The cod were caught using two identical and commercially rigged trawls equipped with two different codend concepts: a conventional codend and a new dual sequential codend (Figure 1).
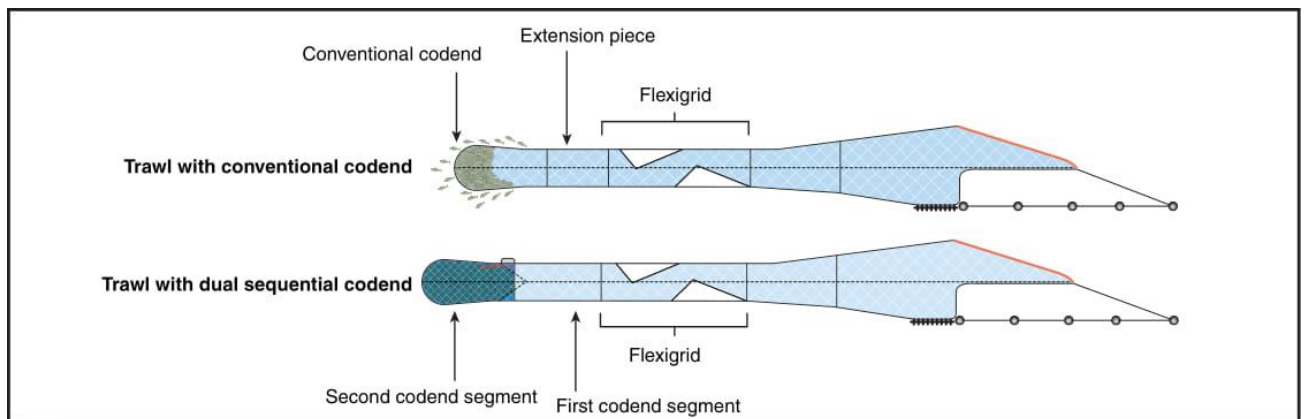
Figure 1. Setup of the trawls with the conventional codend and the dual sequential codend.

The trawls contained a set of Injector Scorpion otter boards for bottom trawling (3100 kg, 8m^2) with 3 m long backstraps followed by a 7 m long chain, which was linked to 60 m long sweeps that were equipped with an Ø53 cm steel bobbin in the center to avoid excessive abrasion of the sweeps. The 46.9 m long ground gear consisted of a 14 m long chain (Ø19 mm) with three equally spaced bobbins (Ø53 cm) on each side and an 18.9 m long rockhopper gear in the center composed of Ø53 cm rubber discs. The ground gear was attached to the 19.2 m long fishing line of the trawl. The trawls used were a two-panel Alfredo 3 fish trawl built from polyethylene with a 155 mm nominal mesh size with a

circumference of 420 meshes. The headline of the trawls was 35.6 m long and equipped with 170 floats (Ø20 cm). Both trawls were equipped with a flexigrid sorting system (55 mm bar spacing), which is one of the compulsory sorting grids for the trawl fishery in the Northeast Atlantic (Sistiaga et al. 2016).

In the conventionally configured trawl, the section with the flexigrid was followed by a 9 m long extension piece (150 mm mesh size), which was preceded by an 11 m long two-panel codend (Figure 2). The codend was 11 m long and built from single-braided Ø8 mm Euroline Premium (Polar Gold) netting in the lower panel and double-braided Ø4 mm polyethylene in the upper panel, with a mean (± standard deviation, SD) mesh size of 133 ± 5.1 mm.
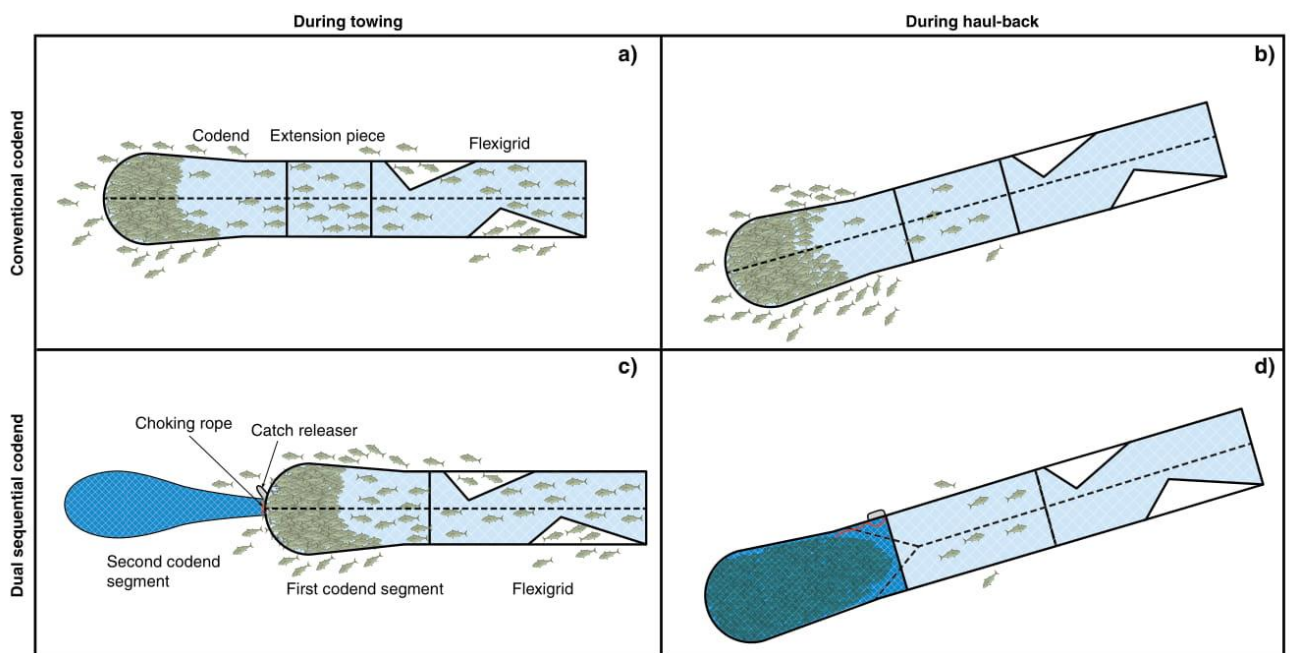

Figure 2. The conventional codend during a) towing and b) haul-back. The dual sequential codend consists of two codend segments: the first codend segment with size-selective properties as legislated, in which the fish are retained during c) trawling, and a second codend segment with expected quality-improvement properties, into which the fish falls during d) haul-back.

The second trawl was equipped with a dual sequential codend mounted directly to the flexigrid section (Brinkhof et al. 2018b), and it consisted of two codend segments: the first codend segment had the legislated selective properties and the second (sequential) codend segment had quality-improving properties (Figure 2). The first codend segment was built the same way as the conventional codend and had a mean ($\pm$ SD) mesh size of 139 $\pm$ 2.5 mm. The second codend segment was 10 m long and consisted of four panels. It had a nominal mesh size of 6 mm and a circumference of 1440 meshes (360 meshes in each panel). The codend segment was strengthened with an outer codend consisting of Ultracross knotless netting with a nominal mesh size of 112 mm (90 meshes in circumference) and four lastridge ropes, which were 5% shorter than the netting in the codend segment (Figure 2). The two codend segments were connected to create a two-panel codend. The entrance of the second codend segment was closed during fishing because this codend does not have the size-selective properties required by law due to its small mesh size. During fishing at the seabed, the fish were retained in the first codend segment, which fulfilled the minimum mesh size requirement (Figure 2). The entrance of the second codend segment was opened at a preset depth of 120 m during haul-back, thereby enabling free passage of fish from the selective codend segment into the codend with quality improving attributes (Brinkhof et al. 2018b) (Figure 2).

Fish sampling

A total of 10 hauls were conducted, alternating between hauls with the conventional codend (5 hauls) and those with the dual sequential codend (5 hauls) (Table 1). Immediately after each haul, 28 cod were randomly sampled (weight: 3325 $\pm$ 779 g, length: 72 $\pm$ 6 cm, mean $\pm$ SD). The fish were split into four groups (n = 7), which were bled 0, 20, 40, and 60 minutes after being brought on board, respectively. Prior to bleeding by cutting the isthmus, the fish

were stunned by a blow to the head, individually tagged, and kept in dry baskets. After

exsanguination in running seawater for 30 minutes, individual length and weight before and

after gutting were recorded. The fish then were beheaded and stored in dry baskets until

freezing. The fish were frozen in blocks in commercial vertical plate freezers down to –18

°C, packed in approved laminated paper bags and then stored at –30 °C until landing. After

the sea trail, the fish were transported to the laboratory in Nofima, Tromsø, and stored for 5

months at –20 °C. Before analyses the fish were thawed in tanks containing 600 L of chilled

water (1 °C) for 24 h and then on ice in 70 L fish crates with the belly cavity facing

downward for another 24 h. Immediately after thawing, the fish were manually filleted with

the skin retained. To enable evaluation of the belly flap, the black peritoneum was removed.

The fillets were then cleaned in running fresh water. Both fillets (right and left side) from

each fish were subjected to analyses. However, one fish from haul 6 was lost, resulting in 558

fillets for evaluation of residual blood.

Table 1. Overview of the hauls showing codend type, towing time, depth, and estimated catch
size.

Haul no.	Codend type	Towing time (min)	Depth (m)	Estimated catch size (kg)
1	Conventional	62	368	441
2	Sequential	62	362	1223
3	Sequential	60	376	1699
4	Conventional	75	349	669
5	Sequential	45	310	926
6	Conventional	60	338	453
7	Conventional	90	351	630
8	Sequential	90	372	793
9	Conventional	75	320	849
10	Sequential	90	326	1608

Hemoglobin measurement by hyperspectral imaging

The hemoglobin content was estimated as a measure of the amount of blood in the muscle. Hyperspectral imaging of the fillets was conducted using an interactance setup (Sivertsen et al. 2012) in the wavelength range 400 to 1000 nm. This assures that the light travels some distance inside the fillet before it is recorded. The muscle hemoglobin concentration in milligrams per gram of muscle (mg Hb/g muscle) was calculated following the procedure outlined in Skjelvareid et al. (2017). To estimate the amount of blood in each of the fillet sections (loin, belly, and tail), the respective sections were marked manually in each image of the fillets (Figure 3), and the amount of hemoglobin was calculated for each section separately. Two fillets were retained per fish (left and right), and the hemoglobin concentrations are reported as the average value of the left and right side.
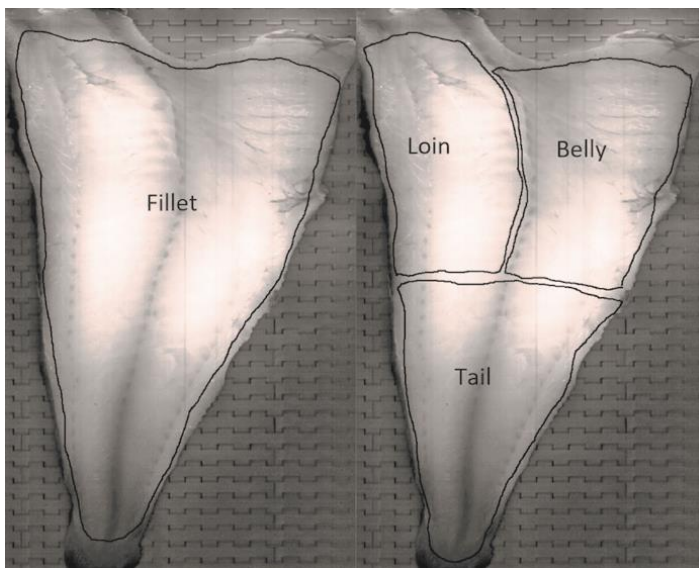

Figure 3. Illustration of the fillet sections used to estimate hemoglobin content by hyperspectral analysis.

Data analysis

Statistical analysis was performed using IBM SPSS Statistics for Windows, version 28.0.0.0. The distribution was tested for normality using the Kolmogorov-Smirnov test and density plots, and further tested for homogeneity of variance using Levene's test. A two-way analysis of covariance was conducted to examine the effects of codend and bleeding time on hemoglobin concentration, after controlling for catch size, towing time and catch depth. Catch size and towing time were included as covariates because previous studies have reported reduction in fish quality with increasing catch size and towing time (Digre et al. 2017; Margeirsson et al. 2007; Olsen et al. 2013; Rotabakk et al. 2011; Veldhuizen et al. 2018). Catch depth was included because capture depth may affect the condition of the fish (Digre et al. 2017) and catch quality (Brinkhof et al. 2018a). A Bonferroni post hoc test and pairwise comparison were used to determine significant differences between the groups. A one-way analysis of variance with Games-Howell post hoc test (the groups had heterogeneity of variance) was conducted to determine whether there were any statistically significant differences in mean hemoglobin concentration between loin, belly, and tail. p-values < 0.05 were considered to be statistically significant.

Results and Discussion

No statistically significant two-way interaction between codend and bleeding time on hemoglobin concentration in cod fillets was detected when controlling for catch size, towing time and catch depth ($F(3, 268) = 0.754$, $p = 0.521$, partial $\eta^2 = 0.008$). Because there was no statistically significant interaction between codend and bleeding time on hemoglobin levels, the data were combined, and the analysis was followed up using main effects of codend and bleeding time.

Effect of codend on hemoglobin concentration in cod fillets

Table 2 shows the concentration of hemoglobin in fillets and fillet compartments from cod caught using the conventional and sequential codends. The adjusted marginal mean hemoglobin concentration was similar in fillets from fish caught using both the conventional and the sequential codend, 0.144 g Hb/g muscle. Thus, no significant effect of codend was demonstrated $F_{(1, 268)} = 0.026$, p = 0,871, partial $\eta2 = 0.00$).

Table 2: Adjusted means with standard error for hemoglobin concentration (mg Hb/g muscle) for fillets and for the different fillet sections (loin, belly, and tail), in fish caught by the conventional and sequential codend.

	Conventional (n=139)	Sequential (n=140)	p-value
Fillet	0.144 (0.003)	0.144 (0.003)	0.871
Loin	0.132 (0.002)	0.131 (0.002)	0.894
Belly	0.184 (0.003)	0.177 (0.003)	0.187
Tail	0.122 (0.001)	0.123 (0.001)	0.543

This result does not align with the findings of Brinkhof et al. (2018b), who reported that the sequential codend improved quality of trawl-caught cod. However, in the study by Brinkhof et al. (2018b), external damages were assessed, whereas residual blood in the muscle are assessed in the present study. Svalheim et al. (2020) showed that exhaustive swimming and crowding cause fillet redness and increased muscle hemoglobin. Thus, one possible explanation for the contradictory results could be that the dual sequential codend reduces external detectable damage caused during haul-back, but not residual blood in muscle caused by exhaustive swimming and crowding during trawling.

On the other hand, it is possible that an effect of the sequential codend on the amount of residual blood in the fish in the present study is concealed by the fact that the catches from the hauls using the sequential codend were generally larger than the catches from the conventional codend, and that the influence of codend type could not be separated from the influence of catch size. Previous studies reported reduction in fish quality with increasing catch size and towing time (Digre et al. 2017; Margeirsson et al. 2007; Olsen et al. 2013; Rotabakk et al. 2011; Veldhuizen et al. 2018). Compared to commercial fisheries, where catches easily exceed 10 tonnes, the catch size in this study was very low, and the towing time for each haul in this study was relatively short (45–90 minutes). It is thus also possible that the small catch size and short towing time may have concealed effects of codend type on the amount of residual blood in the fish. Hence, drawing a definite conclusion about the effects of the different codends on residual blood in cod fillets is not possible from this experiment.

Effect of bleeding time on hemoglobin concentration in cod fillets

The results show that time before bleeding is important for the quality of trawl-caught cod regardless of the codend used, and a statistically significant main effect of bleeding time on adjusted marginal mean hemoglobin concentration in cod fillets was demonstrated ($F(3, 268)$ = 13.682, $p < 0.001$, partial $\eta2 = 0.133$). As the time from catch until bleeding increased, the amount of residual blood in the fillets and fillet compartments increased (Table 3).

Table 3: Adjusted means with standard error for hemoglobin concentration (mg Hb/g muscle) for fillets and for the different fillet sections (loin, belly, and tail) for fish bled 0, 20, 40, and 60 minutes after catch. Different capital letters in the same row indicate significant differences between the bleeding time groups (p < 0.05), while different lower-case letters in the same column indicate significant differences between the different fillet sections (p < 0.01).

	0 minutes (n=70)	20 minutes (n=70)	40 minutes (n=69)	60 minutes (n=70)
Fillet	0.137 (0.002)[Aa]	0.139 (0.002)[ABa]	0.147 (0.002)[BCa]	0.153 (0.002)[CDa]
Loin	0.124 (0.002)[Ab]	0.127 (0.002)[ABb]	0.134 (0.002)[BCb]	0.140 (0.002)[CDb]
Belly	0.171 (0.003)[Ac]	0.171 (0.003)[Ac]	0.185 (0.003)[BCd]	0.194 (0.003)[Cd]
Tail	0.119 (0.002)[Ab]	0.120 (0.002)[Ab]	0.124 (0.002)[Ac]	0.127 (0.002)[Bc]

Marginal mean hemoglobin concentration was significantly higher in fillets from fish bled 40 minutes after catch (0.147 mg Hb/g muscle) than in fillets from fish bled immediately (0 minutes) after catch (0.137 mg Hb/g muscle) ($p < 0.001$). These findings are in accordance with previous studies as reviewed by Erikson et al. (2021), which showed that postponed bleeding negatively affected the quality of the fish. The effect of other factors on the blood drainage of fish, such as slaughter- and cutting method (Digre et al. 2011; Olsen et al. 2006; Roth et al. 2005), temperature (Olsen et al. 2006) and water flow (Eliasson et al. 2020) have also been investigated. However, it has been shown that time before bleeding is crucial. Botta et al. (1986) showed that time was more important than the cutting procedure in trawl-caught cod that were bled 0, 1, 2, and 3 hours after catch. Olsen et al. (2014) studied cod bled after 0, 30, 60, and 180 minutes and recommended that cod should be bled within 30 minutes after

catch. In the latter study, the fish were kept alive after catch; they were carefully netted and stunned before bleeding. According to Svalheim et al. (2019), this recommendation based on results from unstressed fish is likely to be less relevant in commercial fisheries, where fish are exposed to a number of stressors. Svalheim et al. (2019, 2020) showed that exhaustive swimming, crowding, and especially air exposure, are associated with increased metabolic stress, resulting in increased amount of residual blood in muscle after bleeding. In the present experiment, due to fish welfare considerations, the fish were stunned with a blow to the head prior to air exposure and postponed bleeding. This has probably influenced the results, and the effect of postponed bleeding may have been higher if the fish were kept conscious in air prior to bleeding.

