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How does twine thickness and mesh size affect catch efficiency and ways of capture in the Northeast Arctic cod (*Gadus morhua*) gillnet fishery?

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Abstract

The aim of this study is to establish a general pattern for how round-fish get caught in gillnets. Understanding these patterns might further help establishing which gillnet parameters are important to consider when developing new biodegradable materials for gillnets. Developing biodegradable materials is important to reduce impacts from lost, abandoned, and discarded gillnets made of non-biodegradable materials. The study was conducted by comparing catch efficiency and way of capture of Northeast Arctic cod (*Gadus morhua*) in different gillnet types with two different twine thicknesses (0.7 mm and 0.8 mm) and two different mesh sizes (210 mm and 230 mm). The fishing trials were conducted onboard commercial fishing vessel 'Karoline' during the main season for Northeast Arctic cod in Northern Norway, lasting from late January to mid-March 2022. Furthermore, circumference measurements were collected for Northeast Arctic cod to establish a relationship between fish morphology, gillnet mesh size and fish length-dependent capture in gillnets during a cruise with research vessel 'Helmer Hanssen'. During the same cruise, to further support establishing gillnet capture patterns for Northeast Arctic cod, a laboratory experiment was conducted with a gillnet and dead cod by investigating the point of capture when letting fish through a gillnet mesh.

The results from the gillnet fishing experiments did not detect any significant differences in catch efficiency between the two twine thicknesses for either mesh size, implying that capture efficiency has some tolerance regarding this design parameter and therefore also regarding the associated twine elasticity/stiffness. Analysing the ways of capture showed that this was dependent on the length of the fish. Overall, 76 % of the fish were caught by either gilling or wedging, the latter being the overall most dominant of all ways of capture. The remaining fish were mainly caught by snagging, while entangling constituted a minor proportion. Furthermore, the way of capture probability was not affected by an increase in twine thickness, but a significant change was observed when increasing the mesh size, more specifically snagging and wedging. Fall-through results showed similar patterns regarding length dependent ways of capture as the gillnet fishing trials and can therefore be used to supplement investigations based on the latter. For the dominant ways of capture, gilling and wedging, the cod circumference was approximately 20 % larger than

mesh circumference. This knowledge can be applied to select the mesh size for the gillnets, dependent on what size of cod that are targeted at the specific area.

The results from this study have increased the understanding of the effect of twine thickness and mesh size for capture patterns. This is important knowledge for the further development of biodegradable material used in gillnets as an alternative to nylon. We now know that we can operate within a range of twine thicknesses for the same mesh size without significantly influencing the capture pattern.

Keywords*:* gillnets, catch efficiency, capture modes, twine thickness, elasticity, nylon

Sammendrag

Målet med denne studien er å etablere et generelt mønster om hvordan fisk blir fanget i garn. Å forstå dette mønsteret vil forhåpentligvis bidra til å øke kunnskapen rundt hvilke parametere i garn som er viktige når man skal utvikle nye bionedbrytbare materialer i garn. Utviklingen av bionedbrytbare materialer er viktig for å redusere negative konsekvenser som følge av tapte, forlatte eller dumpede garn laget av ikke-nedbrytbare materialer. Denne studien ble gjennomført ved å sammenligne fangsteffektiviteten og måten fisk ble fanget på i garnfiske etter Nordøst Arktisk torsk (*Gadus morhua*) med garn med forskjellig trådtykkelse (0.7 mm og 0.8 mm) og forskjellig maskevidde (210 mm og 230 mm). Forsøkene ble gjennomført ombord det kommersielle fiskefartøyet 'Karoline' i hovedsesongen for Nordøst Arktisk torsk i Nord-Norge fra slutten av januar til midten av mars 2022. I tillegg ble morfologisk data, i form av omkretsmål, samlet inn for samme art under et tokt med forskningsfartøyet 'Helmer Hanssen' for å etablere en sammenheng mellom fiskens morfologi, maskevidde, og den lengdeavhengige måten fisken ble fanget på i garn. Under samme tokt ble det også gjennomført laboratorie-forsøk med garn og død torsk.

Resultatene fra garnforsøkene påviste ingen signifikante forskjeller i fangsteffektivitet mellom de to forskjellige trådtykkelsene for begge maskeviddene. Dette indikerer at relativ små variasjoner i trådtykkelse, og dermed også trådelastisitet, ikke påvirker fangsteffektivitet nevneverdig. Analysen av måten torsk ble fanget på viste en tydelig lengde-avhengig trend, der de forskjellige måtene fisken ble fanget på var avhengig av lengden på fisken. Totalt 76 % av all fisk var fanget ved gjellene eller største omkrets, der sistnevnte var mest dominerende av de to. Resten av fisken hadde hovedsakelig garnmaskene hektet i hoderegionen, og kun en mindre andel var fanget ved innvasing i maskene. Sannsynligheten for å bli fanget ved en bestemt fangstmetode var ikke påvirket av trådtykkelsen, men en signifikant forskjell ble påvist ved endring i maskevidde når fisk ble fanget ved gjellene eller største omkrets. Laboratorie-forsøkene viste et lignende mønster når det gjald den lengdeavhengige måten torsk ble fanget på. For de vanligste fangstmetodene, ved gjellene og største omkrets, var torskens omkrets på disse punktene omtrent 20 % større enn maskens omkrets. Denne kunnskapen kan benyttes når man skal velge maskevidde i garn basert på lengdestrukturen til torsken i området fisket skal foregå i.

Resultatene fra dette studiet har økt kunnskapen om effekten av trådtykkelse og maskevidde for fangstprosessen av torsk. Dette er viktig kunnskap for videre utvikling av bionedbrytbare materialer i garn som et alternativ til nylon. Vi vet nå at vi kan jobbe innenfor et visst spenn av trådtykkelser uten å endre fangstprosessen nevneverdig.

Nøkkelord: garn, fangsteffektivitet, fangstmetoder, trådtykkelse, elastisitet, nylon

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1 Introduction

1.1 Norwegian gillnet fisheries

Gillnets are among the oldest fishing gears in Norway (Dybdahl, 2018). Still today it is a commonly used fishing gear, both in commercial and recreational context. Gillnets are primarily used by the Norwegian coastal fleet, meaning vessels with a length under 28 meters. This vessel group contains 5374 ships, constituting 95.4 % of the entire commercial Norwegian fishing fleet of 5633 vessels as of 2022 (Directorate of Fisheries, 2022a). The coastal fleet is responsible for approximately 88 % of all gillnet catches. The most important target species in the gillnet fishery are Northeast Arctic cod (*Gadus morhua*), Greenland halibut (*Reinhardtius hippoglossoides*) and saithe (*Pollachius virens*). Since 2015 the average gillnet catches compared to the total catches from all fishing gears for these species have been 23.9 % for cod, 17.2 % for Greenland halibut and 16.6 % for saithe (Directorate of Fisheries, 2022b). This illustrates that gillnets are among the most important fishing gear types used in Norwegian fisheries.

1.2 Current challenges in gillnet fisheries

Gillnets are considered to be an efficient type of fishing gear. They are cost efficient, because of its relatively low-cost material, fuel efficient, versatile, and can show good size selectivity for target species compared to other types of fishing gear (Suuronen *et al.*, 2012). Gillnet fisheries are often assumed to have less impact on the environment, considering the low fuel usage (Suuronen *et al.*, 2012) and lower impact on benthic ecosystems compared to active fishing gears like for example bottom trawls (Valdemarsen *et al.*, 2007; Lucchetti *et al.*, 2020). However, this fishery is experiencing several challenges regarding sustainability, most notably regarding abandoned, lost, and discarded fishing gear (also referred to as ALDFG) and the accompanying consequences: marine litter and continuous capture of marine animals, so-called ghost fishing.

ALDFG such as gillnets are considered to be among the largest challenges this fishery is currently experiencing, both in Norway and worldwide (Gilman, 2015). The following incidents are among the most common reasons for this to happen: collision with other gear, vessels or animals, intentionally cut markers/buoys, wind, waves, current or sea ice displacing or damaging lines/buoys, gillnets getting stuck on rocks or wrecks, damaged equipment, and intentionally discarded or abandoned equipment (Brown & Macfadyen, 2007; Gilman *et al.*, 2016).

There are no precise estimates on the annual losses of gillnets in Norway, and the different estimations vary significantly. For instance, the Norwegian Environmental Agency conducted a report which estimated that 13 941 gillnets were lost at sea each year (Sundt *et al.*, 2018). This estimation only includes vessels under 28 meters, indicating that the total number is likely to be higher. On the other hand, the Norwegian Directorate of Fisheries estimates that approximately 1000 gillnets are lost annually (Standal *et al.*, 2020). Another report, conducted by Deshpande *et al*. (2019), showed that 1-2 % of gillnets were reported lost during deployment. These highly varying estimates illustrate the challenges of estimating the full extent of gillnet losses. However, they indicate that the loss rates are likely to be high. This is also confirmed during the Norwegian Directorate of Fisheries annual gear-retrieval program. In the last few years an average of 820 gillnets have been retrieved each year, adding up to about 22 000 gillnets since the program started in 1983 (Directorate of Fisheries, 2022c).

Gillnet losses have several negative consequences. For instance, lost gear can cause obstructions for other fishing gear, both active and stationary gears, and vessels (Macfadyen *et al.*, 2009). In addition, lost gillnets have the potential to transport species over large distances, and in that way introduce invasive species in other ecosystems (Gilman *et al.*, 2016). However, these challenges are of less significance in Norway, considering that most gillnets used here are bottom set and not mid-water set, hereby not posing the same threat. Other challenges associated with lost gillnets that have gained more attention over the years due to the use of synthetic materials in gear, are marine plastic pollution and ghost fishing (Grimaldo *et al.*, 2012), as described in the following sections 1.2.1 and 1.2.2.

1.2.1 Marine plastic pollution

Modern gillnets are made of synthetic plastic materials, primarily nylon, which are highly resistant to degradation. Estimates on degradation time of nylon material vary considerably and are usually ranging from several hundred years to several thousand years (Barnes *et al.*, 2009). The degradation time is believed to be even longer at large depths and in polar regions (Barnes *et al.*, 2009). There are numerous factors that can have impact on the degradation time, including light, water environment, and current (Grimaldo *et al.*, 2020a). In any case, it is believed the plastic does not completely disappear (Weis, 2015), it degrades into smaller particles, creating macro- and microplastics as well as releasing toxic substances into the marine environment (Moore, 2008). The fragmentation process is mainly driven by ultraviolet light and abrasion (Barnes *et al.*, 2009). During the entire life cycle of marine litter, it has the potential to harm marine life in some way. Specifically, plastics consumed by marine wildlife can potentially block the digestive systems leading to fatal consequences (Simmonds, 2012; Gola *et al.*, 2021). This can happen both high up in the food chain, or at lower levels. Plastics can be consumed directly, or it can release toxins, which could potentially enter the food web (Wang *et al.*, 2019).

1.2.2 Ghost fishing

Ghost fishing by lost, abandoned or discarded gillnets is a challenge in the Norwegian gillnet fishery (Directorate of Fisheries, 2021). Ghost fishing is defined as: *"the ability of fishing gear to continue fishing after all control of that gear is lost by the fisherman"* (Smolowitz, 1978). Gillnets and traps constitute the majority of lost fishing gear (Deshpande *et al.*, 2019). Passive gear types, like gillnets and pots, have the highest ghost fishing capacity, which is due to the fact that the catch process relies on the fish swimming into the gear (Macfadyen *et al.*, 2009; Gilman *et al.*, 2016). When marine organisms get caught in the gear, they will eventually die and decompose, something that will attract other marine organisms who then in turn risk getting caught by the gear. In this way the gear experiences a self-baiting process (Gilman *et al.*, 2016). Usually, a gillnet will collapse after some time of being lost at sea due to several reasons, including accumulating catch. A collapsed gillnet will have less catch efficiency compared to an intact net (Kaiser *et al.*, 1996; Erzini *et al.*, 1997), However, in certain conditions the decomposing of entangled ghost catch might eventually result in the net regaining some of its buoyancy, which would potentially again increase its ghost fishing capacity (Humborstad *et al.*, 2003). In any case, a general trend witnessed in different studies is that the catches in lost gillnets decline exponentially over time (Kaiser *et al.*, 1996; Erzini *et al.*, 1997).

The overall ghost fishing potential of a gillnet relies on the environment the gear has been lost, abandoned or discarded in, and the reason of why it ended up in the environment. Specifically, gillnets that have been abandoned or lost will often have a higher fishing capacity considering they are normally deployed in areas with a high fish abundance and deployed in a way to maximize the catch. This is in contrast to discarded gear that ends up in places with no thought regarding to the position the gear keeps in the water. Therefore, discarded gillnets may likely collapse instantly and might thus have less ghost fishing capacity (Macfadyen *et al.*, 2009). Furthermore, factors like species abundance and composition, hydrographic and topographic factors are all important to determine the ghost fishing extent (Macfadyen *et al.*, 2009). Therefore, lost gillnets have a highly varying potential to ghost fish. As a consequence, ghost fishing mortality is challenging to quantify. In order to have precise estimates, one would need reliable numbers on the amount of ghost gear in the ocean, which, as previously shown, is not possible to fully quantify. In addition, the catch rates are highly variable. Therefore, there are no realistic quantifications for ghost fishing in general. However, some estimates do exist on local scales, related to specific fisheries. Specifically, generalization of these estimates shows that the equivalent of 0.5-30 % of commercial catches is caught in ghost gear in North America and Europe (Carr & Cooper, 1988; Humborstad *et al.*, 2003; Sancho *et al.*, 2003; Santos *et al.*, 2003; Tschernij & Larsson, 2003; Gilman *et al.*, 2016). The sources of error in these estimates are still high, mainly due to uncertainties regarding quantifying catch post hauling (Humborstad *et al.*, 2003).

1.3 Biodegradable materials

Biodegradable materials could be a promising solution that might have a significant impact on reducing marine pollution and ghost fishing (Grimaldo *et al.,* 2020a; Brakstad *et al.,* 2022). In Norway, the biodegradable material that has gained most attention is poly-butylene succinate co-adipate-co-terephthalate (PBSAT) (Grimaldo *et al.*, 2018ab, 2019, 2020ab; Cerbule *et al.*, 2022a). This material is attempting to resolve issues experienced with previously tested biodegradable materials like poly-butylene succinate (PBS) and poly-butylene adipate-co-terephthalate (PBAT), related to the mechanical properties of the material (Kim *et al.*, 2017). The PBSAT material has been thoroughly tested in gillnet fisheries in Norway since 2016. The results from these studies show that biodegradable gillnets have significantly lower catch efficiency compared to traditional nylon gillnets (Grimaldo *et al.*, 2018a, 2018b, 2019, 2020a, 2020b; Cerbule *et al.*, 2022b). Therefore, the observed lower catch efficiency represents a barrier for using biodegradable materials in commercial gillnet fishery.

1.4 Objectives

There are several hypotheses attempting to explain the reduced catch efficiency of gillnets made of biodegradable materials, for instance reduced elasticity and breaking strength in biodegradable materials compared to traditional nylon (Grimaldo *et al.*, 2018ab, 2019, 2020ab). However, there is no evidence for such a connection. In general, regardless of the material, there is a knowledge gap in understanding and quantifying how the different parameters in gillnet construction and rigging affect the catch process. One way to investigate this is by analyzing the way individual fish with different lengths get caught in the gillnet. Identifying how different parameters affect the catching process might reveal what parameters have the biggest influence. This information can furtherly be used to explain the differences observed between bio-degradable- and traditional nylon material. Thereby, it could also provide guidelines for which parameters to focus on when developing a biodegradable material that has similar properties regarding catch performance as nylon.

Based on the challenges and knowledge gaps described above, the objective of this thesis is to establish a general pattern for how round fish get caught in gillnets. The purpose of this is to help establish which gillnet material parameters are important when developing new biodegradable materials for gillnets. The fishery on Northeast Arctic cod will be in focus, but the results of this study could be possible to extrapolate to other round fish species with similar morphology.

To address the objective of this thesis the following chapter will describe gillnets thoroughly, describing the existing knowledge about the different parameters in gillnet construction.

1.5 Gillnet characteristics and construction

Gillnets are classified as passive fishing gear. This means that the fishing method is based on the fish swimming into the gear and getting caught in it (Bjordal, 2002). Gillnets are divided into several different categories (Karlsen, 1997). The main categories are bottom-set gillnets, commonly used for benthic species like cod, haddock (*Melanogrammus aeglefinus*) and different flatfish species, and mid-water gillnets, commonly used for pelagic species like herring (*Clupea harengus*) and mackerel (*Scomber scombrus*). Furthermore, gillnets are also categorized based on whether they are stationary or drifting. Stationary gillnets are typically anchored to the seabed, while non-stationary gillnets drift in the water column, for example attached to a fishing vessel. Mid-water gillnets can be either drifting or stationary, while bottom-set gillnets are always stationary. The most common gillnet type used in Norway is bottom-set gillnets for capturing benthic species (Directorate of Fisheries, 2022c).

A gillnet has a relatively simple construction (Figure 1). The typical construction consists of a rectangular net panel/sheet. The top of the net panel is called hanging twine, which is attached to a so-called head rope or float line, with an integrated or attached to floatation device to provide positive buoyancy. The bottom of the net panel is attached to a so-called foot rope or sinker/led line, which can have led integrated into the rope, or some other form of sinking mechanism attached to it to provide negative buoyancy (Bjordal, 2002). These two elements sustain the nets shape in the water column. Most gillnets consist of a single walled net panel, but trammel nets can have three layers where the middle layer has a smaller mesh size to increase catches (Karlsen, 1997). At both ends of a gillnet is the skirt line. From here there is a rope leading from the head rope and the foot rope called bridles that are either attached to the next gillnet or, in case it is the end of a gillnet fleet, end together in a buoy rope. The latter goes to the surface and is attached to a buoy/float to mark the position of the gillnets (He, 2006). Gillnets are usually set in strings[1], which can consist of just a few and up to a hundred gillnets sheets per string. In case of bottom-set gillnets, one or both ends of the gillnet string are anchored to the seabed with an anchor or some other piece of heavy weight (Karlsen, 1997).

[1] Also referred to as fleets or chains.

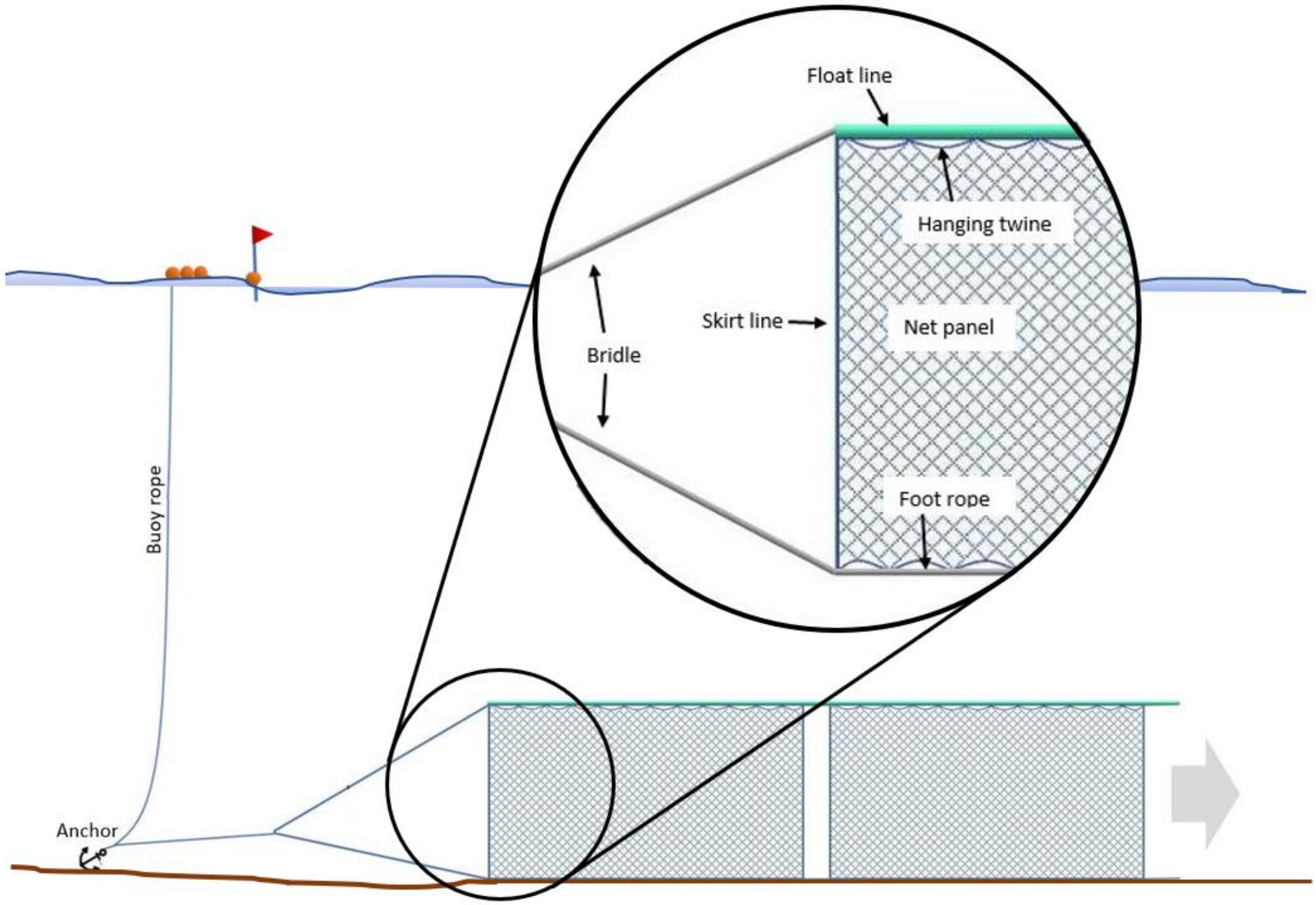

Figure 1: Illustration of a typical bottom set gillnet.

