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Use of biodegradable plastic materials in gillnet and longline fisheries

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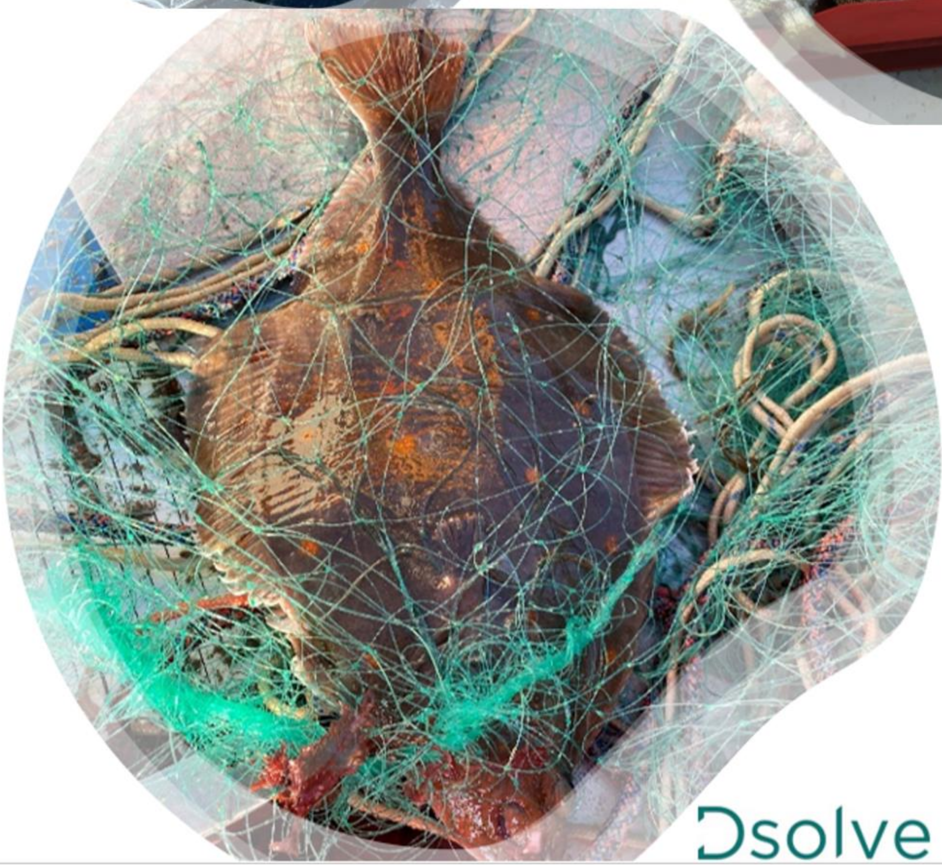

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Summary

Plastic is among the most common types of marine litter, and fisheries represent one of the sources of plastic pollution in the marine environment by abandoned, lost, or otherwise discarded fishing gear (ALDFG). Due to use of plastic materials in fishing gear construction, such ALDFG, including passive fishing gears, has a considerable negative impact on the marine environment. Use of biodegradable plastic materials in fishing gears have a potential to reduce marine plastic pollution and ghost fishing. However, for the new material to be used in commercial fisheries, it should preferably provide similar performance to the fishing gear made of common, non-biodegradable material so that it would not compromise profitability of the industry and gain acceptance in the fishing sector. Therefore, this thesis presents results from five research studies evaluating the performance during fishing with the gear made of recently developed biodegradable polybutylene succinate-co-adipate-co-terephthalate (PBSAT) plastic material in gillnet and longline fisheries.

Gillnets are among the most popular passive fishing gears used. However, the ALDFG in case of gillnets can show high ghost fishing risk, especially during the initial time after being left at sea. The most common type of netting material for gillnets is nylon (polyamide 6.6) which provides high breaking strength, elasticity and durability. Articles I-III tested the performance of biodegradable PBSAT gillnets compared to gear made of commonly used nylon netting. Specifically, Article I presents a method to quantify the catch composition when comparing fishing gear types and investigates whether change of the gillnet material in a Danish multi-species bottom set gillnet fishery would change the catch composition. The results showed no significant differences in catch composition between gillnets made of the two materials. Therefore, the catch composition obtained using the more environmentally friendly biodegradable materials does not represent a barrier in this specific gillnet fishery. However, the main target species, European plaice (*Pleuronectes platessa*) only constituted half of the total catch composition; therefore, considering only the target species would ignore other half of the species affected by the particular fishery. Article II evaluates the catch efficiency of new and used biodegradable PBSAT gillnets in Atlantic cod (*Gadus morhua*) fishery in Northern Norway and uses estimation of capture mode probability to understand the observed differences in catch efficiency between biodegradable and nylon gillnets. The results showed

lower catch efficiency of the biodegradable compared to nylon gillnets and that the capture mode of fish can explain the reduction in catch efficiency which in turn may be related to differences in material properties. Article III applied a similar approach for catch efficiency and capture mode estimations as presented in Article II when assessing the gear performance in the Danish gillnet fishery targeting European plaice and cod. This study is the first quantifying the capture mode of flatfish species in gillnets. Furthermore, this study assessed the material properties of the new biodegradable gillnets aiming at discriminating between the effects of manufacturing, physical strain due to gear operation, and biodegradation on tensile properties. Similarly as in Article II, reduction in catch efficiency when using biodegradable gillnets were observed. The differences in catch efficiency and further in the capture mode probability between gillnets for both species may be explained by the material properties of the biodegradable material. The results showed lower tensile strength for biodegradable compared to nylon gillnets and faster wear and degradation affecting catch efficiency.

Articles IV and V investigated and compared the performance of biodegradable plastic and nylon material when used in set longline fishery for snood lines that are connecting the hooks to the mainline. Article IV developed and presented a new method to estimate the snood loss rate and applied it to a Norwegian coastal set longline fishery targeting haddock (*Melanogrammus aeglefinus*) and cod. In this fishery, a fraction of the nylon snoods are lost during each longline deployment. Therefore, this approach allowed to quantify the extent of the marine plastic pollution in this longline fishery and further to compare it with snoods made of biodegradable PBSAT material. Further, the initial catch efficiency of longlines using the two materials were compared. The results showed no initial difference between new snood lines made of nylon and PBSAT materials regarding catch efficiency and snood loss rate, showing that the PBSAT material can have the potential to be used for snoods in a longline fishery to reduce marine plastic pollution. Based on the results obtained in the Norwegian fishery, Article V further developed and used a similar approach to estimate snood loss rate and catch efficiency in a Croatian coastal set longline fishery. Furthermore, since this is a multi-species fishery, similar approach of estimating and comparing catch compositions as demonstrated in Article I was applied. The results were in line with Article IV showing no initial difference in performance between the two materials.

In general, this thesis provides a knowledge base regarding the use of biodegradable plastic material in gillnet and longline fisheries to reduce negative effects associated with ALDFG such as marine plastic pollution and ghost fishing. Articles I and V are published in Journal for Nature Conservation. Articles II and IV are published in Marine Pollution Bulletin. Article III is submitted for publication in a scientific journal.

List of articles

Article I: Cerbule, K., Savina, E., Herrmann, B., Larsen, R.B., Feekings, J.P., Krag, L.A., Pellegrinelli, A. (2022). Quantification of catch composition in fisheries: A methodology and its application to compare biodegradable and nylon gillnets. Journal for Nature Conservation, 70, 126298. doi: 10.1016/j.jnc.2022.126298.

Article II: Cerbule, K., Herrmann, B., Grimaldo, E., Larsen, R.B., Savina, E., Vollstad, J. (2022). Comparison of the efficiency and modes of capture of biodegradable versus nylon gillnets in the Northeast Atlantic cod (*Gadus morhua*) fishery. Marine Pollution Bulletin, 178, 113618. doi: 10.1016/j.marpolbul.2022.113618.

Article III: Savina, E., Gieysztor Bertelsen, I.M., Cerbule, K., Le Gué, L., Herrmann, B., Krag, L.A. (2024). Weaker tensile properties of biodegradable gillnets reduces catch efficiency much faster than biodegradation. Submitted to a scientific journal.

Article IV: Cerbule, K., Grimaldo, E., Herrmann, B., Larsen, R.B., Brčić, J., Vollstad, J. (2022). Can biodegradable materials reduce plastic pollution without decreasing catch efficiency in longline fishery?. Marine Pollution Bulletin, 178, 113577. doi: 10.1016/j.marpolbul.2022.113577.

Article V: Cerbule, K., Herrmann, B., Trumbić, Ž., Petrić, M., Krstulović Šifner, S., Grimaldo, E., Larsen, R.B., Brčić, J. (2023). Use of biodegradable materials to reduce marine plastic pollution in small scale coastal longline fisheries. Journal for Nature Conservation, 74, 126438. doi: 10.1016/j.jnc.2023.126438.