Hemoglobin concentration in fillet sections

As with whole fillets, no statistically significant two-way interaction between codend and bleeding time was demonstrated for loin, belly, or tail on hemoglobin concentration when controlling for catch size, towing time and catch depth. No significant effect of codend type on hemoglobin concentration was uncovered either. However, a statistically significant main effect of bleeding time on adjusted marginal mean hemoglobin concentration was demonstrated for loin, belly, and tail parts of the fillets (Table 3, Figure 4).
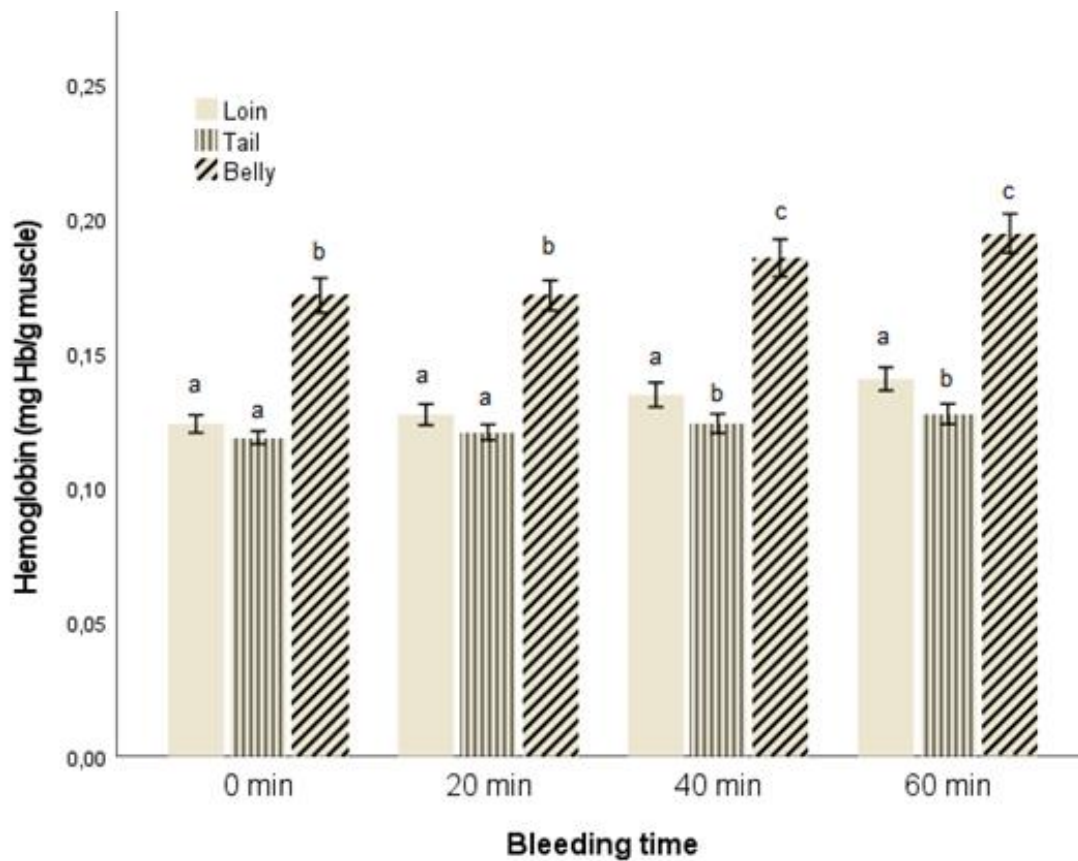
Figure 4. Mean hemoglobin concentration with 95% confidence intervals in the different fillet sections (loin, tail, and belly). Different letters indicate significant differences between the fillet section for each bleeding time ($p < 0.001$).

Comparing the hemoglobin content in the different fillet sections revealed that the belly contained a significantly higher level of hemoglobin than the loin and tail (Table 3, Figure 4). Olsen et al. (2008) studied the distribution of heme-pigments among fillet sections in bled, unbled, stressed, and unstressed Atlantic cod and found that the largest differences in heme-pigments in white muscle from bled and unbled fish were found in the belly flaps, and there was generally more blood in the belly compartment compared to other fillet sections. However, their analyses focused on the effects of stress prior to slaughter and whether the fish was bled or not rather than on differences in blood content between sections within the same fillet.

To the best of our knowledge, reports on how postponed bleeding affects different fillet sections are scarce. There are, however, a few Norwegian reports addressing the topic (Akse et al. 2012; Tobiassen et al. 2019), and the results in the present study are in accordance with these reports. Akse et al. (2012) reported that residual blood in both the belly and loin of Atlantic cod was significantly affected by postponed bleeding and that there was more residual blood in the belly of the cod bled after 30 minutes than in the loin of the cod bled after 180 minutes. Additionally, using hyperspectral imaging, Tobiassen et al. (2019) showed that the belly of haddock *(Melanogrammus aeglefinus)* was more vulnerable to postponed bleeding compared with the other fillet parts.

Conclusion

No significant effect of the sequential codend on the amount of residual blood in cod fillets compared to cod caught using the conventional codend was proven. There was a statistically significant effect of postponed bleeding on the amount of residual blood in cod fillets for both the dual sequential codend and the conventional codend. Postponed bleeding led to a higher amount of residual blood in the fish regardless of the codend used. Furthermore, it is shown that the belly of cod contained significantly higher amounts of residual blood than the loin and tail.

Declaration of interests

The authors declare no competing interests.

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References

Akse L, Joensen S, Heia K, Tobiassen T, Sivertsen AH, Wang PA. 2012. Bleeding of cod – bleeding methods and time before bleeding or direct gutting. Tromsø (Norway): Nofima. Report No: 19/2012. ISBN 978-82-7251-988-8 (in Norwegian).

Borderías AJ, Sánchez-Alonso I. 2011. First Processing Steps and Quality of Wild and Farmed Fish. J Food Sci. 76(1): R1-R5.

Botta JR, Squires BE, Johnson J. 1986. Effect of Bleeding/Gutting Procedures on the Sensory Quality of FreshRaw Atlantic Cod *(Gadus morhua).* Can Inst Food Sci Technol J. 19: 186–190.

Botta JR, Bonnell G, Squires BE. 1987. Effect of method of catching and time of season on sensory quality of fresh raw Atlantic cod *(Gadus morhua).* J Food Sci. 52(4): 928–931. doi:10.1111/j.1365-2621.1987.tb14245.x.

Brinkhof J, Herrmann B, Sistiaga M, Larsen RB, Jacques N, Gjøsund SH. 2021. Effect of gear design on catch damage on cod *(Gadus morhua)* in the Barents Sea demersal trawl fishery. Food Control. 120: e107562. doi:10.1016/j.foodcont.2020.107562.

Brinkhof J, Larsen RB, Herrmann B, Olsen SH. 2018a. Assessing the impact of buffer towing on the quality of Northeast Atlantic cod *(Gadus morhua)* caught with a bottom trawl. Fish Res. 206: 209–219. doi:10.1016/j.fishres.2018.05.021.

Brinkhof J, Olsen SH, Ingólfsson ÓA, Herrmann B, Larsen RB. 2018b. Sequential codend improves quality of trawl-caught cod. PLoS One. 13(10): e0204328. doi:10.1371/journal.pone.0204328.

Digre H, Erikson U, Misimi E, Standal IB, Gallart-Jornet L, Riebroy S, Rustad T. 2011. Bleeding of farmed Atlantic cod: residual blood, color, and quality attributes of pre- and postrigor fillets as affected by perimortem stress and different bleeding methods. J Aquat Food Prod Technol. 20(4): 391–411. doi:10.1080/10498850.2011.576380.

Digre H, Hansen UJ, Erikson U. 2010. Effect of trawling with traditional and 'T90' trawl codends on fish size and on different quality parameters of cod *Gadus morhua* and haddock *Melanogrammus aeglefinus*. Fish Sci. 76: 549–559. doi:10.1007/s12562-010-0254-2.

Digre H, Rosten C, Erikson U, Mathiassen JR, Aursand IG. 2017. The on-board live storage of Atlantic cod *(Gadus morhua)* and haddock *(Melanogrammus aeglefinus)* caught by trawl: fish behaviour, stress and fillet quality. Fish Res. 189: 42–54. doi:10.1016/j.fishres.2017.01.004.

Eliasson S, Arason S, Margeirsson B, Palsson OP. 2020. Onboard Evaluation of Variable Water Flow and Recirculation Effects on Bleeding of Atlantic *Cod (Gadus morhua)*. Foods, *9*(11): 1519.

Erikson U, Uglem S, Greiff K. 2021. Freeze-Chilling of Whitefish: Effects of Capture, On-Board Processing, Freezing, Frozen Storage, Thawing, and Subsequent Chilled Storage—A Review. Foods. 10(11), 2661.

Esaiassen M, Akse L, Joensen S. 2013. Development of a catch-damage-index to assess the quality of cod at landing. Food Control. 29(1): 231–235. https://doi.org/10.1016/j.foodcont.2012.05.065.

Esaiassen M, Nilsen H, Joensen S, Skjerdal T, Carlehög M, Eilertsen G, Elvevoll EO. 2004. Effects of catching methods on quality changes during storage of cod *(Gadus morhua)*. LWT - Food Sci Technol. 37(6): 643–648. doi:10.1016/j.lwt.2004.02.002.

ICES. 2018. ICES advice on fishing opportunities, catch, and effort Arctic Ocean, Barents Sea, Faroes, Greenland Sea, Icelandic Waters, and Norwegian Sea ecoregions - Cod *(Gadus morhua)* in subareas 1 and 2 (Northeast Arctic). ICES. [accessed 2020 Aug 20]. https://doi.org/10.17895/ices.pub.4412.

ICES. 2020. Arctic Fisheries Working Group (AFWG). ICES Scientific Reports. 2:52. 577 pp. [accessed 2020 Aug 20]. http://doi.org/10.17895/ices.pub.6050.

Margeirsson S, Jonsson GR, Arason S, Thorkelsson G. 2007. Influencing factors on yield, gaping, bruises and nematodes in cod *(Gadus morhua)* fillets. J Food Eng. 80(2): 503–508. doi:10.1016/j.jfoodeng.2006.05.032.

Margeirsson S, Nielsen AA, Jonsson GR, Arason S. 2006. Effect of catch location, season and quality defects on value of Icelandic cod *(Gadus morhua)* products. In: Luten JB, Jacobsen C, Bekaert K, Sæbø A, Oehlenschläger J, editors. Seafood research from fish to dish - quality, safety & processing of wild and farmed fish. The Netherlands: Wageningen Academic Publishers. p. 265–274.

Nedreaas KH, Drevetnyak KV, Shamray EA. 2011. Commercial data. In: Jakobsen T, Ozhigin VK, editors. The Barents Sea: ecosystem, resources, management: half a century of Russian-Norwegian cooperation. Trondheim, Norway: Tapir Academic Press. p. 609–620.

Olsen SH, Joensen S, Tobiassen T, Heia K, Akse L, Nilsen H. 2014. Quality consequences of bleeding fish after capture. Fish Res. 153: 103–107. doi:10.1016/j.fishres.2014.01.011.

Olsen SH, Sorensen NK, Stormo SK, Elvevoll EO. 2006. Effect of slaughter methods on blood spotting and residual blood in fillets of Atlantic salmon *(Salmo salar)*. Aquaculture. 258(1-4): 462-469.

Olsen SH, Tobiassen T, Akse L, Evensen TH, Midling KØ. 2013. Capture induced stress and live storage of Atlantic cod *(Gadus morhua)* caught by trawl: consequences for the flesh quality. Fish Res. 147: 446–453. doi:10.1016/j.fishres.2013.03.009.

Rotabakk BT, Skipnes D, Akse L, Birkeland S. 2011. Quality assessment of Atlantic cod *(Gadus morhua)* caught by longlining and trawling at the same time and location. Fish Res. 112(1-2): 44–51. doi:10.1016/j.fishres.2011.08.009.

Roth B, Torrisen OJ, Slinde, E. 2005. The effect of slaughtering procedures on blood spotting in rainbow trout *(Oncorhynchus mykiss)* and Atlantic salmon *(Salmo salar)*. Aquaculture. 250(3-4): 796-803.

Shamray EA, Sunnanå K. 2011. Development of management strategies. In: Jakobsen T, Ozhigin VK, editors. The Barents Sea: ecosystem, resources, management: half a century of Russian-Norwegian cooperation. Trondheim, Norway: Tapir Academic Press. p. 532–540.

Sistiaga M, Brinkhof J, Herrmann B, Grimaldo E, Langård L, Lilleng D. 2016. Size selective performance of two flexible sorting grid designs in the Northeast Arctic cod *(Gadus morhua)* and haddock *(Melanogrammus aeglefinus)* fishery. Fish Res. 183: 340–351. doi:10.1016/j.fishres.2016.06.022.

Sistiaga M, Herrmann B, Brinkhof J, Larsen RB, Jacques N, Santos J, Gjøsund SH. 2020. Quantification of gear inflicted damages on trawl-caught haddock in the Northeast Atlantic fishery. Mar Pollut Bull. 157: e111366. doi:10.1016/j.marpolbul.2020.111366.

Sivertsen AH, Heia K, Hindberg K, Godtliebsen F. 2012. Automatic nematode detection in cod fillets *(Gadus morhua L.)* by hyperspectral imaging. J Food Eng. 111(4): 675–681. doi:10.1016/j.jfoodeng.2012.02.036.

Skjelvareid MH, Heia K, Olsen SH, Stormo SK. 2017. Detection of blood in fish muscle by constrained spectral unmixing of hyperspectral images. J Food Eng. 212: 252–261. doi:10.1016/j.jfoodeng.2017.05.029.
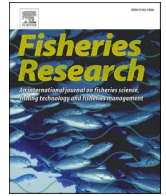
Sogn-Grundvåg G, Zhang D, Henriksen E, Bendiksen BI, Hermansen Ø. 2021. Fish quality and market performance: the case of the coastal fishery for Atlantic cod in Norway. Mar Policy. 127: e104449. doi.org/10.1016/j.marpol.2021.104449.

Svalheim RA, Aas-Hansen Ø, Heia K, Karlsson-Drangsholt A, Olsen SH, Johnsen HK. 2020. Simulated trawling: exhaustive swimming followed by extreme crowding as contributing reasons to variable fillet quality in trawl-caught Atlantic cod *(Gadus morhua).* PLoS One. 15(6): e0234059. doi:10.1371/journal.pone.0234059.

Svalheim RA, Burgerhout E, Heia K, Joensen S, Olsen SH, Nilsen H, Tobiassen T. 2019. Differential response to air exposure in crowded and uncrowded Atlantic *cod (Gadus morhua)*: consequences for fillet quality. Food Biosci. 28: 15–19. doi:10.1016/j.fbio.2019.01.008.

Tobiassen T, Heia K, Olsen SH, Svalheim RA, Joensen S, Karlsen KM, Skjelvareid MH, Stormo SK. 2016. Bleeding and shelf life of cod. Tromsø (Norway): Nofima. Report No: 10/2016. ISBN 978-82-8296-364-0 (in Norwegian).

Tobiassen T, Martinsen G, Kristoffersen S, Hustad A, Olsen SH, Heia K, Joensen S, Ingolfsson O, Nordtvedt TS. 2019. Controlled slaughter of live stored haddock provides great advantages during processing and cold storage. Tromsø (Norway): Nofima. Report No: 10/2019. ISBN 978-82-8296-587-3 (in Norwegian).

Tveit GM, Sistiaga M, Herrmann B, Brinkhof J. 2019. External damage to trawl-caught northeast arctic cod *(Gadus morhua)*: effect of codend design. Fish Res. 214: 136–147. doi:10.1016/j.fishres.2019.02.009.

Veldhuizen LJL, Berentsen PBM, De Boer IJM, Van De Vis JW, Bokkers EAM. 2018. Fish welfare in capture fisheries: A review of injuries and mortality. Fish Res. 204: 41-48.

Yaragina NA, Aglen A, Sokolov KM. 2011. Cod. In: Jakobsen T, Ozhigin VK, editors. The Barents Sea: ecosystem, resources, management: half a century of Russian-Norwegian cooperation. Trondheim, Norway: Tapir Academic Press. p. 225–270.

Paper II

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

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

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

1. Introduction

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

Fish caught by bottom trawls are often associated with reduced quality. For example, Rotabakk et al. (2011) reported that cod caught by bottom trawl have a poorer overall quality compared to cod caught by longline. The most common quality defects in trawl-caught fish are gear marks, skin abrasion, pressure injuries, internal and external bruises,

and insufficient exsanguination (Digre et al., 2017; Olsen et al., 2013; Rotabakk et al., 2011). Such quality defects may lead to downgrading of the fish and subsequent economic loss for the producer, as a negative correlation between the number of catch defects and the proportion of high-value products has been reported (Margeirsson et al., 2006). Poor catch quality limits the types of products in which the fish can be used, thus improving the quality of trawl-caught fish could increase its value and potentially expand the bottom trawl fishery market. In addition, catch quality would likely be improved by improving fish welfare in capture fisheries, which has gained increased research interest in recent years (Veldhuizen et al., 2018).

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

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

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

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

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

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

2. Materials and methods

2.1. Trawling conditions and trawl design

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

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

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

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

2.2. Fish sampling

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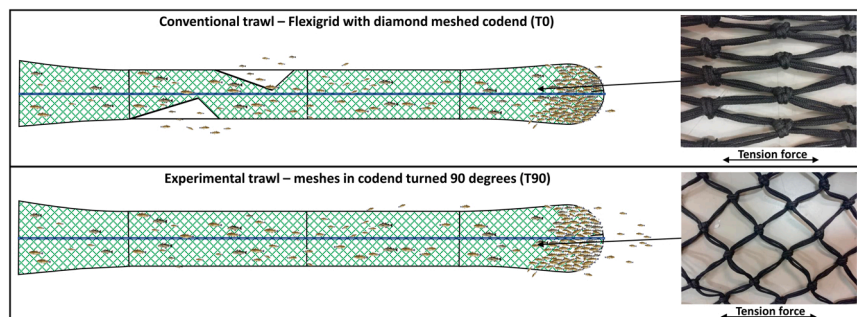

Fig. 1. Setup of the two trawl configurations: the conventional trawl configuration (flexigrid with diamond mesh codend) and the experimental trawl configuration (meshes in codend turned 90 degrees).

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

2.3. Catch-related damage

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

2.4. Residual blood measurement by hyperspectral imaging

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

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

2.5. Data analysis

The CDI data were analysed using the method described in Brinkhof et al. (2018a, 2021), using the analysis tool SELNET (Herrmann et al., 2012). The method estimates the probability of obtaining a given score for a given catch damage type as well as the probability of obtaining a given combination of catch damage types. The method also estimates the probability of not exceeding a given score (i.e., the probability of obtaining a given score or lower). The catch damage data were first analysed for each codend separately, and then the potential difference between the two codends was inferred using the method presented and described in Brinkhof et al. (2021). The method described by Brinkhof

et al. (2018a, 2021) takes into account both within- and between-haul variation by applying a double bootstrap methodology. The method also includes estimation of uncertainties in the form of 95% CIs (Efron, 1982). It enabled a direct comparison of catch quality between cod caught by the conventional configuration and the T90-codend, which also included the effect size.

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

$$Blood\ abundancy \sim Codend \tag{1}$$

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

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

3. Results

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

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

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

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

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

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

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

a 524 Missing value
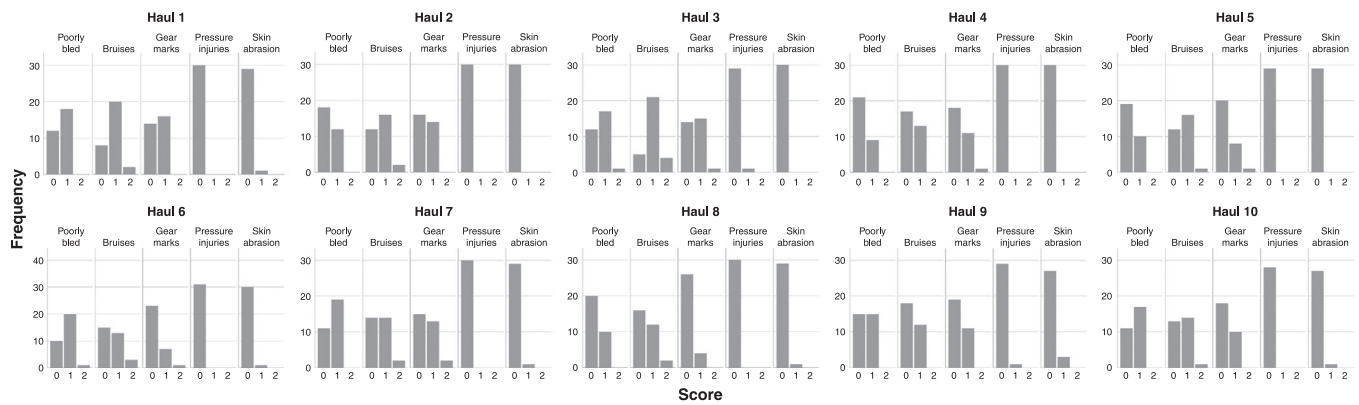
Fig. 2. Catch damage frequency scores for cod caught by the conventional configuration.