1.5.1 Mesh size

The mesh size is among the most significant factors affecting the size selective properties of gillnets. In theory, small fish would have a larger chance to swim straight through a mesh that is larger than its maximum circumference, also called girth, while large individuals with a girth larger than the mesh would not be captured (Karlsen, 1997). Therefore, choice of mesh size in gillnets can affect the catch composition since small meshes are more likely to capture small fish, while large meshes are more likely to capture large fish (Soe *et al.*, 2022). Mesh size chosen for gillnets in a specific fishery corresponds to a certain optimal fish length that gets caught most effectively, a so-called modal length (Jensen, 1986). However, research indicates that this can also be circumference dependent, considering that fish of the same length can have different morphology (Reis & Pawson, 1999; Stergiou & Karpouzi, 2003; Carol & García-Berthou, 2007).

The maximum circumference of a fish captured can be larger than the total circumference of a mesh, considering the elastic properties of nylon and the compressive properties of a fish's body (Potter, 1991). Specifically, Potter (1991) estimated that the salmon (*Salmo salar*) that had the biggest chance of getting enmeshed were those with a maximum circumference between 20-40 % larger than the total circumference of a mesh. A fish's maximum circumference can therefore be used to predict whether it can get stuck in a mesh or not.

1.5.2 Hanging ratio

The hanging ratio of a gillnet describes the relationship between the lengths of the head rope and the net panel. The term can be defined as *"the length of a rope on which a net panel is mounted divided by the actual length of stretched netting on the rope"* (Gray *et al.*, 2005). For instance, if a stretched net panel is 100 meters long, and the head rope is 50 meters long, the resulting hanging ratio would be 0.5. In commercial fisheries the hanging ratio would typically range between 0.25 and 0.65, depending on the target species (Hovgård & Lassen, 2000). For many round-fish species the hanging ratio would often be on the upper side of this range. The typical hanging ratio in the Norwegian cod gillnet fishery is 0.5 (Angelsen *et al.*, 1979). There have been few studies on the effect the hanging ratio has on gillnet performance (e.g., Angelsen *et al.*, 1979; Samaranayaka *et al.*, 1997; Gray *et al.*, 2005). There is an indication that a decrease in hanging ratio results in poorer selectivity, catching a larger number of small individuals, and that an increase of hanging ratio results in fewer fish caught (Angelsen, 1981). However, other studies show the opposite results, catching more large fish, or no trends (Hovgård & Lassen, 2000). Since these studies are all performed on different species, this could indicate that fish morphology might be a decisive factor.

Hanging ratio can also influence how the fish is caught (Karlsen, 1997; Gray *et al.*, 2005). For instance, the proportion of fish getting gilled and wedged is assumed to not change notably when slightly increasing or decreasing the hanging ratio, but the proportion of fish getting entangled is thought to increase when operating with a lower hanging ratio (Holst *et al.*, 1998). This can therefore be adjusted depending on the morphology of the target species. For instance, for many round fish species, gilling and wedging would be an important capture mode (Hickford & Schiel, 1996), and a high hanging ratio would be appropriate. Species that are often caught by entangling rather than gilling, such as fish with a laterally compressed body shape (Hickford & Schiel, 1996), would therefore need a looser webbing and a lower hanging ratio (Karlsen, 1997; Hovgård & Lassen, 2000).

1.5.3 Twine thickness

Twine thickness is another parameter that is thought to have an impact on the catch efficiency of gillnets, affecting the function of the gillnet, both before and after the fish gets in contact with the gear (Gabriel *et al.*, 2005). The effect of twine thickness on catch efficiency and selectivity in gillnets has been investigated in several studies (Hansen, 1974; Turunen, 1996; Holst *et al.*, 2002; Grati *et al.*, 2015; Kim *et al.*, 2016). The general belief is that a thinner twine in gillnets is positively correlated with increased catch efficiency (He & Pol, 2010). For example, Grati *et al.* (2015) showed that an increase in twine thickness resulted in a decrease in catch of common sole (*Solea solea*). Furthermore, Holst *et al*. (2002) found a similar trend with thinner twine exhibiting a higher catch efficiency compared to thicker twine in the Baltic cod fishery. In addition, there was an indication that gillnets using thinner twine caught larger individuals (Holst *et al.*, 2002). On the other hand, Yokota *et al*. (2001) found that thinner twine caught smaller fish. Other studies investigating the effect of twine thickness did not observe similar trends. For instance, Gray *et al.* (2005) did not find any correlation between twine thickness and catch efficiency when investigating the effect of three different twine diameters.

It is also suggested that twine thickness in gillnets can influence the capture mechanisms (Yokota *et al.*, 2001; Holst *et al.*, 2002; Grati *et al.*, 2015). A study on the effect of twine thickness conducted by Grati *et al.* (2015) showed that an increase in twine thickness resulted in an increase in the proportion of fish getting gilled and a decrease in snagged fish.

Twine thickness has also proven to affect the selectivity of gillnets. Specifically, thinner twines have shown to catch fish in a wider length range, both smaller and larger individuals, while thicker twines have a narrower selection range (He, 2006; Kim *et al.*, 2016). However, this does not always seem to be the case, since other studies did not show similar results (Turunen, 1996). Furthermore, it is suggested that thicker twines are more easily detected by fish's lateral line system, based on the assumption that larger objects reflect stronger signals that can be detected by fish (Gabriel *et* *al.*, 2005). Furthermore, thinner twines are assumed to be less visually detectable for the fish (Hansen, 1974).

The results showing that gillnets using thinner twine catch more fish, in a wider length range, are mostly explained with the mechanical properties of the nylon. Specifically, thinner twines are more elastic and flexible, being able to stretch more easily than thicker twines (Hamley, 1975; Turunen, 1996; Gray *et al.*, 2005; He, 2006; Kim *et al.*, 2013; Kim *et al.*, 2016). Inferred from this, a thicker twine will be stiffer compared to thinner twine (Kim *et al.*, 2013). Also, a stiffer twine will require a larger force in order to elongate (Su *et al.*, 2019).

1.5.4 Netting material

The most common material for gillnet construction during the Middle Ages and up to the 19th century, was linen and hemp (Dybdahl, 2018). This was gradually replaced by cotton (Dybdahl, 2018), and today all gillnets are made from synthetic material (Deroiné *et al.*, 2019). Most commonly used is polyamide (PA), also called nylon (He, 2006). This material was invented in the first half of the 20th century. The material was introduced in Norway around the 1950s, and shortly after several trials with the nylon used in cod gillnets were conducted. The trials showed promising results, leading to a breakthrough of the new material in the Norwegian gillnet sector in 1954/55 (Martinussen, 2006). This was also due to a coinciding drop in sales of cotton material used in cod gillnets and a general lower demand of fishing gear. The transition from natural fibres to synthetic material was sped up by the government offering loans (and eventually also subsidies) to fishermen so that they could buy nylon nets. Therefore, as of 1960, the transition to nylon was complete (Martinussen, 2006).

Nylon is a versatile material that has excellent mechanical properties like high breaking strength, elongation, flexibility, and durability (Grimaldo *et al.*, 2020a). There are several different types of nylon. The ones that are most commonly used in fishing gear are nylon 6.6 (PA 6.6) and nylon 6 (PA 6). Nylon is hydrophilic, meaning it absorbs water (Parodi *et al.*, 2018; Shinzawa & Mizukado, 2020; Krauklis *et al.*, 2022). When exposed to water, some of the hydrogen bonds, mainly the ones in the amorphous region, that connect the different polymer chains together, form new bonds with the water molecules. The water, working as a plasticizer, makes the material softer and more flexible. This reduces the materials mechanical strength (Parodi *et al.*, 2018; Shinzawa

& Mizukado, 2020). Therefore, this also changes the materials Young's modulus, which is a measurement of how much force is needed to stretch a material. Nylon that has gone through a plasticization process will have a significantly lower Young's modulus compared to the materials state before this structural change. This is therefore negatively correlated to the elongation at break, because a reduction in Young's modulus often leads to an increase in elongation at break (Parodi *et al.*, 2018). This is important when performing tests on the mechanical properties of the nylon.

1.5.5 Filament type

There are several different filament types used in Norwegian fisheries. These types are primarily monofilament, multifilament, mono-twine, multi-mono, super multi-mono and mono-ace (Holst *et al.*, 1998). The most common of these is monofilament, which is consists of a single twine. This filament type is highly efficient, resistant for abrasions and known for being easy to handle on board (Tveit & Vollstad, 2015). However, despite its high fishing efficiency, use of monofilament in gillnets can cause problems regarding catch quality since the twine can damage the fish (Joensen *et al.*, 2017). Multifilament is another filament type that has many of the opposite qualities from monofilament. As the name suggests, multifilament consists of many thin twines with a diameter less than 0.05 mm spun together (Karlsen, 1997). It has a lower catch efficiency compared to monofilament (e.g., Balik, 2001; Thomas *et al.*, 2003; Eighani *et al.*, 2020), however, it results in a more gentle treatment of the catch, and therefore has better fish quality (Tveit & Vollstad, 2015). Furthermore, there are filament types containing more than one twine, but less than traditional multifilament, often combining properties of both twine types (Holst *et al.*, 1998).

1.5.6 Twine colour

Netting colour might affect gillnets in terms of fishing performance (Cui *et al.*, 1991; Balik, 2001; He & Pol, 2010). Effect of gillnet colour has been a source of debate for decades (Karlsen, 1997). However, despite numerous trials there is little explicit evidence regarding the effect of specific colours in gillnet netting material. Nevertheless, some studies show indication of certain trends. For instance, Balik & Cubuk (2001) showed that certain fish species avoid gillnets in certain colours. However, this would only be the case in circumstances where the nets and its colour would be visible to the fish. Netting colour is assumed to have little impact in the conditions commonly experienced in the north Norwegian cod fisheries for instance, because of darkness due to large fishing depth and/or prolonged seasonal periods of darkness (Grimaldo *et al.*, 2019).

1.6 Research questions

Based on the technical review of gillnet characteristics and construction in section 1.5 we can concretize the objectives in section 1.4 into specific research questions. The focus is on the gillnet characteristics that show most potential at explaining and resolving the current challenges regarding the development of new biodegradable materials for gillnets. Reduced twine elasticity appears to be a leading hypothesis in explaining observed differences in catch efficiency between gillnets made of biodegradable and nylon materials (Grimaldo *et al.*, 2020b). As previously explained, the elasticity of the nylon twine is primarily affected by the thickness (section 1.5.3). Therefore, this study will focus on the effect of twine thickness on the capture process of gillnets in cod fishery. To generalize the results, this study will investigate the effect of twine thickness on gillnets with different mesh sizes. Based on this, the objective of this thesis is achieved by investigating the following research questions:

- To what extent does twine thickness affect gillnet catch efficiency?
- In what way does gillnet mesh size influence what lengths of cod get captured in different ways?
- In what way does twine thickness affect the way cod get captured in gillnets?
- How do cod get captured in gillnets?

2 Materials and methods

2.1 Gillnet fishing trials

Fishing trials were conducted onboard fishing vessel 'Karoline' (LOA 10.9 m), an electric coastal gillnetter, under commercial fishing conditions. The data collection area was located north of Vannøya, outside the coast of Troms in North Norway between N70^{o}19.69 – N70^{o}22.40 and E19^{o}38.90 – E19^{o}48.75 (Figure 2), at depths between 75 – 142 m.

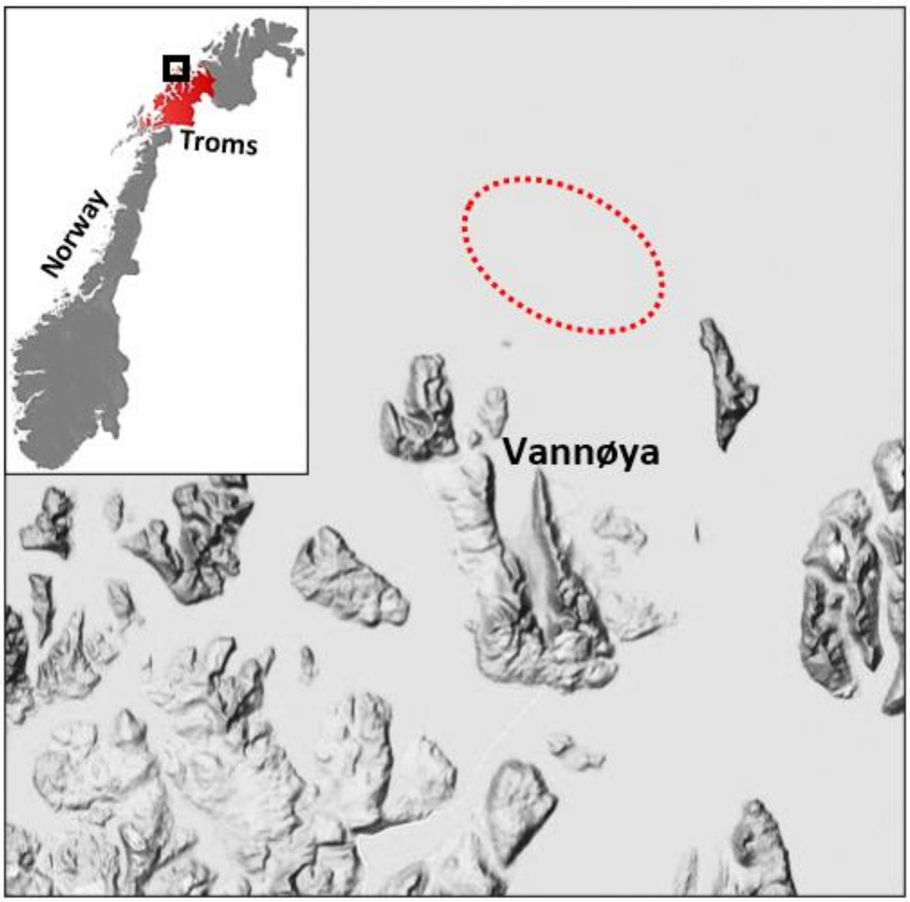

Figure 2: Data collection area during fishing trials. Red dotted circle highlights the area of gillnet deployments.

2.1.1 Experimental setup

The gillnets used in this study were made of nylon. The following rigging was used during the experimental fishing trials. Each gillnet was 30 meshes deep and 275 meshes long, with a stretched length of 55 meters. Two different mesh sizes where used, 210 mm and 230 mm. For both types, two different twine thicknesses were used, 0.7 mm and 0.8 mm, resulting in a total of four different gillnet types. Considering the gillnets had the same number of meshes but different mesh size the total height of the nets was different. The net with 210 mm mesh size was 6.3 m high, while the

230 mm mesh net was 6.9 m high. The netting was mounted on a float- and lead line, both of 27.5 meters length, resulting in a hanging ratio of 0.5. The float line was a 23 mm VSKflyt with 110 g/m buoyancy and the lead line was 14 mm in diameter and hade a buoyancy of 400 g/m. A total 38 gillnets were used, 20 nets with 210 mm stretched mesh size (Fleet 1), and18 nets with 230 mm stretched mesh size (Fleet 2) (Figure 3).

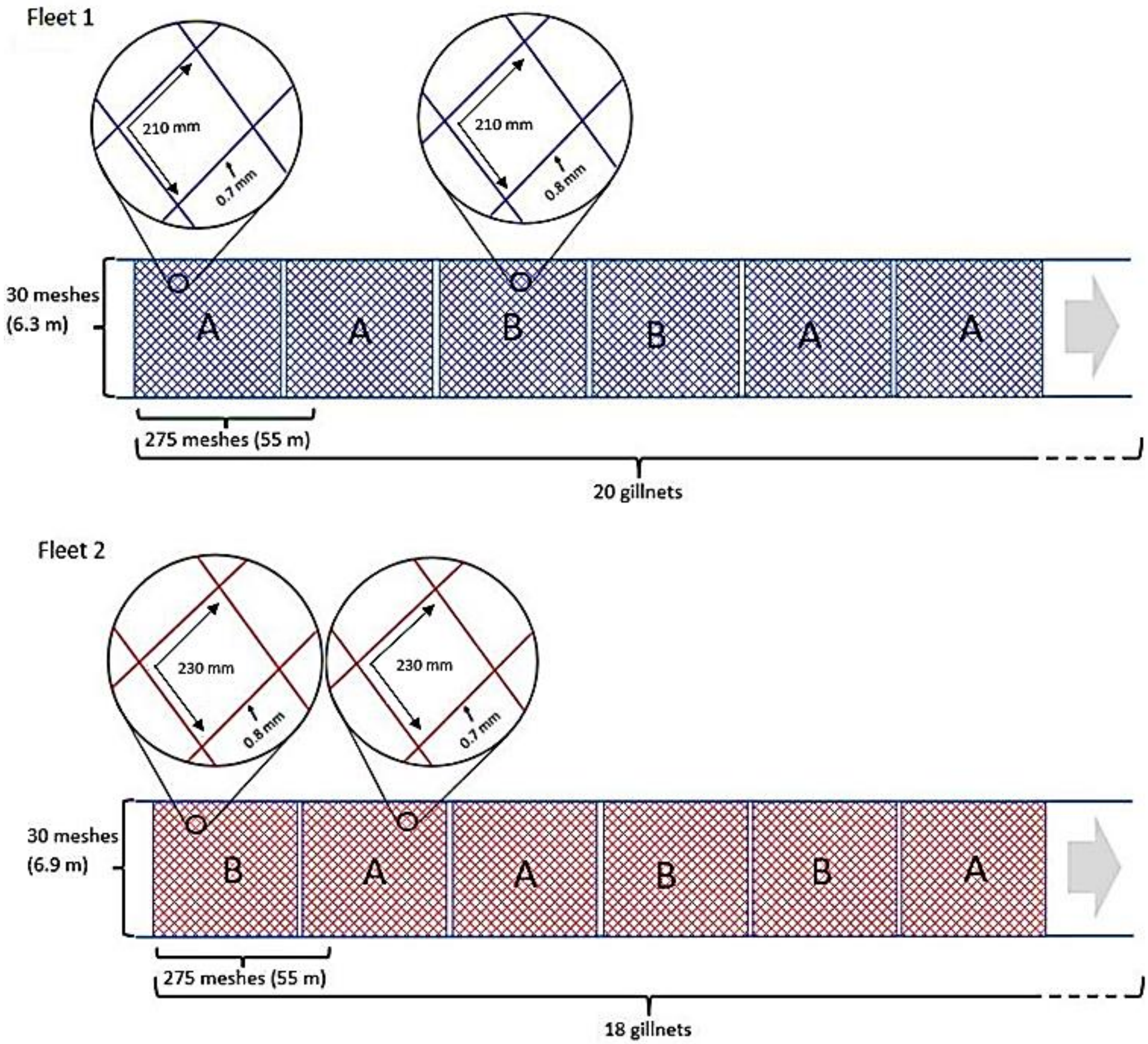

Figure 3: Experimental gillnet design used in the fishing trials. A showing the gillnets with 0.7 mm twine and B showing the gillnets with 0.8 mm twine.

In both fleets, half of the nets were made of 0.7 mm twine (A) and half of 0.8 mm twine (B). Fleet 1 was arranged as follows: AA-BB-AA-BB-AA-BB-AA-BB-AA-BB and fleet 2 was arranged as: B-AA-BB-AA-BB-AA-BB-AA-BB-A (Figure 3). Each fleet was hauled in the morning and deployed immediately after processing the catch, resulting in a fishing time of approximately 23 hours on each deployment. The trials lasted from 29 of January 2022 to 13 of March 2022, lasting approximately one fishing season. All gillnets were used continuously throughout this period, and data from a total of 21 deployments was gathered for both fleets.