Thesis structure

This thesis is structured in ten chapters as follows:

Chapter one introduces the challenges associated with lost, abandoned or otherwise discarded passive fishing gear to be addressed in the thesis.

Chapter two describes the two types of commonly used passive fishing gear, gillnets and longlines, and the associated challenges, plastic pollution and ghost fishing, resulting from lost gear.

Chapter three introduces the new biodegradable plastic material being tested to reduce the challenges described in Chapters one and two.

Chapter four defines the overall objective of the thesis, based on the challenges identified for the two passive fishing gear types described in Chapter two.

Chapter five reviews the currently available knowledge from testing biodegradable plastic materials in gillnet and longline fisheries.

Chapter six describes the specific gillnet and longline fisheries investigated in this thesis.

Chapter seven describes the methodologies that could be used to address the thesis objective, and the associated challenges to adapt these methods in the selected fisheries using gillnets and longlines, as well as the need for new methods to be developed.

Chapter eight formulates specific research questions to be addressed by the research in this thesis based on the thesis objective (Chapter four).

Chapter nine presents the research articles and explains how and to what extent the research answers each of the specific research questions of this thesis (Chapter eight) and describes the new approaches applied to address the thesis objective (Chapter four).

Chapter ten discusses the extent to which the conducted research has fulfilled the overall objective of this thesis (Chapter four) and identifies the future research directions regarding testing biodegradable plastic materials in passive fishing gears, and final remarks.

1. Challenges by passive fishing gear-related marine litter

1.1 Commonly used passive fishing gear types

A large variety of fishing gear types are being used worldwide to target different species. Among those, a number of design variations are common depending on the specific fisheries the gear is being used for. The fishing gears are often classified as either active (also called mobile or towed) or passive (stationary) gear depending on the capture process in each of them (Bjørdal, 2002; Gabriel et al., 2005). In contrast to mobile fishing gears such as trawls or seines that are actively moved over the seabed or in the water column to capture the targeted species, in passive fishing the capture is primarily based on the target species approaching such gear. Specifically, when using passive fishing methods, animals, such as different fish or crustacean species, are captured in one of the two ways - either by being attracted to the gear by, for example, using bait or lures, or when they approach and contact the gear without noticing it before being captured as in gillnets. Thus, the capture process is dependent on natural behavior and movements of the targeted aquatic animals.

Examples of commonly used passive fishing gears include gillnets and entangling nets (Fig. 1A), pots and traps (Fig. 1B), and hooks and lines (Fig. 1C) (Hubert et al., 2012; He et al., 2021). Gillnets and trammel nets are common examples of entanglement gears holding the captured animals ensnared or tangled in netting or mesh (Hubert et al., 2012). Since the netting of such gear is aimed to be invisible in the water column, the fish get caught by swimming into the gillnet or trammel net and further being retained by the meshes. Entrapment devices such as pots and traps are designed as enclosures that capture organisms that enter through one or more entrances which further aims at preventing subsequent escape of an animal. Pots or traps are often deployed in lines with a mainline connecting several deployed pots. The gear is set at the sea bottom and the target species are usually attracted to it using bait placed inside the gear. Hook and line fishing gears also often use bait to attract target species. Longlines are a common example of hook and line fishing gears. The capture principle in the longline fishery is to attract fish to hooks using bait. However, there are large variations regarding designs, deployments and scale the fishery is operating (i.e., He et al., 2021).

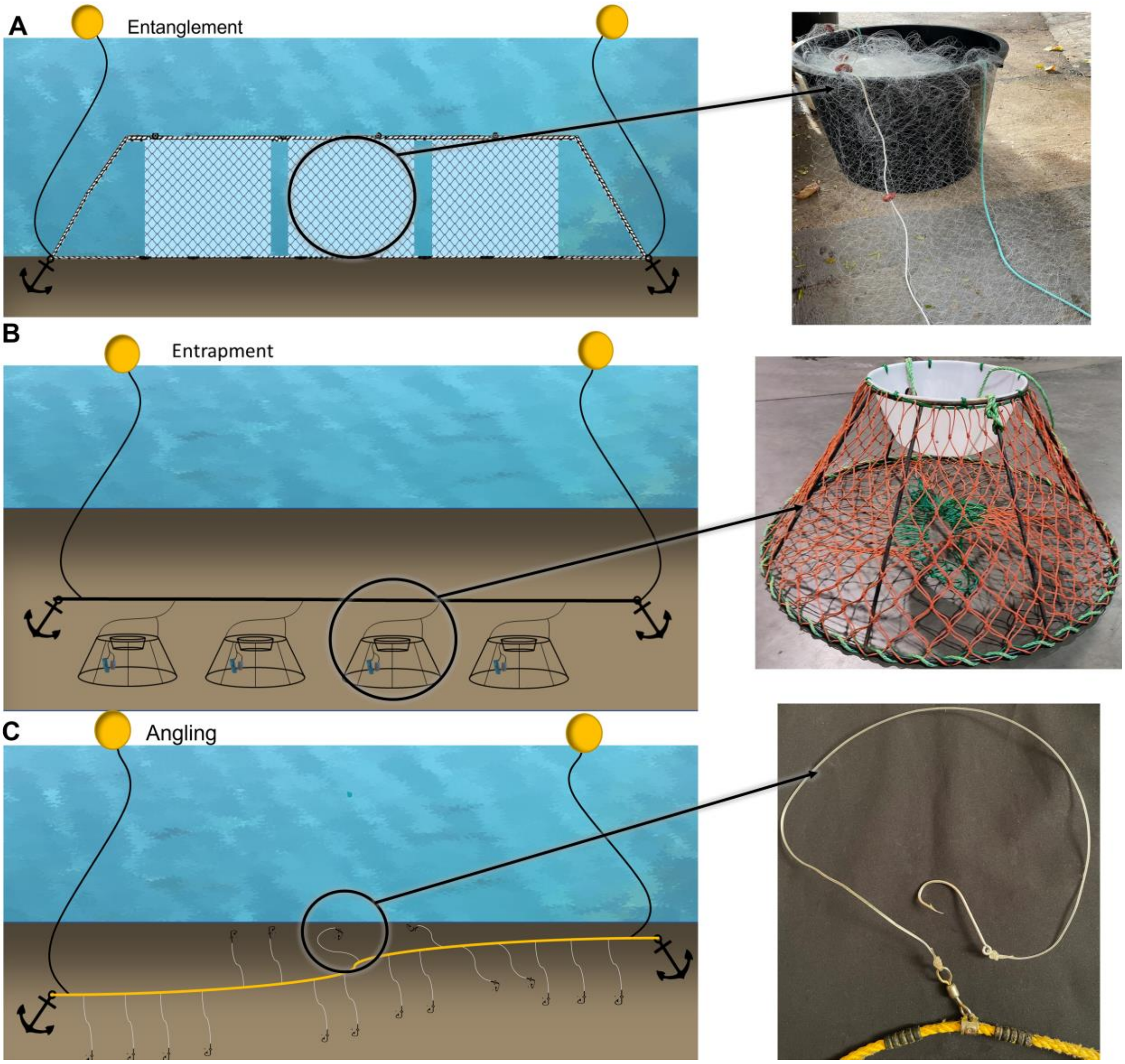

Figure 1. Examples of commonly used passive fishing methods for (A) entangling in a bottom-set gillnet fishery; (B) entrapment when using pots; and (C) angling in a set longline fishery.

1.2 Environmental challenges caused by passive gear-related marine litter

Generally, fisheries using passive fishing gears, such as gillnets, longlines and pots, are characterized by a simple gear construction and operation, and are often considered sustainable compared to fisheries using active gears such as trawls when environmental impacts and fuel consumption are compared (Schau et al., 2009; Suuronen et al., 2012). For example, the estimated fuel consumption in pot, gillnet and longline fishery is 0.1–0.4 l of fuel per kg of catch, while for the same amount of catch in bottom trawls it is estimated to range from 0.5 to 1.5 l (Suuronen et al., 2012). The fuel consumption increases for the passive gear fisheries operating far off the coast such as snow crab (*Chionoecetes opilio*) pot fishery in the Barents Sea. Furthermore, fisheries using several passive fishing gear types often can provide high quality catches. For example, in both pot and longline fisheries, the catch is usually alive when brought aboard the vessel. Therefore, in such fisheries bycatch species or undersized individuals of the target species can often be released alive.