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

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

Catch damage frequency scores for cod caught by the T90-codend in each haul are shown in Fig. 3. The probability of obtaining fish with no damage (all categories combined, score = 0) was 21.2% (CI: 15.4–27.2%) (Table 4). Similar to cod caught using the conventional configuration, bruising was the damage type with the highest

probability of being severe (score = 2). The probability of obtaining fish with severe bruising damage was 7.1% (CI: 3.8–10.8). The probability of obtaining fish that were properly bled (score = 0) was 49.8% (CI: 42.5–58.7%), and the probability of obtaining fish that suffered from insufficient exsanguination (score = 2) was 0.0% (CI: 0.0–0.0%). Also, like cod caught using the conventional configuration, pressure injuries and skin abrasion were the damage types with the lowest probability of being severe (Table 4).

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

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

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

|	0	1	2	≤ 1
All categories	23.41% (16.33–31.08%)	0.33% (0.00–1.67%)	0.33% (0.00–1.67%)	92.98% (88.59–96.66%)
Poorly bled	50.17% (40.13–60.27%)	48.83% (38.67–58.61%)	0.67% (0.00–2.01%)	99.00% (97.32–100.00%)
Bruises	43.48% (34.11–52.01%)	50.50% (42.67–58.67%)	5.69% (2.68–9.09%)	93.98% (90.33–97.00%)
Gear marks	61.20% (52.19–70.71%)	36.45% (27.24–45.67%)	2.01% (0.33–4.04%)	97.66% (95.30–99.66%)
Pressure injuries	99.00% (97.30–97.30%)	0.67% (0.00–2.03%)	0.00% (0.00–0.00%)	99.67% (98.33–100.00%)
Skin	96.99% (93.92–99.33%)	2.68% (0.66–5.65%)	0.00% (0.00–0.00%)	99.67% (98.33–100–00%)
Poorly & Bruises	27.76% (20.07–36.45%)	29.10% (21.55–36.7%)	0.33% (0.00–1.67%)	93.65% (89.30–97.32%)
Poorly & Gear	35.45% (26.76–45.15%)	22.07% (13.95–29.87%)	0.33% (0.00–1.68%)	97.32% (94.61–99.66%)
Poorly & Press	50.17% (41.00–60.34%)	0.67% (0.00–2.35%)	0.33% (0.00–1.67%)	99.33% (97.67–100.00%)
Poorly & Skin	50.17% (40.47–59.20%)	2.68% (0.66–5.65%)	0.33% (0.00–1.67%)	99.33% (97.99–100.00%)
Bruises & Gear	34.78% (25.83–44.48%)	25.08% (17.67–32.11%)	1.67% (0.00–3.72%)	93.65% (89.60–96.98%)
Bruises & Press	43.81% (34.23–52.82%)	1.00% (0.00–2.69%)	0.33% (0.00–1.36%)	94.31% (91.00–97.64%)
Bruises & Skin	43.14% (33.77–52.00%)	1.67% (0.00–3.99%)	0.33% (0.00–1.35%)	94.31% (90.67–97.65%)
Gear & Press	61.20% (51.51–71.14%)	0.67% (0.00–2.33%)	0.33% (0.00–1.35%)	97.99% (95.96–99.67%)
Gear & Skin	60.54% (52.01–70.17%)	1.67% (0.00–4.38%)	0.33% (0.00–1.67%)	97.99% (95.95–99.67%)
Press & Skin	96.66% (93.29–99.33%)	0.33% (0.00–1.68%)	0.33% (0.00–1.68%)	100.00% (100.00–100.00%)
Poorly, Bruises & Gear	23.75% (16.56–31.76%)	15.72% (9.90–21.89%)	0.33% (0.00–1.67%)	92.98% (88.12–96.98%)
Poorly, Bruises & Press	27.76% (20.00–35.91%)	0.67% (0.00–2.35%)	0.33% (0.00–1.68%)	93.65% (89.33–97.32%)
Poorly, Bruises & Skin	27.42% (19.60–35.91%)	1.67% (0.00–4.03%)	0.33% (0.00–1.35%)	93.65% (89.11–97.65%)
Poorly, Gear & Press	35.12% (26.00–44.33%)	0.67% (0.00–2.03%)	0.33% (0.00–1.35%)	97.32% (94.65–99.66%)
Poorly, Gear & Skin	35.12% (26.76–44.78%)	1.67% (0.00–4.35%)	0.33% (0.00–1.35%)	97.32% (94.65–99.33%)
Poorly, Press & Skin	49.83% (40.67–60.20%)	0.33% (0.00–1.68%)	0.33% (0.00–1.68%)	99.33% (97.67–100.00%)
Bruises, Gear & Press	34.78% (25.83–43.62%)	0.67% (0.00–2.03%)	0.33% (0.00–1.35%)	93.65% (89.33–96.99%)
Bruises, Gear & Skin	34.45% (25.58–43.33%)	1.34% (0.00–3.68%)	0.33% (0.00–1.36%)	93.65% (89.67–97.00%)
Bruises, Press & Skin	43.14% (34.00–52.33%)	0.33% (0.00–1.67%)	0.33% (0.00–1.67%)	94.31% (90.40–97.65%)
Gear, Press & Skin	60.20% (51.34–69.10%)	0.33% (0.00–1.68%)	0.33% (0.00–1.68%)	97.99% (95.70–99.67%)
Poorly, Bruises, Gear & Press	23.75% (16.33–30.98%)	0.67% (0.00–2.34%)	0.33% (0.00–1.68%)	92.98% (87.92–96.97%)
Poorly, Bruises, Gear & Skin	23.41% (16.28–31.31%)	1.34% (0.00–3.69%)	0.33% (0.00–1.35%)	92.98% (88.12–96.98%)
Poorly, Bruises, Press & Skin	27.42% (20.67–35.14%)	0.33% (0.00–1.67%)	0.33% (0.00–1.67%)	93.65% (89.70–97.33%)
Poorly, Gear, Press & Skin	34.78% (25.25–44.26%)	0.33% (0.00–1.68%)	0.33% (0.00–1.68%)	97.32% (94.70–99.33%)
Bruises, Gear, Press & Skin	34.45% (25.08–43.62%)	0.33% (0.00–1.36%)	0.33% (0.00–1.36%)	93.65% (89.97–96.67%)
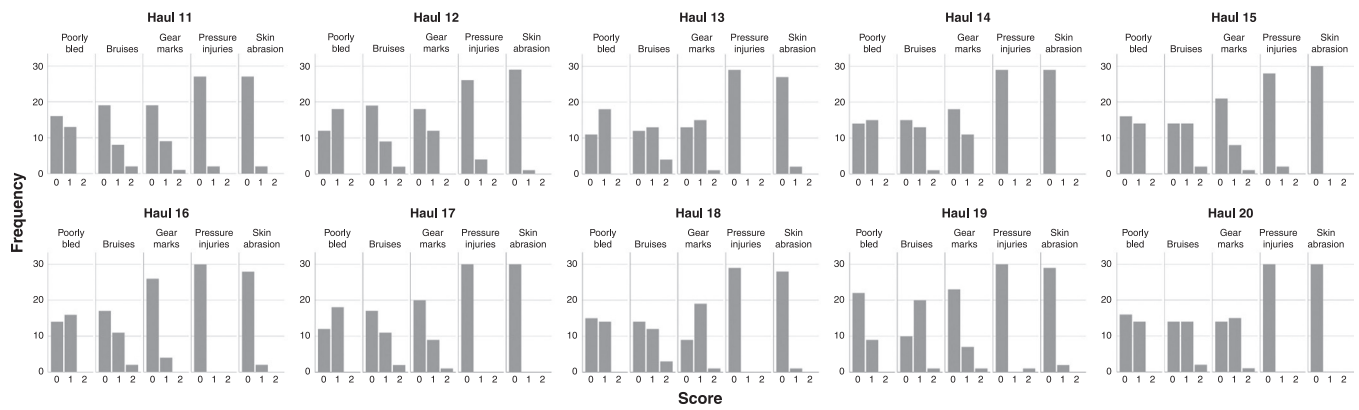
Fig. 3. Catch damage frequency scores for cod caught by the T90-codend without a sorting grid.

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

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

3.4. Residual blood levels

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

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

4. Discussion

It is difficult to improve catch quality if damage occurs during the

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

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

Table 5

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

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

Table 5 (*continued*)

|	0	1	2	≤ 1
marks & Skin				
Bruises, Press & Skin	5.00% (−7.07 to 16.84%)	− 0.33% (−1.67 to 0.00%)	− 0.33% (−1.67 to 0.00%)	− 1.72% (−6.84 to 2.61%)
Gear, Press & Skin	− 1.95% (−17.37 to 12.04%)	− 0.33% (−1.68 to 0.00%)	− 0.33% (−1.68 to 0.00%)	− 0.69% (−3.35 to 2.33%)
Poorly, Bruises, Gear & Press	− 1.86% (−11.45 to 7.77%)	0.34% (−1.68 to 2.70%)	− 0.33% (−1.68 to 0.00%)	− 2.07% (−7.60 to 4.36%)
Poorly, Bruises, Gear & Skin	− 2.20% (−11.74 to 7.77%)	− 1.00% (−3.38 to 0.67%)	− 0.33% (−1.35 to 0.00%)	− 1.73% (−7.73 to 40%)
Poorly, Bruises, Press & Skin	− 2.51% (−12.13 to 6.53%)	− 0.33% (−1.67 to 0.00%)	− 0.33% (−1.67 to 0.00%)	− 1.05% (−6.71 to 4.25%)
Poorly, Gear, Press & Skin	− 1.11% (−13.22 to 10.83%)	− 0.33% (−1.68 to 0.00%)	− 0.33% (−1.68 to 0.00%)	− 0.02% (−3.68 to 3.29%)
Bruises, Gear, Press & Skin	0.57% (−11.37 to 13.22%)	− 0.33% (−1.36 to 0.00%)	− 0.33% (−1.36 to 0.00%)	− 2.74% (−8.48 to 2.68%)
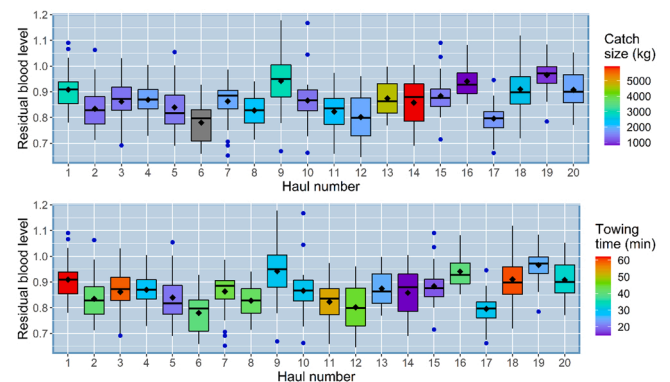
Fig. 4. Box plots showing blood abundance (in arbitrary unit) in the cod in the different hauls, coloured according to catch size and towing time. The conventional configuration was used for hauls 1–10, and the T90-codend was used for hauls 11–20. The catch size was not recorded for haul number 6, hence the box is coloured grey.

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

Previous studies of how to improve the catch quality of trawl-caught cod have focused on the trawl configurations (e.g., the codend). Tveit et al. (2019) investigated the effect of substituting conventional knotted codends with knotless netting, and they further tested the effect of changing the codend construction from a 2-panel to a 4-panel codend. They found that the probability of obtaining fish with no catch damage was 9.4% (4.7–15.8%) for the 2-panel knotted codend, 11.6% (5.9–18.6%) for the 2-panel knotless codend, and 11.3% (6.7–17.4%) for the 4-panel knotless codend. However, those codend designs did not significantly decrease the catch damage compared to the conventional
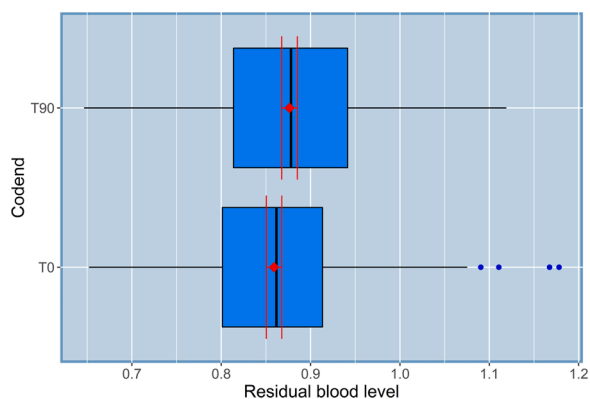
Fig. 5. Overall average blood abundance (in arb. unit) for cod caught with the T0 and T90 trawl configurations. The red diamond marks the mean and the vertical red lines shows the 95% CIs for the mean. The length of the whiskers was set to a maximum of 1.5 times the interquartile range.

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

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

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

The catch damage evaluation is subjective, whereas the residual blood level measurements are objective. The two methods yielded the same statistical results, which strengthens our premise that the catch

quality did not differ between cod caught by the two different trawl configurations. Furthermore, the "poorly bled" catch damage category results provided by experienced personnel corresponded with the results of the hyperspectral imaging assessment of residual blood.

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

CRediT authorship contribution statement

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

Declaration of Competing Interest

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References

Botta, J., Bonnell, G., Squires, B., 1987. Effect of method of catching and time of season on sensory quality of fresh raw Atlantic cod (*Gadus morhua*). J. Food Sci. 52 (4), 928–931. https://doi.org/10.1111/j.1365-2621.1987.tb14245.x.

Brinkhof, J., Larsen, R.B., Herrmann, B., Olsen, S.H., 2018a. Assessing the impact of buffer towing on the quality of Northeast Atlantic cod (*Gadus morhua*) caught with a bottom trawl. Fish. Res. 206, 209–219. https://doi.org/10.1016/j.fishres.2018.05.021.

Brinkhof, J., Olsen, S.H., Ingolfsson, O.A., Herrmann, B., Larsen, R.B., 2018b. Sequential codend improves quality of trawl-caught cod. PLoS One 13 (10), e0204328. https://doi.org/10.1371/journal.pone.0204328.

Brinkhof, J., Herrmann, B., Sistiaga, M., Larsen, R.B., Jacques, N., Gjøsund, S.H., 2021. Effect of gear design on catch damage on cod (*Gadus morhua*) in the Barents Sea demersal trawl fishery. Food Control. 120, e107562 https://doi.org/10.1016/j.foodcont.2020.107562.

Brinkhof, J., Larsen, R.B., Herrmann, B., 2022. Make it simpler and better: T90 codend improves size selectivity and catch efficiency compared with the grid-and-diamond mesh codend in the Northeast Atlantic bottom trawl fishery for gadoids. Ocean Coast. Manag. 217, e106002 https://doi.org/10.1016/j.ocecoaman.2021.106002.

Cheng, Z., Winger, P.D., Bayse, S.M., Kebede, G.E., DeLouche, H., Einarsson, H.A., Pol, M.V., Kelly, D., Walsh, S.J., 2020. Out with the old and in with the new: T90 codends improve size selectivity in the Canadian redfish (*Sebastes mentella*) trawl fishery. Can. J. Fish. Aquat. Sci. 77 (10), 1711–1720. https://doi.org/10.1139/cjfas-2020-0063.

Digre, H., Hansen, U.J., Erikson, U., 2010. Effect of trawling with traditional and 'T90' trawl codends on fish size and on different quality parameters of cod *Gadus*

morhua and haddock *Melanogrammus aeglefinus*. Fish. Sci.. 76 (4), 549–559. https://doi.org/10.1007/s12562-010-0254-2.

Digre, H., Rosten, C., Erikson, U., Mathiassen, J.R., Aursand, I.G., 2017. The on-board live storage of Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) caught by trawl: fish behaviour, stress and fillet quality. Fish. Res. 189, 42–54. https://doi.org/10.1016/j.fishres.2017.01.004.

Efron, B., 1982. *The Jackknife, the bootstrap and other resampling plans.* Society for industrial and applied matemathics. Monograph no. 38. CBSM-NSF.

Esaiassen, M., Nilsen, H., Joensen, S., Skjerdal, T., Carlehög, M., Eilertsen, G., Elvevoll, E. O., 2004. Effects of catching methods on quality changes during storage of cod (Gadus morhua). LWT Food Sci. Technol. 37 (6), 643–648. https://doi.org/10.1016/j.lwt.2004.02.002.

Esaiassen, M., Akse, L., Joensen, S., 2013. Development of a catch-damage-index to assess the quality of cod at landing. Food Control 29 (1), 231–235. https://doi.org/10.1016/j.foodcont.2012.05.065.

Herrmann, B., Sistiaga, M.B., Nielsen, K.N., Larsen, R.B., 2012. Understanding the size selectivity of redfish (*Sebastes* spp.) in North Atlantic trawl codends. J. Northwest Atlantic. Fish. Sci. 44, 1–13. https://doi.org/10.2960/J.v44.m680.

ICES., 2018. ICES Advice on fishing opportunities, catch, and effort Arctic Ocean, Barents Sea, Faroes, Greenland Sea, Icelandic Waters, and Norwegian Sea ecoregions - Cod (Gadus morhua) in subareas 1 and 2 (Northeast Arctic). ICES, June, 2018. https://doi.org/10.17895/ices.pub.4412.

Madsen, N., Herrmann, B., Frandsen, R.P., Krag, L.A., 2012. Comparing selectivity of a standard and turned mesh T90 codend during towing and haul-back. Aquat. Living Resour. 25 (3), 231–240. https://doi.org/10.1051/alr/2012021.

Margeirsson, S., Nielsen, A.A., Jonsson, G.R., Arason, S., 2006. Effect of catch location, season and quality on value of Icelandic cod (*Gadus morhua*) products. Seafood Research from Fish to Dish: Quality, safety and processing of wild and farmed fish, 265–274.

Margeirsson, S., Jonsson, G.R., Arason, S., Thorkelsson, G., 2007. Influencing factors on yield, gaping, bruises and nematodes in cod (*Gadus morhua*) fillets. J. Food Eng. 80 (2), 503–508. https://doi.org/10.1016/j.jfoodeng.2006.05.032.

Ministry of Trade, Industry and Fisheries, 2020. Regulations on the practice of fishing in the sea – fish below the minimum landing size.

Nedreaas, K.H., Drevetnyak, K.V., Shamray, E.A., 2011. Commercial data. In: Jakobsen, T., Ozhigin, V.K. (Eds.), The Barents Sea: Ecosystem, Resources, Management: Half a Century of Russian-Norwegian Cooperation. Tapir Academic Press, Trondheim, Norway, pp. 609–620.

Olsen, S.H., Tobiassen, T., Akse, L., Evensen, T.H., Midling, K.O., 2013. Capture induced stress and live storage of Atlantic cod (*Gadus morhua*) caught by trawl: consequences for the flesh quality. Fish. Res. 147, 446–453. https://doi.org/10.1016/j.fishres.2013.03.009.

Olsen, S.H., Joensen, S., Tobiassen, T., Heia, K., Akse, L., Nilsen, H., 2014. Quality consequences of bleeding fish after capture. Fish. Res. 153, 103–107. https://doi.org/10.1016/j.fishres.2014.01.011.

Petetta, A., Herrmann, B., Virgili, M., De Marco, R., Canduci, G., Veli, D.L., Bargione, G., Vasapollo, C., Lucchetti, A., 2020. Estimating selectivity of experimental diamond

(T0) and turned mesh (T90) codends in multi-species Mediterranean bottom trawl. Mediterr. Mar. Sci. 21 (3), 545–557. https://doi.org/10.12681/mms.22789.

Rotabakk, B.T., Skipnes, D., Akse, L., Birkeland, S., 2011. Quality assessment of Atlantic cod (*Gadus morhua*) caught by longlining and trawling at the same time and location. Fish. Res. 112 (1), 44–51. https://doi.org/10.1016/j.fishres.2011.08.009.