2.1.2 Data collection

When the gillnets were hauled, the catch was sorted according to the gillnet type and the observed capture mode. Four different capture modes were assessed during the experimental fishing trials. These were snagging, gilling, wedging, and entangling as described in Cerbule *et al.* (2022b). Any entanglement in front of the gill covers was considered as snagging, not differentiating between maxillae, teeth, or head (Figure 4A). Gilled fish where those who had the meshes over the gill cover (Figure 4B). The capture mode wedging was appointed to all fish that got caught in the meshes behind the gill covers and back to the largest circumference of the body (Figure 4C). Fish that came up without showing any of the mentioned capture modes, or that did not show any clear marks on the body were considered as entangled (Figure 4D). In cases where the fish was loose in the net or fell out on deck during hauling the gear marks on the body were examined in order to establish the initial capture mode. In cases where more than one capture mode was observed, the principle of likely sequence, described in Savina *et al.* (2022), was applied. Considering the conical shape of a fish's body from snout up to its largest girth, the net will first get stuck on the part that is furthest towards the rear. For example, if a fish was caught by both gills and body, then the latter would be the primary mode of capture. Finally, each individual cod was length measured to the closest cm below.

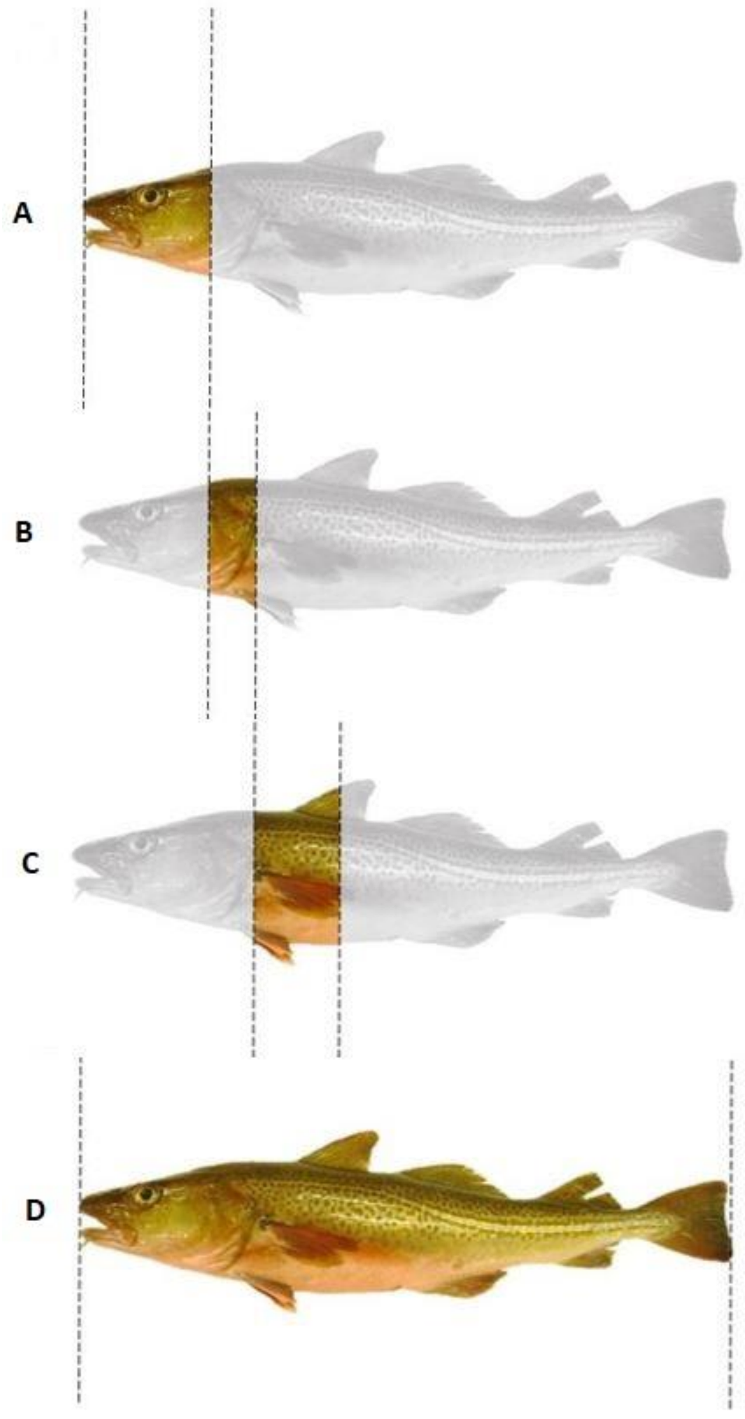

Figure 4: Capture modes: highlighted areas show where meshes can get stuck when snagged (A), gilled (B), wedged (C) and entangled (D).

2.1.3 Modelling the size-dependent catch efficiency between gillnet types

Catch comparison rate

The difference in relative length-dependent catch efficiency between the gillnets with different twine thickness in each fleet separately was assessed by comparing the catch data between gillnet types, using the method described in Herrmann *et al.* (2017). This method models the length dependent catch comparison rate (CC_l) summed over all gillnet fleet deployments during the entire data collection period. CC_l is expressed by the following Equation:

$$CC_l = \frac{\sum_{j=1}^{m}\{nt_{lj}\}}{\sum_{j=1}^{m}\{nt_{lj}+nc_{lj}\}} \qquad (1)$$

where nc_{lj} and nt_{lj} are the numbers of cod caught in each length class l for the gillnet with 0.8 mm twine (control) and the gillnet with 0.7 mm twine (treatment) in deployment j of a gillnet fleet (first or second fleet). m is the number of deployments carried out with one of the two fleets. The functional form for the catch comparison rate $CC(l,\boldsymbol{v})$ was obtained using maximum likelihood estimation by minimizing the following expression:

$$-\sum_l\left\{\sum_{j=1}^{m}\left\{nt_{lj}\times ln\left(CC(l,\boldsymbol{v})\right)+nc_{lj}\times ln\left(1.0-CC(l,\boldsymbol{v})\right)\right\}\right\} \qquad (2)$$

where v represents the parameters describing the catch comparison curve defined by $CC(l,\boldsymbol{v})$. The outer summation in Expression (2) is the summation over length classes l. If the two gillnet types have the same catch efficiency, the value for the summed catch comparison rate is 0.5. In order to evaluate any potential differences in the gillnets performance compared to each other this value acts as a baseline. The experimental CC_l (Equation (1)) was modelled by the function $CC(l,\boldsymbol{v})$ using the following Equation:

$$CC(l,\boldsymbol{v}) = \frac{exp\left(f(l,v_0,\ldots,v_k)\right)}{1+exp\left(f(l,v_0,\ldots,v_k)\right)} \quad (3)$$

where f is a polynomial of order k with coefficients v_0 to v_k. The values of the parameters v describing $CC(l,\boldsymbol{v})$ were estimated by minimizing Expression (2), which was equivalent to maximizing the likelihood of the observed catch data. We considered f of up to an order of 4 with parameters v_0, v_1, v_2, v_3, and v_4. Leaving out one or more of the parameters $v_0 \ldots v_4$ led to 31 additional models that were also considered as potential models for the catch comparison rate $CC(l,\boldsymbol{v})$. Among these models, estimations of the catch comparison rate were made using multi-model inference to obtain a combined model (Burnham & Anderson, 2002; Herrmann *et al.*, 2017).

The ability of the combined model to describe the experimental data was evaluated based on the *p*-value. This was calculated based on the model deviance and the degrees of freedom. In order for the combined model to adequatly describe the experimental data the *p*-value should not be < 0.05, except for cases experiencing overdispersion in the data (Wileman *et al.*, 1996; Herrmann *et al.*, 2017).

Catch ratio

Based on the estimated catch comparison function $CC(l,\boldsymbol{v})$, we obtained the relative catch efficiency (or catch ratio) $CR(l,\boldsymbol{v})$ between the two gillnet types using the following Equation:

$$CR(l,\boldsymbol{v}) = \frac{CC(l,\boldsymbol{v})}{(1-CC(l,\boldsymbol{v}))} \qquad (4)$$

$CR(l,\boldsymbol{v})$ is a value that represents the relationship between the catch efficiency of two gillnet types. For instance, if the two gillnet types have an identical catch efficiency, then this value will always be 1.0. Also, if $CR(l,\boldsymbol{v})$ = 1.5 this shows that the gillnets with 0.7 mm twine would catch 50 % more cod with length *l* than the gillnets with 0.8 mm twine. On the other hand, if $CR(l,\boldsymbol{v})$= 0.8 this tells us that the gillnet with 0.7 mm twine catches 80 % of the cod with length *l* compared to the cathces from gillnet with 0.8 mm twine.

The confidence limits for $CC(l,\boldsymbol{v})$ and $CR(l,\boldsymbol{v})$ were estimated using a double bootstrapping method (Herrmann *et al.*, 2017). The bootstrapping method accounts for between-set variability (uncertainty in the estimation resulting from set deployment variation of catch efficiency in the gillnets and in the spatial-temporal availability of cod) as well as within-set variability (uncertainty about the size structure of the catch for the individual deployments). However, contrary to the double bootstrapping method (Herrmann *et al.*, 2017), the outer bootstrapping loop used in the current study (accounting for the variability between deployments) was carried out in pairs to take full advantage of the experimental design of deploying the biodegradable gillnet and nylon gillnet simultaneously. By using multi-model inference in each bootstrap iteration, the method also accounted for the uncertainty in model selection. 1000 bootstrap repetitions were performed and the Efron 95 % confidence limits (Efron, 1982) was calculated. To identify the sizes of cod with significant differences in catch efficiency between gillent types, we checked for length classes in which the 95 % confidence limits for the catch ratio curve did not contain 1.0.

The length-integrated average catch ratio ($CR_{average}$) value was estimated directly from the experimental catch data using the following equation:

$$CR_{average} = \frac{\sum_l \sum_{j=1}^{m} \{nt_{lj}\}}{\sum_l \sum_{j=1}^{m} \{nc_{lj}\}} \qquad (5)$$

where the outer summation covers the length classes in the catch during the experimental fishing period.

2.1.4 Modelling the length-dependent probability for capture modes

The capture modes described in section 2.1.2 were analyzed using the statistical software SELNET (Herrmann *et al.*, 2012). Conditioned capture, the length-dependent probability for capture by the specific mode, was quantified. Each deployment for both gillnet fleets were considered as the base units of the analysis. Each capture mode was analyzed independently from the other modes, following the description outlined in Savina *et al.* (2022) which is described below.

Conditioned capture, the expected probability for the capture mode *q* for fish length *l* will be:

$$CPq_l = \frac{\sum_{j=1}^{h} n_{qlj}}{\sum_{j=1}^{h} \sum_{i=1}^{Q} n_{ilj}} \qquad (6)$$

where n_{qlj} is the number of cod caught for length class *l* with capture mode *q* in deployment *j*. Q is the number of capture modes and *h* is the total number of gillnet deployments. The functional form for the capture mode probability $CPq(l,\boldsymbol{v})$ was obtained using maximum likelihood estimation by minimizing the expression (7) with respect to parameters $\boldsymbol{v}$:

$$-\sum_{j=1}^{h} \sum_l \left\{ n_{qlj} \times ln[CPq(l,\boldsymbol{v})] + \left[-n_{qlj} + \sum_{i=1}^{Q} n_{ilj}\right] \times ln[1.0 - CPq(l,\boldsymbol{v})] \right\} \qquad (7)$$

$\boldsymbol{v}$ represents the parameters describing the capture mode probability curve defined by $CPq(l,\boldsymbol{v})$ that has values in the range from 0.0 to 1.0. Combined, Equation (6) and Expression (7) are commonly applied for modelling the length-dependent catch comparison rate between two fishing gears (Krag *et al.*, 2014). Therefore, the same approach for modelling $CPq(l,\boldsymbol{v})$ was used, as is often applied for catch comparison rate (section 2.1.3), such:

$$CPq(l,\boldsymbol{v}) = \frac{exp[f(l,v_0,\ldots,v_4)]}{1+exp[f(l,v_0,\ldots,v_4)]} \qquad (8)$$

f is a polynomial of order 4 with coefficients $v_0 - v_4$, such that $\boldsymbol{v} = (v_0, \ldots, v_4)$. Excluding one or more of the parameters $v_0, \ldots, v_4$, at a time resulted in 31 additional candidate models for the capture mode probability function $CPq(l,\boldsymbol{v})$. Multi-model inference was applied when estimating the capture mode probability based on these models to obtain a combined model (Burnham and Anderson, 2002; Herrmann *et al.*, 2017). The combined model's ability to describe the experimental data was, as for the catch comparison rate, based on the obtained *p*-value.

Similar as for the catch comparison rate uncertainties for $CPq(l,\boldsymbol{v})$ was obtained with the double bootstrapping method (section 2.1.3).

We presented the length distribution of the sampled population as the modelled mean number of fish caught for the four capture modes. Length-integrated average value for the capture mode probability ($CPq_{average}$) was estimated directly from the experimental data applying (Cerbule *et al.*, 2022b; Savina *et al.*, 2022):

$$CPq_{average} = \frac{\sum_l \sum_{j=1}^{h} n_{qlj}}{\sum_l \sum_{j=1}^{h} \sum_{i=1}^{Q} n_{ilj}} \quad (9)$$

In Equation (9) the outer summations include the length classes for captured cod during the gillnet fishing trials. The $CPq_{average}$ values are specific for the population structure found during the gillnet fishing trials and cannot be extrapolated to other cases where the size structure of the fish species may be different. This is in contrast to the length-dependent analysis of the capture mode probability (Cerbule *et al.*, 2022b; Savina *et al.*, 2022).

Assessing top points for bell-shaped capture mode probability curves

To assess the top points for the probability curves, the software SELNET was used (Herrmann *et al.*, 2012). Values for the top points (R_{max}) on the bell-shaped capture mode probability curves, and the correlating fish lengths (LR_{max}), were achieved using a numerical method in SELNET (Sistiaga *et al.*, 2019) (Figure 5). This was only done in cases where capture mode probability plots depicting a bell-shaped curve.

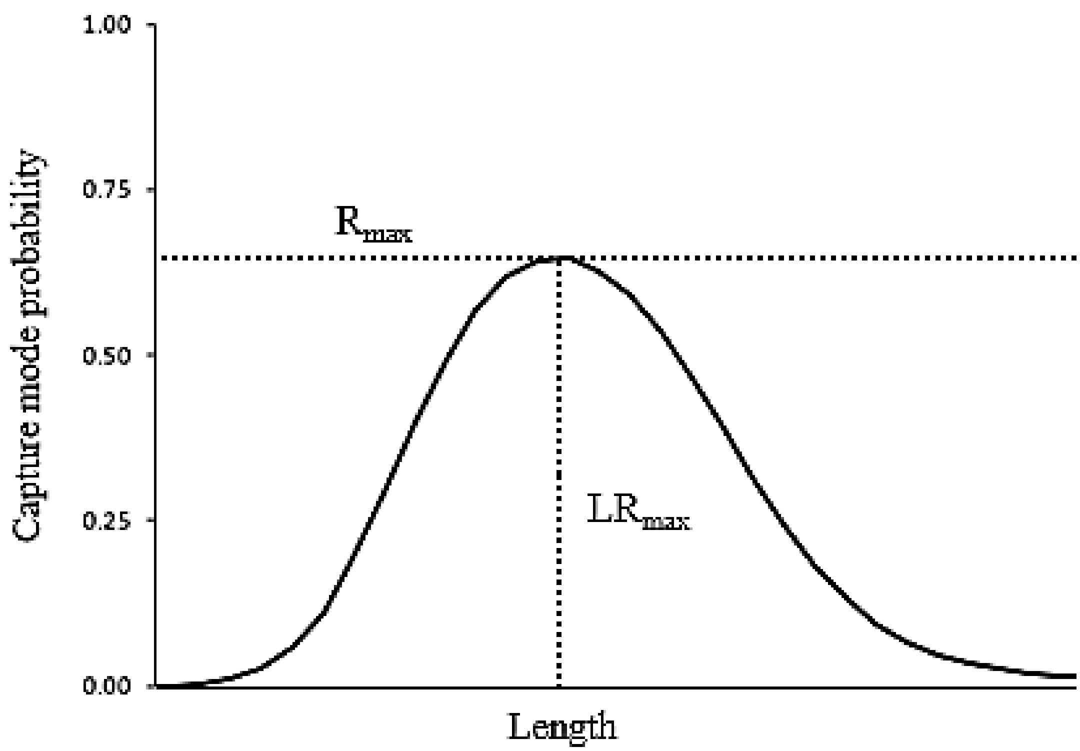

Figure 5: Example of a bell-shaped curve, showing the R_{max} (horizontal line) and LR_{max} (vertical line).

2.1.5 Inference of the difference in the length-dependent probability for capture modes between gillnet designs

To investigate the effect of changing from gillnet (Y) to gillnet (Z) on the capture mode probability curve $CP_{q,gillnett}(l, \boldsymbol{v}_{gillnet})$ for mode q the length-dependent change $\Delta\mathrm{CPq}(l)$ in the values was estimated using:

$$\Delta CPq(l) = CP_{q,Z}(l) - CP_{q,Y}(l) \qquad (10)$$

In Equation (10) $CP_{q,Y}(l)$ represents the probability for gillnet design (*Y*) and $CP_{q,Z}(l)$ represents the probability for gillnet design (*Z*). The bootstrap populations (both containing 1000 repetitions) of results for both $CP_{q,Y}(l)$ and $CP_{q,Z}(l)$ were used to estimate 95 % percentile (Efron, 1982) confidence limits for $\Delta \text{CPq}(l)$. Because these were obtained independently, a new bootstrap population of results was created for $\Delta \text{CPq}(l)$ by:

$$\Delta CP_q(l)_i = CP_{q,Z}(l)_i - CP_{q,Y}(l)_i \quad i \in \; [1 \ldots 1000] \quad (11)$$

In Equation (11) *i* denotes the bootstrap repetition index. As the bootstrap resampling was random and independent for the two groups of results, it is valid to generate the bootstrap population of results for the difference based on using the two independently generated bootstrap files (Herrmann *et al.*, 2018). Based on the bootstrap population, Efron 95% percentile confidence limits were obtained for $\Delta \text{CPq}(l)$ as described above.

The methodology applied in this section for difference in capture mode probability is similar to the one applied by Larsen *et al.* (2018) for obtaining difference in size selectivity.

2.2 Circumference measurements

To better understand the relation between gillnet mesh size and capture patterns for cod, we estimated the relationship between fish's length and circumference at specific points corresponding as close as possible to the observed capture modes described in section 2.1.2. Hence, morphological data was collected in a laboratory on research vessel 'Helmer Hanssen', a 56.5 m research vessel, during a cruise in the Barents Sea from 22nd of February to 10th of March 2022. Cod were sampled for as wide length range as possible. On every individual the total length was measured, and three circumference measurements (Figure 6) were taken down to the closest millimetre: in front of the eyes over the rear part of the maxillae (Figure 6A), over the far end of the gill cover (Figure 6B), and the largest circumference of the body following a vertical line down from the first dorsal fin (Figure 6C). The measurements were taken without compressing the body of the fish.

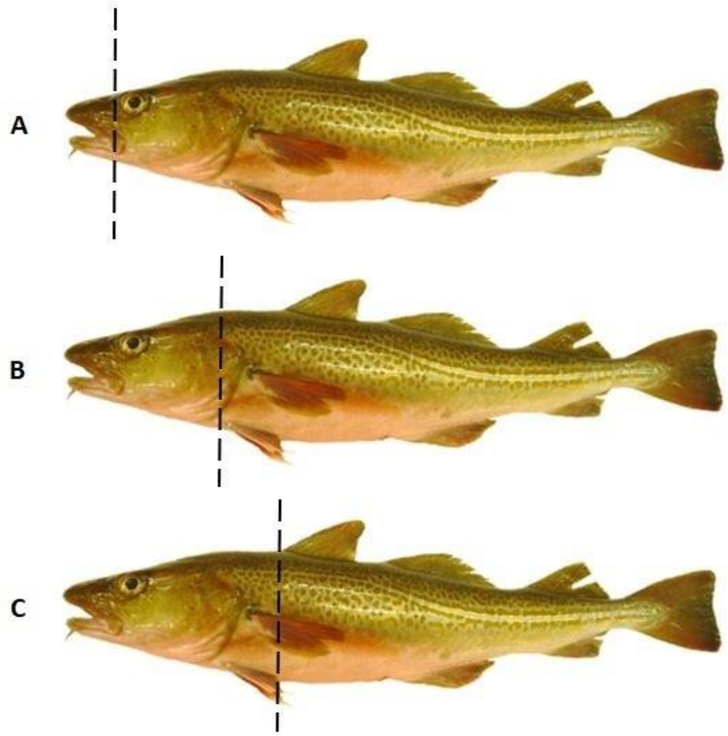

Figure 6: Circumference measurements. Dotted line showing where the measurements were taken.