However, one of the largest sustainability challenges associated with passive gears is caused by intentional or unintentional loss of the gear and due to use of slowly degrading plastic materials in their construction. Generally, plastic products are among the most common types of marine litter (Pham et al., 2014; Novikov et al., 2021) that constitute threats to the marine environment. Fisheries represent one of the sources of plastic pollution in marine environment (Pham et al., 2014; Novikov et al., 2021; Richardson et al., 2019; Gilman et al., 2021) by abandoned, lost, or otherwise discarded fishing gear (ALDFG). Globally, the ALDFG amount is estimated to be around 640 000 tons each year (Macfadyen et al., 2009); however quantitative information regarding the fishing gear losses is limited and often complicated to estimate (Richardson et al., 2022). The rate of fishing gear loss varies between different fisheries and fishing areas based on different variables, such as the environmental and seabed conditions, potential gear collisions and other operational variables (Brown and Macfadyen, 2007; Richardson et al., 2019). Such ALDFG can remain in the marine environment for many years due to the material properties that provide high resistance to degradation. Furthermore, ALDFG has a disproportionally higher impact on the marine environment compared to other types of plastic marine litter due to the potential to entangle, ensnare or be ingested by the marine animals (Richardson et al., 2019). Thus, ALDFG can contribute to the mortality of marine organisms by continuing to fish after all control of the fishing gear is lost, so-called "ghost fishing" (Matsuoka et al., 2005), and pollution by plastic materials.

The amount of lost fishing gear has risen in recent decades because of the expansion of fishing effort (Suuronen et al., 2012) and is causing concerns due to transition to synthetic more durable materials used in fishing gear construction (Deshpande et al., 2020). Specifically, biodegradation-resistant materials such as polyamide (PA; nylon), polyethylene (PE) or polyester (PES) have replaced easier degradable natural materials like cotton, sisal or hemp since they are more durable and provide optimal material properties such as high tensile strength and elasticity. The properties like tensile strength, elasticity and abrasion resistance of these synthetic fibers are of outmost importance for their applicability and efficiency in fishing gears (Valdemarsen, 2001). Furthermore, the production form (multifilament, monofilament, staple, spun) provides additional properties to fine-tune catch performance and durability of fishing gear. This has contributed to the increase in the world's fisheries (FAO, 2022). However, such plastic materials are highly resistant to degradation and, therefore, if lost can remain intact in the marine environment for decades (i.e., Good et al., 2010; Gilman et al., 2022). Plastics contribute to 85% of the estimated 9-14 million tons of litter entering the oceans annually (UNEP, 2022), whereof as much as 20% comes from fisheries (Morales-Caselles et al., 2021). Fishing and supply industries are aware of the increasing public demand for actions against marine littering and focus on using more eco-friendly fishing gears to reduce the negative impacts from ALDFG.

Ghost fishing is especially associated with passive fishing gear that were set and subsequently lost or abandoned (Gilman, 2015). According to Gilman (2021), gillnets possess the highest gear-specific risk for ALDFG, while pot and set longline fisheries are estimated to have one of the highest rates for production of ALDFG. Because the passive fishing gears are designed to catch marine organisms, such lost gear, relative to other plastic litter, can potentially continue ghost fishing for long periods of time catching both commercial species and bycatch (Fig. 2). Therefore, this both increases the unaccounted fishing mortality of commercially important marine species and negatively affects the fish stocks, undermining the principles for sustainable fisheries management (Standal et al., 2020). Specifically, ghost fishing negatively affects fishing industry by increasing the fishing mortality, therefore causing economic losses (Standal et al., 2020). The increase in fishing mortality due to ghost fishing is often not considered when estimating total allowable catch for commercial species. This results in destabilization of fish populations and unaccounted mortality which can further negatively affect marine food web. The economic effects of ghost fishing are not negligible. For example, Hébert et al. (2001) estimated that 1000 lost conical traps would kill around 84 000 snow crab (corresponds to around 48 t per year) in the snow crab fishery in Canada. The reduction of unnecessary mortality of the stocks are important for the fisheries sector and management. However, studies quantifying the possible extent of ghost fishing by different fishing gear left at sea are scarce.

Figure 2. Example image of a gillnet recovered after being abandoned, lost, or otherwise discarded at sea. Source: Standal et al. (2020).

Furthermore, even after a certain amount of time, non-biodegradable plastic material of the fishing gear does not disappear entirely but breaks down into smaller plastic particles that may continue to affect the marine ecosystem. Therefore, other adverse consequences associated to ALDFG include, among others, pollution with macro-plastics (Novikov et al., 2021), transfer of micro-plastics (plastic particles with a size of less than 5 mm) (Andrady, 2011) and toxins into marine food web (Gilman et al., 2021) and damage of the marine habitat and the benthic environment (i.e., Stevens, 2020).

Other negative effects of ALDFG include disturbances of fishing operations caused by nets being caught up in boat propellers, damage of fishing gear by attaching to old, lost gear and waste on hooks and in gears (Olsen et al., 2020). Such gears can also damage the benthic environment through, for example, abrasion and result in animal entanglement also when washed ashore as beach litter (Brown and Macfadyen, 2007; Tekman et al., 2022).

Because of the above mentioned consequences, solving ALDFG related problems is considered a global challenge. To reduce these negative effects, clean-up operations are one of the possible measures. The Food and Agriculture Organization of the United Nations (FAO)'s Committee on Fisheries, the FAO Code of Conduct for Responsible Fisheries and FAO's Voluntary Guidelines for the Marking of Fishing Gear highlighted the importance of fishing gear marking and ALDFG reporting and recovery (Food and Agriculture Organization of the United Nations, 2019; Richardson et al., 2019; Giskes et al., 2022). However, ALDFG clean-up operations require additional costs (Standal et al., 2020) and are often complicated and time consuming (Richardson et al., 2019). Specifically, by using this approach, only small areas of fishing grounds can be covered, and the recovery efficiency can be low due to, for example, large areas and fishing depths and challenging weather conditions. Furthermore, even if the gear eventually is recovered during such clean-up programs, ALDFG would remain at sea for a period between loss and retrieval often resulting in some catches of commercial (and non-commercial) species (Brown and Macfadyen, 2007). Therefore, recovery programs are just one form of mitigation of ALDFG associated effects, and other measures are necessary to keep up with the pace at which litter enters marine systems (Olsen et al., 2020; Giskes et al., 2022). One such measure would be to replace the commonly used plastic materials with biodegradable materials in whole fishing gear or part of the gear that has a high potential of being lost at sea. However, between different fisheries using passive fishing methods, the extent of the problem and possible mitigation strategies depend on the fishing gear type considered.

2. Selected fishing gear types and associated challenges regarding plastic pollution and ghost fishing

The topic of this thesis focuses on two important and widely used passive fishing gear types, anchored bottom set gillnets and longlines (He et al., 2021). This chapter introduces the operating principles of bottom set gillnet and longline fisheries, and associated challenges regarding plastic pollution and ghost fishing in these fisheries.

2.1. Bottom set gillnet fishery

Gillnets are among the most used fishing gears in the world. Specifically, this fishing gear type contributes to about 10% of global fish landings (He et al., 2021). Gillnets are used in demersal and pelagic fisheries, from small boats to large industrial vessels. All gillnets are designed as netting walls with uniform mesh size that are deployed vertically in the water column by weights along the leadline and floats along the float line and are capturing the marine animals that contact the netting and get caught in it. Gillnets are normally deployed in fleets containing several nets connected and deployed together. The sizes of such fleets vary between different fisheries and the size and capacity of the fishing vessels.

The gillnets are divided into drift (pelagic) gillnets and bottom set (demersal) gillnets depending on where the nets are being deployed in the water column. Specifically, the drift gillnets are deployed closer to the surface or mid-water, while the bottom set gillnets are deployed along the seabed to capture demersal fish species. Furthermore, other gillnet types such as encircling gillnets, fixed gillnets and trammel nets are common in different fisheries and differ in both construction and deployment (He et al., 2021). Bottom set gillnets are deployed and held in a stationary position at the seabed using anchors, usually at both ends of the fleet (Fig. 3). This is the most used gillnet type (He et al., 2021).