Shamray, E.A., Sunnanå, K., 2011. Development of management strategies. In: Jakobsen, T., Ozhigin, V.K. (Eds.), The Barents Sea: Ecosystem, Resources, Management: Half a Century of Russian-Norwegian Cooperation. Tapir Academic Press, Trondheim, Norway, pp. 532–540.

Sistiaga, M., Brinkhof, J., Herrmann, B., Grimaldo, E., Langård, L., Lilleng, D., 2016. Size selective performance of two flexible sorting grid designs in the Northeast Arctic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) fishery. Fish. Res. 183, 340–351. https://doi.org/10.1016/j.fishres.2016.06.022.

Sistiaga, M., Herrmann, B., Brinkhof, J., Larsen, R.B., Jacques, N., Santos, J., Gjøsund, S. H., 2020. Quantification of gear inflicted damages on trawl-caught haddock in the Northeast Atlantic fishery. Mar. Pollut. Bull. 157, 111366 https://doi.org/10.1016/j.marpolbul.2020.111366.

Sivertsen, A.H., Heia, K., Hindberg, K., Godtliebsen, F., 2012. Automatic nematode detection in cod fillets (*Gadus morhua L.*) by hyperspectral imaging. J. Food Eng. 111 (4), 675–681. https://doi.org/10.1016/j.jfoodeng.2012.02.036.

Skjelvareid, M.H., Heia, K., Olsen, S.H., Stormo, S.K., 2017. Detection of blood in fish muscle by constrained spectral unmixing of hyperspectral images. J. Food Eng. 212, 252–261. https://doi.org/10.1016/j.jfoodeng.2017.05.029.

Svalheim, R.A., Burgerhout, E., Heia, K., Joensen, S., Olsen, S.H., Nilsen, H., Tobiassen, T., 2019. Differential response to air exposure in crowded and uncrowded Atlantic cod (*Gadus morhua*): consequences for fillet quality. Food Biosci. 28, 15–19. https://doi.org/10.1016/j.fbio.2019.01.008.

Svalheim, R.A., Aas-Hansen, Ø., Heia, K., Karlsson-Drangsholt, A., Olsen, S.H., Johnsen, H.K., 2020. Simulated trawling: exhaustive swimming followed by extreme crowding as contributing reasons to variable fillet quality in trawl-caught Atlantic cod (*Gadus morhua*). PLoS One 15 (6), e0234059. https://doi.org/10.1371/journal.pone.0234059.

Tveit, G.M., Sistiaga, M., Herrmann, B., Brinkhof, J., 2019. External damage to trawl-caught northeast arctic cod (*Gadus morhua*): effect of codend design. Fish. Res. 214, 136–147. https://doi.org/10.1016/j.fishres.2019.02.009.

Veldhuizen, L.J.L., Berentsen, P.B.M., De Boer, I.J.M., Van De Vis, J.W., Bokkers, E.A.M., 2018. Fish welfare in capture fisheries: a review of injuries and mortality. Fish. Res. 204, 41–48. https://doi.org/10.1016/j.fishres.2018.02.001.

, 1996Wileman, D.A., Ferro, R.S.T., Fonteyne, R., Millar, R.B. (Eds.) 1996. Manual of Methods of Measuring the Selectivity of Towed Fishing Gears. ICES Cooperative Research Report No. 215. 126 pp.

Yaragina, N.A., Aglen, A., Sokolov, K.M., 2011. Cod. In: Jakobsen, T., Ozhigin, V.K. (Eds.), The Barents Sea: Ecosystem, Resources, Management: Half a Century of Russian-Norwegian Cooperation. Tapir Academic Press, Trondheim, Norway, pp. 225–270.

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*)

1 **The effect of buffer towing on quality aspects of frozen and thawed Atlantic**

2 **cod** *(Gadus morhua)*

3

4

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The effect of buffer towing on quality aspects of frozen and thawed Atlantic cod *(Gadus morhua)*

A large part of the Northeast Atlantic cod caught with trawls, is landed frozen, processed and sold thawed. Many trawlers have adapted a fishing practice termed "buffer towing", causing probability for poor exsanguination and increased fillet redness. In this work the effect of buffer towing upon colour and haemoglobin concentration in cod loin is studied, as well as the development of TVB-N during chilled storage of thawed cod. No significant differences were proven on redness or haemoglobin concentration in loin from cod exposed to regular haul-back or buffer towing. Neither were significant differences found in TVB-N levels during chill storage at 0 and 4 ⁰C.

Introduction

Thawed, or "refreshed" cod fillets have been available in supermarkets in many countries as a response to consumers demand for continuous availability (Martinsdottir and Magnusson 2001; Sørensen et al. 2020), and a study by Altintzoglou et al. (2012) showed that consumers in England may prefer thawed over fresh cod fillets.

The use of frozen and thawed cod may also be beneficial for the seafood industry: The cod fisheries in Norway is highly seasonal, most cod are caught during the first four months of the year. The large volumes of fish caught during a limited period leads to processing capacity challenges in the land-based industry, a challenge that can be met by applying fish frozen at sea and subsequent thawing (Erikson et al. 2021; Roiha et al. 2018; Svendsen et al. 2022).

During the last four years (2018-2021), 52 % of cod landed in Norway was landed frozen, and 81 % of this was caught by trawl (The Norwegian Directorate of Fisheries 2022). As described by Brinkhof et al. (2018), the dense aggregations of Northeast Atlantic cod (*Gadus morhua*) in the Barents Sea have led to a fishing practice among many trawlers termed "buffer towing": To secure a continuous supply of fish and avoid stops during processing, the trawl is redeployed immediately after taking the catch onboard. If the desired volume of fish is caught 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 ($\sim$1–2 knots), until the production capacity of the onboard factory is restored. Brinkhof et al. (2018) showed that this practice has a negative impact on fish quality, and cod subjected to buffer towing had an increased probability for poor exsanguination and increased fillet redness compared to regular (direct) haul-back.

In the study by Brinkhof et al. (2018), a fillet index evaluating the redness in the whole fillet was used. However, fish processors today commonly produce different fillet products like loins and tails, whereof cod loins are more expensive than cod fillets (Sogn-Grundvag et al. 2013). Olsen et al. (2008) and Jensen et al. (2022) showed uneven distribution of haeme-pigment in different parts of the fillets when studying the effects of stress and bleeding upon blood content in cod fillets, and generally, there were lower concentrations of haemoglobin in loins. However, when lifting the trawl off the seabed the rapid decompression causes the swim bladder to expand and eventually rupture (Humborstad and Mangor-Jensen 2013; Midling et al. 2012), which may result in bruises in the loin part of the fillet adjacent to the

59 swim bladder. Thus, cod caught by demersal trawling, both with and without buffer towing,

60 may have more blood in the loins compared to cod not exposed to barotrauma.

61

62 Studies have shown that thawed cod fillets may have longer shelf-life after thawing compared

63 to fresh cod fillets (Guldager et al. 1998; Magnusson and Martinsdóttir 1995; Skjerdal et al.

64 1999) and the reason is probably inactivation of spoilage bacteria by freezing and frozen

65 storage (Bøknæs et al. 2000; Skjerdal et al. 1999; Sørensen et al. 2020). However, the storage

66 stability of frozen fish and the shelf life of chilled fish may be reduced both due to residual

67 blood in the muscle leading to oxidation (Eliasson et al. 2020; Larsson et al. 2007; Richards

68 and Hultin 2002; Secci and Parisi 2016) and increased microbial growth (Sternisa et al. 2018).

69 The objectives of the present work were thus to compare the amounts of residual blood in cod

70 loin after trawling with and without buffer towing during catch, and study if buffer towing

71 affected the shelf life, as measured by TVB-N, of thawed cod fillets.

72

73 **Materials and methods**

74 *Catch and sample preparation*

75 Atlantic cod was caught with the research trawler R/V "Helmer Hanssen" (63.8 m, 4080 HP)

76 as described by Brinkhof et al. (2018) in the central part of the Barents Sea (N 74°59'–N

77 75°26', E 30°54'–E31°17') November 2016. The trawl setup was similar to commercial

78 fisheries, and the trawl was a standard two-panel Alfredo 3 fish trawl with a standard codend

79 (8 mm polyethylene twine, 150 mm nominal mesh size). To reduce catch-size variations

80 between hauls, the codend was set to allow capture of around 2 metric tons of fish. A total of

81 6 hauls were conducted (3 pairs), alternating between hauls with and without buffer towing.

82 Catch data for each haul are shown in Table 1.

83 Immediately after catch the fish was bled by cutting the isthmus, and exsanguinated in

84 running sea water (ca. 50 l/min) for 30 min. Next, the fish were beheaded, gutted and cleaned,

85 laid in 50 kg blocks in commercial vertical plate freezers, frozen to a core temperature of –18

86 °C, and finally packed in commercial type laminated paper bags and stored at -30 °C until

87 landing. On land, the fish was thawed in tanks containing 1000 L of chilled water (1 °C) for

88 24 hours and then further thawed on ice for additional 24 hours at 0-1°C.

89

90 After thawing, a total of 144 fish, twenty-four randomly chosen fish from each of the three

91 hauls from each of the two trawling procedures were manually filleted. Fillets from seven fish

92   from each haul were subjected to colour measurements and determination of haemoglobin,

93   while fillets from seventeen fish were applied to chilled storage and analyses of total volatile

94   nitrogen.

95

96   *Colour measurement*

97   Colour was measured on the anterior (L1), middle (L2) and posterior (L3) part of the loin, as

98   indicated with red circles in Figure 1, by the CIE L*a*b* system using a colourimeter

99   (Minolta Chroma Meter CR-200, Minolta Camera Co. Ltd., Osaka, Japan). Whiteness (W*)

100   was calculated as $W^* = 100 - [(100-L)^2 + a^2 + b^2]^{1/2}$. To reduce the source of error due to

101   contamination of residual blood in the neck flesh after decapitation, the flesh closest to the

102   neck cut was not included when sampling the three loin sections.

103

104   *Measurement of haemoglobin*

105   The middle (L2) and posterior (L3) parts of the loin were cut and used for determination of

106   haemoglobin as a measure of residual blood. The muscle was minced twice using an electric

107   meat mincer (Bosch Pro Power 2200 W, Germany), and then by hand blender (Wilfa AS,

108   Norway) for 30 seconds. Haemoglobin content in minced muscle was assessed according to

109   Chaijan and Undeland (2015).

110

111   *Chill storage and analyses of Total Volatile Basic Nitrogen (TVB-N)*

112   The left-side fillets from five fish from each of the three hauls, from each of the two trawling

113   procedures, were used as control groups, *N*=15 for each trawling procedure. Fillets from the

114   remaining 12 fish from each of the three hauls, from each of the two trawling procedures,

115   were used in the in the storage experiment, *N*=72 for each trawling procedure. The fillets were

116   divided into four experimental groups, consisting of either left- or right-side fillets from six

117   fish from each haul (*N*=18), as illustrated in Table 2. The fillets were stored individually in

118   non-sealed plastic bags (PA/PE 120µ) at two different temperatures: on ice at 0 °C, and in a

119   cold cabinet at 4 °C. After chilled storage, the fillets were frozen at -30 ⁰C for simultaneously

120   analyses of total volatile nitrogen (TVB-N).

121   Prior to analyses of TVB-N, the fillets were thawed at 1 °C for approximately 18 hours. The

122   fillets were skinned, and loin was cut and homogenized in a food processor (Kenwood FP 110

123   300 W, United Kingdom). TVB-N was determined by the Kjeldahl method (Tecator 1992)

124   and expressed as mg TVB-N per 100 g fish muscle.

126 *Statistics*

127 To test for differences in colour and haemoglobin content between loin from cod caught using

128 regular haul-back and buffer towing techniques, and between different parts of the loins, two-

129 tailed unpaired t-tests in Excel were used.

130 The TVB-N-data were analysed using IBM SPSS Statistics (Version 26) predictive analytics

131 software. The significance of any difference between the groups, or the impact of buffer

132 towing, was determined by using one-way analysis of variance (ANOVA) generally followed

133 by a post hoc Tukey's test. P-values lower than 0.05 are regarded as statistically significant.

134 The TVB-N-results are given as mean ± confidence interval (CI). It was also investigated if

135 the cofactors catching depth, towing time and catch size affected the results.

136

137 **Results and discussion**

138 *Colour and haemoglobin*

139 Brinkhof et al. (2018) proved that buffer towing significantly reduced the quality of cod. They

140 showed that cod subjected to buffer towing had an increased relative probability of 209 % for

141 fillet redness compared to cod subjected to regular (direct) haul-back as assessed by sensory

142 evaluation. In contrast, in the present work, only slightly higher and non-significant redness

143 (a*) and haemoglobin concentration were demonstrated in loin from cod exposed to buffer

144 towing compared to regular haul-back (Table 3). However, in the study by Brinkhof et al.

145 (2018), discoloration was assessed by "Fillet index", in which the visual appearance of the

146 whole fillets is evaluated. It is shown by Olsen et al. (2008) and Jensen et al. (2022) that cod

147 loins contain significant less residual blood than belly in both unstressed and stressed fish. It

148 is thus possible that the redness and residual blood in the whole fillet are influenced by buffer

149 towing, as demonstrated by Brinkhof et al (2018), while the loin part of the fillet is less

150 affected.

151 Table 3 also shows that there are differences in colour parameters between different loin

152 sections within both experimental groups. For cod exposed to regular haul-back, the anterior

153 part of the loin, L1, is significantly darker (lower L*) and significantly more red (higher a*)

154 than the middle (L2) and posterior (L3) part of the loin. For cod exposed to buffer towing, L1

155 is significantly darker and significantly redder in the flesh colour than L3. The red

156 discolouration of L1 could be due to contamination of residual blood on the surface of the

157 neck flesh after decapitation, or spontaneous blood coagulation in the wound after

158 decapitation (Olsen et al. 2014; Tavares-Dias and Oliveira 2009).

159 Since the swim bladder is located along to L2 and L3, the haemoglobin content was measured

160 in these sections to investigate whether the different trawl procedures affected swim bladder

161 rupture and ecchymosis differently. As shown in Table 3, there were only slightly and non-

162 significant higher levels of haemoglobin in the loin sections from buffer towed cod. Thus,

163 more severe barotrauma caused by buffer towing could not be proven. When comparing the

164 haemoglobin content in L2 and L3, a significantly higher concentration is found in the

165 posterior loin section (L3) compared to the middle (L2) in cod both from regular haul-back

166 and buffer-towing. The higher levels in L3 are probably due to the swim bladder being

167 located more adjacent to L3 than L2 (Fig. 1). Thus, L3 is more subjected to ecchymosis when

168 the swim bladder ruptures. Similar differences were not detected when measuring the colour

169 parameters in the middle of L2 and L3 (Fig. 1), indicating that the increased concentration of

170 haemoglobin in L3 is probably due to more blood in the lower part of the loin, adjacent to the

171 swim bladder.

172

173 ***TVB-N***

174 As seen by the overlapping confidence intervals in Figure 2, there were no significant

175 differences in shelf life of thawed cod caught by regular haul-back and buffer towing as

176 measured by TVB-N. On the other hand, as expected, both storage time and storage

177 temperature had significant effect on the TVB-N-levels. During chill storage for up to 12 days

178 at 0 or 4 ⁰C, none of the fillets exceeded the EU critical limit of 35 mg-N TVBN/100 g (EC,

179 2008). The TVB-N content is in accordance to what is reported in previous studies for cod

180 frozen for a few months prior to thawing and ice storage (Sørensen et al. 2020; Vyncke 1983)

181 and lower than for fish stored frozen for six weeks or less (Roiha et al. 2018; Vyncke 1983).

182 The reason for the low TVB-N content is probably inactivation of spoilage bacteria by

183 freezing and frozen storage (Bøknæs et al. 2000; Skjerdal et al. 1999; Sørensen et al. 2020).

184

185 It is known that the fish quality is reduced both by increased catch size and towing time

186 (Digre et al. 2017; Olsen et al. 2013; Rotabakk et al. 2011; Veldhuizen et al. 2018). Compared

187 to commercial trawl fisheries, where catches easily exceed 10 tonnes and more (Olsen et al.

188 2013), the catch size in this study is limited, as are the number of investigated individuals.

189 Thus, it is possible that some possible differences in fish quality, due to different trawling

190 procedures, may have been concealed in this experiment.

191

192

Conclusion

No significant increased redness (a*) and haemoglobin concentration were proven in loin from cod exposed to buffer towing compared to cod caught by regular haul-back. The posterior part of the loin has higher levels of haemoglobin, indicating ecchymosis in loin caused by rupture of the swim bladder.

Regarding shelf-life of thawed cod fillets, no significant differences were found in TVB-N levels during chill storage at 0 and 4 ⁰C of cod from regular haul-back and buffer towing.

References

Altintzoglou T, Nøstvold BH, Heide M, Østli J, Egeness FA. 2012. The influence of labelling on consumers'evaluations of fresh and thawed cod fillets in England. Br Food J. 114: 1558–1570.

Bøknæs N, Osterberg C, Nielsen J, Dalgaard P. 2000. Influence of freshness and frozen storage temperature on quality of thawed cod fillets stored in modified atmosphere packaging. LWT-Food Sci Technol. 33: 244-248.

Brinkhof J, Larsen R, Herrmann B, Olsen SH. 2018. Assessing the impact of buffer towing on the quality of Northeast Atlantic cod (*Gadus morhua*) caught with a bottom trawl. Fisheries Res. 206: 209-219. doi: 10.1016/j.fishres.2018.05.021

Chaijan M, Undeland I. 2015. Development of a new method for determination of total haem protein in fish muscle. Food Chem. 173: 1133-1141. doi: 10.1016/j.foodchem.2014.11.010

Digre H, Rosten C, Erikson U, Mathiassen JR, Aursand IG. 2017. The on-board live storage of Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) caught by trawl: fish behaviour, stress and fillet quality. Fish Res. 189: 42–54. doi:10.1016/j.fishres.2017.01.004.

223 EC (2008). Commission Regulation (EC) No 1022/2008 of 17 October 2008 amending

224 Regulation (EC) No 2074/2005 as regards the total volatile basic nitrogen (TVB-N) limits.

225 European Commission, 277, 18–20. Retrieved from https://eur-lex.europa.eu/legal-

226 content/EN/TXT/PDF/?uri=CELEX:32008R1022andfrom=en.

227 Eliasson S, Arason S, Margeirsson B, Palsson OP. 2020. Onboard Evaluation of Variable

228 Water Flow and Recirculation Effects on Bleeding of Atlantic Cod (*Gadus morhua*). Foods.

229 9: 1519. doi:10.3390/foods9111519.

230 Erikson U, Uglem S, Greiff K. 2021. Freeze-Chilling of Whitefish: Effects of Capture, On-

231 Board Processing, Freezing, Frozen Storage, Thawing, and Subsequent Chilled Storage-A

232 Review. Foods 10(11): 2661; https://doi.org/10.3390/foods10112661.

233 Guldager HS, Bøknæs N, Østerberg C, Nielsen J, Dalgaard P. 1998. Thawed cod fillets spoil

234 less rapidly than unfrozen fillets when stored under modified atmosphere at 2 degrees C. J

235 Food Prot. 61: 1129–1136.

236 Humborstad OB, Mangor-Jensen A. 2013. Buoyancy adjustment after swimbladder puncture

237 in cod Gadus morhua: An experimental study on the effect of rapid decompression in capture-

238 based aquaculture. Mar Biol Res. 9: 383-393.

239 Jensen TK, Tobiassen T, Heia K, Møllersen K, Larsen RB, Esaiassen M. 2022. Effect of

240 codend design and postponed bleeding on hemoglobin in cod fillets caught by bottom trawl in

241 the Barents Sea demersal fishery. Journal of Aquatic Food Product Technology, *in press*.