2.2.1 Modelling length dependent circumference

The circumference measurements collected during the laboratory experiments were modelled using a simple linear regression, using the equation (12) below:

$$C = a \times l \qquad (12)$$

where the dependent variable circumference C is expressed by the relationship between the independent variable length l and the slope of the regression line a. The models R^2 was used to quantify how well the model explained the variation in the data. Intercept was excluded from the equation due too structural requirements. In theory, a fish with length = 0 will also have a circumference measurement of 0. Therefore, there is no intercept term in the model. The analysis would make it possible to predict the different circumference measurements of fish of certain lengths, and thereby also predict the relationship between a fish's length and the meshes it could potentially get enmeshed by.

2.3 Fall-through experiments

To support the understanding on gillnet capture patterns, so-called fall-through experiments were conducted during the same cruise as the morphological data gathering. A gillnet with 168 mm meshes (84 mm bar length) and 0.5 mm monofilament twine was stretched out on an aluminium frame (Figure 7). The frame was 64.0 cm long and 51.0 cm wide. The net was stretched out with a little bit of tension, only enough to open the meshes, but without elongating the material.

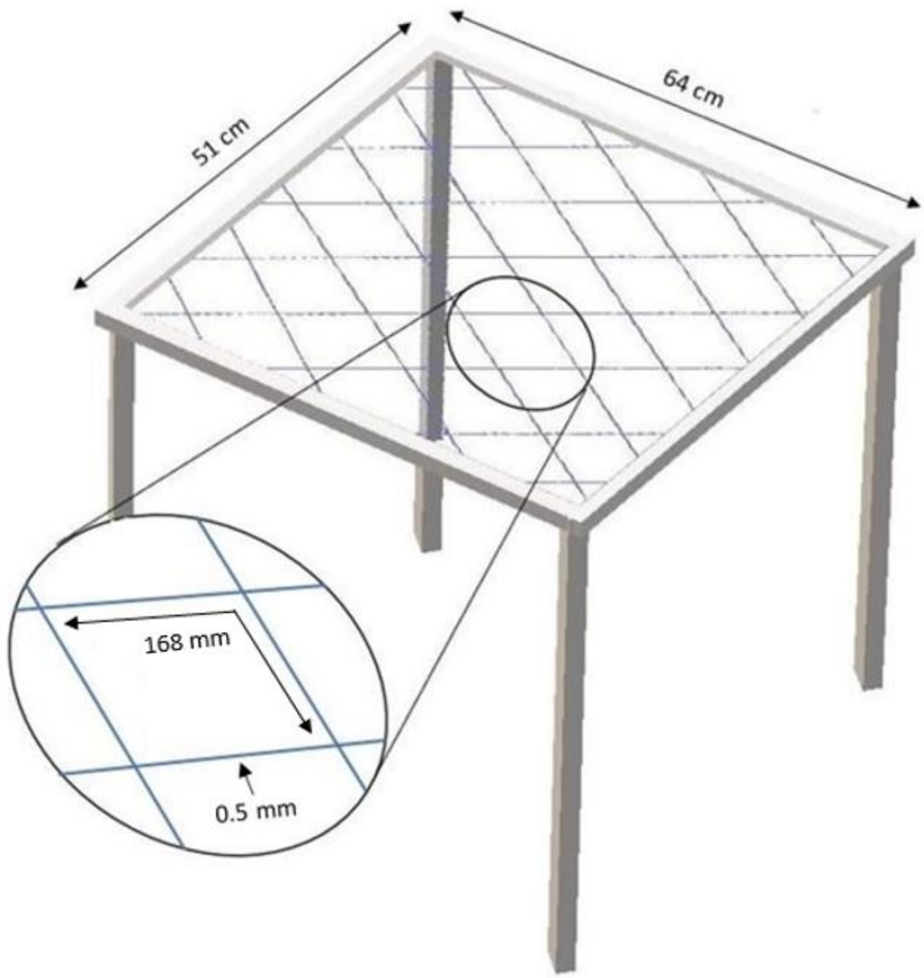

Figure 7: Stretched gillnet over the frame used to perform fall-through experiments.

Fish were measured to the nearest mm, and then individually let down into a mesh with the head-first in order to register the point of where the mesh got stuck around the fish (Figure 8). It is uncertain how much force a fish would use in a real environment to force itself through a mesh. Therefore, to standardize this, gravity was the only force affecting the enmeshment of the fish, similar to other studies conducting fall through experiments (Herrmann *et al.*, 2009; Krag *et al.*, 2011; Herrmann *et al.*, 2012). This standardization was based on the assumption that this force positively correlates with increasing fish weight (Krag *et al.*, 2011), which therefore corresponds to the assumption that larger fish will use more force when going into a mesh (Efanov *et al.*, 1987). There were four different modes registered, equivalent to capture mode snagging (A), gilling (B) and wedging (C) in Figure 4 in section 2.1.2. In addition, a fourth mode was registered where the fish went through the mesh without getting stuck. Not all capture modes described in section 2.1.2 were practically possible to perform during the laboratory experiments, namely snagging by the mouth/teeth and maxillae, and entangling. Length measurements and observations were registered and later used in further analysis.

Figure 8: Fall-through experiments with cod conducted onboard research vessel 'Helmer Hanssen'. A: cod passing through the mesh. B: cod getting the mesh stuck over the gill covers (Photo: Manu Sistiaga).

2.3.1 Modelling fall-through experiment data

The data collected during the fall through laboratory experiments was modelled using the same approach described in section 2.1.4 (Modelling the length-dependent probability for capture modes). This was due to the similar nature of the data, both expressing capture mode probabilities.

3 Results

A total of 2819 cod were caught during the gillnet fishing trials at Vannøya (Figure 2), of which 2696 individuals were used in the analysis (Table 1). Fleets that caught fewer than 20 fish on a single deployment were excluded from the analysis, explaining the omitted 123 individuals. Out of these 2696 cod, the gillnets with 210 mm mesh size (Fleet 1) captured a total of 1954 fish, divided between the gillnets with thin- (0.7 mm) and thick (0.8 mm) twine, catching 1027 and 927 fish, respectively (Table 1). The gillnet with 230 mm mesh size (Fleet 2) caught a total of 742 cod, where gillnets with the thin twine caught 385 fish and the thick twine caught 357 fish (Table 1).

Table 1: Data collected during gillnet fishing trials onboard 'Karoline'. Number of cod captured in each gillnet type for both fleets. Deployments containing less than 20 individuals that were excluded from the table.

Date (dd/mm/yyyy)	Fleet	Mesh size (mm)	Number cod 0.7 mm	Number cod 0.8 mm
31/01/2022	1	210	31	33
31/01/2022	2	230	36	25
01/02/2022	1	210	53	43
01/02/2022	2	230	21	30
02/02/2022	1	210	89	62
02/02/2022	2	230	55	44
03/02/2022	1	210	77	77
03/02/2022	2	230	14	11
09/02/2022	1	210	60	49
09/02/2022	2	230	16	16
10/02/2022	1	210	95	74
10/02/2022	2	230	24	21
13/02/2022	1	210	86	76
13/02/2022	2	230	43	35
14/02/2022	1	210	86	87
14/02/2022	2	230	36	36
15/02/2022	1	210	16	15
15/02/2022	2	230	18	29
21/02/2022	1	210	61	70
21/02/2022	2	230	21	13
22/02/2022	1	210	37	31
22/02/2022	2	230	11	12
23/02/2022	1	210	63	58
23/02/2022	2	230	14	11
24/02/2022	1	210	41	42
04/03/2022	1	210	47	44
05/03/2022	1	210	15	21
05/03/2022	2	230	19	17
06/03/2022	1	210	30	22
06/03/2022	2	230	30	14
07/03/2022	1	210	28	16
12/03/2022	1	210	68	73
12/03/2022	2	230	27	43
13/03/2022	1	210	44	33

3.1 Effect of twine thickness on catch efficiency

The results investigating the effect of twine thickness on gillnet catch efficiency (the analysis outlined in section 2.1.3 regarding length dependent catch comparison rate and catch ratio) are as follows (Figure 9, Table 2).

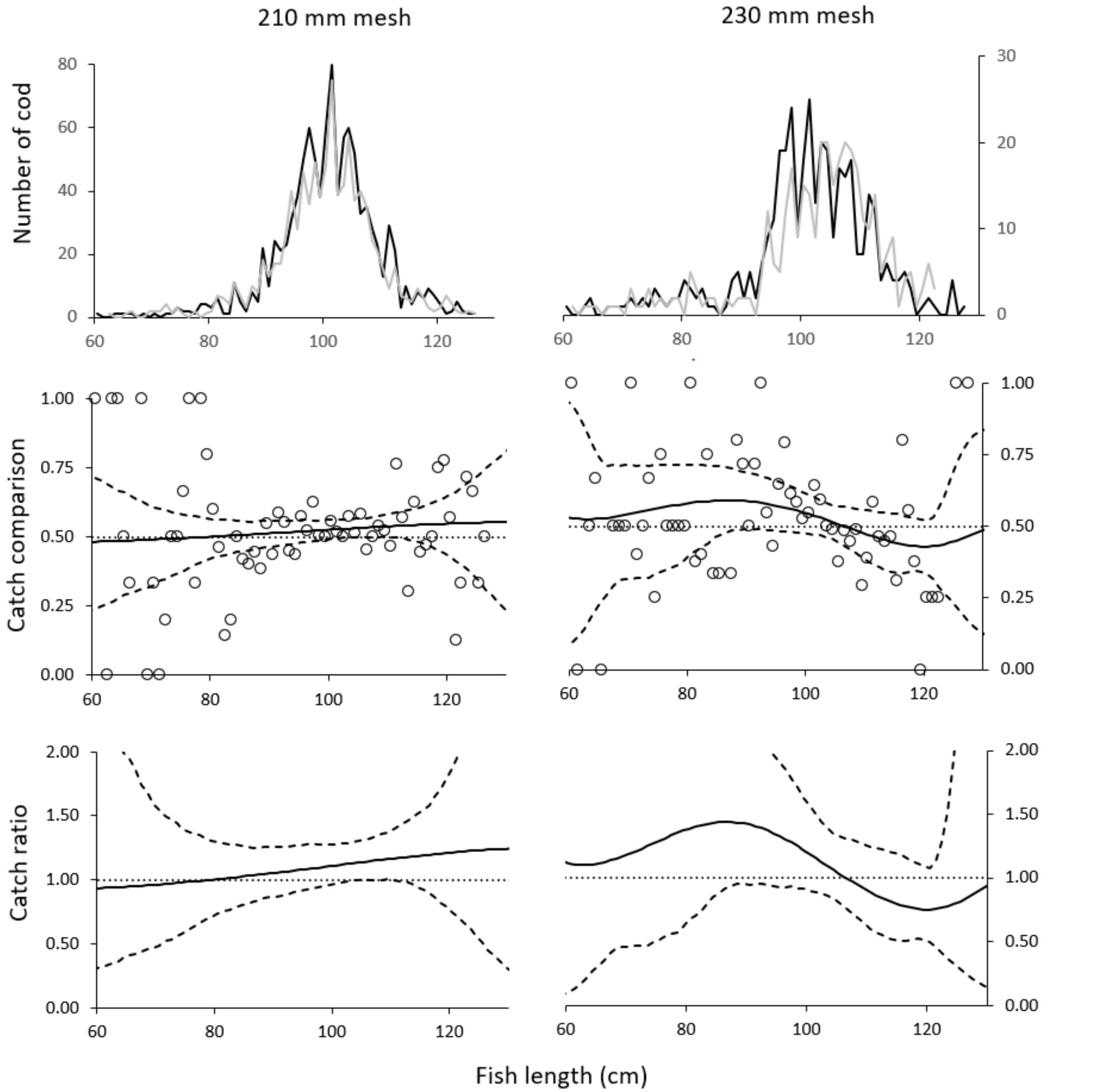

Figure 9: Catch comparison rate (CC) and catch ratio (CR) for the two mesh sizes (210 mm (left column) and 230 mm (right column)). Upper graphs show the number of cod caught with the 0.7 mm twine (grey) and 0.8 mm twine (black). Middle graph shows the catch comparison rate. Bottom graph shows the catch ratio. Black stippled lines mark the 95 % confidence intervals. Horizontal lines in the CC- and CR-plots at 0.5 and 1.0, respectively, represent a baseline were gillnets with different twine thicknesses catch equal.

When comparing the 0.7 mm and 0.8 mm twine for both the 210 mm gillnet and the 230 mm gillnet the fit statistics show that there is no discrepancy between the fitted model and the experimental data (p-value > 0.05) (Table 2). Thus, the models used fit the data well.

Table 2: Catch ratio results and fit statistics for the 210- and 230 mm mesh gillnets. Values in brackets are the 95 % confidence intervals). Significant results are marked in bold.

Length (cm)	Catch ratio (%)	
	210 mm	230 mm
70	96.44 (48.10 – 154.20)	118.76 (46.18 – 248.63)
75	98.37 (60.41 – 138.14)	129.16 (51.21 – 250.25)
80	100.57 (73.70 – 129.52)	138.67 (67.13 – 251.92)
85	103.00 (81.33 – 125.98)	143.64 (87.86 – 242.36)
90	105.61 (87.07 – 125.84)	141.70 (94.71 – 217.54)
95	108.36 (92.12 – 127.93)	132.77 (93.02 – 190.45)
100	111.18 (97.03 – 128.12)	118.83 (90.01 – 156.62)
105	**113.99 (100.26 – 131.61)**	103.06 (80.25 – 132.45)
110	116.72 (99.33 – 139.65)	88.87 (60.19 – 124.54)
115	119.26 (92.24 – 154.58)	78.83 (50.80 – 118.43)
120	121.15 (74.91 – 187.28)	75.20 (49.90 – 107.44)
Average	110.91 (99.30 – 123.66)	107.84 (84.94 – 130.74)
p–value	0.0902	0.6831
Deviance	75.13	51.43
DOF	60	57

The average catch ratio for the 210 mm gillnet is 110.91 (CI: 99.30 – 123.66), meaning there is an indication that the 0.7 mm twine on average catches 10.9 % more cod than the 0.8 mm twine. The average catch ratio for the 230 mm gillnets is 107.84 (CI: 84.94 – 130.74), indicating that the 0.7 mm twine on average catches 7.8 % more than the 0.8 mm twine. The 95 % confidence intervals for the two mesh sizes (99.30 – 123.66 for the 210 mm gillnets and 84.94 – 130.74 for the 230 mm mesh size gillnets) shows that there is no significant difference observed in catch ratio between the twine thicknesses for either mesh size. However, when looking at specific length classes, there is a significant difference between the two twines for fish length around 105 cm for the 210 mm gillnets (113.99 (CI: 100.26 – 131.61)) (Table 2). Otherwise, for this gillnet type, there is an indication of a trend showing that the catch efficiency of thin twine increases with increasing fish length. For the gillnets with 230 mm meshes there are no significant differences between the 0.7 mm- and 0.8 mm twines. However, there is a slight indication for smaller length classes of cod that the thinner 0.7 mm twine has a higher catch efficiency compared to the thicker 0.8 mm twine, while for larger length classes of cod this trend is opposite, and the thicker twine is more efficient. Comparing the two catch ratio plots for both mesh sizes show opposite trends for the length classes ranging from approximately 80 cm to 120 cm. While the 210 mm gillnets show an upward trend in catch efficiency for 0.7 mm twine with an increase in fish length, an opposite trend is observed for the 230 mm gillnets, indicating a downward trend in catch efficiency for 0.7 mm twine with an increase in fish length.

3.2 Length dependent capture mode probability in different gillnets

The results of assessing the length dependent capture mode probability, outlined in section 2.1.4, which was done separately for the four different gillnets, is presented in the following sections.

3.2.1 Capture pattern for gillnets with mesh size 210 mm and 0.7 mm twine

For the gillnets with 210 mm mesh size and 0.7 mm twine a total of 200 cod were snagged, 318 cod were gilled, 497 cod were wedged and 12 cod were entangled. For the 210 mm gillnet with 0.7 mm twine, the fit statistics show a *p*-value >0.05 for all capture modes, meaning there is no significant discrepancy between the fitted model and the experimental data (Table 3). Clear trends are observed in the length dependent capture mode probability for cod (Figure 10).

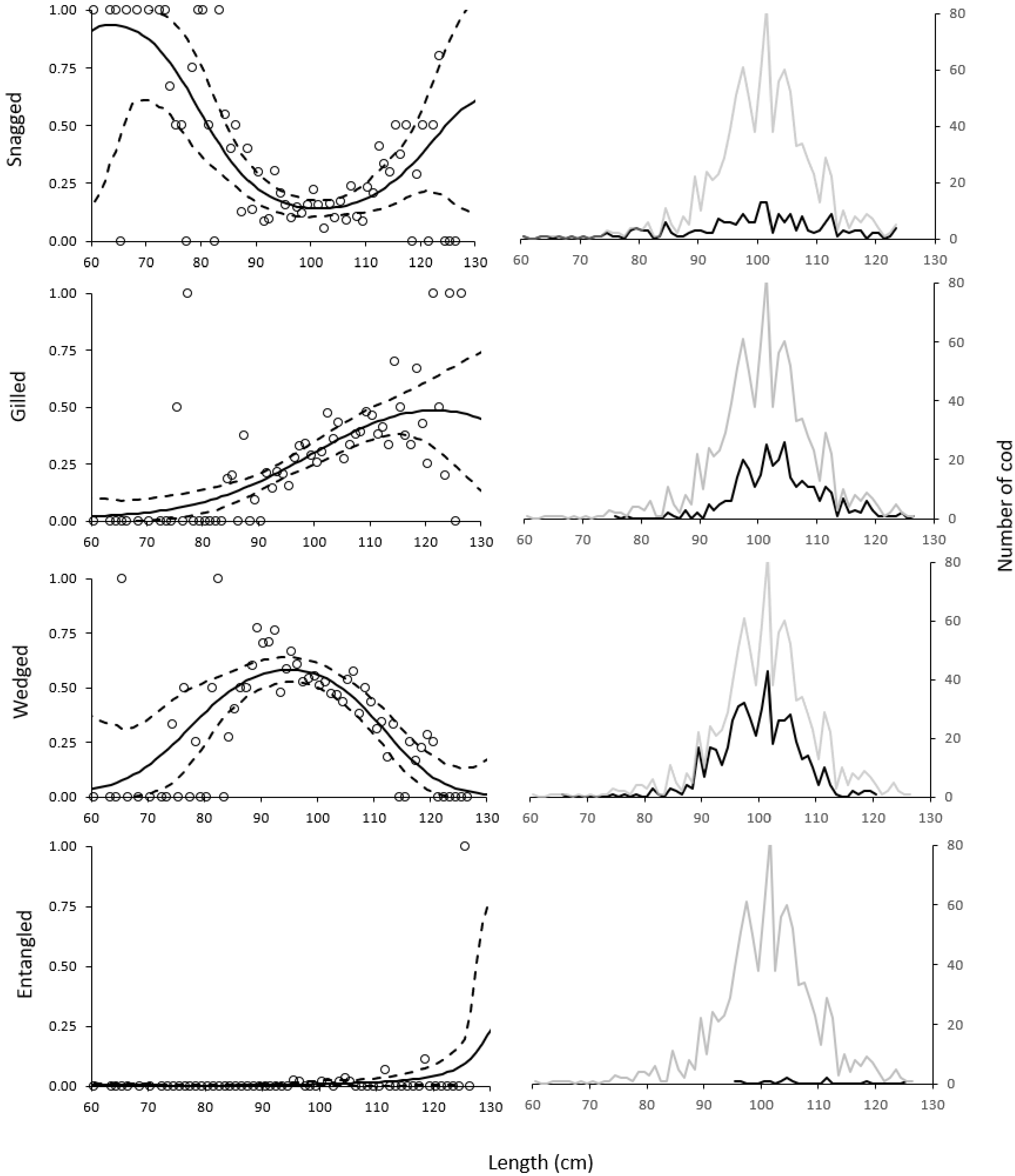

Figure 10: Capture mode probability (left) and population structure (right) for 210 mm mesh size and 0.7 mm twine thickness. Dotted lines show the 95 % confidence intervals around the main trendline (black line). Black line in the population structure shows the share of the total catch (grey line) for each capture mode in this gillnet type.

Table 3: Capture mode probability and fit statistics for snagging, gilling, wedging, and entangling for cod caught with 210 mm gillnet with 0.7 mm twine thickness. Numbers in parentheses show the 95 % confidence intervals.