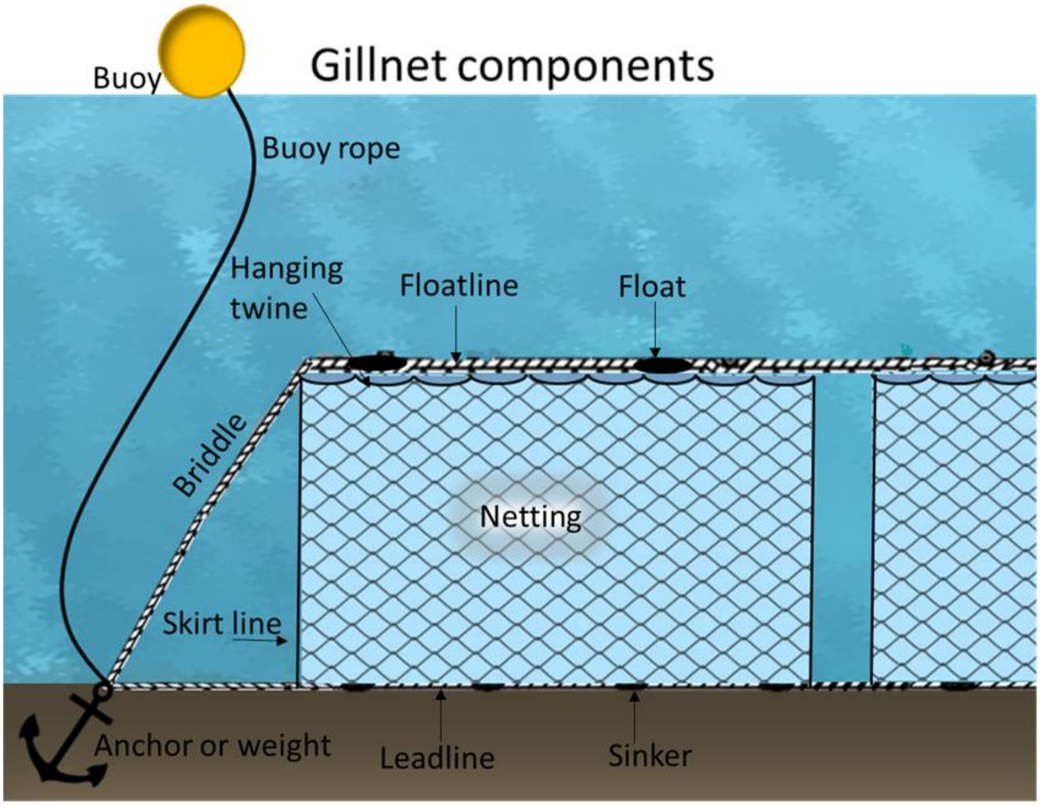

Figure 3. Basic components of a bottom set gillnet. Source: adapted from He et al. (2021).

Gillnets can be designed to capture a variety of species and are size selective depending on the mesh sizes, material elasticity and hanging ratio, i.e., the ratio of the length of rope to the stretched length of netting attached to it in the horizontal direction (He et al., 2021). Therefore, often the gear can have minor impact on small and juvenile individuals. The main capture mechanism for fish that is often observed in gillnets is gilling; however, fish can also be captured by other modes such as wedging, snagging, and entangling (He, 2006; He et al., 2021; Savina et al., 2022).

A common type of netting material for this gear is monofilament nylon. However, multifilament and multi-monofilament nettings are also used in some fisheries (He et al., 2021). Similarly, the twine thickness of the netting varies between different fisheries and depends on the species being targeted. The nylon material in gillnet netting has replaced natural materials like cotton or hemp since the nylon material provides an optimal elasticity and breaking strength for high catch efficiency of the gear (Kim et al., 2016; He et al., 2021). Thus, the gear mainly consists of slowly degrading materials that, if lost, abandoned, or discarded at sea, can cause the above-described challenges, especially regarding marine plastic pollution and ghost fishing.

The ALDFG in case of gillnets can have high efficiency at capturing different species, especially during initial time after being left at sea (Humborstad et al., 2003; Pawson, 2003; Tschernij and Larsson, 2003; Thomas et al., 2023). Accumulated catches resulting from ghost fishing cause the nets to collapse after which they can attract scavenging animals which also can end up being captured by such gillnet. This may in some instances lead to several cycles of ghost fishing. Specifically, it would consist of, first, capture of the animals due to ghost fishing, the subsequent decay of the catch and attraction of the scavengers (Pawson, 2003).

The extent of ghost fishing for gillnets may depend on the seabed type on the fishing grounds, currents, the net geometry, and whether it ends up at sea being either lost, abandoned, or discarded. For example, ghost fishing of the gear deployed on flat and muddy seabed declines, often due to increasing visibility of it compared to ALDFG remaining on rocky or uneven seabed (Pawson, 2003; Matsuoka et al., 2005). Therefore, the total catch of animals by lost gillnets during the ghost fishing cycle varies between different fisheries and environmental conditions; however, the extent of it can be considerable. Furthermore, even when the gillnet material eventually degrades to a state that limits its ghost fishing potential, the material still contributes to the marine plastic pollution with the resulting potential consequences of negative effects on the marine food web.

2.2. Set longline fishery

Longlining is a widely used passive fishing method. Some of the world's longline fisheries are conducted with large vessels using mechanized baiting and hauling units, operating between 40 000 – 70 000 hooks a day. However, most of the small-scale longline fisheries are taking place using smaller number of hooks (from few hundred to 15 000), and the majority of them use hand baited gears. The following section of this thesis focuses on small-scale longline fisheries operated from small vessels (up to 15 m).

The longline gear consists of three components: a mainline, snood lines (also called branch lines or gangions), and hooks (Fig. 4). The hooks are connected to snood lines which are then attached to the mainline at certain intervals by a knot or connected to the mainline using a swivel with a spinner. Baited longlines, similar to gillnets, are usually set for a certain amount of time (soak time). Longline fishery can be divided into stationary longlines (also set or bottom-set longlines), stationary midwater longlines and pelagic (drifting) longlines depending on where the gear is deployed. Set longlines are deployed on the seabed to capture demersal species (He et al., 2021). Longline design varies in hook types and sizes, snood line lengths, snood line thickness, material, and the interval between the snood lines. These parameters vary depending on the target species (Herrmann et al., 2017).

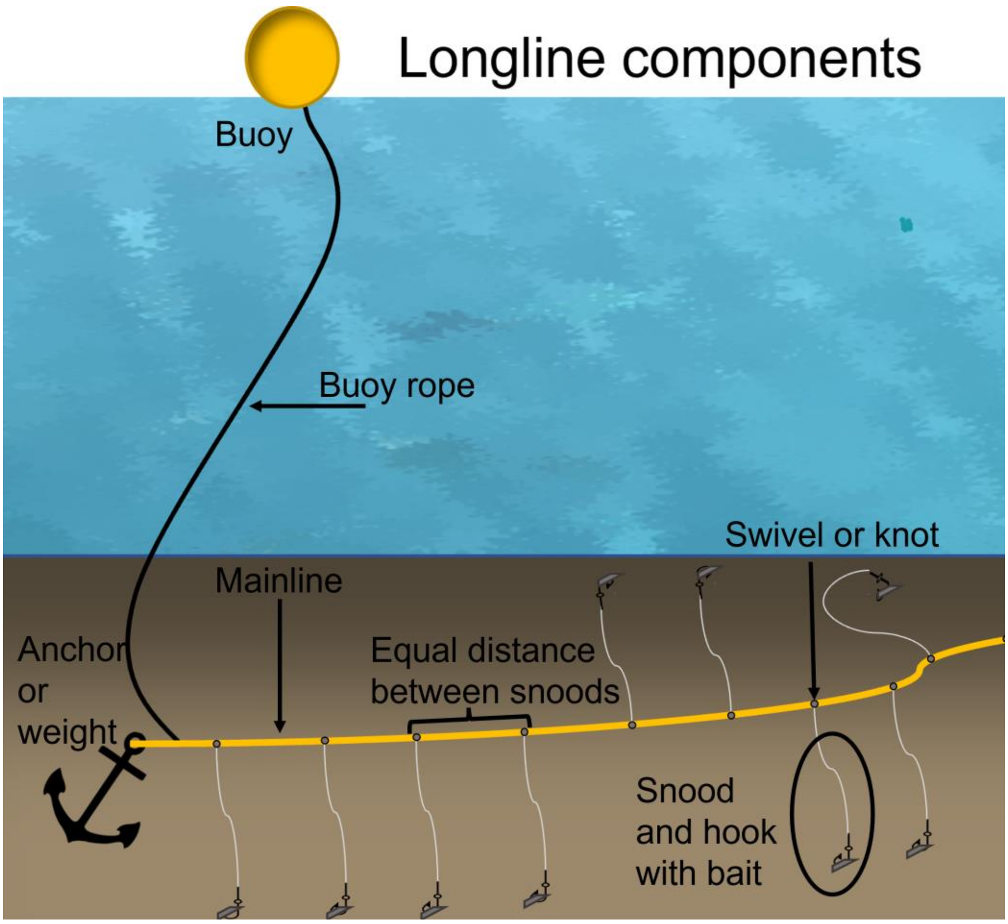

Figure 4. Basic components of a set longline. Source: adapted from He et al. (2021).

Initially, the longlines, including the snoods, were made of natural materials similar to gillnets, for example hemp which was replaced by plastic materials due to its high tensile strength (Ward and Hindmarsh, 2007). Thus, the longline mainlines are now commonly made of spun polyester or nylon, and snoods from nylon or polyester. In coastal set longline fisheries, nylon monofilament snoods are often being used. Snood losses have a potential to contribute to the plastic pollution. Specifically, in set longline fisheries, a fraction of snoods is often lost at sea during the fishing process and subsequently replaced with new monofilament lines (and hooks) between the deployments. Such losses can often result during the fisheries when, for example, the hook gets snagged at some irregular objects at the seabed or when the fish is able to break the snood line and escape with whole snood line or part of it.