242 Larsson K, Almgren A, Undeland I. 2007. Hemoglobin-mediated lipid oxidation and

243 compositional characteristics of washed fish mince model systems made from cod (*Gadus

244 morhua*), herring (*Clupea harengus*), and salmon (*Salmo salar*) muscle. J Agric Food Chem.

245 55: 9027–9035.

246 Magnusson H, Martinsdottir E. 1995. Storage quality of fresh and frozen-thawed fish in ice. J

247 Food Sci. 60: 273–278.

248 Martinsdottir E, Magnusson H. 2001. Keeping quality of sea-frozen thawed cod fillets on ice.

249 J Food Sci. 66(9): 1402-1408.

250 Midling K O, Koren C, Humborstad OB, Saether BS. 2012. Swimbladder healing in Atlantic

251 cod (Gadus morhua), after decompression and rupture in capture-based aquaculture. Mar Biol

252 Res. 8: 373-379.

253 Olsen SH, Sørensen NK, Larsen R, Elvevoll EO, Nilsen H. 2008. Impact of pre-slaughter
254 stress on residual blood in fillet portions of farmed Atlantic cod (Gadus morhua) - Measured
255 chemically and by Visible and Near-infrared spectroscopy. Aquaculture. 284: 90-97.

256 Olsen SH, Tobiassen T, Akse L, Evensen TH, Midling KØ. 2013. Capture induced stress and
257 live storage of Atlantic cod (*Gadus morhua*) caught by trawl: consequences for the flesh
258 quality. Fish Res. 147: 446–453. doi:10.1016/j.fishres.2013.03.009.

259 Olsen SH, Joensen S, Tobiassen T, Heia K, Akse L, Nilsen H. 2014. Quality consequences of
260 bleeding fish after capture. Fisheries Research. 153: 103-107.

261 Richards MP, Hultin HO. 2002. Contributions of blood and blood components to lipid
262 oxidation in fish muscle. J Agric Food chem. 50: 555-564.

263 Roiha IS, Jónsson Á, Backi CJ, Lunestad BT, and Karlsdóttir MG. 2018. A comparative study
264 of quality and safety of Atlantic cod (*Gadus morhua*) fillets during cold storage, as affected
265 by different thawing methods of pre-rigor frozen headed and gutted fish. J Sci Food Agric. 98:
266 400–409. https://doi. org/10.1002/jsfa.8649.

267 Rotabakk BT, Skipnes D, Akse L, Birkeland S. 2011. Quality assessment of Atlantic cod
268 (*Gadus morhua*) caught by longlining and trawling at the same time and location. Fish Res.
269 112(1-2): 44–51. doi:10.1016/j.fishres.2011.08.009.

270 Secci G, Parisi G. 2016. From farm to fork: Lipid oxidation in fish products. A review. Ital J
271 Anim Sci. 15: 124-136.

272 Skjerdal OT, Esaiassen M, Løkken GB. 1999. The quality and marketing possibilities can be
273 improved by optimising the freezing conditions. In Kennedy C, editor. Proceedings of the
274 fifth plenary meeting in the concerted action project ''The preservation of frozen food quality
275 and safety throughout the distribution chain''. Leeds: University of Leeds. p. 89–92.

276 Sogn-Grundvag G., Larsen TA, Young JA. 2013. The value of line-caught and other
277 attributes: An exploration of price premiums for chilled fish in UK supermarkets. Marine
278 Policy, 38: 41-44.

279 Sørensen JS, Ørnfeld-Jensen O, Bøknæs N, Mejlholm O, Jessen F, Dalgaard P. 2020. Thawed
280 and chilled Atlantic cod (*Gadus morhua* L.) from Greenland - Options for improved
281 distribution. LWT-Food Sci. Technol. 131: 109473.
282 https://doi.org/10.1016/j.lwt.2020.109473.

283 Sternisa M, Dvorak P, Lunda R, Linhartova Z, Mozina SS, Mraz J. 2018. Bleeding of

284 Common Carp (*Cyprinus carpio*) Improves Sensory Quality of Fillets and Slows Oxidative

285 and Microbiological Changes During Refrigerated Aerobic Storage. Food Technol Biotech.

286 56: 524-532.

287 Svendsen ES, Widell KN, Tveit GM, Nordtvedt TS, Uglem S, Standal I, Greiff K. 2022.

288 Industrial methods of freezing, thawing and subsequent chilled storage of whitefish. J. Food

289 Eng., 315, 110803. https://doi.org/10.1016/j.jfoodeng.2021.110803

290 Tavares-Dias M, Oliveira SR. 2009. A review of the blood coagulation system of fish. Braz. J.

291 Biosci. 7: 205–224.

292 Tecator. 1992. Kjeltec Auto 1035/38 Sampler System manual. Part no 1000 4305 Rev 1.0

293 Tecator AB Sweden.

294 The Norwegian Directorate of Fisheries 2022, Statbank; [accessed 2022 March 29].

295 https://www.fiskeridir.no/Tall-og-analyse/Statistikkbanken.

296 Veldhuizen LJL, Berentsen PBM, De Boer IJM, Van De Vis JW, Bokkers EAM. 2018. Fish

297 welfare in capture fisheries: A review of injuries and mortality. Fish Res. 204: 41-48.

298 Vyncke W. 1983. Shelf-life of thawed cod fillets kept in ice. Z Lebensm Unters. 177: 19-21.

299

Fundings

Legends to figures

305

306 Figure 1. The red circles indicate the points for colour measurements. Section L2 and L3 are

307 used for determination of haemoglobin. The dotted line shows blood stain after swim bladder

308 rupture.

309

310

311 Figure 2. TVB-N mean values (mgN/100g) with 95% confidence intervals in frozen-thawed

312 Atlantic cod fillets stored for 0 days, 7 days at 0°C and 4°C and 12 days at 0°C and 4°C. Cod

313   from regular haul-back are shown as whole black line, while cod from buffer towing are

314   showed by dotted line. Different letters indicate significant differences.
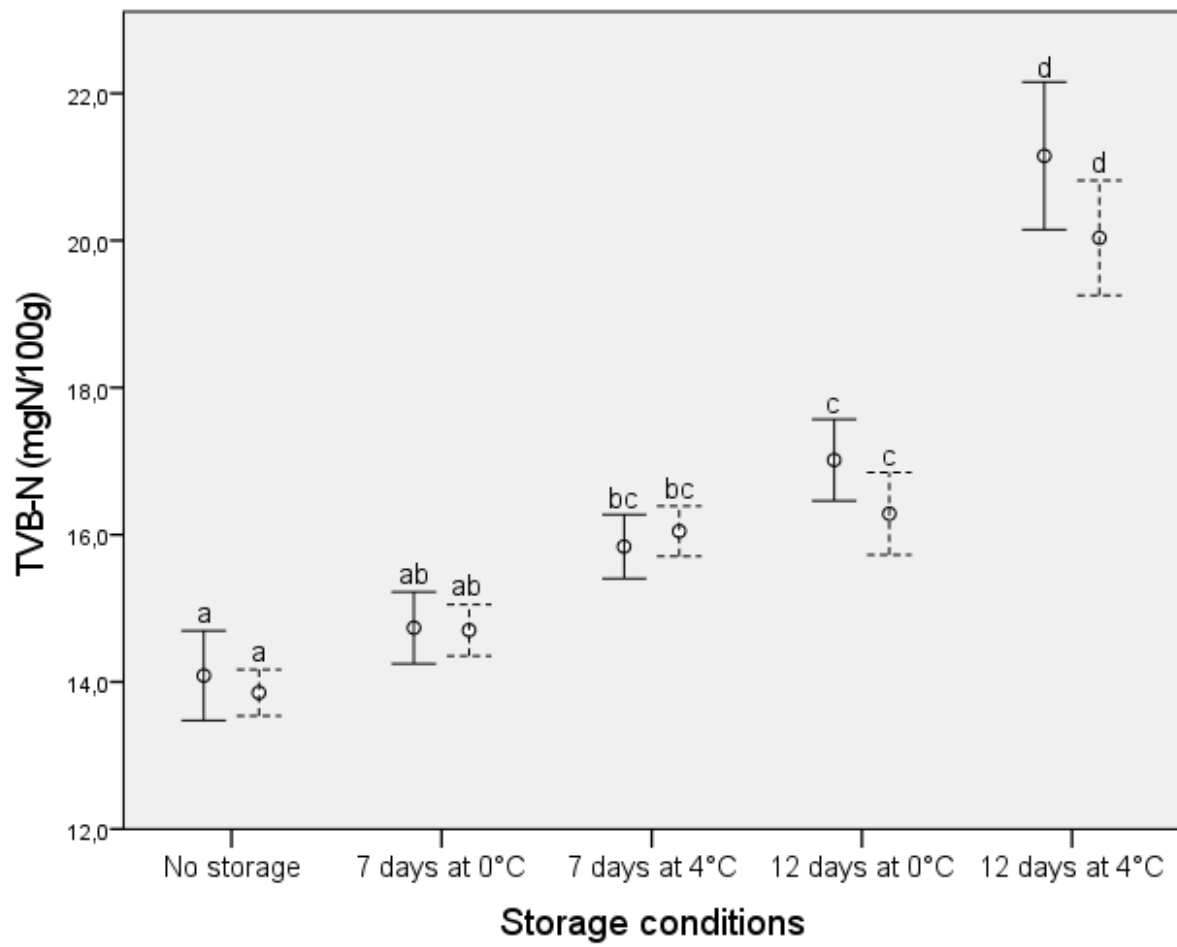
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316   Figure 1
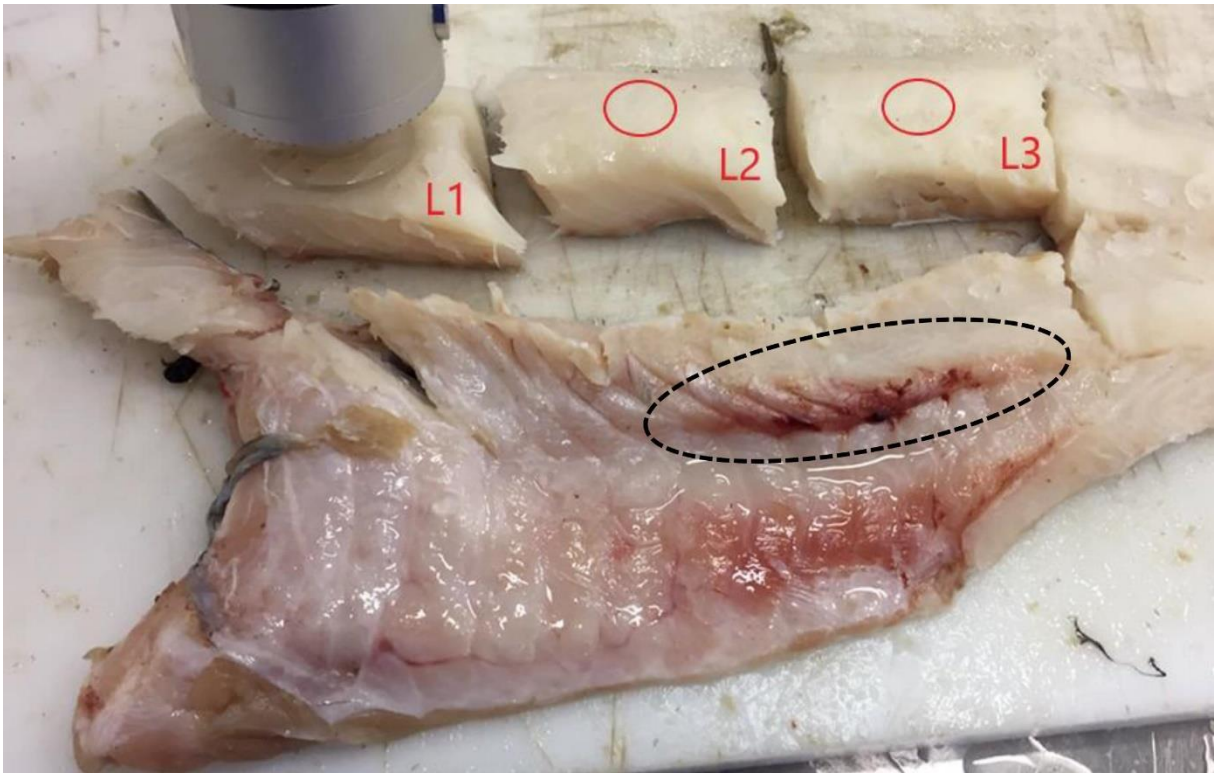
317

318

319   Figure 2

320
321

322   Table 1. Overview of the hauls conducted showing the towing start time, towing time, haul

323   type, depth, mean buffer towing depth, the percentage depth reduction during buffer towing,

324   number of fish caught, and average length of fish.

Pair No.	Haul No.	Time start UTC	Towing time (min)	Buffer towing	Depth (m)	Mean buffer towing depth (m)	Depth reduction (%)	# fish	Length of fish [cm]
1	1	17:09	120	No	347.9	-	-	336	75.5
1	2	20:06	195	Yes	341.9	205	40	223	74.5
2	3	00:00	120	No	351.1	-	-	365	72.7
2	4	03:13	199	Yes	354.3	192	46	204	71.7
3	5	23:01	100	No	359.3	-	-	391	73.6
3	6	01:26	175	Yes	358.8	218	39	451	74.9

325

326

327 Table 2: Time and temperature conditions for chilled storage of thawed cod fillets. N=18 in

328 the storage experiment, six fillets from each of the three hauls using each trawl procedure. As

329 control, five left-side fillets from each of the three hauls using each trawl procedure were

330 used.

Storage	Regular haul-back	Buffer towed
Control, 0 days	N=15	N=15
0 °C, 7 days – left side fillets	N=18	N=18
4 °C, 7 days – right side fillets	N=18	N=18
0 °C, 12 days – left side fillets	N=18	N=18
4 °C, 12 days – right side fillets	N=18	N=18

331

332

333 Table 3. Colour parameters and haemoglobin content of the different loin sections in fish caught by regular haul-back and buffer towing.

334 Values are presented as mean ± SD. $N = 21$, seven fillets from each of the three hauls using each trawl procedure. Different letters in the

335 same column indicate significant differences ($p < 0.05$) between loin sections.

336

Loin section	Regular haul-back N=21					Buffer towed N=21				
	L^*	a^*	b^*	Whiteness	Haemoglobin [mg/g muscle]	L^*	a^*	b^*	Whiteness	Haemoglobin [mg/g muscle]
L1 (anterior)	56.1 ± 3.6 [a]	-2.40 ± 0.43[a]	-0.70 ± 1.44 [a]	56.04 ±3.62		57.3 ± 3.1[a]	-2.34 ± 0.38[a]	0.94 ± 1.48	57.21 ± 3.0[a]	
L2 (middle)	58.6 ± 3.6[b]	-2.67 ± 0.40[b]	-2.44 ± 1.47[b]	58.40 ± 3.54	0.149 ±0.027 [a]	58.2 ± 2.2[ab]	-2.52 ± 0.22[ab]	-1.84 ± 1.98	58.07 ± 2.09[a.b]	0.155 ±0.027[a]
L3 (posterior)	59.5 ± 3.0[b]	-2.65 ± 0.33[b]	-1.49 ± 1.58[a.b]	59.38 ± 3.03	0.167 ± 0.028[b]	59.5 ± 2.3[b]	-2.56 ± 0.22[b]	-1.74 ± 1.25	59.35 ± 2.24[b]	0.175 ± 0.045[b]

337

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   **Experimental gillnet fishery: Effect of soaking time on survival, blood physiology and**

2   **muscle haemoglobin**

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ABSTRACT

The aim of this study was to investigate the effects of gillnet soaking time to better understand fish mortality, stress, and quality measured as muscle haemoglobin during gillnet fishery of Atlantic cod (*Gadus morhua*). An experimental study with four different gillnet soaking times (0, 2, 12, and 24 hours) was conducted on a total of 131 fish (23-34 fish per group). Longer soaking time caused higher mortality with a mortality rate of 0, 7, 18 and 25 % mortality in the 0, 2, 12- and 24-hours groups, respectively. The blood levels of lactate were significantly affected by soaking time and was highest with the largest confidence interval after two hours and lowest at 0 and 24 hours. Soaking time also significantly affected blood levels of glucose and serum levels of cortisol. Magnesium, creatinine, and iron increased significantly in all groups compared to control levels, but there was no significant difference between soaking times. When examining the quality of the fillet products, it was found that the haemoglobin content in loin increased significantly only after 24 hours soaking time for both alive and dead fish. There was no significant increase in haemoglobin in belly as a function of soaking time. However, during all soaking times, there was significantly more haemoglobin in belly compared to loin. Physiological evidence of traumatic injuries and stress happened before an increase in muscle haemoglobin, meaning good quality does not necessarily equal good welfare, but poor quality is a strong indication of poor welfare.

Introduction

The welfare of fish remains a relatively novel concept in the practice of commercial fisheries and has received little attention in research and development to date (Huntingford et al. 2006, Lambooij et al., 2012). In capture fisheries, several different fishing gears are used depended on target species, area, legislations, and traditions. Each fishing gear works and is operated differently and evidently, the effect on fish welfare will vary between the gears (Metcalfe, 2009). Research on animal welfare in fisheries has focused more on trawls and hooks than on purse seines, gillnets, traps and seines (Veldhuizenet al., 2018). Hence, an investigation into the impact of the capture process on fish welfare should acknowledge these differences in gear types.

Although animal welfare can be defined in various ways (Broom 2011; Hagen et al., 2011; Korte et al., 2007; Ohl & Van der Staay, 2012) key to all definitions is that poor welfare is associated with exceeding the coping capacity of animals, which may result in chronic stress-related physiology and behaviour, pathology and increased mortality. The general data collected on catch-related damage registrations over the years 2014–2020, conducted by The Norwegian Institute of Food, Fisheries and Aquaculture Research (NOFIMA), show that cod caught using gillnets have a higher incidence of gear marks, bruising, and discoloured fillets compared those caught by other gears, such as demersal seines, longlines and handlines (Joensen et al., 2021; Sogn-Grundvåg et al., 2022), and almost 40% of the fish caught by gillnet had serious quality degradation related to poor bleeding.

In a systematic review by Veldhuizenet al. (2018) it was found only 9 articles dealing with capture injuries using gillnets. Most of these studies focused on discard or escape mortality and capture injuries relevant for final quality of raw fish material, and not directly the gear's effect on stress, physiology, or welfare of the fish. Yet, there are some studies that found that fish caught with gillnets show higher stress levels compared to jigged (Toledo-Guedes et al.,

76 2016) and that quality tends to be better in fish caught by hook (e.g., longline, jigging)

77 compared to gillnetting (Botta et al., 1987; Özyurt et al., 2007; Santos et al., 2002).

78   Some of the quality challenges with gillnets are that the fish can die in the gear when

79 the net is soaked, and the netting can cause marks on the skin which consequently can lead to

80 blood stains in the muscle. Fish that die in the fishing gear before being brought on board are

81 very difficult to bleed out properly (Olsen et al., 2014), and in some cases the muscle

82 discoloration can be so severe that the whole fish must be discarded (Ministry of Trade,

83 Industry and Fisheries, 2022). Toledo-Guedes et al. (2016) documented that mortality was

84 27.3% for saithe *(Pollachius virens)* caught by gillnet, while all fish (100%) captured by jigging

85 were hauled on board alive. Santos et al. (2002) reported that discards of European

86 hake (*Merluccius merluccius*) represented 42% of the gillnets total catch and 7% of the long-

87 lines total catch. The higher incidents of mortality from the gillnet fishery indicate that gillnets

88 are less than optimal regarding animal welfare.   However, to our knowledge physiological

89 stress and welfare has not directly been linked to level of quality, nor is there scientific

90 documentation on how different soaking times affects survival, stress, and quality in Atlantic

91 cod (*Gadus morhua*). Therefore, the aim of this study was to investigate the effects of gillnet

92 soaking times to better understand fish mortality, stress, and quality measured as muscle

93 haemoglobin during gillnet fishery of Atlantic cod.