Length (cm)	Capture mode probability (%) Snagging	Gilling	Wedging	Entangling
70	87.25 (61.00 – 100.75)	3.99 (0.36 – 10.11)	15.17 (1.75 – 36.53)	0.39 (0.07 – 0.87)
75	73.55 (50.79 – 93.55)	5.83 (1.41 – 11.57)	26.70 (9.03 – 46.16)	0.35 (0.07 – 0.79)
80	53.51 (35.89 – 73.74)	8.58 (3.58 – 13.94)	39.61 (25.50 – 53.09)	0.35 (0.08 – 0.75)
85	34.61 (25.65 – 46.27)	12.49 (7.85 – 16.95)	50.23 (41.58 – 58.16)	0.38 (0.09 – 0.80)
90	22.40 (16.08 – 28.99)	17.64 (13.87 – 21.26)	56.62 (49.95 – 62.76)	0.46 (0.10 – 0.98)
95	16.30 (11.50 – 20.91)	23.86 (20.13 – 27.95)	58.39 (52.76 – 63.91)	0.65 (0.07 – 1.63)
100	14.19 (10.58 – 17.76)	30.64 (25.38 – 35.72)	55.42 (49.37 – 60.65)	0.93 (0.04 – 2.47)
105	15.03 (11.23 – 18.76)	37.22 (30.98 – 43.33)	47.38 (40.66 – 53.42)	1.27 (0.26 – 2.72)
110	18.94 (12.81 – 26.12)	42.81 (35.86 – 50.16)	34.64 (27.20 – 43.18)	1.79 (0.27 – 3.41)
115	26.63 (16.37 – 38.24)	46.77 (38.20 – 55.50)	20.17 (11.58 – 29.80)	2.71 (0.42 – 5.33)
120	38.44 (21.62 – 58.59)	48.61 (33.91 – 61.31)	8.98 (2.30 – 18.73)	4.54 (0.62 – 9.36)
Average	19.47 (15.90 – 23.20)	30.96 (26.85 – 35.01)	48.39 (43.93 – 52.44)	1.79 (0.37 – 2.16)
p–value	0.1423	0.6749	0.5257	0.9998
Deviance	68.46	51.66	55.65	26.85
DOF	57	57	57	57

The smallest length classes are primarily caught by snagging. The probability of capture by snagging quickly decreases with increasing fish length with a low point just after 100 cm. Then, the most dominant mode of capture is wedging, which has a top around 95 cm, having a catch probability of 58 % at this point, after which it rapidly declines (Figure 10, Table 3, Table 5). With further increasing length classes, the most dominant mode of capture is gilling, which reaches a top point around approximately 122 cm and having a catch probability of 49 % at this point (Table 3, Table 5). Low statistical strength among the largest individuals makes the observed trend above 120 cm less certain. The last mode of capture, entangling, was observed in few cases, thus being the least likely mode of capture, and not showing any clear trends. It is important to note that top points on the curves do not necessarily imply that the corresponding capture mode is most efficient, but rather show the highest probability of cod of certain length getting caught in this capture mode. For example, snagging has top points for the smallest and largest cod, meaning this is the most likely mode of capture for cod of these sizes. However, the highest frequency of snagged cod is for medium sized individuals, where the probability of snagging is the lowest compared to the other modes of capture (Figure 10).

3.2.2 Capture pattern for gillnets with mesh size 210 mm and 0.8 mm twine

For the gillnets with 210 mm mesh size and 0.8 mm twine a total of 177 cod were snagged, 273 cod were gilled, 463 cod were wedged and 14 cod were entangled (Figure 11, Table 4).

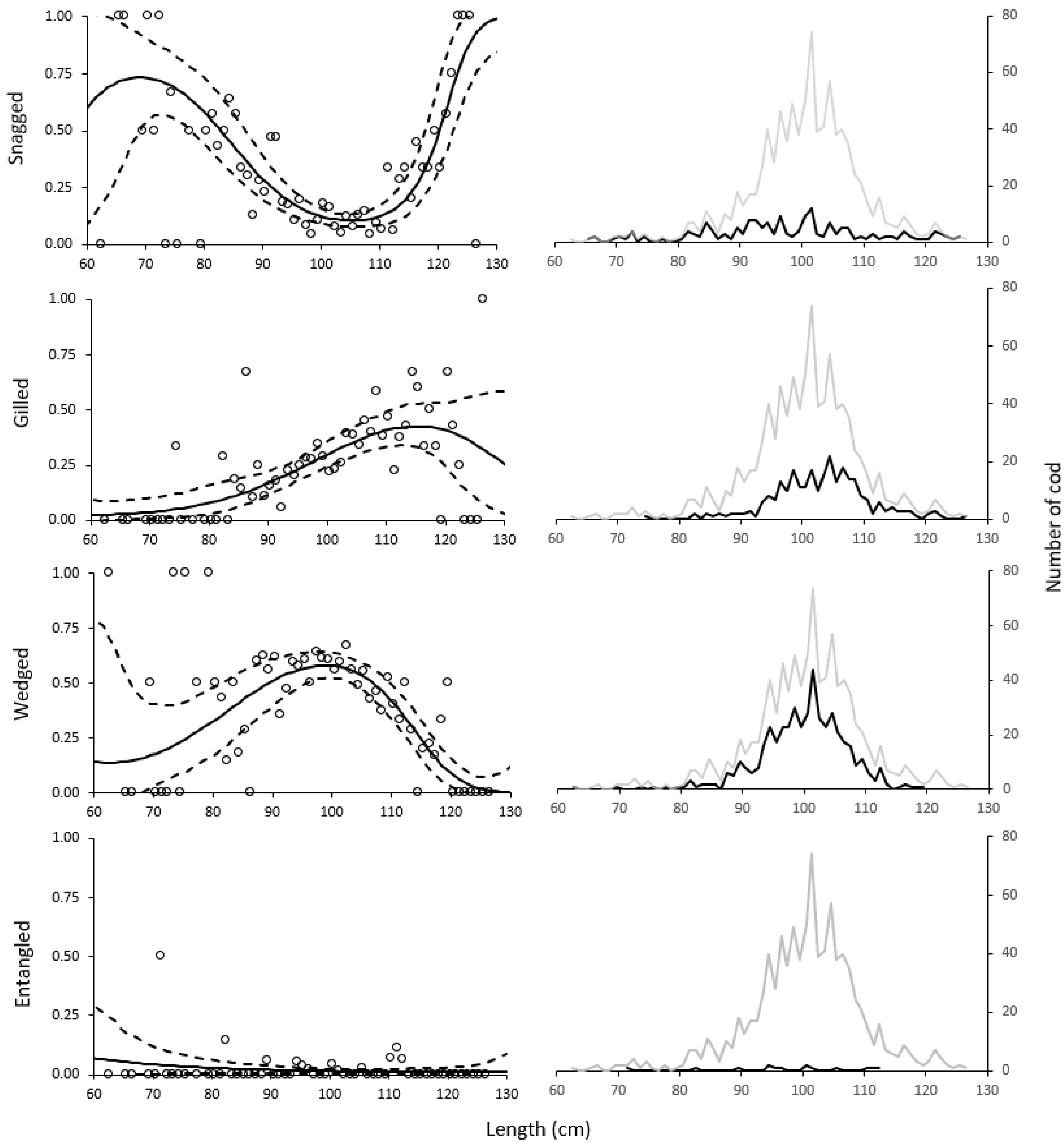

Figure 11: Probability of capture mode (left) and population structure (right) for 210 mm mesh size and 0.8 mm twine thickness. Dotted line shows the 95 % confidence intervals around the main trendline (black line). Black line in the population structure shows the share of the total catch (grey line) for each capture mode in this gillnet type.

Table 4: Capture mode probability and fit statistics for snagging, gilling, wedging, and entangling caught with 210 mm gillnet with 0.8 mm twine thickness. Numbers in parentheses show the 95 % confidence interval.

Length	Capture mode probability (%)			
(cm)	Snagging	Gilling	Wedging	Entangling
70	73.13 (54.78 – 90.11)	3.89 (0.92 – 10.42)	18.00 (3.66 – 40.24)	4.22 (0.24 – 11.62)
75	68.87 (54.38 – 82.16)	5.60 (1.54 – 12.56)	24.61 (9.91 – 41.52)	3.41 (0.41 – 8.07)
80	56.79 (42.51 – 71.65)	8.25 (3.16 – 16.29)	33.52 (17.94 – 48.83)	2.77 (0.42 – 5.96)
85	41.86 (29.50 – 55.90)	12.09 (6.54 – 19.19)	43.21 (29.41 – 56.42)	2.28 (0.44 – 4.53)
90	27.54 (18.86 – 37.26)	17.27 (12.06 – 22.58)	51.61 (40.71 – 61.05)	1.91 (0.51 – 3.63)
95	17.51 (12.39 – 23.01)	23.60 (18.66 – 28.51)	56.89 (49.58 – 63.91)	1.62 (0.62 – 2.78)
100	12.19 (9.08 – 15.12)	30.41 (24.98 – 36.40)	57.74 (52.33 – 63.54)	1.40 (0.64 – 2.25)
105	10.57 (7.90 – 13.36)	36.63 (30.23 – 43.73)	52.78 (46.12 – 58.49)	1.24 (0.47 – 2.10)
110	12.78 (8.73 – 17.91)	41.05 (33.76 – 49.73)	40.56 (32.19 – 48.12)	1.13 (0.21 – 2.23)
115	22.90 (14.77 – 34.01)	42.59 (32.83 – 53.05)	22.63 (13.95 – 31.19)	1.05 (0.07 – 2.26)
120	52.70 (35.94 – 75.92)	40.34 (22.84 – 53.45)	7.77 (2.19 – 14.03)	1.03 (-0.05 – 3.08)
Average	19.09 (15.63 – 22.44)	29.45 (24.80 – 33.71)	49.94 (44.76 – 54.95)	1.51 (0.73 – 2.38)
p–value	0.2936	0.8387	0.5554	0.9714
Deviance	59.13	43.77	51.91	36.04
DOF	54	54	54	54

For the gillnet with 210 mm mesh size and 0.8 mm twine thickness, the fit statistics show that the fitted model fits the experimental data well (*p*-value >0.05) for all capture modes (Table 4). Figure 11 shows similar trends as the gillnets with 210 mm mesh size and 0.7 mm twine. However, the curves are moved slightly to the right, i.e., up in length class of cod. The bottom point for snagging is around 105 cm, while the top point for wedging is at 99 cm at which point it has a catch probability of 58 % (Figure 11, Table 5). The top point for gilling is at fish lengths around 115 cm, where it has a catch probability of 43 % (Figure 11, Table 5). Like before, due to few fish getting entangled this capture mode does not show any trends.

Table 5: Top points (R_{max}) and correlating fish lengths (LR_{max}) on the bell-shaped capture mode probability curves for gilling and wedging for the 210 mm gillnets for both twine thicknesses. Numbers in parentheses show the 95 % confidence intervals. LR_{max} is measured in cm, and R_{max} denotes a probability rate (0.0 – 1.0).

Capture mode	Parameter	0.7 mm	0.8 mm
Gilling	R_{max}	0.49 (0.34 – 0.78)	0.43 (0.32 – 0.60)
	LR_{max}	121.77 (108.28 – 137.64)	115.20 (108.29 – 139.31)
Wedging	R_{max}	0.58 (0.52 – 0.64)	0.58 (0.52 – 0.75)
	LR_{max}	94.91 (90.46 – 98.44)	98.86 (66.73 – 106.45)

3.2.3 Capture pattern for gillnets with mesh size 230 mm and 0.7 mm twine

For the gillnet with 230 mm mesh size and 0.7 mm twine thickness a total of 99 cod were snagged, 104 cod were gilled, 177 cod were wedged and 5 cod were entangled (Figure 12, Table 6).

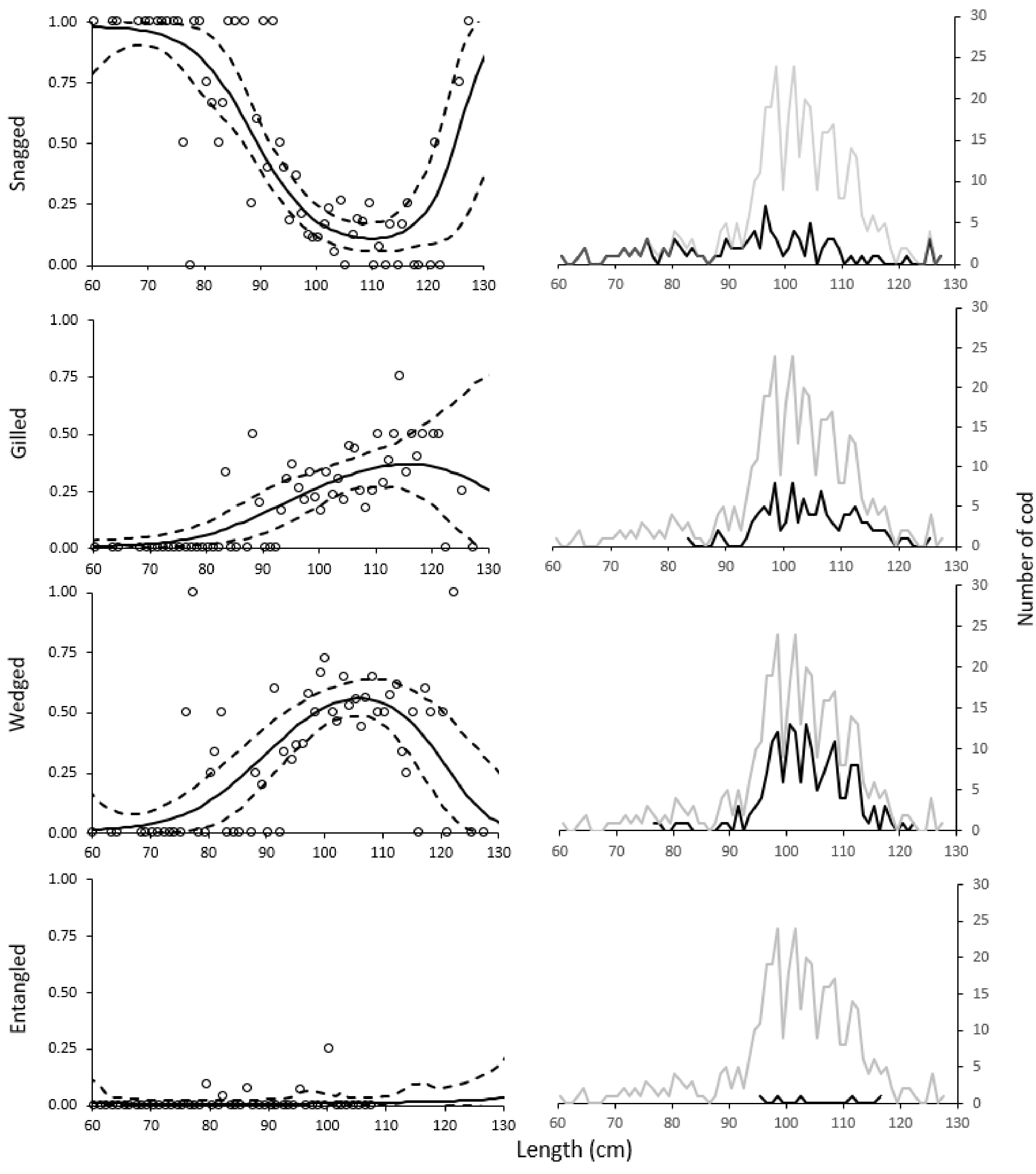

Figure 12: Probability of capture mode (left) and population structure (right) for 230 mm mesh size and 0.7 mm twine thickness. Dotted lines show the 95 % confidence intervals around the main trendline (black line). Black line in the population structure shows the share of the total catch (grey line) for each capture mode in this gillnet type.

Table 6: Capture mode probability and fit statistics for snagging, gilling, wedging, and entangling caught with 230 mm gillnet with 0.7 mm twine thickness. Numbers in parenthesis show the 95 % confidence intervals.

Length	Capture mode probability (%)			
(cm)	Snagging	Gilling	Wedging	Entangling
70	95.96 (90.03 – 99.67)	2.32 (0.56 – 5.65)	4.19 (0.11 – 9.46)	0.97 (0.36 – 2.72)
75	91.80 (82.12 – 99.18)	3.77 (1.11 – 7.81)	7.71 (0.87 – 15.55)	0.88 (0.34 – 2.44)
80	82.69 (68.27 – 95.52)	6.42 (2.07 – 11.86)	13.92 (3.42 – 24.95)	0.85 (0.33 – 2.39)
85	66.58 (55.01 – 80.85)	10.68 (3.87 – 19.02)	23.21 (10.50 – 35.02)	0.88 (0.34 – 2.54)
90	46.14 (37.62 – 56.45)	16.05 (7.14 – 25.72)	34.47 (22.80 – 45.36)	0.95 (0.31 – 3.00)
95	28.53 (21.34 – 36.72)	21.88 (12.81 – 30.94)	45.18 (35.35 – 53.64)	1.06 (-0.37 – 6.00)
100	17.60 (11.39 – 24.33)	27.55 (19.63 – 35.08)	52.88 (45.76 – 59.85)	1.20 (-0.04 – 4.93)
105	12.37 (7.07 – 18.36)	32.40 (25.68 – 39.13)	56.09 (48.70 – 63.39)	1.38 (0.36 – 3.61)
110	11.09 (5.80 – 17.73)	35.78 (26.95 – 43.82)	53.79 (44.23 – 63.89)	1.58 (0.20 – 4.29)
115	13.81 (6.44 – 23.52)	37.12 (25.41 – 49.35)	44.82 (29.55 – 58.92)	1.81 (-0.63 – 9.83)
120	24.83 (8.97 – 44.30)	35.83 (18.34 – 57.75)	29.27 (10.65 – 50.38)	2.13 (1.08 – 8.44)
Average	25.72 (19.64 – 31.66)	27.01 (22.02 – 32.17)	45.98 (40.14 – 51.37)	1.30 (0.02 – 2.96)
p–value	0.6356	0.9983	0.8624	1.0000
Deviance	48.87	27.80	41.96	19.60
DOF	53	53	53	53

The fit statistics for the gillnets with 230 mm mesh size and 0.7 mm twine thickness show that the fitted model fits the experimental data well (*p*-value > 0.05) (Table 6). Figure 12 show similar trends for both types of 210 mm mesh size gillnet, and also here the curves are shifted slightly to the right, catching larger fish. Here the bottom point for snagging is at approximately 110 cm, while the top point for wedging is around 106 cm where it has a catch probability of 56 % (Figure 12, Table 8). The top point for gilling is at 116 cm, at which point it has a catch probability of 37 % (Figure 12, Table 8). Like before, it is not possible to assess a general trend for entangling.

3.2.4 Capture pattern for gillnets with mesh size 230 mm and 0.8 mm twine

For the gillnet with 230 mm mesh size and 0.8 mm twine thickness a total of 87 cod were snagged, 105 cod were gilled, 159 cod were wedged and 6 were entangled (Figure 13, Table 7).