Therefore, in case of set longlines, it is important to distinguish between loss of entire gear (mainline or fraction of it together with snoods) and loss of snood lines during the fishing process. The extent for each of those two cases depends on several factors such as seabed type and targeted fish species. This rate is unknown for most fisheries; therefore, the extent of the resulting plastic pollution is difficult to estimate. However, considering that the longline gear is among the most common fishing gears used in fisheries worldwide, this volume can be considerable. Therefore, while snood loss rates are not typically used to estimate the gear losses in the longline fishery, such data could provide valuable information about the scale of such problem in these fisheries (as also highlighted by Richardson et al., 2019). Specifically, a recent study suggests that an annual average loss rates for the longline mainlines constitute 3.3% and 3.6% for the snood lines (Richardson et al., 2022). However, this loss rate can vary significantly when considering such aspects as whether the longline fishery is performed as pelagic or demersal fishery, size of the vessel, seabed type in the fishing grounds and target species. Therefore, this loss rate can vary between different fisheries.

The ghost fishing associated to ALDFG from longline fisheries is believed to be negligible (Løkkeborg, 2003). Specifically, longlines are not associated with ghost fishing risk to the same level as, for example, gillnet or pot fisheries where animals can entangle in the gear or be captured in it, and more organisms can be attracted to the gear due to self-baiting over time. However, lost quantities of plastic material increase plastic pollution in the marine environment.

3. Use of biodegradable plastic materials in gillnet and longline fishery

The main working hypothesis for this thesis is that use of biodegradable plastic materials can reduce the challenges related to marine plastic pollution and ghost fishing in gillnet and longline fisheries.

Research and industrial development have revealed the potential to develop different biodegradable plastic materials that would allow replacing conventional non-biodegradable plastics commonly used in fisheries (i.e., Park et al., 2007; Deroiné et al., 2019). Such biodegradable plastic materials, in contrast to commonly used non-biodegradable plastics, are polymers that can be biodegraded by naturally occurring microorganisms (Le Gué et al., 2023). Some earlier studies have suggested using polybutylene succinate (PBS) or polybutylene succinate co-adipate-co-terephthalate (PBSAT) (patent EP3214133 A1; Kim et al., 2017) as potential biodegradable plastic materials for replacing commonly used materials that are not biodegradable in fishing gears (Kim et al., 2014a; Kim et al., 2014b; Kim et al., 2016; Kim et al., 2019).

Use of biodegradable materials in fisheries, such as gillnet and longline fishery, aims at maintaining similar mechanical properties of the gear during fishing but degrading in seawater when dispersed in the marine environment in case of the gear loss by such microorganisms as bacteria, fungi, algae (Brakstad et al., 2022). Thereby, the biodegradable plastic fishing gear is designed to be fully degradable in seawater due to chemical-biological processes induced by interactions on the surface of the polymer with enzymes secreted by microorganisms. Biodegradation causes changes in both the physicochemical properties and mechanical properties of the polymer. Thus, the biodegradable materials are designed to break down after certain time. Therefore, if fishing gear made of such material is lost, it will break down and loose its capture ability and finally disappear, reducing the occurrence of ghost fishing and other impacts related to lost fishing gear (Standal et al., 2020).

The biodegradable plastic materials should be degraded into non-toxic substances such as carbon dioxide, methane, and water not to have a negative impact on the marine ecosystem (Lucas et al., 2008; Laycock et al., 2017). In contrast, for currently used plastic materials in fishing gear such as nylon, weakening of the material due to normal use in fishery almost stops for the ALDFG, and the degradation of the material then takes place very slowly (Andrady, 2011). For example, during material aging for 36 months in laboratory conditions, the results showed the degradation (cracks in degraded areas) for the biodegradable PBSAT material while nylon filaments exposed to the same conditions remained undamaged (Fig. 5) (Brakstad et al., 2022).

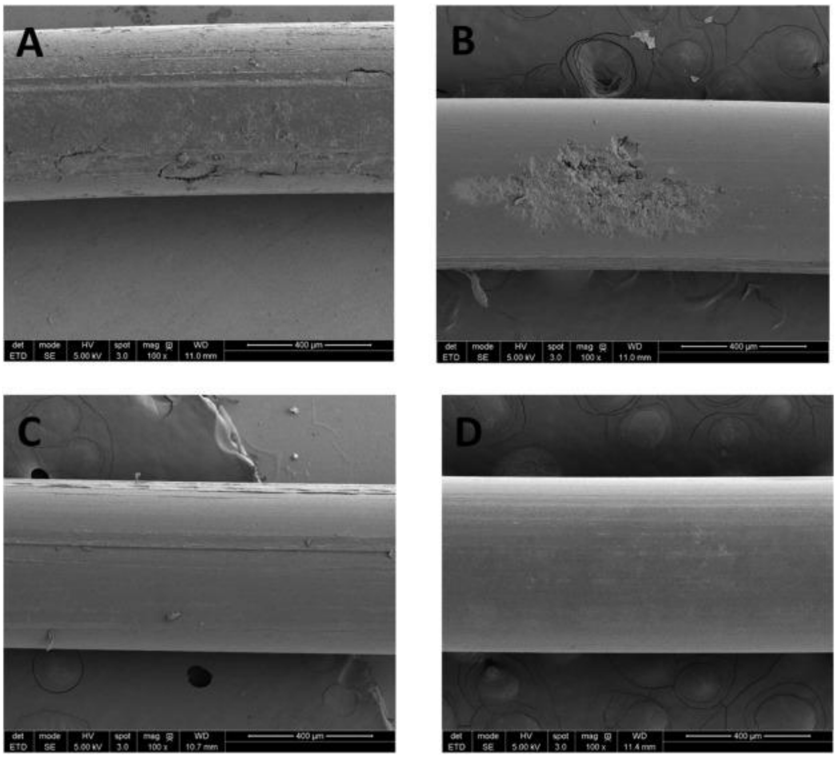

Figure 5. Scanning electron microscope images of surface morphologies of biodegradable plastic (PBSAT) monofilament (A-C) and nylon (PA) monofilament (D) after a 36-month incubation in seawater. Source: Brakstad et al. (2022).

The slow gradual effect of weathering of the plastic material is taking place with main factors contributing to the decomposition of the polymers in the marine environment being such physical factors as UV radiation, temperature, oxidation, chemical and physical interactions with the seawater, mechanical abrasion, and biodegradation (Dąbrowska et al., 2021). Since commonly used plastic materials are not biodegradable, degradation of these plastics further results in microplastic pollution. The resulting small particles of the plastic materials may continue to disturb processes in the marine ecosystem. Therefore, the use of biodegradable materials would help to reduce the amount of marine plastic litter and its associated effects (macro- and microplastics and ghost fishing) on the marine environment.

4. Objective

Use of biodegradable materials in fishing gear have been considered as a potential solution for reducing marine plastic pollution and ghost fishing caused by the ALDFG. For biodegradable materials to be adopted by the fishing industry, they should provide a comparable performance as conventionally used materials in order not to compromise the profitability of the fishery. Therefore, the overall objective of this thesis is to *investigate whether recently developed biodegradable plastic materials (PBSAT) can be used in gillnet and longline fisheries to reduce the marine plastic pollution and ghost fishing by abandoned, lost, or otherwise discarded fishing gear.*

5. Review of the use of biodegradable plastic materials in gillnet and longline fisheries

Prototype testing of first-generation biodegradable materials has showed promising results for application in fisheries to reduce marine plastic pollution and ghost fishing resulting from ALDFG (i.e., Kim et al., 2014a; 2014b; 2016; Seonghun et al., 2020). However, to be applied in commercial fisheries, the biodegradable material must show a similar performance during fishing to that of the nylon material so that it would not compromise the profitability of the fishing operations.

5.1. Gillnet fisheries

In gillnet fisheries, the PBSAT material has been tested in several studies as a potential alternative to replace nylon. Specifically, several experiments testing the performance of the biodegradable PBSAT gillnets regarding their material properties and catch efficiency have been performed in different fisheries. In some of these fisheries, the PBSAT material and other biodegradable plastic materials such as PBS/PBAT have shown a potential of being a viable alternative to non-biodegradable materials (Kim et al., 2016; Seonghun et al., 2020). However, some decrease in catch efficiency when using biodegradable materials in bottom set gillnets was shown in gillnet fisheries in South Korea targeting yellow croaker (*Larimichthys polyactis*) (Seonghun et al., 2020).

The results from experiments conducted in fisheries in Norway have demonstrated a reduced catch efficiency of biodegradable compared to nylon gillnets. Specifically, some small-scale tests conducted in Norway revealed a reduced catch efficiency of the tested fishing gear using biodegradable PBSAT materials in fisheries targeting Greenland halibut (*Reinhardtius hippoglossoides*) (Grimaldo et al., 2018a), Atlantic cod (*Gadus morhua*) (Grimaldo et al., 2019; 2020a) and cod and saithe (*Pollachius virens*) (Grimaldo et al., 2018b; 2020b). Such reduction in catches would negatively impact the cost-effectiveness of the fishing operation and acceptance of biodegradable gillnets by fishers.