94

95 **Materials and methods**

96 *Animals and husbandry*

97 A total of 200 wild Atlantic cod (weight 1.2 ± 0.8 kg, mean ± standard deviation) (see Table 1

98 for detailed biological data) were captured by commercial cod pots in Malangen outside

99 Tromsø, Norway (69°36'40.9"N–18°54'48.6"E at 74.43 m depth, and 69°38'53.3"N–

100 18°53'13.8"E at 71.32 m depth) on the 29th of September 2021, of which 131 were used in the

101 experiment. Immediately after capture, the fish were placed in an on-board holding tank

102 supplied with running seawater and transported to the Aquaculture Research Station in Tromsø,

103 Norway. At the research station, the fish were held indoors under natural photoperiod

104 (transparent roof, 69°N) in a 5 m diameter tank with a volume of 50 000 L for 16 days prior to

105 the experiment. The tank was supplied with ambient (9.0°C) sand filtered seawater (200

106 L/min), pumped from the sea outside the aquaculture station. Temperature of the seawater

107 decreased from 9.0 to 5.0 °C during the liveholding and experiment. Oxygen levels in the tank

108 was measured once a week (YSI Pro ODO), all oxygen values during live holding were above

109 83.6%. The fish were offered thawed Atlantic herring (*Clupea harengus*) and were not starved

110 prior to the experiment.

111

112 Table 1: Soaking time and number of fish (N), weight (g), length (cm), Fulton's condition factor (K),

113 hepatosomatic index (HSI) and gonadosomatic index (GSI).

Soaking time	N	Weigth (g) mean ± SD	Length (cm) mean ± SD	K mean ± SD	HSI mean ± SD	GSI mean ± SD
Control	23	1890 ± 1266	55,7 ± 13,8	0,95 ± 0,11	0,03 ± 0,01	0,02 ± 0,01
0	23	1134 ± 669	47,8 ± 8,4	0,94 ± 0,09	0,02 ± 0,01	0,02 ± 0,01
2	27	980 ± 443	55,4 ± 33,1	0,91 ± 0,19	0,03 ± 0,01	0,02 ± 0,01
12	34	1006 ± 320	46,8 ± 4,6	0,96 ± 0,13	0,03 ± 0,02	0,01 ± 0,01
24	24	932 ± 331	46,5 ± 5,0	0,90 ± 0,12	0,03 ± 0,02	0,02 ± 0,01

114

115 *Ethics statement*

116 All experimental protocols were authorized by the Norwegian animal welfare authority

117 (Mattilsynet, FOTS licence ID: 23410). The experiment was designed in accordance with the

118 3R's. There was no alternative to the use of live animals. Numbers used were the minimum

119 required proper statistical testing of data and to precisely estimate survival while accounting

120 for removals for sampling. All fish were euthanized using a percussive blow to the head prior

121 to any invasive sampling beyond gillnet capture.

122

123 *Experimental set-up*

124 The experiment was conducted in three replicates over 13 days in the period October-

125 November 2021. Four soaking times of 0, 2, 12 and 24 hours were used. In addition, fish were

126 randomly sampled from the tank using a hand net at three different time points prior to the

127 netting event per replica, as controls and to establish baseline levels for measured parameters.

128   A large gillnet consisting of two separate nets with mesh sizes 45 and 60 mm attached

129 into one 720 cm long and 260 cm high gillnet was run across the diameter of the holding tank

130 the fish had been stored since arrival at the facility. After 7-13 min the desired amount

131 (minimum 7 fish per replica) of fish were caught in the gillnet. Then, the gillnet was hauled

132 and placed in a dry fish bin and immediately transported to a smaller tank (4000 L), where the

133 fish were kept in the gillnet for 0, 2, 12 and 24 hours prior to sampling.

134

135 *Sampling procedure*

136 One and one fish were lifted from the water and the conscious state of the fish was quickly

137 evaluated on physical responses to handling and the vestibulo-ocular reflex was quickly

138 checked, while the fish was in the net. Alive fish were euthanized by a percussive blow to the

139 head and individually tagged with Floy t-bar anchor tag in the operculum. Then blood was

140 collected from the caudal vessels using 3 mL clot activator serum vacutainer (Vacutest Kima,

141 Arzengrande, Italy) with $0{,}9 \times 38$ mm needles (BD Diagnostics, Franklin Lakes, NJ, USA).

142 Blood was only sampled from alive fish. Concentrations of lactate and glucose were obtained

143 from samples of whole blood, using the hand-held meters LactatePro™2 (Arkray Europe.B.V,

144   The Netherlands) and Accu-Chek (Roche Diabetes Care, GmbH., Germany), respectively.

145   Blood samples were centrifuged (3000×g, 10 min, 4 ⁰C) and serum was frozen at −80 ⁰C for

146   analyses. Serum cortisol was quantified using a solid-phase Enzyme-linked Immunosorbent

147   Assay (ELISA) Kit (Demeditec Diagnostics GmbH, Kiel, Germany) following the

148   manufacturer's instructions. Fish that died in the gillnet were individually tagged and followed

149   from now one the same procedures as the alive fish.

150   Immediately after blood collection, the fish were removed from the gillnet, bled by

151   cutting the isthmus and exsanguinated in running water for 30 minutes in a 200 L tank (6.9 –

152   8.3 °C). Next, weight (g), length (cm) and gender of each fish were registered. The liver and

153   gonads were also weighted (g) to determine hepatosomatic indices (HSI) and gonadosomatic

154   indices (GSI) by tissue weight × 100/total weight. The fish were then gutted, cleaned in running

155   water and placed on ice in 70 L fish crates with the belly cavity facing downward for 72 hours

156   to ensure post-rigor filleting. Then, the fish were manually filleted with the skin retained and

157   the black peritoneum was removed. Next, the fillets were cleaned in running freshwater,

158   vacuum packed and stored for 4 weeks at −20 °C before thawing and analysis. Chemical

159   analysis of haemoglobin was conducted using left fillet, and both fish that died in the net and

160   fish that survived were used for haemoglobin measurements. Gentle handling of the fish and

161   fillets were emphasized to minimize its influence on quality during processing.

162

163   *Chemical analysis of haemoglobin*

164   Prior to chemical analyses of haemoglobin, the sealed, vacuum-packed fillets were thawed in

165   a clean container with 50 L of chilled water (1 °C) for 1 hour. Next, the fillets were taken out

166   of the vacuum bag, skinned, and the loin and belly were cut and minced in a food processor

167   (Bosch MultiTalent 3 MCM3110W). Total heam protein was determined as described by

168   Chaijan & Undeland (2015) by weighing approximately 2 g of minced fish sample (loin and

169   belly) in a 50 mL centrifuge tube (Falcon Blue MacTM, Polypropylene Conial Tube, Becton

170   Dickinson Labware, NJ, USA) and adding 6 mL 0.1 M phosphate buffer, pH 7.0 containing

171   5% SDS. The samples were homogenized using an Ultra Turrax T25 homogeniser (IKA Werke

172   GmbH, Staufen, Germany) for 30 sec at 6000 rpm. The homogenate was subjected to 85 °C

173   for 1 hour in a temperature-controlled water bath (Julabo SW22, JULABO Labortechnik

174   GmbH, Germany). After cooling for 10 min at room temperature (25 °C), the solution was

175   centrifuged at 5000×g for 15 min (Eppendorf®, Germany). The absorbance of the supernatant

176   was read at 535 nm using a Visible Spectrophotometer Genesys 20 (Thermo Scientific™,

177   Waltham, MA, USA) and compared to a standard curve based on bovine haemoglobin with

178   concentrations ranging between 0 and 50 μM.

179

180   *Statistical treatment*

181   The data was analysed with the statistical software R Studio (R Studio Team, 2022). The

182   relationships between response variables (mortality, plasma cortisol (ng L $^{-1}$), lactate (mmol

183   L^{-1}), glucose (mmol L^{-1}), magnesium (mmol L^{-1}), creatinine (μmol L^{-1}), iron (μmol L^{-1}) and

184   muscle haemoglobin (mg/g muscle) and corresponding explanatory variables (as factor;

185   soaking time: 0, 2,12 or 24 hrs and control), were investigated using Generalised Linear

186   Modelling (GLM) (Buckley, 2015; McCullagh & Nelder, 2019). Before proceeding with the

187   GLM analysis, the data were checked and prepared for modelling following procedures

188   previously described (Zuur et al., 2010).

189   Briefly, most of the response variables had only positive values and were therefore best

190   modelled using Gamma distribution, which accounts for skewed distribution of model errors

191   and prevents negative predictions. In those cases where distribution was normal and there was

192   no risk of predicting negative values, data was modelled using Gaussian (Normal) error

193   distribution. In the case for mortality, data were recorded as 0 and 1 and therefore fitted to a

194 binomial distribution. Link function (identity, log, inverse or logit) was chosen based on which

195 link gave the best fit to data in terms of lowest Akaike information criterion (AIC) and by visual

196 evaluation of the graphics.

197

198 **Results**

199 All runs resulted in fish getting caught in the gillnet. It took 10 ± 3 minutes to capture 9 ± 3

200 (mean, SD) fish in each run. All fish struggled in the net immediately after being caught, which

201 involved rapid bursts and strong tail beats. We also observed strong tail flaps and lateral

202 flexions creating a rotation that in most caused the net to entangle more around their heads and

203 bodies. The physical struggle was primarily happening the first 1-2 minutes following capture,

204 after this the fish would make few rapid jerks whenever a new fish got caught. The fish that

205 were already in the net would only jerk a few times but did not undergo the intense struggle as

206 the newly caught fish.

207   Most of the fish were caught by entangling and gilling (He & Pol, 2010) (Figure 1). A

208 total of 5 fish were caught by snagging, but these would escape the net during/after transfer to

209 second tank and were excluded from the experiment. All fish that died in this experiment were

210 caught with gilling with net keeping the operculum entirely closed (Figure 2). There was a total

211 of 0, 7, 18 and 25 % mortality in the 0, 2, 12- and 24-hours groups respectively (Table 2).

212   Mortality was significantly affected by soaking time ($p < 0.001$), with significantly

213 higher mortality in the 12- and 24-hours groups, compared to 0 and 2 hours, but there was no

214 significant difference in mortality between 12- and 24-hours groups.

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219   Table 2: Number of alive and dead fish in each group during each trial (replicate).

Trial	Control		0		2		12		24	
	Alive	Dead	Alive	Dead	Alive	Dead	Alive	Dead	Alive	Dead
1	9	0	7	0	11	0	10	2	9	1
2	7	0	10	0	11	1	11	3	5	4
3	7	0	6	0	3	1	7	1	4	1
Total	23	0	23	0	25	2	28	6	18	6
%	100	0	100	0	93	7	82	18	75	25

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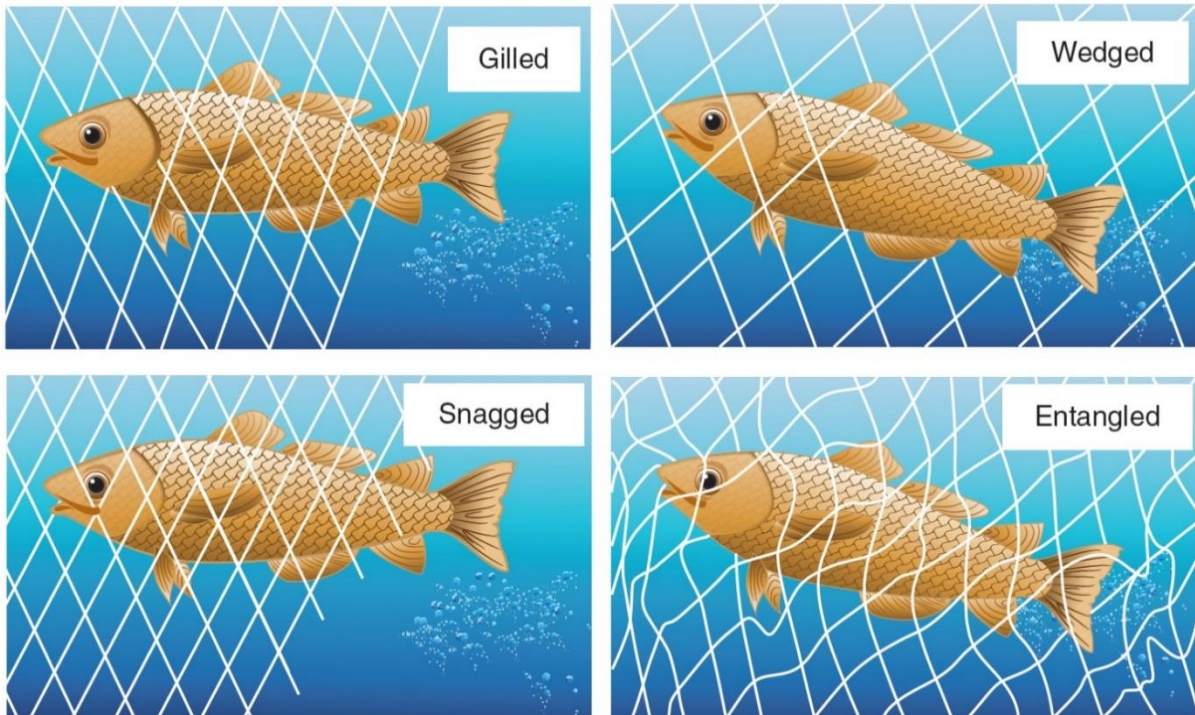
Figure 1: Illustration of the four modes of gillnet capture: gilling, wedging, snagging, and entangling. Gilling means when the net twine gets hooked behind the gills, wedging means when the largest part of the body is caught in the mesh, snagging is when the fish is caught by the mount or other parts of its head and entangling occurs when the spine, fins or other parts of the body gets stuck (modified from He & Pol, 2010).

Figure 2: 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.

There was significantly more haemoglobin in the belly compared to the loin ($p < 0.001$) for all fish regardless of soaking times (Figure 3). The haemoglobin in the loin increased significantly after 24 hours soaking time for both fish that were alive ($p < 0.001$) and fish that died ($p = 0.029$) (Figure 4). Prior to this timepoint, there were no significant differences in haemoglobin in loin.

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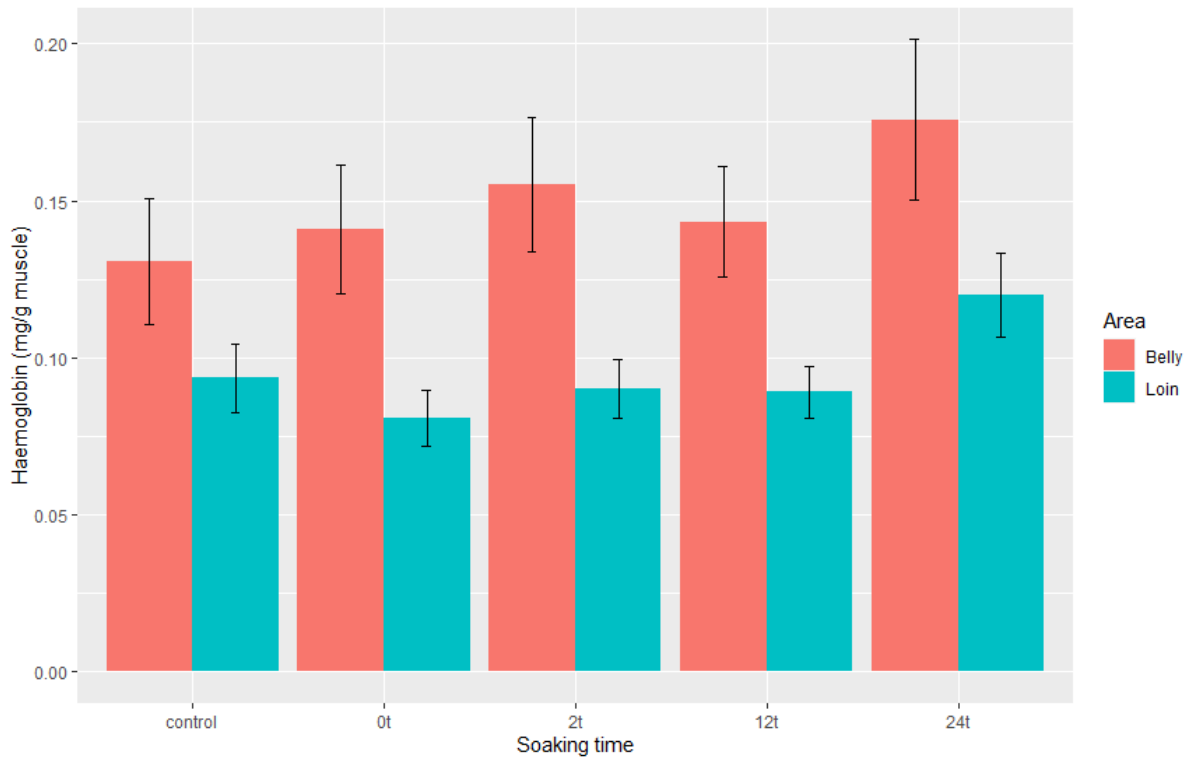
Figure 3: Haemoglobin content in loin and belly as function of soaking times. Bars are predicted means from GLM and error
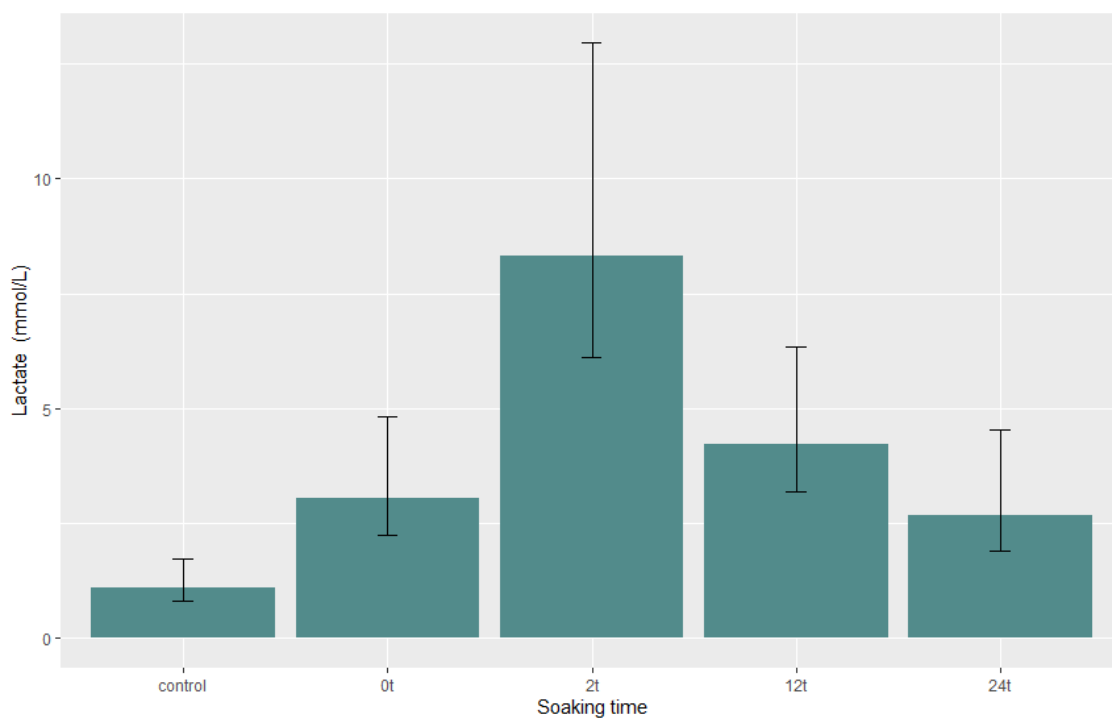
bars represent 95% confidence intervals.