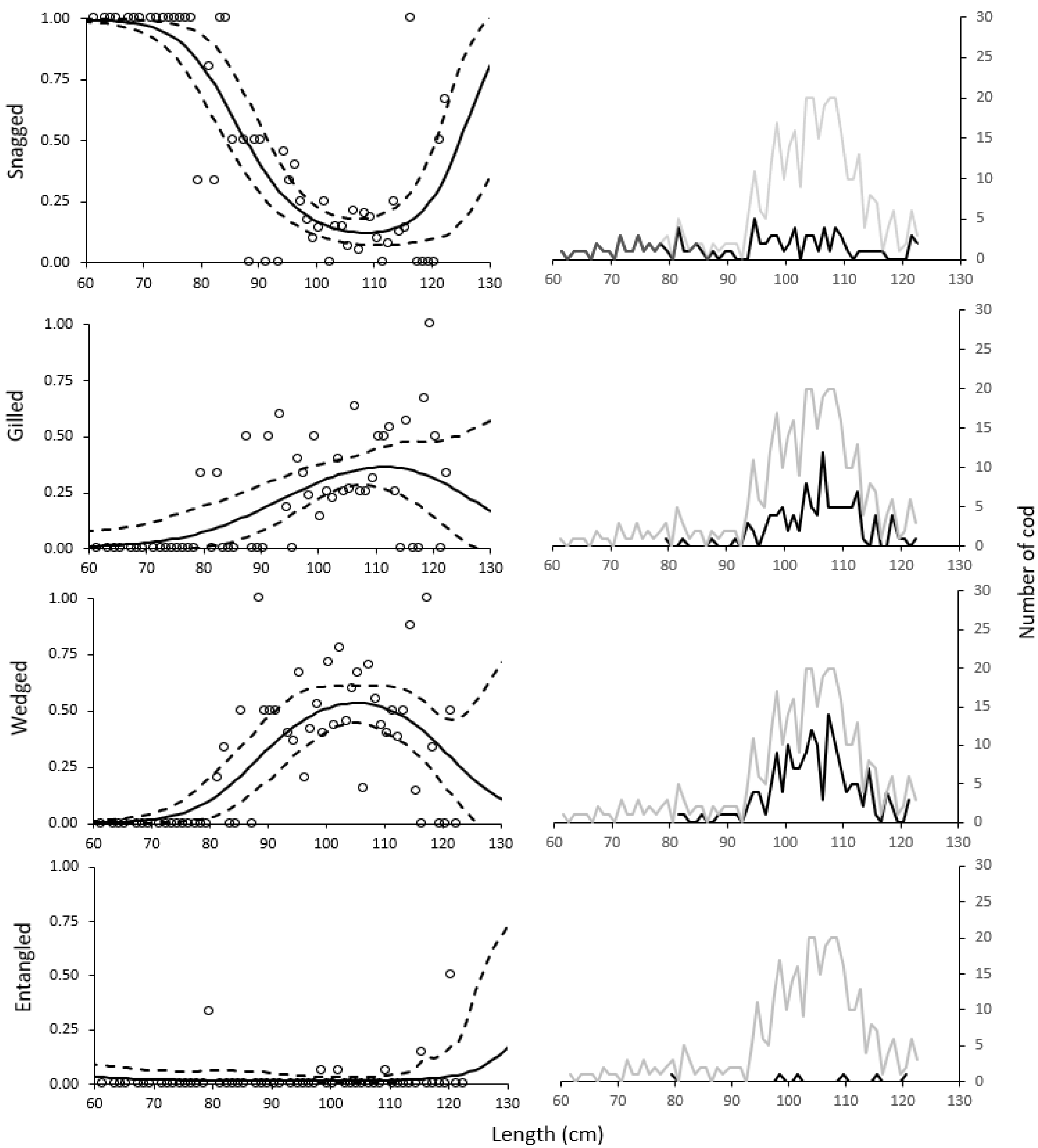

Figure 13: Probability of capture mode (left) and population structure (right) for 230 mm mesh size and 0.8 mm twine thickness. Dotted lines show the 95 % confidence intervals around the main trendline (black line). Black line in the population structure shows the share of the total catch (grey line) for each capture mode in this gillnet type.

Table 7: Capture mode probability and fit statistics for snagging, gilling, wedging, and entangling caught with 230 mm gillnet with 0.8 mm twine thickness. Numbers in parentheses show the 95 % confidence interval.

Length (cm)	Capture mode probability (%)			
	Snagging	Gilling	Wedging	Entangling
70	97.07 (93.56 – 99.37)	2.81 (-0.29 – 11.49)	1.95 (0.32 – 5.03)	2.06 (-0.07 – 6.36)
75	91.90 (84.48 – 97.91)	4.72 (-0.04 – 15.58)	4.78 (1.05 – 10.78)	1.78 (-0.22 – 5.91)
80	79.57 (66.58 – 92.66)	7.93 (0.98 – 19.60)	11.15 (3.09 – 21.55)	1.60 (-0.48 – 6.35)
85	59.80 (45.09 – 78.17)	12.55 (3.60 – 23.86)	21.90 (10.19 – 34.77)	1.44 (-0.34 – 5.98)
90	39.32 (27.77 – 55.25)	18.29 (8.40 – 29.02)	34.34 (20.01 – 48.70)	1.33 (-0.18 – 4.90)
95	24.67 (16.75 – 33.98)	24.53 (15.58 – 33.79)	44.88 (32.53 – 58.43)	1.29 (0.01 – 3.72)
100	16.52 (11.07 – 22.73)	30.31 (23.09 – 38.18)	51.47 (41.53 – 60.99)	1.32 (0.10 – 3.28)
105	12.92 (8.26 – 18.37)	34.61 (28.22 – 40.90)	53.55 (44.83 – 61.25)	1.46 (0.21 – 3.32)
110	12.66 (7.63 – 19.16)	36.55 (27.62 – 44.89)	50.98 (39.95 – 61.05)	1.75 (0.11 – 4.45)
115	16.28 (8.02 – 26.82)	35.46 (22.22 – 47.78)	43.56 (31.19 – 56.53)	2.36 (-0.58 – 10.74)
120	27.70 (10.21 – 48.61)	31.01 (13.33 – 48.00)	31.82 (16.09 – 46.59)	3.75 (-1.60 – 18.89)
Average	24.37 (17.16 – 31.98)	29.41 (23.31 – 35.57)	44.54 (37.10 – 51.94)	1.68 (0.27 – 3.40)
p–value	0.7134	0.2057	0.2266	0.9986
Deviance	44.90	59.02	58.23	26.03
DOF	51	51	51	51

For gillnets with mesh size 230 mm and 0.8 mm twine the fit statistics show a *p*-value > 0.05, implying there is no discrepancy between the fitted model and the experimental data (Table 7). Figure 13 shows similar trends as the previously mentioned gillnet types. Snagging has a low point around 110 cm. Wedging has a top point at 105 cm where the catch probability is 54 %, and gilling has a top point at 111 cm, where the catch probability is 37 % (Figure 13, Table 8).

Table 8: Top points (R_{max}) and correlating fish lengths (LR_{max}) on the bell-shaped capture mode probability curves for gilling and wedging for the 230 mm gillnets for both twine thicknesses. Numbers in parentheses show the 95 % confidence intervals. LR_{max} is measured in cm, and R_{max} denotes a probability rate (0.0 – 1.0).

Capture mode	Parameter	0.7 mm	0.8 mm
Gilling	R_{max}	0.37 (0.23 – 0.78)	0.37 (0.28– 0.50)
	LR_{max}	115.71 (101.56 – 135.76)	111.33 (101.39 – 122.58)
Wedging	R_{max}	0.56 (0.49 – 0.65)	0.54 (0.44 – 0.62)
	LR_{max}	106.07 (101.58 – 110.93)	105.27 (98.55 – 111.56)

3.3 Effect of twine thickness on length dependent capture mode probability

The results of assessing the effect of twine thickness on length dependent capture mode probability, outlined in section 2.1.5, which was done separately for both mesh sizes, is presented in Figure 14 – 15.

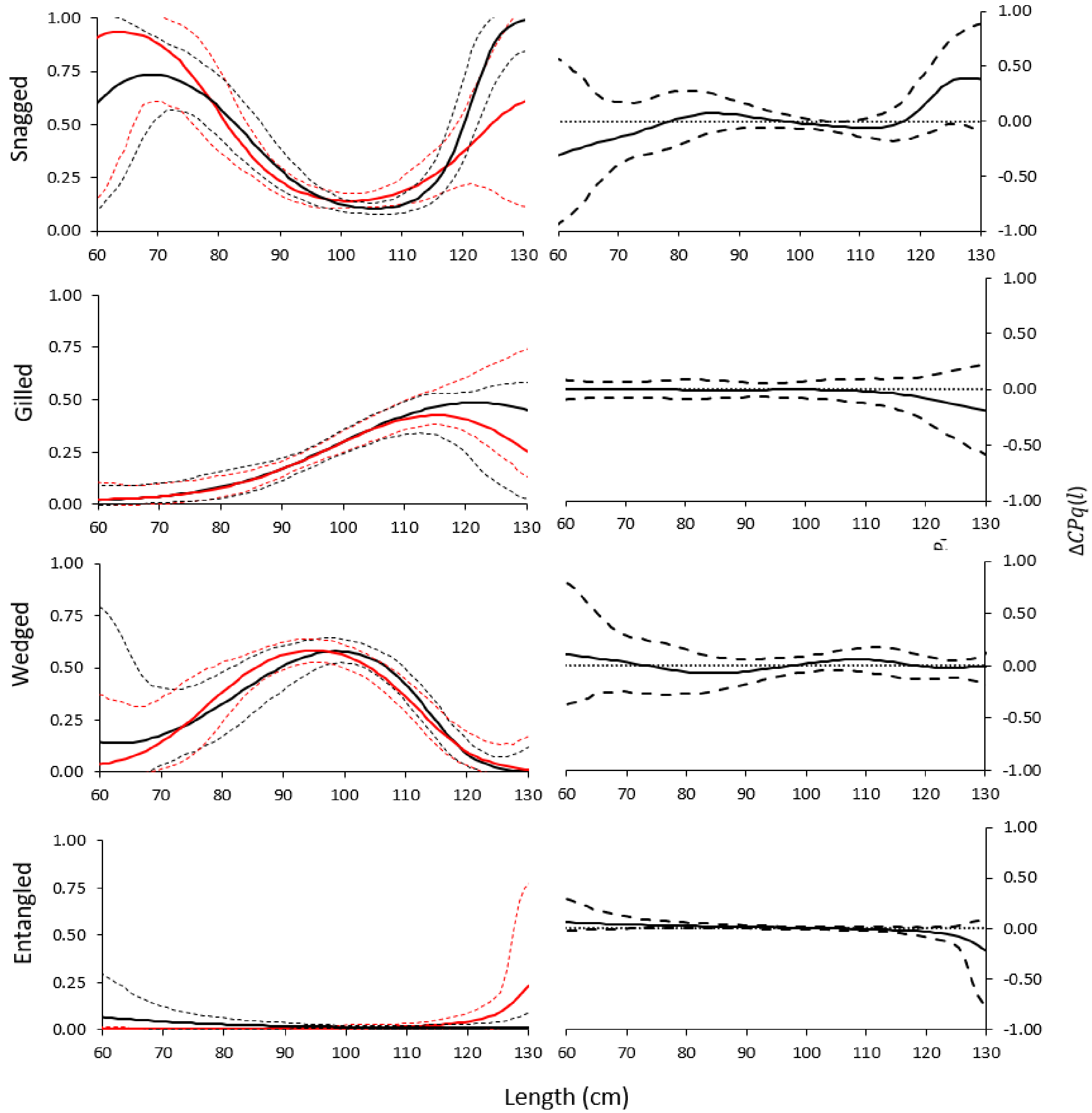

Figure 14: Left column: capture mode probability curves for 0.7 mm twine thickness (red) and 0.8 mm twine thickness (black) for gillnets using 210 mm mesh size. Right column: delta plots showing the effect on capture mode probability (ΔCPql) when increasing twine thickness in 210 mm gillnets. The horizontal line at 0 in the right column shows the baseline where there is no difference between the gillnets with the two twine thicknesses. Stippled lines represent 95 % confidence intervals.

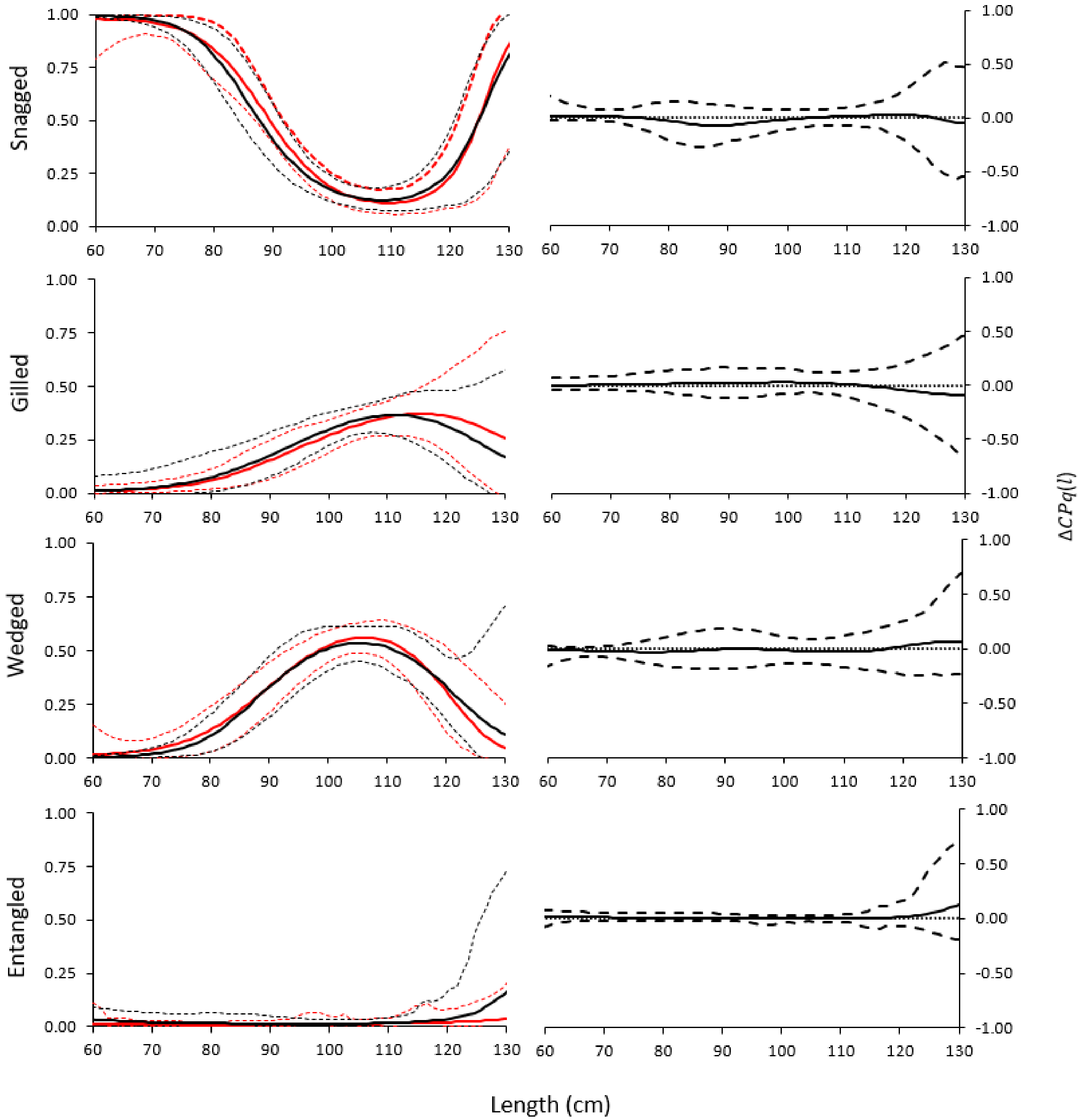

Figure 15: Left column: capture mode probability curves for 0.7 mm twine thickness (red) and 0.8 mm twine thickness (black) for gillnets using 230 mm mesh size. Right column: delta plots showing the effect on capture mode probability (ΔCPql) when increasing twine thickness in 230 mm gillnets. The horizontal line at 0 in the right column shows the baseline where there is no difference between the gillnets with the two twine thicknesses. Stippled lines represent 95 % confidence intervals.

The baseline, showing where there is no difference between the twine thicknesses, is within the 95 % confidence interval for all capture modes (Figure 14 – 15). This is the case for both mesh sizes. This means there is no clear effect on the capture mode probability for cod when increasing the twine thickness from 0.7 mm to 0.8 mm.

3.4 Effect of mesh size on length dependent capture mode probability

The results of assessing the effect of twine mesh size on length dependent capture mode probability, outlined in section 2.1.5, which was done separately for both twine thicknesses, is presented in Figure 16 – 17.

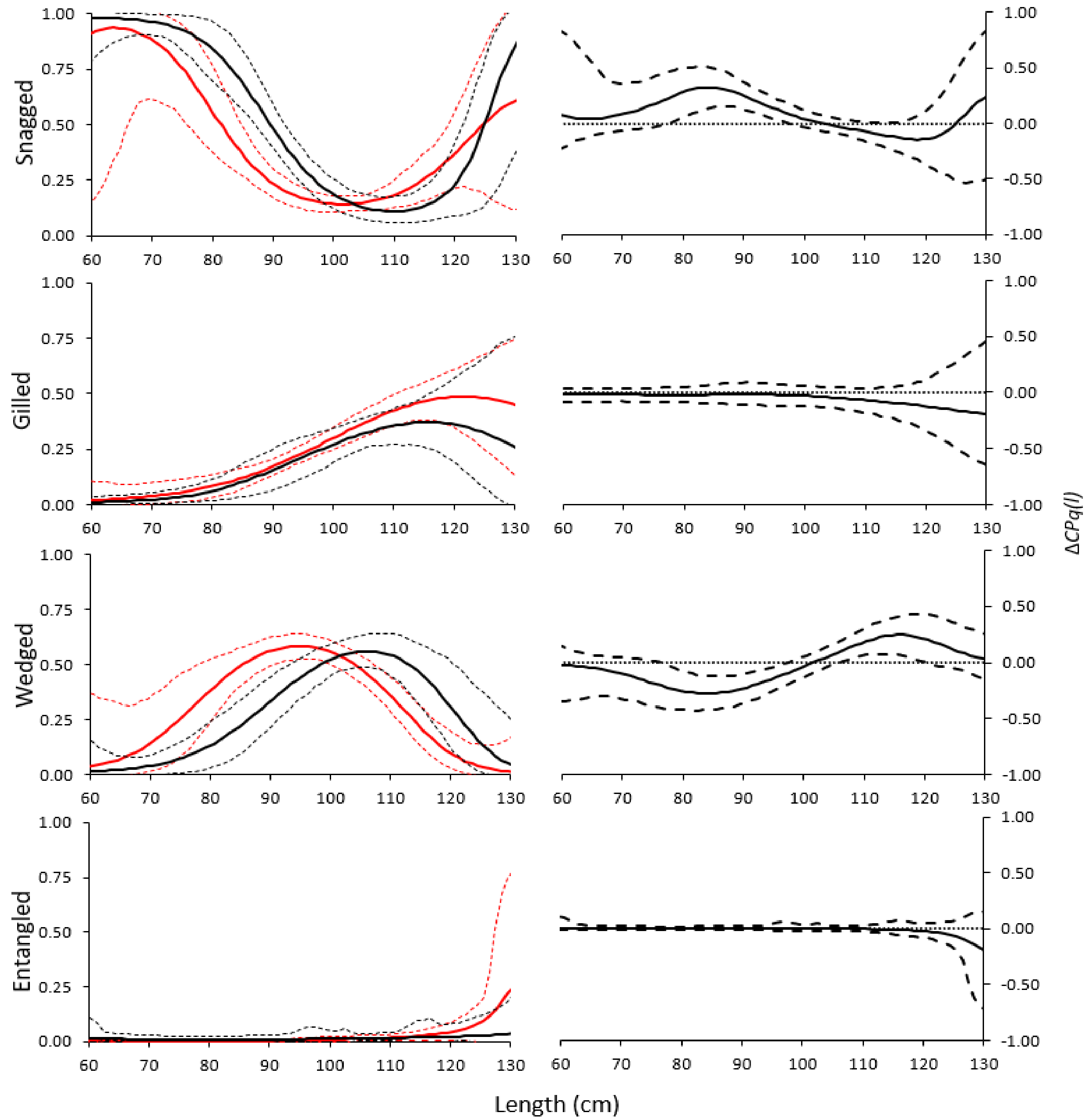

Figure 16: Left column: capture mode probability curves for gillnets using 210 mm mesh size (red) and 230 mm mesh size(black). Right column: delta plots showing the effect on capture mode probability (ΔCPql) when increasing the mesh size for gillnets with 0.7 mm twine thickness. The horizontal line at 0 in the right column shows the baseline where there is no difference between gillnets with the two mesh sizes. Stippled lines represent 95 % confidence intervals.