The studies conducted in Norway showed significant reductions in catch efficiency for all species considered. Biodegradable PBSAT gillnets showed a reduced catch efficiency compared to nylon nets starting from initial use of the material. Furthermore, when tested over several consecutive seasons during long-term studies, a further decrease in catch efficiency was observed. Specifically, the biodegradable plastic gillnets lost their catch efficiency over time during long-term trials by catching 18%, 40% and 47% fewer cod compared to nylon gillnets during the first, second and third fishing season, respectively (Grimaldo et al., 2020a). The reduction in catch efficiency throughout the trials usually was higher especially for large fish (i.e., Grimaldo et al., 2018a; 2018b).

This could indicate that such reduced catch efficiency can result from reduced tensile strength of the biodegradable material compared to nylon of the same monofilament twine diameter. Therefore, Grimaldo et al. (2020b) studied the effect of increasing the twine diameter of PBSAT monofilament to compensate for the differences in breaking strength in both materials. However, the results of this study nevertheless showed significantly reduced catch efficiency for biodegradable PBSAT gillnets with increased monofilament diameter despite equal tensile strength to the nylon gillnets. Therefore, these results indicate that other gillnet parameters should be considered for explaining the observed differences in catch efficiency. In gillnet fisheries, certain material properties, such as optimal tensile strength combined with elasticity are required to provide an optimal catch efficiency of the gear. These characteristics depend on fish species targeted due to, for example, different morphologies and swimming abilities. Therefore, it is important to identify those parameters when designing the biodegradable gillnets, also by quantifying how fish of different species get captured in gillnets.

5.2. Longline fisheries

In longline fisheries, no previous studies testing biodegradable plastic materials have been conducted. Specifically, no studies were found regarding estimations of the performance of biodegradable materials in either snood lines or mainlines of the longline gear. Therefore, currently there is no existing information regarding how such biodegradable plastic material could perform when used in this fishing gear type regarding the catch efficiency. Furthermore, the rate at which the non-biodegradable plastic snoods are lost during the fishing process in different bottom set longline fisheries is not quantified, and only some general estimates are available (i.e., Richardson et al., 2022). Other studies have mentioned potential use of biodegradable (or biodegradable plastic) materials in longline fisheries and the need to improve the sustainability by reducing the plastic pollution (Scott et al., 2022).

Therefore, further studies determining the initial performance of the biodegradable plastic material used in longline fisheries, as well as estimation of the snood loss rate are necessary to evaluate whether biodegradable plastic materials can replace non-biodegradable materials in longline fisheries.

6. Description of selected fisheries

This chapter introduces four bottom set gillnet and longline fisheries in Norway, Denmark, and Croatia where the objective of this thesis was investigated (Fig. 6).

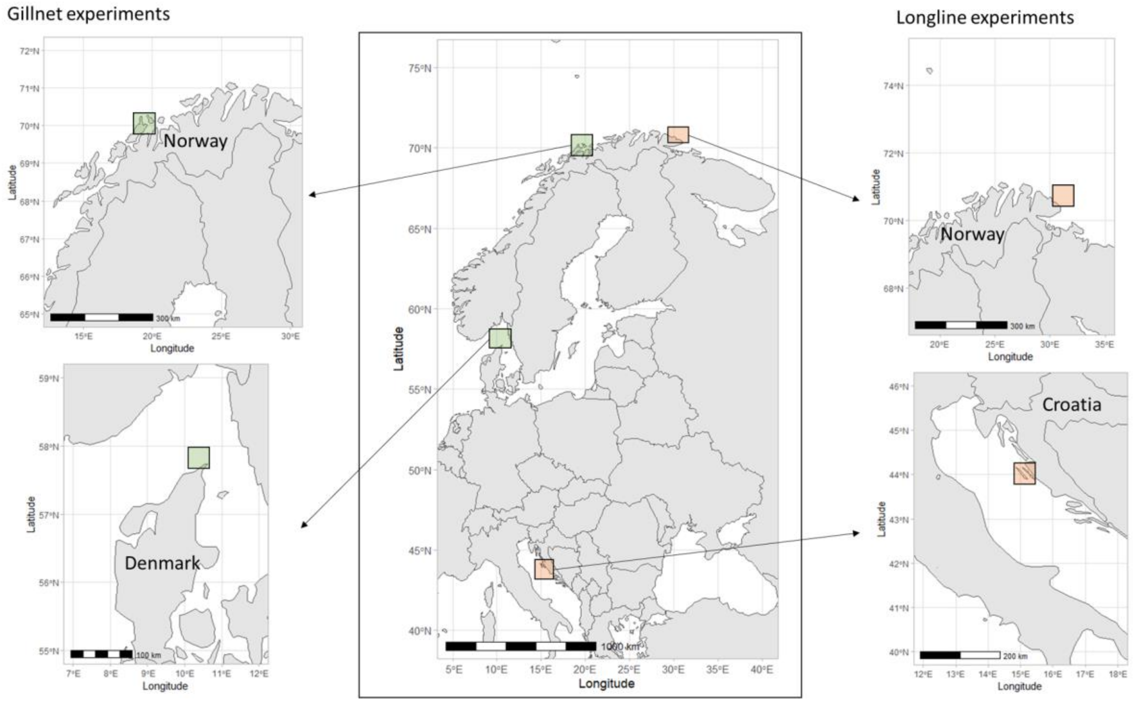

Figure 6. Map of the areas where the experimental sea trials described in this thesis were conducted with gillnets (marked in green) in Norway (Article II) and Denmark (Articles I and III) and longlines (marked in red) in Norway (Article IV) and Croatia (Article V).

6.1. Norwegian gillnet fishery targeting cod

In Norwegian fisheries, 5 607 vessels were registered in 2023 (Norwegian Directorate of Fisheries, 2024a). The majority of these are coastal vessels, and the rest belong to ocean fishing fleets (Deshpande and Haskins, 2021). Within the cod fisheries, the coastal fleet traditionally consists of vessels up to 28 m length (Standal and Hersoug, 2022). In 2023, the Norwegian fleet consisted of 4636 vessels being up to 14.99 m (length overall); therefore, 83% of the fleet consists of vessels below 15 m length (Norwegian Directorate of Fisheries, 2024a). Passive fishing gears such as gillnets, longlines and pots are typical for coastal fisheries in Norway. The gillnet and longline fisheries in Norway target such fish species as cod, haddock, saithe, ling (*Molva molva*), tusk (*Brosme brosme*) and Greenland halibut (Clegg and Williams, 2020).

In Norway, gillnets are among the most important fishing gears, especially for the coastal fishing fleet (Grimaldo et al., 2019; Standal and Hersoug, 2022). The cod fishery represents the most economically important single species fishery (Grimaldo et al., 2020a). In 2023, the gillnet coastal fleet captured 77 803 tons (26.7%) of cod of the overall cod catches, which in 2023 were 291 042 tons (Norwegian Directorate of Fisheries, 2024b). The gillnet fishery for cod is seasonal, with largest fishing activity conducted during the winter season from January to April (Standal et al., 2020). The number of gillnet sheets operated on the vessel varies depending on the vessel size (between 80-220 gillnets) (Standal et al., 2020).

In Norway, a large part of pollution by fishing gears is related to losses during the operation (Deshpande et al., 2020), in particular gillnets, pots and longlines. Specifically, Deshpande et al. (2020) estimated that the annual loss of gillnets constitutes the primary source of ALDFG in Norway. Norway has an official annual fishing gear recovery program aiming at systematically retrieving lost fishing gear (Grimaldo et al., 2020a). Since 1983, more than 22 000 gillnets have been retrieved in Norway, the annual number of retrieved gillnets varying from 106 to 1 180 gillnets (Standal et al., 2020). Although the ghost fishing extent in lost gillnets in Norway has not been quantified (Standal et al., 2020), upon retrieval of lost gears, considerable amounts of fish and other marine organisms are often found (Grimaldo et al., 2020a; Standal et al., 2020), demonstrating that lost gillnets contribute to ghost fishing.

Considering that the retrieval program can recover only part of the lost fishing gear, only a fraction of gillnets is retrieved each year, while a part of the lost gear continues accumulating at sea. The low rate of fishing gear recovery, including gillnets, is due to both, low rate of reporting of lost gears and challenging retrieving operations (Grimaldo et al., 2019). Specifically, this is the case when the gear is lost in deep waters, areas with strong currents, and with some uncertainties regarding the exact position where the gear was lost along with potential gear collisions where the gillnets may be displaced from their original position (Standal et al., 2020). Therefore, other approaches to reduce the negative effects of abandoned, lost, or discarded gillnets are being sought.