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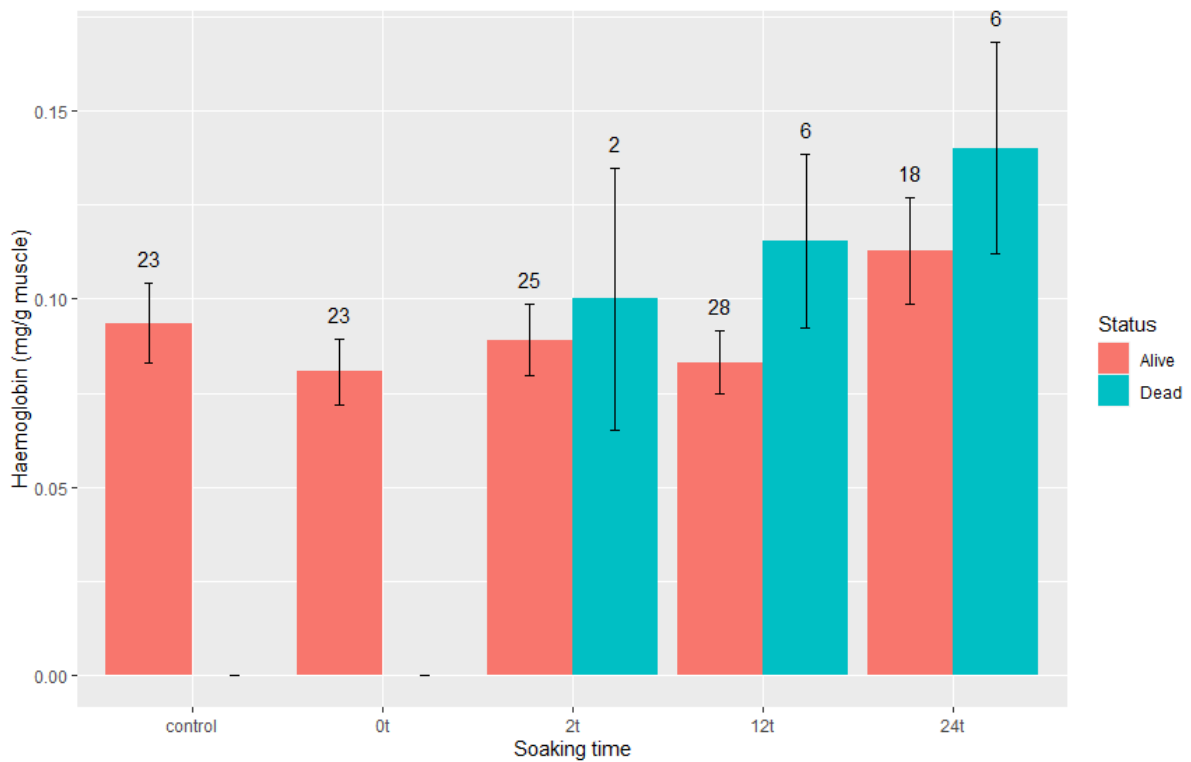
Figure 4: Haemoglobin content in loin from fish that were alive (red bars) and dead (blue bars) after soaking times of 0, 2,

12 and 24 hours. Bars are predicted from GLM, and error bars represents 95% confidence intervals (CI). Number above CI

are number of fish in the respective groups.

269   Of the physiological parameters measured, soaking time significantly affected blood

270   levels of lactate ($p < 0.001$) (Figure 5), glucose ($p < 0.001$) (Figure 6), and serum levels of

271   cortisol ($p < 0.001$) (Figure 7). The blood levels of lactate were significantly affected by

272   soaking time ($p < 0.001$) and was highest with the largest confidence interval after two hours

273   and lowest at 0 and 24 hours, but there were no significant differences between 0, 12 and 24

274   hours.

275   Magnesium (Figure 8), creatinine (Figure 9) and iron (Figure 10) increased significantly

276   compared to control levels ($p < 0.001$, $p < 0.001$ and $p = 0.001$, respectively), but prolonged

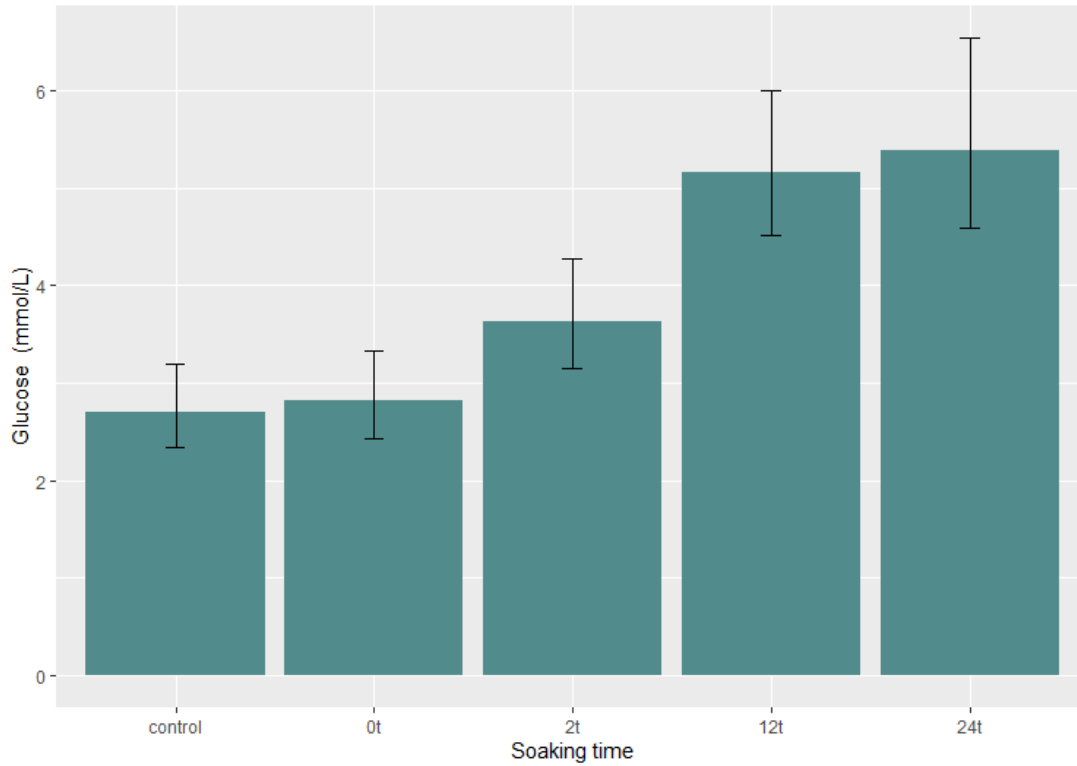277   soaking time led to no significant increase or decrease in these parameters.

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280   *Figure 5: Blood levels of lactate at different soaking times. Bars show predicted means from GLM and error bars represent*
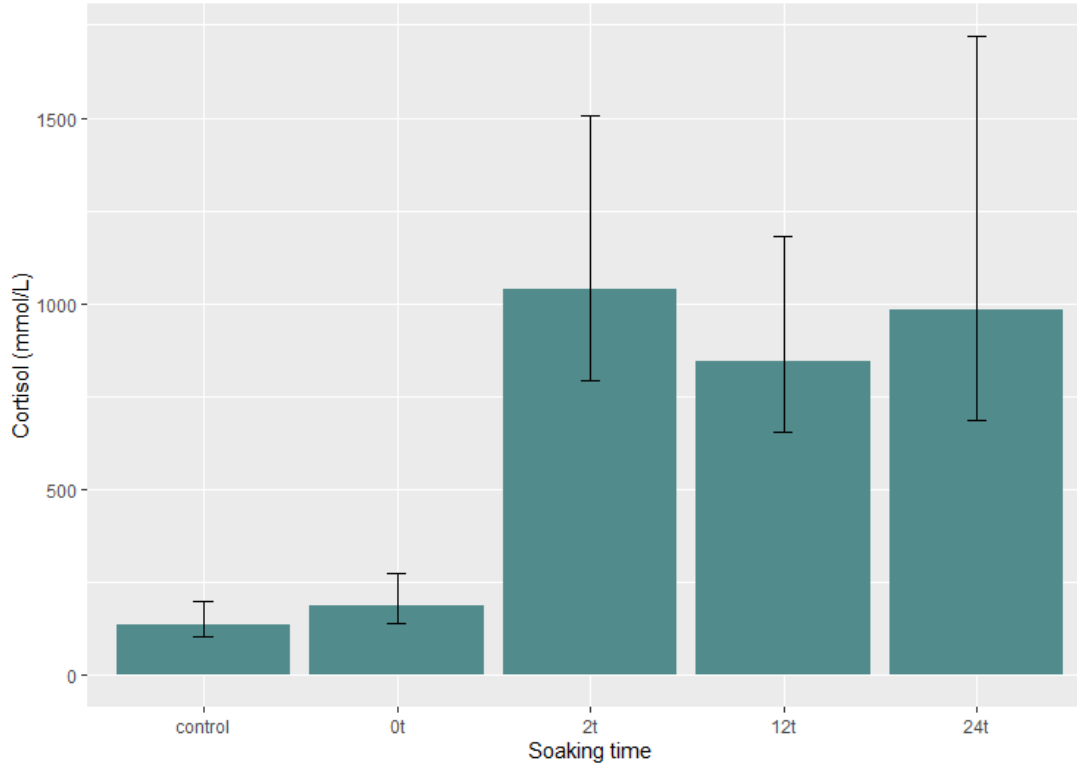
281   *95% confidence intervals.*

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Figure 6: Blood levels of glucose at different soaking times. Bars show precited means from GLM and error bars represent
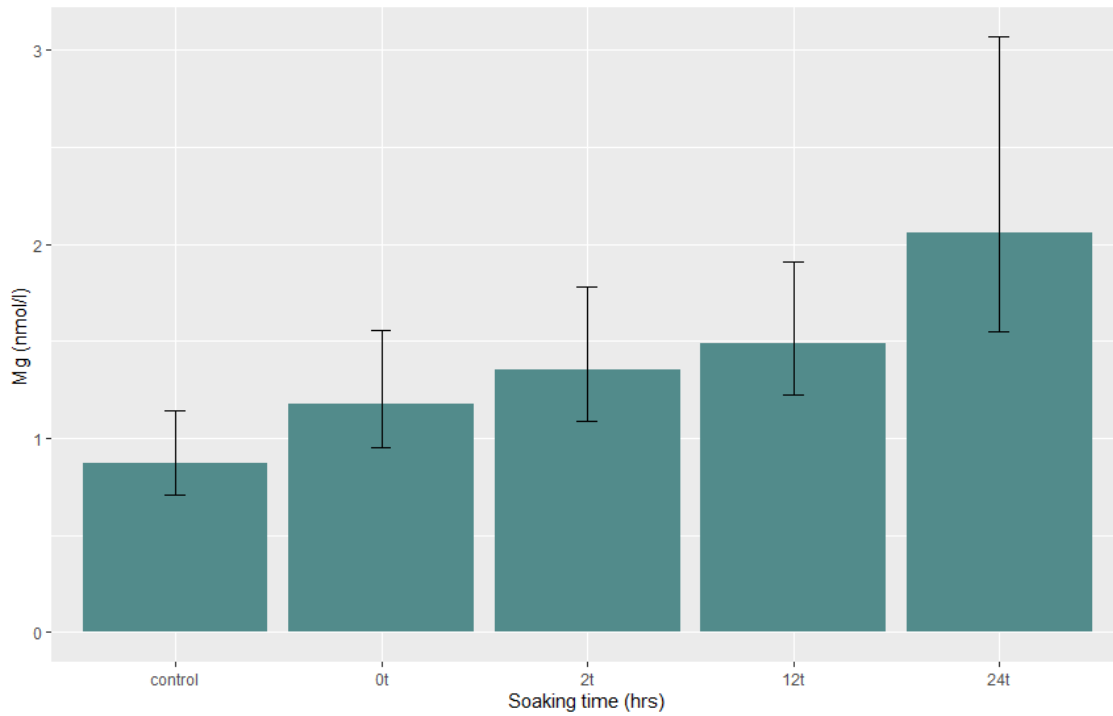
95% confidence intervals.

285

Figure 7: Serum levels of cortisol at different soaking times. Bars show precited means from GLM and error bars represent
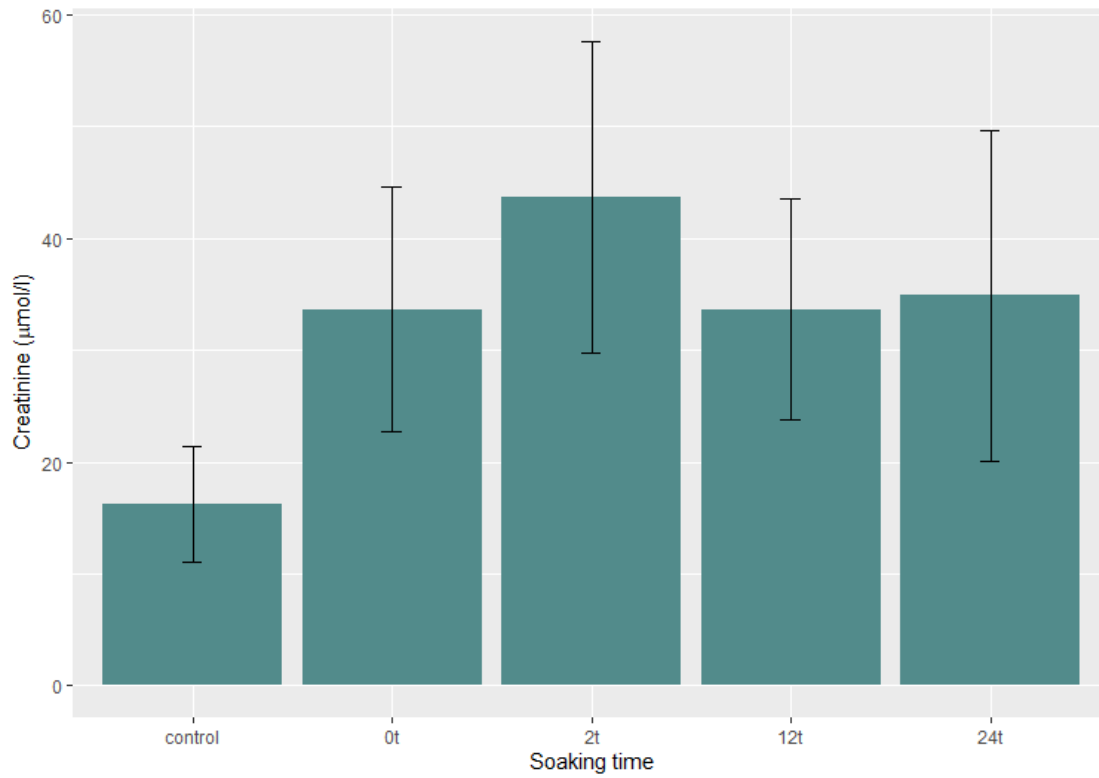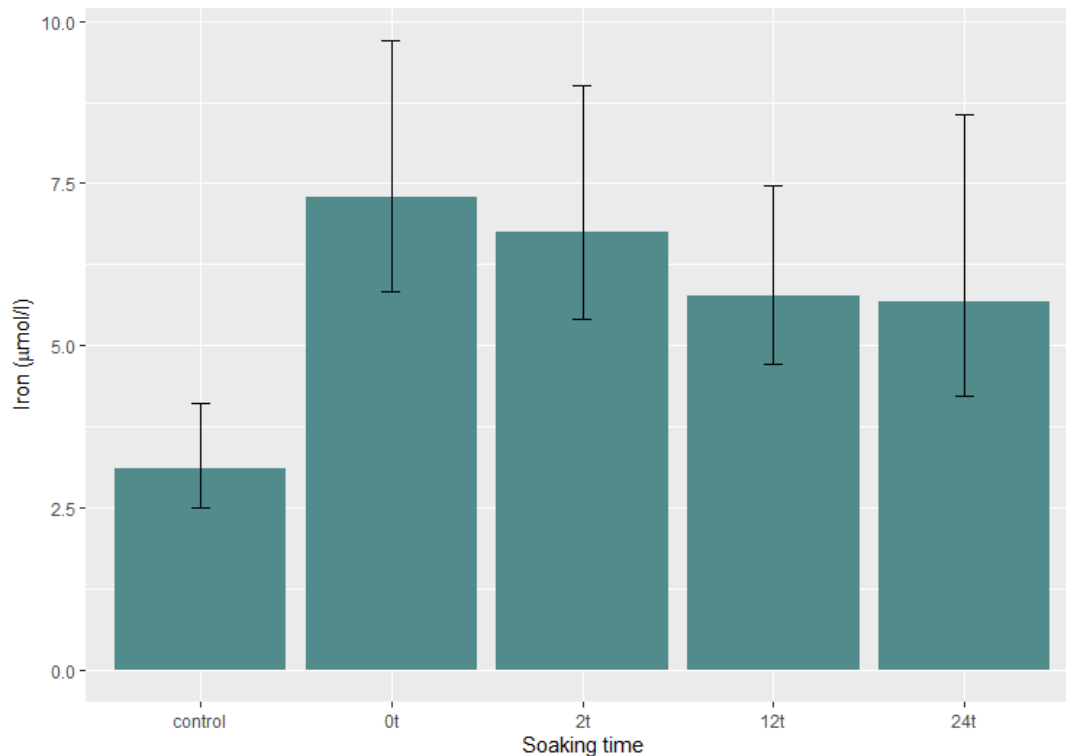
95% confidence intervals.

288

Figure 8: Serum levels of magnesium (Mg) at different soaking times. Bars show precited means from GLM and error bars represent 95% confidence intervals.

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Figure 9: Serum levels of creatinine at different soaking times. Bars show precited means from GLM and error bars represent 95% confidence intervals.

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Discussion

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300   We investigated how different soaking times of gillnets affected mortality,

301   physiological stress and muscle haemoglobin of Atlantic cod. Of the tested physiological stress

302   parameters, gillnet capture significantly affected blood levels of glucose and lactate and serum

303   levels of cortisol, magnesium, creatinine, and iron.

304   Lactate levels increased significantly after two hours soaking time and of the measured

305   time points the lactate levels were highest after 2 hours and significantly lower at 24 hours.

306   Lactate is a commonly used indicator for oxidative stress in fish (Moon, 2011; Sopinka et al.,

307   2016), and the observed increase in lactate shows that the fish struggle enough to switch to

308   anaerobic metabolism and the production of lactate in the white muscle. The peak after 2 hours

309   is well in line with other studies of oxidative stress (Milligan, 1996; Olsen et al., 2008;

310   Svalheim et.al., 2017; Svalheim et al., 2020) and fits with our observations that the struggling

311 was most prominent directly after capture and that the fish remained calm for the rest of the

312 soaking time. We only sampled blood from fish that were still alive and because oxygen is

313 required to resynthesize lactate to glycogen, the reduction of lactate after 12 to 24 hours indicate

314 that these fish were able to ventilate. However, the large confidence interval seen after 2 hours,

315 may indicate that some of these fish were struggling to acquire enough oxygen, whereas other

316 are ventilating and even recovering from the anoxic stress. If we were to look at lactate isolated,

317 we could assume that the fish were recovering from the initial struggle of capture, while being

318 in the net. Indeed, the behaviour of the cod would indicate a calm and rested fish, as they were

319 sparsely moving, even when not fully entangled. However, when investigating the other stress

320 parameters affected by soaking time, no indications of recovery was found.

321   Cortisol is a well-known mediator of the stress response and is expected to rise as a

322 response to capture and return to basal levels after 24–48 hours (Wendelaar Bonga, 1997). In

323 the present study, the serum level of cortisol remained elevated for 24 hours in the gillnet.