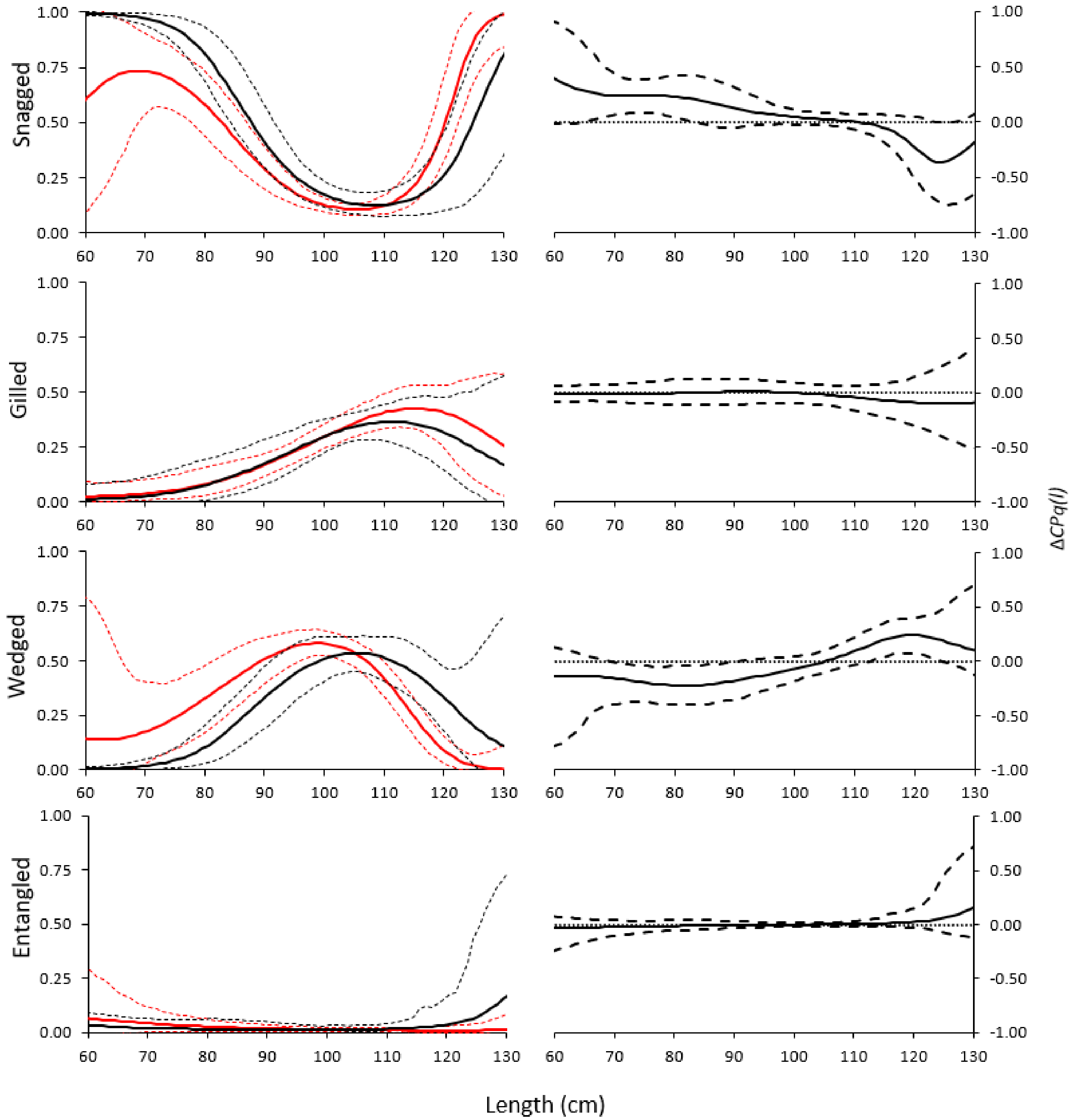

Figure 17: Left column: capture mode probability curves for gillnets using 210 mm mesh size (red) and 230 mm mesh size(black). Right column: delta plots showing the effect on capture mode probability (ΔCPql) when increasing the mesh size for gillnets with 0.8 mm twine thickness. The horizontal line at 0 in the right column shows the baseline where there is no difference between gillnets with the two mesh sizes. Stippled lines represent 95 % confidence intervals.

For gillnets with both mesh sizes the baseline of 0.0 is outside the 95 % confidence interval in two instances, namely snagging and wedging (Figure 16 – 17). This implies that there is a significant change in capture patterns when increasing the mesh size. Specifically, for snagging, increasing the mesh size results in an increase in capture probability by this mode for length classes of cod between 80 and 90 cm. The probability of capture by snagging decreased, following a downward trend, for larger length classes of cod resulting in a significant change for fish around 110 cm. For wedging, the trend appears to be opposite compared to snagging. Increasing the mesh size results in a lower capture probability, followed by an upward trend resulting in a significant higher probability. The same patterns are observed for both twine thicknesses (Figure 16 – 17).

3.5 Length dependent circumference measurements

A total of 135 cod, between the sizes of 27 and 120.5 cm of length, were sampled during the trials onboard R/V 'Helmer Hanssen' and used for the morphological data modelling (Figure 18).

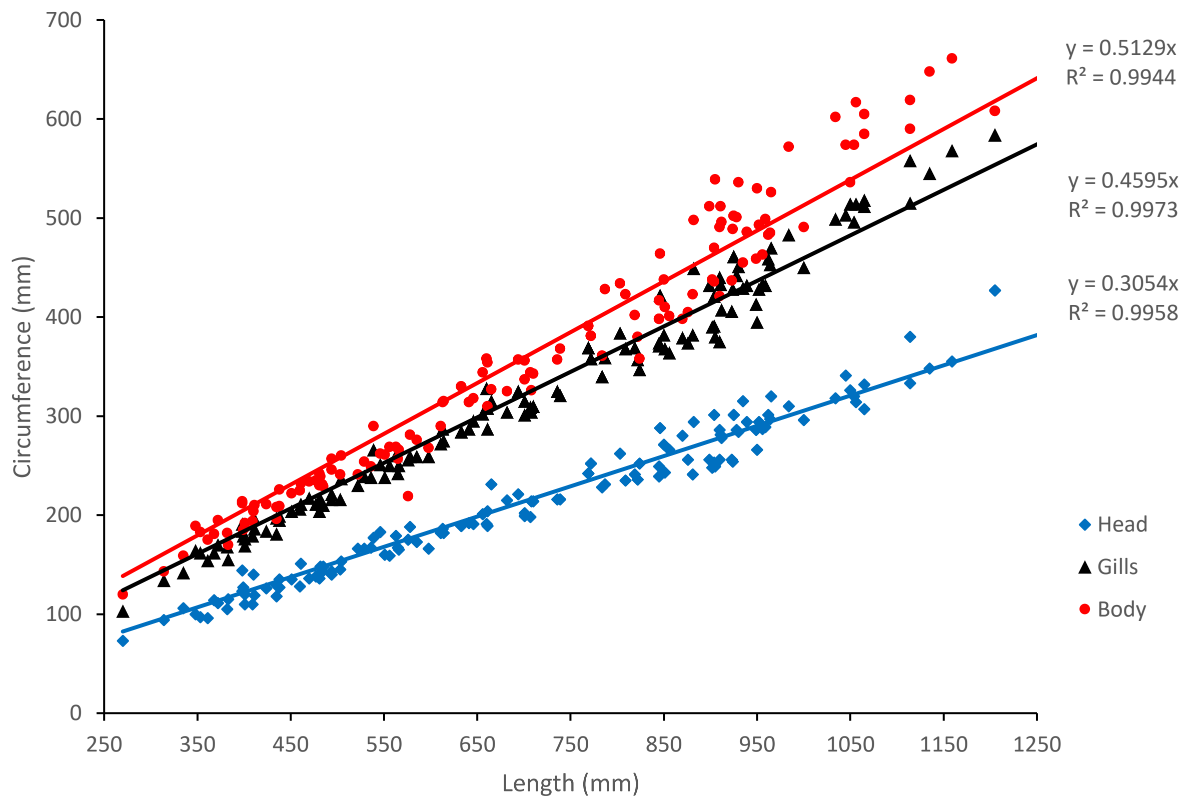

Figure 18: A simple linear regression plot for circumference measurements taken on three different parts of the fish body: head (blue squares), gills (black triangle) and body (red circle).

The results show that there is a clear linear relationship between fish length and different circumference measurements on a fish's body (Figure 18). Body- and gill circumference show the largest increase when the fish's length increases, while the increase in head circumference is slightly lower. The R^2 – values in figure 18 all show that the model fits the data well.

3.6 Fall-through experiments

For the fall-through experiments, conducted during the same research cruise onboard research vessel 'Helmer Hanssen', a total of 346 cod were sampled between the size of 70 and 114 cm of length (Figure 19, Table 9).

Table 9: Distribution of different fall-through modes observed in the fall-through experiments.

Fall-through mode	Number of cod
Snagged	84
Gilled	83
Wedged	25
Passed through	154

Figure 19 shows clear trends regarding the size dependent mode of capture for cod during the laboratory experiments. Different modes shift on being the most likely capture mode to occur for cod of different lengths. For instance, individuals in the smaller length classes appear to pass straight through the meshes. This changes for cod that are reaching about 80 cm of length when wedging becomes more frequent, followed by gilling and, finally, snagging. Maximum fall-through mode probability for wedging is only 0.14, where the corresponding length is 88.60 cm (Table 10). Maximum fall-through mode probability for gilling is 0.50, where the corresponding length is 93.56 cm (Table 10).

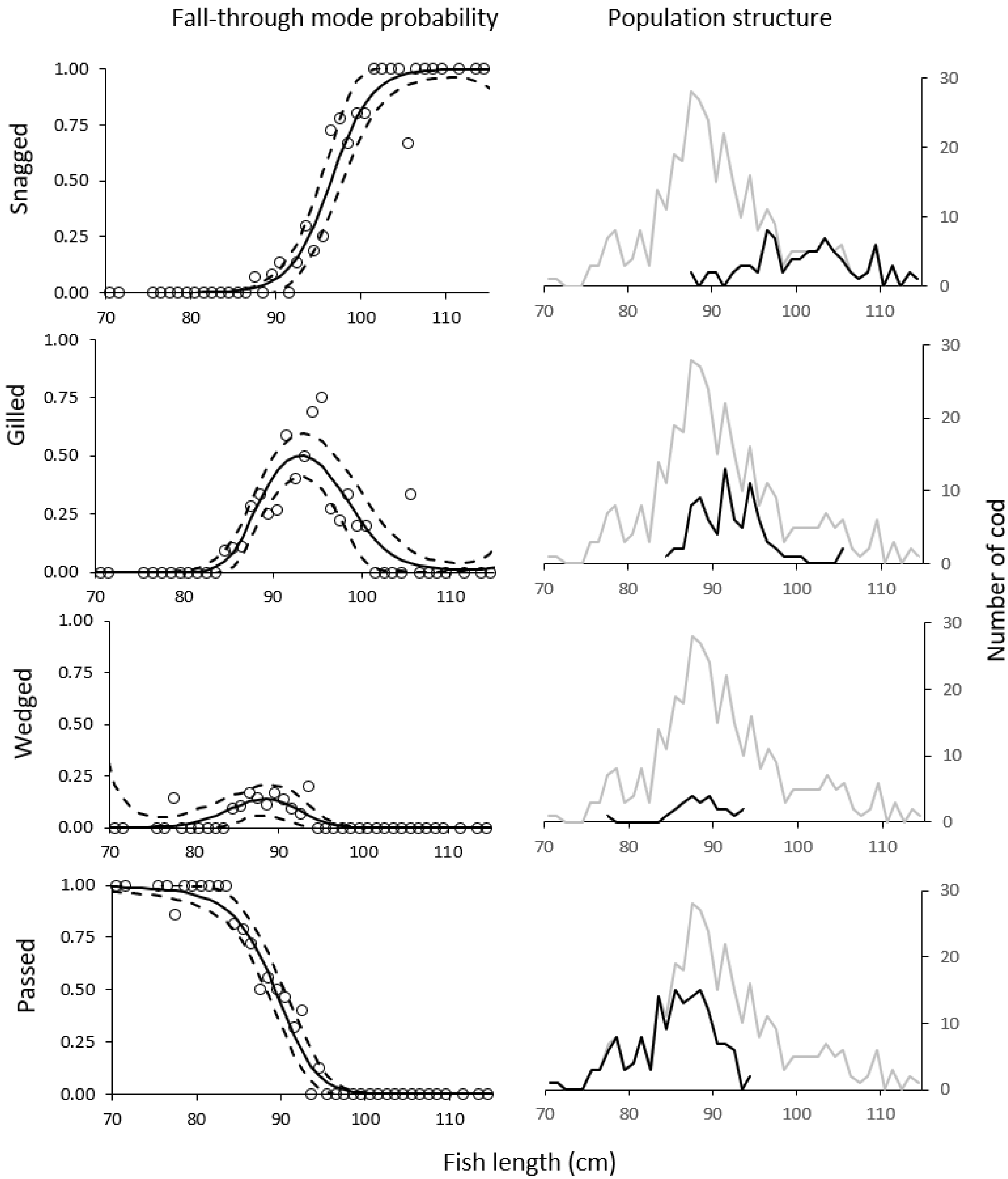

Figure 19: Left column shows the length dependent fall-through probability mode for the sampled cod. Black dotted line marks the 95 % confidence interval. Right column shows the population structure for the sample cod. Light grey line is the total population while the black lines show the population belonging to the respective fall-through modes.

The trend observed in this data makes sense considering the conical shape of a fish's body from the snout up to its largest girth. The point of largest circumference of the fish will logically be the first place that will get in touch with the fish when increasing body size and keeping the same mesh size. When fish get bigger, i.e., the maximum circumference increases, the mesh will get stuck earlier, meaning around the gills of the fish. Furthermore, when increasing the fish's size further, the fish will become enmeshed even earlier, i.e., around the head. It is worth noting that when performing this experiment, when fish were removed from the meshes, the maxillae, and sometimes the pre-operculum, tended to tangle up in the twine. Even though this experiment does not mimic fish behaviour when getting caught, considering this was a laboratory experiment using dead cod, this does show that the maxillae can get easily tangled up in the nets when a fish first gets in contact with the gear.

Table 10: Top points (R_{max}) and correlating fish lengths (LR_{max}) on the bell-shaped fall-through probability mode curves for gilling and wedging observed during the fall through experiments with the gillnet with 168 mm mesh size and 0.5 mm twine thickness. Numbers in parentheses show the 95 % confidence intervals. LR_{max} is measured in cm, and R_{max} denotes a probability rate (0.0 – 1.0).

Fall-through mode	Parameter	
Gilling	R_{max}	0.50 (0.44 – 0.55)
	LR_{max}	93.56 (93.56 – 93.78)
Wedging	R_{max}	0.14 (0.07 – 0.22)
	LR_{max}	88.60 (85.86 – 90.54)

3.7 General capture pattern for cod in gillnets

The capture mode probability data obtained from the fishing trials at 'Karoline', described in section 2.15, were combined with the morphological data, described in section 2.2, and fall-through experiments, described in section 2.3, conducted onboard 'Helmer Hanssen' to create a general pattern for how fish are captured. The resulting figure (Figure 20) shows the relationship between mesh size and fish length at LR_{max}, which is the fish length corresponding to the maximum probability of capture for different capture modes and fall-through modes. The linear regression plot in Figure 20 makes it possible to predict the LR_{max} for the mentioned capture modes based on the mesh size. Combining data found in Figure 18 and Figure 20 (Table 11 for gilling and Table 12 for wedging) results in Figure 21, showing the relationship between mesh size and the ratio between mesh- and fish circumference for capture- and fall-trough modes gilling and wedging.

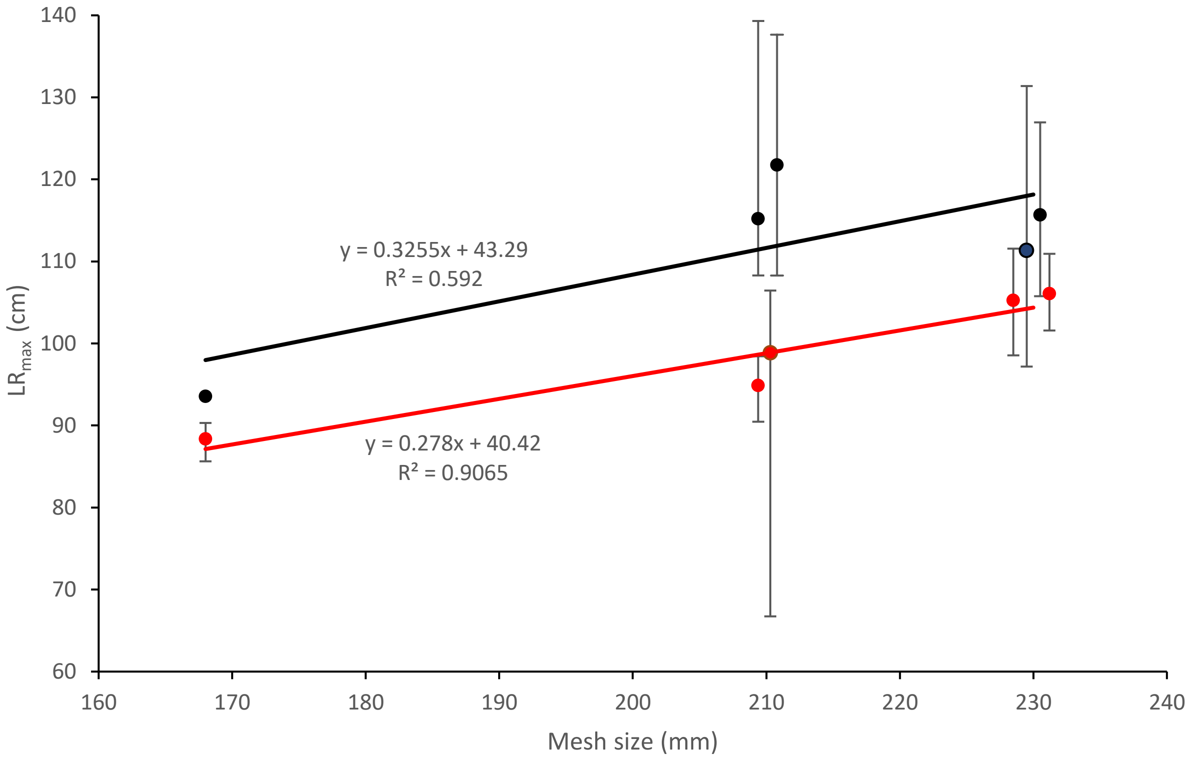

Figure 20: A simple linear regression plot showing the relationship between mesh size and fish length at LR_{max} for gilling (black line) and wedging (red line). Vertical bars on each side of the data points show the 95 % confidence intervals.

Table 11: LR_{max} for capture- and fall-through mode gilling for each mesh size and twine thickness, with the corresponding circumference measurement and the ratio between mesh size and circumference. Values in brackets show the 95 % confidence intervals.

Mesh size (mm)	Twine thickness (mm)	LR_{max} (cm)	Circumference (cm)	Ratio
230	0.7	115.71 (101.56 – 135.76)	531.7 (466.67 – 623.82)	1.16 (1.01 – 1.36)
230	0.8	111.33 (101.39 – 122.58)	511.6 (465.89 – 563.26)	1.11 (1.01 – 1.22)
210	0.7	121.77 (108.28 – 137.64)	559.5 (497.55 – 632.46)	1.33 (1.18 – 1.51)
210	0.8	115.20 (108.29 – 139.31)	529.3 (497.59 – 640.92)	1.26 (1.18 – 1.52)
168	0.5	93.56 (93.56 – 93.78)	429.9 (429.91 – 430.92)	1.28 (1.28 – 1.28)

Table 12: LR_{max} for capture- and fall-through mode wedging for each mesh size and twine thickness, with the corresponding circumference measurement and the ratio between mesh size and circumference. Values in brackets show the 95 % confidence intervals.

Mesh size (mm)	Twine thickness (mm)	LR_{max} (cm)	Circumference (cm)	Ratio
230	0.7	106.07 (101.58 – 110.93)	544.03 (521.00 – 568.96)	1.18 (1.13 – 1.24)
230	0.8	105.27 (98.55 – 111.56)	539.93 (505.46 – 572.19)	1.17 (1.10 – 1.24)
210	0.7	94.91 (90.46 – 98.44)	486.79 (463.97 – 504.90)	1.16 (1.10 – 1.20)
210	0.8	98.86 (64.66 – 115.92)	507.05 (331.64 – 594.55)	1.21 (0.79 – 1.42)
168	0.5	88.37 (71.03 – 100.64)	453.25 (364.31 – 516.18)	1.35 (1.08 – 1.54)

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The linear regression in Figure 21 allows us to predict the ratio between the gillnet mesh size and fish circumference around the gills and the body. From this plot we can infer how much larger the circumference around the gills, or the body of a fish will be compared to the mesh circumference when getting enmeshed in a gillnet with certain mesh size. The results in Figure 21 show us that the cod circumference measured during the gillnet fishing trials is around 20 % larger than the mesh circumference. These observations and the fall-through experiments regarding LR_{max} fit reasonably well within the predicted range[2] described in Potter (1991) when considering the uncertainties to these data points.