6.2. Danish gillnet fishery targeting European plaice and cod

In Danish fisheries, vessels using gillnets represent a large part of the fishing fleet (Savina et al., 2017). The coastal gillnet fleet in Denmark targets such species as cod and European plaice (*Pleuronectes platessa*). However, capture of other species is common in gillnet fisheries in this area. Therefore, this gillnet fishery is considered as a multi-species fishery where a fraction of the catch is consisting of target species (i.e., species with a commercial value), while the other fraction, the unwanted catch, contains species without any commercial value. For example, Savina et al. (2017) reported that 27 different species were caught in a gillnet fishery mainly targeting European plaice in Skagerrak area. Further, some species are subjected to minimum conservation reference size (MCRS) and catches of undersized individuals are prohibited (European Commission, 2020).

The European plaice fishery in the Skagerrak area has been one of the most important commercial gillnet fisheries in Denmark (Ulrich and Andersen, 2004; Savina et al., 2017). This fishery is conducted in coastal areas on sandy and shallow fishing grounds. Only few studies reported the amount of lost fishing gear and the associated effects in this area (i.e., Egekvist et al., 2017). However, this fishery is also being conducted in areas including wrecks where the risk of the gear being snagged at irregular objects during deployment increases. Thus, the use of biodegradable materials in this fishery could have a potential to reduce the negative environmental effect if the gillnets are lost in these areas.

6.3. Norwegian coastal set longline fishery targeting cod and haddock

In Norway, set longlines are commonly used in coastal fisheries. These fisheries target demersal fish species such as cod, haddock, and land fresh catches to local fish plants after each trip. Nylon snood lines are normally used in the coastal longline fishery. The longlines in coastal fishery are manually baited between the deployments, and during this process the snoods and hooks that were lost during the previous deployment are replaced.

It is estimated that 4 to 7% of total longlines owned by the Norwegian fishing fleet are lost in the ocean every year constituting one of the most significantly recovered fraction of ALDFG

(Deshpande et al., 2020). However, loss of snood lines are common during the fishing process (Richardson et al., 2022) and often during each deployment due to, for example, snagging at the seafloor when deployed along rough fishing grounds. However, the rate of the snood loss is not quantified in this fishery. Since the snoods are made of nylon, lost material would contribute to the challenges described in Chapter 2 of this thesis.

6.4. Croatian coastal small-scale bottom-set longline fishery

In the Adriatic Sea, a large part of the fisheries sector is constituted by small-scale multi-species fisheries. In this area, small-scale fisheries often use different fishing gear types that are changed both spatially and seasonally to optimize catches and thus maximize the profit from the fisheries (Matić-Skoko and Stagličić, 2020). Thus, in Croatia, small-scale fisheries are operating from vessels smaller than 12 m, and use different passive fishing gear types, such as gillnets, trammel nets, pots and longlines that are operated by a crew consisting of one or two fishers (Matić-Skoko and Stagličić, 2020). The Fishing Fleet Register includes a total of 7757 vessels, where over 90% belong to the category of small-scale fishing boats (Državni zavod za statistiku, 2022.). The fishery normally takes place close to the coast, and at depths up to 80 m.

Set longlines are used by commercial as well as sport and recreational fishers and are often made of monofilament nylon mainlines and thinner monofilament nylon snoods that connect the hooks to the mainline. No scientific information regarding losses of longline fishing gear was found in the literature. However, a survey on marine litter collected on the seafloor of the central and northern Adriatic Sea over a six-year period, revealed that pollution by fishing gear, including longlines and gillnets, constitute a considerable part of the marine debris (Strafella et al., 2019). The northern and central part of the Adriatic Sea is highly affected by fishing activities. The lost fishing nets were found mainly close to the coast (within 3 nautical miles), mainly gillnets used by small-scale commercial fisheries (Strafella et al., 2019). Therefore, the risk for loss of the longlines (whole gear or the snood lines) is unknown.

7. Overview of current methodologies to assess fishing gear performance

The objective of this thesis as described in Chapter 4 is to investigate whether recently developed biodegradable plastic materials can be used in gillnet and longline fisheries. To assess this, the performance of the fishing gear made of the new biodegradable plastic material should be compared to that of commonly used non-biodegradable materials through experimental sea trials. This chapter provides a brief overview of (a) the estimation of relative length-dependent catch efficiency of the fishing gear and (b) capture mode estimation for gillnet fisheries. The focus of this chapter is on sampling during the sea trials and the estimation of the fishing gear performance used in the articles presented in Chapter 9 of this thesis. Further, this chapter highlights the research needs for additional methodologies to estimate gillnet and longline gear performance when the nylon material is changed to biodegradable plastics.

7.1. Catch comparison method

To estimate the catch efficiency of fishing gear and compare the catch efficiency of a gear using different materials or gear configurations based on the data from sea trials, the estimation of the absolute catch efficiency is often applied. Such absolute catch efficiency estimations, also called catch per unit of effort (CPUE), require the information on the catch data from each fishing gear type compared, and is dependent on the spatial and temporal availability of the animals on the fishing grounds. However, this abundance is often unknown and thus the CPUE estimates can provide only a limited general value and cannot be extrapolated to other situations where the abundance and sizes of the animals can be different (Olsen et al., 2019; Cerbule et al., 2021; 2023). This is especially the case with passive fishing gear types such as in gillnet and longline fisheries. Due to these considerations, estimation of the CPUE of gillnets or longlines comparing commonly used nylon and new biodegradable plastic materials would be difficult and would provide little information that could be generalizable to other situations.

However, estimation of the effect of changing the material type on the length-dependent relative catch efficiency does not depend on the temporal and spatial availability of the target species since the effect is quantified by the relative catch efficiency between the two gear types as a ratio between the catches. Thus, the data needed for the estimations are the catch data from the fishing trials (experimental fishing). Therefore, the results of experiments using this method often can be of more general interest compared to results that depend on the conditions specific to the abundance of the target species at the time and place the study was conducted.

To apply the relative catch efficiency estimation method, the two compared fishing gear types/configurations need to be deployed simultaneously in the same area and same deployment pattern (i.e., similar soak time or same bait type in case of longline fisheries). The relative length-dependent catch efficiency between the two fishing gear types is often termed "catch ratio" in scientific literature (i.e., Herrmann et al., 2017; Grimaldo et al., 2018a; 2018b; 2019; 2020a; 2020b; Cerbule et al., 2021). The method is applied for estimating catch efficiency of different fishing gear modifications, including studies focusing on passive fishing gear types such as gillnets and longlines. For the reasons mentioned in this chapter, the catch ratio estimation has been a preferred technique applied in experimental trials conducted within this thesis. Although this method is not restricted to passive fishing gears and can be as well used for different active gear configurations, in this chapter the focus will be on passive fishing gears such as longlines and gillnets.

Depending on the experimental design used during the sea trials, the estimation of the length-dependent relative catch efficiency can differ between paired or unpaired catch ratio which is briefly described in the following chapters (Chapter 7.1.1. and 7.1.2., respectively).

7.1.1. Paired length-dependent relative catch efficiency estimation

The length-dependent relative catch efficiency estimates whether there is a significant difference in catch efficiency between the gear types compared and whether the potential differences between them could be related to the size of the targeted animals. Using the paired approach, the fishing gear of both types compared must be deployed simultaneously, in the same fishing area and fishing conditions. In practice, this means that the fishing gear of the two compared configurations is deployed in an alternate order in close proximity to avoid spatial variation in fish abundance. Furthermore, to provide the best information for paired comparison, the same number of gears of each type is often deployed (i.e., same number of gillnet sheets and same number of longline snoods of each type) (Fig. 7).