324 Other studies on Atlantic cod have showed that if allowed to recover, cortisol levels

325 significantly decreased or even recovers to basal levels 24 hours after acute stress (King &

326 Berlinsky, 2006; Olsen et al., 2008; Svalheim et al., 2017; Svalheim et al., 2020), indicating

327 that being caught in a gillnet is a continuous traumatic stressor up until slaughter. Increased

328 level of blood glucose is a consequence of stress induced liver and muscle glycogenolysis

329 (break down of glycogen) allowing the use of glucose for local glycolysis and energy

330 production (Milligan, 1996). Furthermore, we found that blood glucose also remained elevated

331 throughout the experiment. A slow return of glucose to basal levels is a common finding in

332 Atlantic cod after stress (Hemre et al., 1991, King et al., 2006; Olsen et al 2008) and in this

333 study the elevated levels of glucose is probably due to the prolonged elevated levels of serum

334 cortisol which stimulates the process of glycogenolysis and gluconeogenesis (Wendelaar

335 Bonga, 1997).

336   Stress can also cause a shift from intracellular to extracellular magnesium, which acts

337 to diminish the stress response mediated by catecholamines (i.e., epinephrine) and

338 glucocorticoids (i.e., cortisol) (Cuciureanu & Vink, 2011) and positively affecting the affinity

339 of haemoglobin for oxygen (Flatman, 2003; Wells, 2009). We found an immediate increase in

340 serum levels of magnesium. However, it is unclear if this is primarily a result of shift from

341 intracellular to extracellular magnesium or for example dehydration and osmotic imbalance.

342 Olsen et al (2008) found that intestinal permeability increase following an acute stressor, and

343 as most of magnesium in saltwater fishes is excreted via the faeces, it is possible that the fish

344 were experiencing osmotic water loss and excess ion gains in addition. However, as magnesium

345 is involved in a wide variety of cellular processes including anaerobic and aerobic metabolism,

346 bioenergetic reactions, regulation of metabolic pathways, signal transduction, ion channels

347 activity, cell proliferation, differentiation, apoptosis, angio-genesis, and membrane

348 stabilization (Nishizawa et al, 2007; Szewczyk et al., 2008; Wolf et al. 2007), the exact cause

349 of the increase is difficult to determine.

350   Serum creatinine and iron were found to increase immediately after capture and

351 remained elevated throughout the experiment. Both biomarkers are associated with stress and

352 traumatic unsustainable injuries in humans. For example, has increased levels of serum iron

353 been found to be a useful marker in patients with a life-threatening conditions, such as acute

354 respiratory distress and coronavirus disease, where the lungs cannot provide the body's vital

355 organs with enough oxygen (Duca et al. 2021; Sharky et al., 1999). The observed increase in

356 serum iron may indicate that gillnets are obstructing possibility for the fish to fully ventilate

357 and puts them at a risk for organ failure. When compared to control levels, serum creatinine

358 increased significantly immediately after capture. Creatinine is produced in muscle and

359 represents an energy buffer that stabilizes and maintains cellular energy balance, but prolonged

360 elevation can indicate kidney damage as creatinine is secreted via glomerular filtration (Suski

361 et al., 2007). The observed increase in creatinine in the present study, could come from a

362 reduced glomerular filtration rate, but on the other hand, there was no increase in urea

363 concentration as might be expected during severe kidney failure. Increased creatinine may also

364 come be due to muscular damage and studies have found evidence of increased rate of excretion

365 of creatinine in human patients with traumatic injuries (Iapichino et al., 1985; Threlfall et al.,

366 1984). The fish in our study had a 2-fold increase in creatinine after 24 hours in the gillnet

367 compared to control levels. Whereas other studies have showed that rainbow trout regain basal

368 levels of creatine 24 hours post stressor, when allowed to recuperate (Milligan, 1996). This

369 supports or hypothesis that being caught in a gillnet is a continuous traumatic stressor up until

370 slaughter.

371   Longer soaking time is associated with higher mortality and stress levels and a reduction

372 in quality as measured by amount of muscle haemoglobin. This is in line with Toledo-Guedes

373 et al. (2016), who found a mortality of 27.3 % in saithe caught by gillnets soaked between 12-

374 17 hours. Our experimental study showed a mortality in cod between 18 and 25 % after 12 to

375 24 hours, respectively. All though our findings are quite in line with the work done by Toledo-

376 Guedes et al. (2016), the studies are not directly comparable as the experimental conditions are

377 different from the commercial setting, where predators, currents, lights etc. probably will play

378 a major role in stress levels and potentially mortality. Furthermore, the fish in the present study

379 were much smaller than what is usually caught by commercial vessels operating with gillnets

380 (gillnet mesh size of 45 and 60 mm in the present study versus minimum mesh size of 156 mm

381 in the commercial fishery for cod north of 62º) (Ministry of Trade, Industry and Fisheries,

382 2022). In the commercial fishery, there will always be uncertainty on how long the fish has

383 been in the net as it can (legally) be anywhere from 0 – 24 hours, therefore a major advantage

384 with experimental set-ups is that it is possible to control the environment and the timing of fish

385 entering the fishing gear. Svalheim et al. (2020) also demonstrated the difficulties of comparing

experimental set-ups with commercial capture. In a study simulating trawl fisheries with extreme crowding, Svalheim et al. (2020) found 18% mortality after 3 hours crowding and 91% with 5 hours of crowding, but Olsen et al. (2013) found 27 % mortality with 5 hours hauling time. Most likely some of the discrepancy between the experiment such as the present study and the observation from commercial fisheries is attributed to fish entering the gear at different times and therefore experienced different levels of stress. However, the findings from the trawl studies, whether experimental or commercial, still presented higher mortality numbers at lower exposure times (i.e., time in gear), whereas we found 7 % mortality after two hours soaking time with gillnets and 25 % after 24 hours. This might indicate that gillnets are a gentler per time unit compared to densely packed trawls or seines. This does not necessarily mean that gillnets are to be considered a gentler fishing gear as whole fishing operation normally are much longer for gillnets (legally up 24 hours in Norway) (Ministry of Trade, Industry and Fisheries, 2022), than trawl hauls (30 minutes–5 hours) and time of potential suffering should be considered when discussing how gentle a fishing gear is.

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 hours, compared with 12 and 24 hours, but even when soaking time was short (i.e., 2 hours), dead fish were registered with the gillnet wrapped around the operculum. Fish caught in the net by snagging or wedging (He & Pol, 2010) 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 (Olsen et al., 2014).

410   With respect to quality measures, we found that there was significantly more

411   haemoglobin in the loin of fish who were left in the net for 24 hours. This means that the

412   physiological evidence of traumatic injuries and stress happens before quality degradation

413   becomes evident, meaning that muscle haemoglobin itself is not necessarily a functional

414   welfare indicator for level of stress. However, this does mean that although good quality does

415   not necessarily equal good welfare, poor quality certainly is evidence of poor welfare. This was

416   demonstrated by a significantly higher haemoglobin concentration in fish that died compared

417   to fish that were alive at time of slaughter. However, if this is a direct cause of a deadly stress

418   situation or a cause of late bleeding or perhaps a combination, is unclear.

419

420   **Conclusion**

421   This study demonstrates that capture by gillnets cause a major physiological distress and that

422   longer soaking time caused higher mortality and reduction in quality measured as haemoglobin

423   in loin. Capture by gillnets appeared to result in a traumatic continuous stress response in

424   Atlantic cod. Blood and serum levels of cortisol, magnesium, creatine and iron and blood

425   glucose were useful biomarkers identifying this particular stress response, whereas whole

426   blood lactate identified a struggle at the beginning of capture, but not the continuing

427   physiological trauma response. Physiological evidence of traumatic injuries and stress happens

428   before quality degradation becomes evident, meaning good quality does not necessarily equal

429   good welfare, but poor quality is a strong indication of poor welfare.

430

431   **Declaration of interests**

432   The authors declare no competing interests.

433

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References

Borderías, A. J., & Sánchez-Alonso, I. (2011). First processing steps and the quality of wild and farmed fish. *Journal of Food Science*, *76*(1), R1–R5.

Botta, J. R., Squires, B. E., & Johnson, J. (1986). Effect of bleeding/gutting procedures on the sensory quality of fresh raw Atlantic cod (Gadus morhua). *Canadian Institute of Food Science and Technology Journal*, *19*(4), 186–190.

Broom, D. M. (2011). A history of animal welfare science. *Acta biotheoretica*, *59*(2), 121-137.

Buckley, Y. M. (2015). Generalised linear models. In G. A. Fox, S. Negrete-Yankelevich & V. J. Sosa (Eds.) *Ecological Statistics* (pp. 131-143). Oxford University Press, Oxford.

Chaijan, M., & Undeland, I. (2015). Development of a new method for determination of total haem protein in fish muscle. *Food Chemistry*, *173*, 1133-1141.

Duca, L., Ottolenghi, S., Coppola, S., Rinaldo, R., Dei Cas, M., Rubino, F. M., Paroni, R., Samaja, M., Chiumello, A. A., & Motta, I. (2021). Differential redox state and iron regulation in chronic obstructive pulmonary disease, acute respiratory distress syndrome and coronavirus disease 2019. *Antioxidants*, *10*(9), 1460.

Cuciureanu, M. D., & Vink, R. (2011). *Magnesium and stress* (pp. 251-268). University of Adelaide Press.

Farrell, A. P., Thorarensen, H., Axelsson, M., Crocker, C. E., Gamperl, A. K., & Cech Jr, J. J. (2001). Gut blood flow in fish during exercise and severe hypercapnia. *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology*, *128*(3), 549–561.

459   Flatman, P. W. (2003). Magnesium transport. In *Red Cell Membrane Transport in Health and*

460   *Disease* (pp. 407-434). Springer, Berlin, Heidelberg.

461   Hagen, K., R. Van den Bos & T. de Cock Buning (2011). Editorial: Concepts of Animal

462   Welfare. *Acta Biotheoretica 59*(2): 93-103.

463   He, P., & Pol, M. (2010). Fish Behaviour near Gillnets: Capture Process and Influencing

464   Factors. In P. He (Ed.), *Behavior of Marine Fishes: Capture Processes and*

465   *Conservation Challenges* (pp. 315–337). WileyBlackwell, Ames Iowa.

466   Hemre, G. I., Lambertsen, G., & Lie, Ø. (1991). The effect of dietary carbohydrate on the stress

467   response in cod *(Gadus morhua). Aquaculture*, *95*(3-4), 319-328.

468   Huntingford, F. A., Adams, C., Braithwaite, V. A., Kadri, S., Pottinger, T. G., Sandøe, P., &

469   Turnbull, J. F. (2006). Current issues in fish welfare. *Journal of fish biology*, *68*(2),

470   332-372.

471   Iapichino, G., Radrizzani, D., Solca, M., Bonetti, G., Leoni, L., & Ferro, A. (1985). Influence

472   of total parenteral nutrition on protein metabolism following acute injury: Assessment

473   by urinary 3-methylhistidine excretion and nitrogen balance. *Journal of Parenteral and*

474   *Enteral Nutrition*, *9*(1), 42-46.

475   Joensen, S., Bendiksen, B. I., Martinsen, G., Tobiassen, T., & Nilsen, H. (2021). Catch

476   damage registration 2014–2020 – Assessment of the quality inspection by Norges

477   Råfisklag. Nofima Report 6/2021. ISBN 978-82-8296-670-2. (In Norwegian).

478   King, W., & Berlinsky, D. L. (2006). Whole-body corticosteroid and plasma cortisol

479   concentrations in larval and juvenile Atlantic cod *Gadus morhua* L. following acute

480   stress. *Aquaculture Research*, *37*(13), 1282-1289.

481   King, W., Buckley, L. J., & Berlinsky, D. L. (2006). Effect of acclimation temperature on the

482   acute stress response in juvenile Atlantic cod, *Gadus morhua* L., and haddock,

483   *Melanogrammus aeglefinus* L. *Aquaculture Research*, *37*(16), 1685-1693.

Korte, S. M., B. Olivier and J. M. Koolhaas (2007). A new animal welfare concept based on allostasis. *Physiol Behav 92*(3), 422-428.

Lambooij, E., H. Digre, H. G. M. Reimert, I. G. Aursand, L. Grimsmo and J. W. van de Vis (2012). Effects of on-board storage and electrical stunning of wild cod *(Gadus morhua)* and haddock *(Melanogrammus aeglefinus)* on brain and heart activity. *Fisheries Research 127-128,* 1-8.

McCullagh, P., & Nelder, J. A. (2019). *Generalized linear models*. Routledge.

Metcalfe, J. D. (2009). Welfare in wild-capture marine fisheries. *Journal of Fish Biology*, *75*(10), 2855-2861.

Margeirsson, S., Jonsson, G. R., Arason, S., & Thorkelsson, G. (2007). Influencing factors on yield, gaping, bruises and nematodes in cod (*Gadus morhua*) fillets. *Journal of Food Engineering*, *80*(2), 503–508.

Milligan, C. L. (1996). Metabolic recovery from exhaustive exercise in rainbow trout. *Comparative Biochemistry and Physiology Part A: Physiology*, *113*(1), 51-60.

Ministry of Trade, Industry and Fisheries. (2022). Regulations on the implementation of harvesting of wild marine resources (harvesting regulations). https://lovdata.no/dokument/LTI/forskrift/2021-12-23-3910. [Accessed: 14 July 2022]

Moon, T. W. (2011). Stress effect on growth and metabolism. In A. P. Farrel (Ed), *Encyclopedia of fish physiology - from genome to environment*, Vol. 2 (pp. 1534–1540) Academic Press, London.

Nishizawa, Y., Morii, H., & Durlach, J. (2007). *New perspectives in magnesium research*. Springer-Verlag London Limited.

Ohl, F., & Van der Staay, F. J. (2012). Animal welfare: At the interface between science and society. *The Veterinary Journal*, *192*(1), 13-19.

508   Olsen, R. E., Sundell, K., Ringø, E., Myklebust, R., Hemre, G.-I., Hansen, T., & Karlsen, Ø.

509   (2008). The acute stress response in fed and food deprived Atlantic cod, *Gadus*

510   *morhua* L. *Aquaculture, 280*(1), 232-241.

511   Olsen, S. H., Tobiassen, T., Akse, L., Evensen, T. H., & Midling, K. O. (2013). Capture

512   induced stress and live storage of Atlantic cod (*Gadus morhua*) caught by trawl:

513   consequences for the flesh quality. *Fisheries Research*, 147, 446–453.

514   Olsen, S. H., Joensen, S., Tobiassen, T., Heia, K., Akse, L., & Nilsen, H. (2014). Quality

515   consequences of bleeding fish after capture. *Fisheries Research*, 153, 103–107.

516   Özyurt, G., Özogul, Y., Özyurt, C. E., Polat, A., Özogul, F., Gökbulut, C., Beyza, E., &

517   Küley, E. (2007). Determination of the quality parameters of pike perch Sander

518   lucioperca caught by gillnet, longline and harpoon in Turkey. *Fisheries*

519   *Science*, *73*(2), 412-420.

520   RStudio Team (2022). RStudio: Integrated Development Environment for R. RStudio, PBC,

521   Boston, MA URL http://www.rstudio.com/.

522   Santos, M. N., Gaspar, M. B., Monteiro, C. C., & Vasconcelos, P. (2002). Gill net and long

523   line catch comparisons in a hake fishery: the case of southern Portugal. *Scientia*

524   *Marina*, *66*(4), 433-441.

525   Savina, E., Karlsen, J. D., Frandsen, R. P., Krag, L. A., Kristensen, K, & Madsen, N. (2016).

526   Testing the effect of soak time on catch damage in a coastal gillnetter and the

527   consequences on processed fish quality. *Food Control*, *70*(1), 310–317.

528   Sharkey, R. A., Donnelly, S. C., Connelly, K. G., Robertson, C. E., Haslett, C., & Repine, J. E.

529   (1999). Initial serum ferritin levels in patients with multiple trauma and the subsequent

530   development of acute respiratory distress syndrome. *American journal of respiratory*

531   *and critical care medicine*, *159*(5), 1506-1509.

532 Sogn-Grundvåg, G., Zhang, D., Henriksen, E., Joensen, S., Bendiksen, B. I., & Hermansen,

533   Ø. (2022). Fishing tactics and fish quality: The case of the coastal fishery for Atlantic

534   cod in Norway. *Fisheries Research*, *246*, 106167.

535 Sopinka, N. M., Donaldson, M. R., O'Connor, C. M., Suski, C. D., & Cooke, S. J. (2016).

536   Stress indicators in fish. In *Fish physiology* (Vol. 35, pp. 405–462). Academic Press.

537 Suski, C. D., Cooke, S. J., Danylchuk, A. J., O'Connor, C. M., Gravel, M. A., Redpath, T., ...

538   & Goldberg, T. L. (2007). Physiological disturbance and recovery dynamics of bonefish

539   (Albula vulpes), a tropical marine fish, in response to variable exercise and exposure to

540   air. *Comparative Biochemistry and Physiology Part A: Molecular & Integrative*

541   *Physiology*, *148*(3), 664-673.

542 Svalheim, R. A., Karlsson-Drangsholt, A., Olsen, S. H., Johnsen, H. K., & Aas-Hansen, Ø.

543   (2017). Effects of exhaustive swimming and subsequent recuperation on flesh quality in

544   unstressed Atlantic cod (*Gadus morhua*). *Fisheries Research, 193*, 158-163.

545 Svalheim, R. A., Burgerhout, E., Heia, K., Joensen, S., Olsen, S. H., Nilsen, H., Tobiassen, T.

546   (2019). Differential response to air-exposure in crowded and uncrowded Atlantic cod

547   (*Gadus morhua*): consequences for fillet quality. *Food Bioscience*, *28*, 15–19.

548 Svalheim, R. A., Aas-Hansen, Ø., Heia, K., Karlsson-Drangsholt, A., Olsen, S. H., & Johnsen,

549   H. K. (2020). Simulated trawling: exhaustive swimming followed by extreme crowding

550   as contributing reasons to variable fillet quality in trawl-caught Atlantic cod (*Gadus*

551   *morhua*). *PLoS One*, *15*(6), e0234059.

552 Szewczyk, B., Poleszak, E., Sowa-Kucma, M., Siwek, M., Dudek, D., Ryszewska-

553   Pokrasniewicz, B., ... & Nowak, G. (2008). Antidepressant activity of zinc and

554   magnesium   in   view   of   the   current   hypotheses   of   antidepressant

555   action. *Pharmacological Reports*, *60*(5), 588.

556 Toledo-Guedes, K., Ulvan, E. M., & Uglem, I. (2016). Commercial gillnetting is more stressful
557   for saithe (Pollachius virens L.) than jigging: but is fillet quality affected?
558   *Aquatic Living Resources*, *29*(2), 203.

559 Threlfall, C. J., Maxwell, A. R., & Stoner, H. B. (1984). Post-traumatic creatinuria. *The Journal*
560   *of trauma*, *24*(6), 516-523.

561 Veldhuizen, L. J. L., Berentsen, P. B. M., De Boer, I. J. M., Van De Vis, J. W., & Bokkers, E.
562   A. M. (2018). Fish welfare in capture fisheries: a review of injuries and mortality.
563   *Fisheries Research*, *204*, 41–48.

564 Wells, R. M. (2009). Blood-gas transport and hemoglobin function: Adaptations for functional
565   and environmental hypoxia. In *Fish physiology* (Vol. 27, pp. 255-299). Academic
566   Press.

567 Wendelaar Bonga, S. E. (1997). The stress response in fish. *Physiological Reviews, 77*(3), 591-
568   625.

569 Wolf, F. I., Maier, J. A. M., Nasulewicz, A., Feillet-Coudray, C., Simonacci, M., Mazur, A., &
570   Cittadini, A. (2007). Magnesium and neoplasia: from carcinogenesis to tumor growth
571   and progression or treatment. *Archives of biochemistry and biophysics*, *458*(1), 24-32.

572 Zuur, A. F., Ieno, E. N., & Elphick, C. S. (2010). A protocol for data exploration to avoid
573   common statistical problems. *Methods in ecology and evolution*, *1*(1), 3-14.