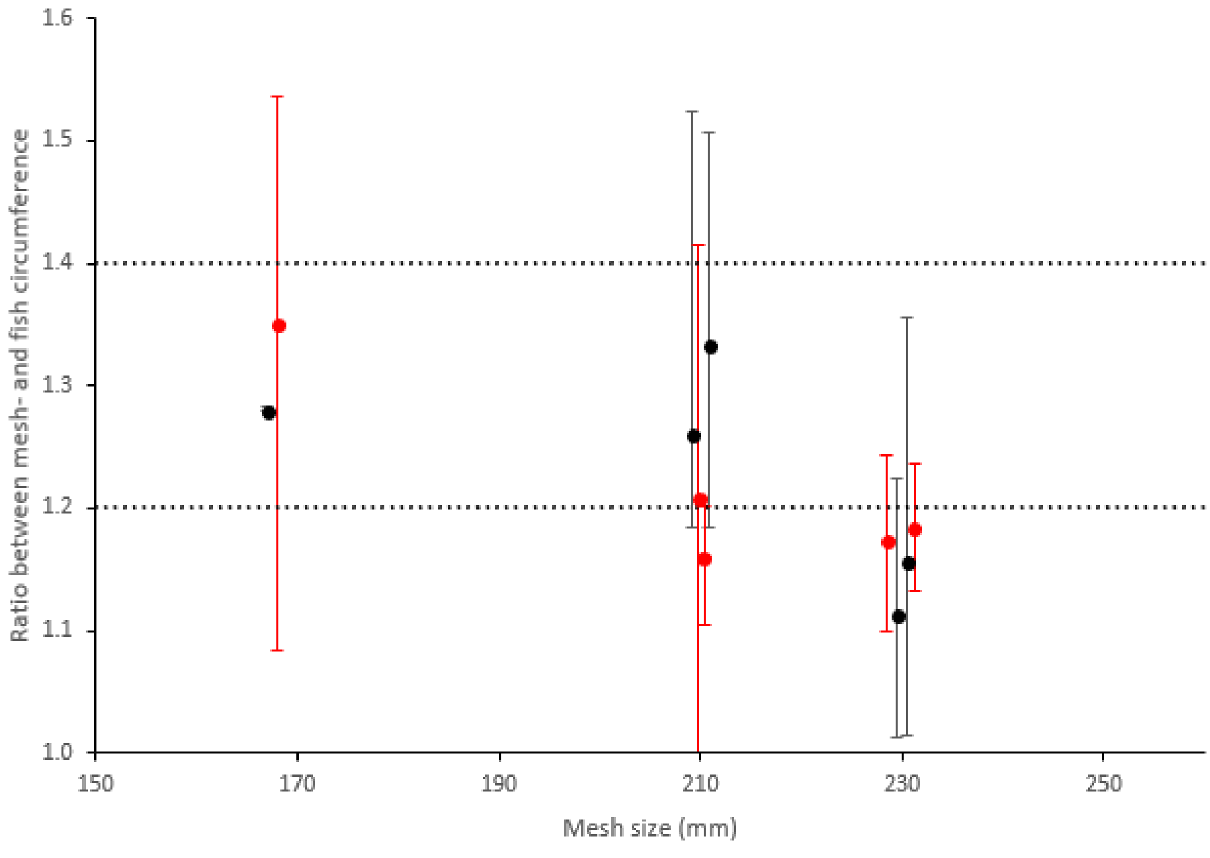

Figure 21: Shows the relationship between mesh size and the ratio between mesh- and fish circumference for capture- and fall-through modes gilling (black) and wedging (red). The horizontal dotted lines at 1.2 and 1.4 highlight the range in which most fish are predicted to be captured in according to Potter (1991). Vertical bars on each side of the data points show the 95 % confidence intervals.

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[2] A study by Potter (1991) showed that salmon with a girth between 20 and 40 % larger than the circumference of the mesh have the highest chance of getting caught by the gillnet

4 Discussion

The aim of this study was to establish a general pattern to quantify how round-fish get caught in gillnets. This is to fill the knowledge gap regarding the understanding of how different gillnet parameters affect the capture process. This is important because the current challenges in gillnet fisheries, mainly marine plastic pollution and ghost fishing, have led to the development of new biodegradable materials used for gillnet construction. However, we lack the knowledge base to fully understand and explain the observed difference in capture efficiency of biodegradable compared to nylon gillnets (Grimaldo *et al*. 2020b) and therefore what parameters to focus on when furtherly developing biodegradable materials that could provide at least similar catch efficiency as nylon gillnets. A leading hypothesis in explaining observed differences between gillnets made of nylon and biodegradable material is reduced twine elasticity (Grimaldo *et al.*, 2018ab, 2019, 2020ab; Cerbule *et al.*, 2022b). The elasticity of gillnet twine material correlates with its diameter, hence making it possible to measure the effect of material elasticity by comparing different twine thicknesses. Therefore, the research questions of this study investigated the effect of twine thickness for different mesh sizes on catch efficiency and quantifying how cod get caught in the gillnets. The results from these investigations might inform us on what material properties are important to consider, and to which extent, when developing new biodegradable materials for gillnets.

4.1 The effect of twine thickness on gillnet catch efficiency

The results from investigating the effect of twine thickness on gillnet catch efficiency, presented in section 3.1, showed that there was no proof of any overall significant difference in catch efficiency between the two twine thicknesses for both mesh sizes investigated. The only exception was observed for cod with a length of around 105 cm caught by the gillnets with 210 mm mesh size. Here the gillnets with the 0.7 mm twine caught 14 % more than the gillnets with the 0.8 mm twine. However, despite the overall non-significant result, there is an indication of a weak trend for the gillnet with 210 mm mesh size, showing a slight increase in catch efficiency for the 0.7 mm twine when fish length increased and average 10.9 % higher catch efficiency. This is in accordance with several previous studies (Hansen, 1974; Turunen, 1996; Yokota *et al.*, 2001; Kim *et al.*, 2016) who reported larger catches, and in general larger fish, caught by gillnets made of thinner twine. A possible explanation for this is that thinner twine requires a smaller force to be elongated compared to thicker twine, and it can therefore stretch more easily and enhance the capture of fish from a larger length range. In accordance with this, a large fish will be able to exert more force on the twine compared to a smaller fish, and therefore stretch the twine more. As long as the twine does not break, the thinner twine can catch larger, and more, individuals compared to thicker twine. Also, since thicker twine will stretch less, it will only be more suitable for species with a girth that matches the chosen mesh size. Therefore, thicker twine will capture fish in a narrower length range, as observed in He (2006) and Kim et al. (2016). Another possible explanation for thinner twine having a higher catch efficiency compared to thicker twine can be that the latter might be easier detectable for fish, both visually (Hansen, 1974) and by the sensory system on the lateral line (Gabriel *et al.*, 2005). This would, however, be dependent on the environment and could also be species dependent, some fish having better sensory organs than others (Arimoto *et al.*, 2010). Also. the general fish behaviour and swimming ability can be a species dependent factor that might influence the effect of twine thickness on gillnet catch efficiency. How much impact species dependent factors like sensory organs and/or swimming behaviour had on the results in the present study is unknown.

The same indication of a trend showing a slightly higher catch efficiency for thinner twine was not observed for the gillnet with the 230 mm mesh size. This might be explained by relatively few individuals caught by this gillnet type and looking at the catch comparison results in Figure 8, there is substantial dispersion of the data points. Subsequently, the uncertainty levels are high, making it difficult to speculate on a trend. Therefore, based on these findings, one can assume that mesh size is not proven to change the effect of twine thickness on catch efficiency.

It is important to note that the lack of proof of significant difference in catch efficiency between the two twine thicknesses in this study does not mean twine thickness is a negligible parameter in gillnet construction. One can speculate that a significant result might have been obtained if the dataset was bigger, i.e., higher fish count, or if the contrast between the twine thicknesses was larger. For instance, Grati *et al.* (2015) investigated five different twine thicknesses, and even though there was only a slight decrease in catch efficiency when lightly increasing twine thickness, the difference was substantial when looking at the thinnest (0.18 mm) versus the thickest (0.30 mm) twine. It is possible to assume that a similar pattern could have been obtained in this study if the contrast between the twine thicknesses would have been bigger.

Investigating the effect of twine thickness on capture efficiency and pattern for the same material can be considered an indirect way of investigating the effect of material elasticity and the effect of material properties in terms of Young's modulus. Therefore, it is a way of investigating the sensitivity of catch efficiency and pattern on basic material properties in terms of elasticity. In this way the investigation of twine thickness can be linked to ongoing development of biodegradable materials as a replacement for nylon.

Young's modulus changes with material properties, and thus, since only nylon was tested in this study, the Young's modulus was the same for all gillnets. Therefore, to be able to mimic the effect of changing the Young's modulus we can obtain a similar effect by changing the twine thickness. By doing so, and analysing the results, we learned that the catch efficiency is not proven to be very sensitive to small changes in twine thickness. With this in mind, there is potential range of twine thicknesses to work within when adjusting the different design parameters of the twine. For instance, if the biodegradable material has a higher Young's modulus compared to nylon, we can reduce the thickness of the twine to compensate for this. A high Young's modulus means the material is less elastic and requires more force to elongate. On the other hand, if the biodegradable material has a lower Young's modulus compared to nylon, we can increase the thickness of the twine to compensate for this. In this way, when we develop new biodegradable materials for gillnets, we could adjust the twine thickness to some extent without significantly reducing the catch efficiency of the new material.

Regarding the elongation of the twine, it is important to note that when a force is applied to the twine, e.g., an enmeshed fish, and this force is removed, the material does not go back to its original form immediately (Klust, 1982). Furthermore, one can speculate that with repeated stretching over time (i.e., the same mesh catching fish multiple times) this effect can become gradually more permanent, and thereby leading to larger meshes with weaker twines. This can thereby potentially reduce the catch efficiency of the gillnets and explain reduced catch efficiency over time or between different gillnet twine materials. However, this is outside the scope of this thesis.

In addition to elasticity, twine thickness is also highly relevant when it comes to a mechanical property like breaking strength. This has previously been investigated by Grimaldo *et al.* (2020b) who tested two different twine thicknesses of PBSAT gillnets in order investigate if this could explain the previously experienced results showing a substantial difference in catch efficiency between biodegradable and nylon gillnets. The results showed that there was no proof of a difference in catch efficiency between the two gillnet types with different thicknesses of PBSAT twine, implying that the difference in catch efficiency could not be explained by the difference in breaking strength (Grimaldo *et al.*, 2020b). In the sense that two different diameters of the same material had the same catch efficiency, those results are consistent with the findings in the present study.

The results from this study, corroborated by Grimaldo *et al.* (2020b), show that small changes in mechanical properties like elasticity and/or breaking strength when changing the twine thickness, will not significantly change the catch efficiency of the gillnets, and this is not proven to be affected by the mesh size. Therefore, when developing a biodegradable material with the aim to replace nylon, one must compensate for differences in material properties like elasticity/Young's modulus, stiffness, or breaking strength, one can operate within a range of twine thicknesses for the same mesh size without affecting the overall catch efficiency of the material.

4.2 Capture mechanisms for cod of different lengths

When investigating how cod of different lengths get captured in different ways, some clear patterns were observed. The capture mode probability for the different capture modes changes for different lengths of cod. For small cod snagging is most dominant. When increasing cod length wedging become more dominant, then gilling, and finally again snagging for the largest individuals. The latter shows a u-shaped capture mode probability curve. This trend can be explained by the increasing circumference of the body up the first dorsal fin. The first position in which the fish can get stuck while swimming forward will be at the maximum circumference (i.e., girth), after which the point of capture will get closer towards the snout when moving up in length class. This trend regarding a shift in capture mode probability is also witnessed in Savina *et al.* (2022) and Cerbule *et al.* (2022b). In Savina *et al.* (2022), the capture mode snagging is classified differently, differentiating between the twine getting stuck in the mouth, maxillary, or head. However, merging these three capture modes together gives the same results as observed in this study. It is clear however, considering the u-shaped probability curve, that the different ways of snagging are length dependent. This was observed during the fishing trials and fall-through experiments and can also be inferred from observing the capture mode probability curves (Figure 10 - 13) and considering cod morphology. Fish with a circumference smaller than the mesh circumference can theoretically swim through the mesh without getting caught. Therefore, the only way these individuals might get captured is if the twine gets stuck in the mouth. This could therefore explain the first top of the capture mode probability curve for snagging. On the second top, when the circumference around the body and gills has become too large to get enmeshed at these points, the twine can get stuck around the head, possibly the pre-operculum. When even larger cod encounter the net, this will be less likely, and when attempting to swim out of the mesh, the twine can get stuck on the maxillae. Also capture by the teeth might be possible for large individuals. This could thereby explain the observed trends for capture mode snagging, supported Savina *et al.* (2022) and partly by the fall-through data.

Furthermore, as described in section 3.2, when fish length increases, the probability of fish becoming wedged also increases. The curve is bell-shaped, clearly showing that only fish between a specific length-range can be captured this way. This observation is also witnessed in other studies regarding capture mechanisms (Cerbule *et al.*, 2022b; Savina *et al.*, 2022). Also, the fall-through experiments show a similar bell-shaped curve. However, wedging constitutes a significantly smaller proportion of the total capture modes in the fall-through data compared to the gillnet fishing trials. A possible explanation for this is that the fish might not exert as much force on the mesh during the capture process as gravity does during the fall-through experiments when moving through the mesh. In any case, one needs to be cautious when comparing the two different results, because even though the fall-through experiments support the trends witnessed in the catch mode analysis, they do not inform us about catch efficiency. The fall-through data thereby provides information, helping to establish a pattern on length dependent capture mechanisms.

When fish length increases furtherly, so does the probability of capture by gilling. The capture probability curve for gilling resembles a bell-shaped curve, however, due to the lack of large cod, the uncertainty levels are high at this point, make it uncertain to assess the precise shape of the probability curve. However, analysing the results from the fall-through experiments (a smaller mesh size was used), the results showed a distinct bell-shaped curve. It can therefore be speculated that this might have been achieved during the fishing trials if larger fish were captured. This trend is also observed in Savina *et al.* (2022), furtherly supporting these findings.

As shown, the laboratory experiments (i.e., fall-through) have provided valuable information that contributed to identify and understand the capture process of cod in gillnets. These experiments let us investigate certain mechanisms in a controlled environment, in contrast to the fishing trials where we cannot always control the entire process or aspects related to this. For instance, as this study has shown in several situations, the fall-through data has not only supported, but also confirmed assumptions that would not be possible without these experiments. For example, based on the fishing trials, we can only assume that capture mode gilling follows a bell-shaped curve. This is because we simply did not catch big enough cod to prove this. However, the fall-through experiments proved this assumption to be correct, since the experiment allowed us to select the size of fish more proper too the mesh size. For this reason, laboratory experiments (i.e., fall-trough experiments) will be a valuable and necessary tool in future investigations of technical gillnet and material parameters and their effect on capture mechanisms.

4.3 The effect of twine thickness and mesh size on the way cod get captured in gillnets

The results from investigating the effect of twine thickness on the way cod get captured, presented in section 3.3, show no significant differences for both mesh sizes. Specifically, the probability of getting caught by the different capture modes did not show significant differences between the 0.7 mm- and the 0.8 mm twine for cod of all lengths. It is unlikely that a larger dataset would have given a significant difference, considering that the probability curves, including the narrow 95 % confidence intervals, show no indication of a difference in capture mode probability. However, one can speculate that a larger contrast between the twine thicknesses would have resulted in a difference in the way cod would be captured.

These results are consistent with the observations in Holst *et al.* (2002), who did not find any difference in capture modes between different twine thicknesses in gillnets targeting Baltic cod. These results are in contrast to the study conducted by Grati *et al.* (2015) who found that an increase in twine thickness increases the chance of gilling while decreasing the chance of snagging. However, this study investigated common sole, which has a different morphology. Considering that capture mechanisms are possibly morphology-dependent (Reis & Pawson, 1999), this might explain the discrepancy between the present study and the findings in Grati *et al*. (2015). Differences in behaviour and swimming ability between the species mentioned here might also contribute to this explanation. To the knowledge of the author of this thesis there are few other studies that thoroughly investigate the effect of twine thickness on the way fish get caught, and it is therefore challenging to compare the findings in the current study to other studies.

When investigating the effect of mesh size on the way cod of different lengths get captured, presented in section 3.4, significant differences are observed. Specifically, an increase in mesh size led to an increase in snagging of small cod and a decrease for large cod. At the same time, this also led to a decrease in wedging for small cod and an increase for large cod. These observations are in accordance with the capture patterns described earlier and can be explained by the cod's morphology. Increasing mesh size will require an increase in circumference of the fish for it to be caught by gilling or wedging. This can also be inferred from morphological data in section 3.5. The trend observed for snagging, i.e., a large mesh has a higher chance of snagging small cod than a smaller mesh, needs to be seen in context with the trend observed for capture mode wedging. That is, a smaller mesh would at this point primarily be wedging fish for cod of the observed length classes. The opposite is the case when the small mesh has a higher chance of snagging large fish compared to a bigger mesh. That is, at this point the large mesh would primarily be capture fish by wedging and gilling, hence explaining the mirrored trend seen in Figure 15 - 16. These trends were similar for both the 0.7 mm- and the 0.8 mm twine.

Based on the results of investigating the effect of twine thickness and mesh size on the way cod get captured in gillnets, we can assume that small change in twine thickness has little effect on the different ways that cod get capture. This thereby supports the investigation of the effect of twine thickness on the overall catch efficiency where no difference was observed. However, the mesh size, together with the circumference at different points on the fish, appears to be the most dominant factors deciding the length dependent capture mode probability.

4.4 General pattern on how cod of different lengths get captured in gillnets

Combining the results from the gillnet trials and the laboratory experiments allows us to furtherly develop the general pattern for how round-fish get caught. Previous research indicated that fish (salmon) with a maximum circumference between 20- and 40 % larger than the circumference of the mesh have the highest probability of getting caught (Potter, 1991). To test this finding of Potter (1991), the results found in section 3.7 must be considered. Here, Figure 20 allows us to predict the length of the fish for capture mode wedging and gilling when operating with a specific mesh size. The results showing a 20- to 40 % increase in fish circumference is found in cod between the lengths of 99- and 113 cm for the 210 mm gillnet and 107- to 125 cm for the 230 mm gillnet. To generalize, it is helpful to express this in a ratio between gillnet mesh- and fish circumference and mesh size, seen in Figure 21. Here we can see that all data points with uncertainty levels are within a ratio of 1.2 and 1.4. This thereby indicates that the findings in Potter (1991) is consistent with the present study. Therefore, even though the study in Potter (1991) was performed on salmon, the assumption appears to be possible to extrapolate to other round-fish species with a comparable morphology. In addition to confirming the assumption found in Potter (1991), we also get an approximate estimation on how much the twine deforms the tissue of the fish and how much the twine elongates. However, we did not assess how these two factors interact with each other in the capture process. Therefore, further investigation is required to evaluate to which extent the mesh stretches and how much the body of the fish will compress.

The LR_{max} values are obtained from different mesh sizes, different twine thicknesses and different capture modes. Nevertheless, they all fit into a similar pattern regarding the effect of mesh size on the LR_{max} value. Thereby they ignore the potential effect of twine thickness that this study has not found proof of, and the fact that some of the results are based on a mix experimental fishing and laboratory experiments. Considering the different origin of the data, the observed trend is therefore reasonably clear. Furthermore, since the most dominant ways of capture are gilling and wedging, cumulatively explaining about 76 % of the captured cod, this trend can be used to improve the efficiency when targeting cod. Specifically, if the population structure in an area is known, we can choose the mesh size that will most effectively capture those fish.

4.5 Final remarks

This present study has established a general pattern for how round-fish get caught in gillnets. The understanding of the effect of twine thickness and mesh size on capture patterns is improved and can thereby potentially have implications for future development of biodegradable gillnets. Future investigations should shed light on other gillnet parameters that might aid in explaining capture patterns further. For instance, hanging ratio could be a mechanism that is likely to have an impact on the capture process, both efficiency and way of capture. Considering the knowledge obtained in this study (most cod are gilled and wedged) it would make sense to test which hanging ratio would be most efficient regarding these capture modes. Furthermore, the hanging ratio might also be investigated in combination with twine thickness. Twine thickness is a major factor influencing how much force a fish can apply to be caught. However, the force a fish will be able to apply might also be affected by the hanging ratio. Specifically, when operating with a low hanging ratio (loose web) the net might "give in" when a fish encounters the net panel, and therefore more force is required for a fish to be gilled or wedged (Potter, 1991). A low hanging ratio might also result in a larger proportion of fish getting captured by multiple meshes, considering the web is loose, and when a fish attempts to turn around and swim back it might swim into other meshes (Potter, 1991).

Future research might also focus on other gillnet parameters which potentially could influence the target species ability to perceive the gillnet. For instance, twine colour might explain some differences in catch efficiency. Even though this was not considered to be of much importance in the present study, considering the large depths and time of the year the trials took place. But in other fisheries this can be of more importance. Related to this, the surface of the twines could also be subject for further investigations. Specifically, it can be speculated that a rougher surface, as observed on used biodegradable PBSAT twines (Grimaldo *et al.*, 2020a), could collect more sediments and/or particles in the water, making them more visible. Future investigations of these factors might further deepen our understanding of how gillnets work, and thereby contribute to create a solid knowledge base that is necessary for developing a biodegradable material that can replace nylon material in gillnets.

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