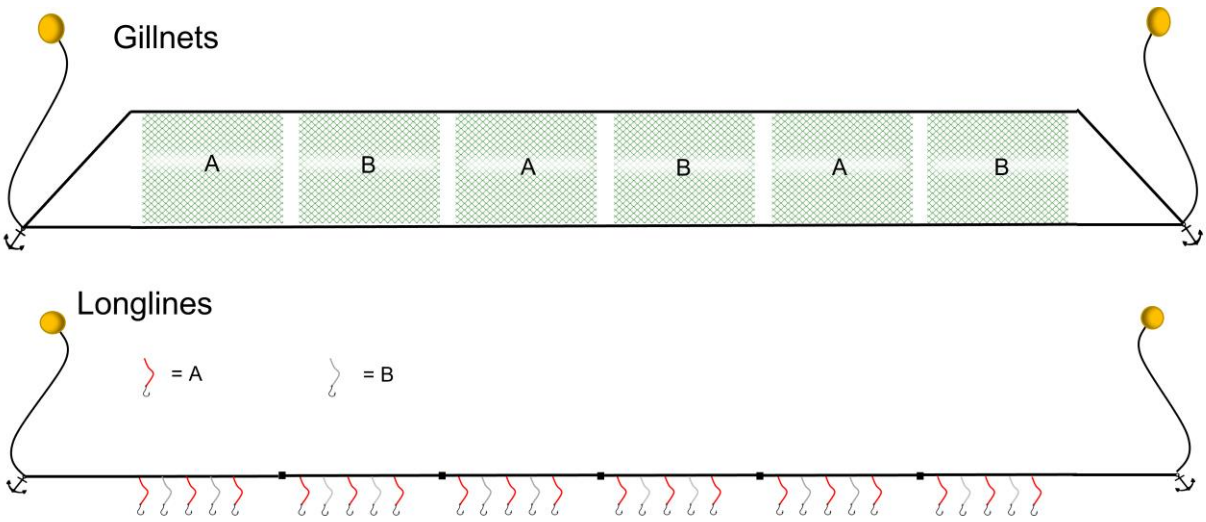

Figure 7. A schematic representation of an example of fishing gear deployment during fishing trials for paired length-dependent relative catch efficiency estimation. In the upper drawing, gillnet sheets of two types (A and B) are deployed in an alternated order with the same number of sheets for A and B, respectively. Similar approach is represented for longline gear (lower drawing) where snood types A and B are compared.

The method then uses the numbers and sizes of individuals of each observed species measured in each fishing gear type A or B (Fig. 7) in each deployment to determine whether there are significant differences in the catch efficiency between the two gear types.

For the estimations of paired relative catch efficiency between the two gears A (test) and B (baseline), the following experimental length-dependent catch comparison (CC_l) rate is used:

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

where nA_{lj} and nB_{lj} are numbers of individuals caught in each length class l for the test gear A and baseline gear B, respectively, in deployment j. m is the number of deployments with the gear conducted during the trials. Often the catch for one fleet deployed once is considered as base unit for the analysis (one deployment). Fig. 7 illustrates the fleet for gillnet and longlines, respectively. The functional form of the experimental catch comparison rate $CC(l, \boldsymbol{v})$ is obtained using maximum likelihood estimation by minimizing the expression:

$$-\sum_l \sum_{j=1}^{m} \{nA_{lj} \times \ln(CC(l,\ \boldsymbol{v})) + nB_{lj} \times \ln(1.0 - CC(l, \boldsymbol{v}))\} \quad (2)$$

where $\boldsymbol{v}$ represents the parameters describing the catch comparison curve defined by $CC(l, \boldsymbol{v})$. The outer summation in the Expression (2) is the summation over the length classes *l*. When the catch efficiency of both gears A and B are equal, the expected value for the summed catch comparison rate would be 0.5 which is used to judge whether there is a difference in catch efficiency between two fishing gear types. The experimental CC_l is modeled by $CC(l, \boldsymbol{v})$ as follows:

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

In Equation (3), *f* is a polynomial of order *k* with coefficients v_0 to v_k. The values of parameters v are estimated by minimizing the Expression (2), which is equivalent to maximizing the likelihood of the observed catch data. *f* up to order of 4 with parameters v_0, v_1, v_2, v_3, v_4 is often considered. Leaving out one or more of the parameters v_0- v_4 leads to 31 additional models that are also considered as candidates for the catch comparison $CC(l, \boldsymbol{v})$. Among these models, estimations of the catch comparison rate are made using multimodel inference to obtain a combined model (Burnham and Anderson, 2002; Herrmann et al., 2017). The ability of the combined model to describe the experimental data is evaluated based on *p*-value that quantifies the probability for by coincidence obtaining at least as big discrepancy between the experimental obtained CC_l and the modelled $CC(l, \boldsymbol{v})$. Specifically, the *p*-value should not be < 0.05 for the combined model to describe the experimental data sufficiently well, except the cases where data are subject to overdispersion (Wileman et al., 1996; Herrmann et al., 2017).

Based on the modelled catch comparison rate $CC(l, \boldsymbol{v})$, the relative catch ratio $CR(l, \boldsymbol{v})$ between fishing gears A and B can be obtained using:

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

The catch ratio quantifies the relative catch efficiency between fishing gears A and B. $CR(l, \boldsymbol{v})$ of 1.5 would mean that the A or the test fishing gear is catching 50% more animals of length *l* than the B or the baseline fishing gear. However, if, for example, the $CR(l, \boldsymbol{v})$ = 0.4, then the A gear is catching only 40% of the given species with length l compared to B gear.

The confidence limits for catch comparison and catch ratio are estimated using nested bootstrapping method (i.e., Herrmann et al., 2017; Grimaldo et al., 2019), accounting for between- and within- deployment variability. Such nested bootstrap (often called double bootstrapping in the literature) approach is often used in estimating uncertainty in fishing gear studies and has also been applied to several passive gear performance studies. The outer loop is resampling over the group of individual deployments by selecting m deployments with replacement. Once a deployment is selected in the outer loop, the data for individual length classes are resampled individually between gear A and B in the inner resampling loop, thereby taking full advantage of the paired nature of the data collection (Fig. 7). In this way, the outer bootstrapping loop is accounting for the between deployment variations in catch performance of the two gear types while the inner loop accounts for the uncertainty in the individual deployment due to the catch of only a finite number of individuals in the specific deployment. By multimodel inference in each bootstrap iteration, the method also accounts for the uncertainty in model selection. The estimated Efron 95% percentile (Efron, 1982) confidence intervals allow identifying sizes of animals with significant differences in catch efficiency when checking for length classes in which the 95% confidence intervals for the catch ratio curve do not contain 1.0. The results of catch comparison and catch ratio analysis are showed graphically by plotting the catch comparison rate or catch ratio and corresponding animal length (Fig. 8). When interpreting such results graphically, significant differences in catch efficiency are detected when checking for length classes in which the 95% confidence intervals for the catch comparison and catch ratio curve do not contain 0.5 and 1.0 values, respectively (Fig. 8).

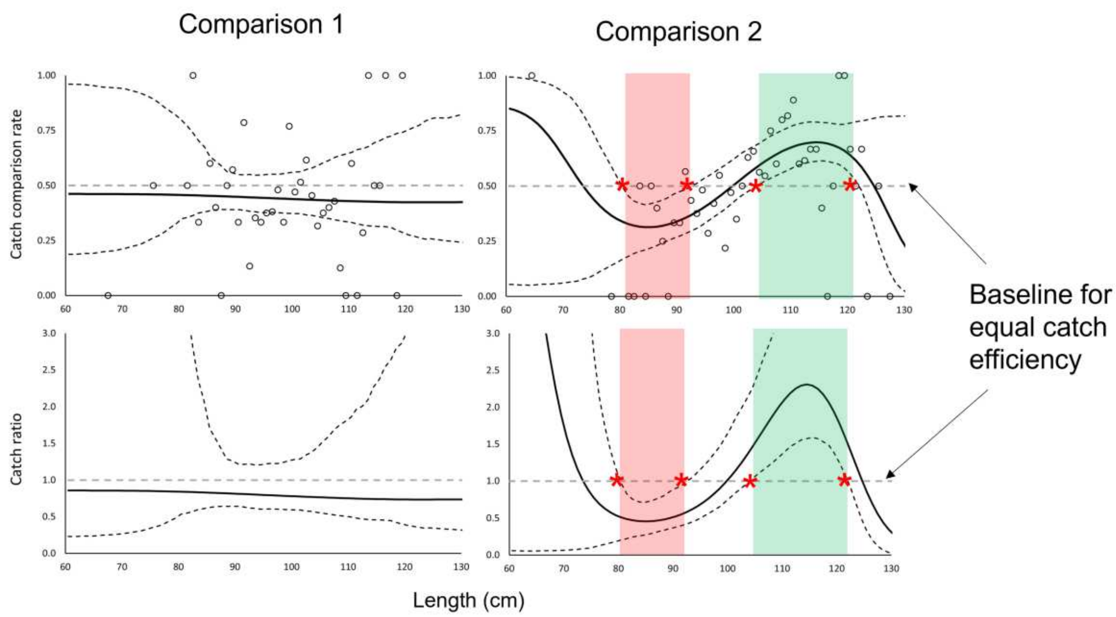

Figure 8. Catch comparison rate plots (upper) and catch ratio plots (lower) resulting from the length-dependent relative catch efficiency estimations. In catch comparison rate plots, circle marks represent the experimental rate (Equation (1)), and the curves are the modelled catch comparison rate (Equation (3)). The stippled line at 0.5 for the catch comparison rate is the baseline at which both gear types A and B have equal catch efficiency. Similarly, the stippled line at 1.0 for catch ratio curve represent the baseline at which both gears have equal catch rates. The stippled curves represent the 95% confidence intervals estimated for catch comparison and catch ratio curves, respectively. Left plots (Comparison 1) show no difference between the two gears tested since the baseline is within the confidence intervals while plots on the right (Comparison 2) show a reduced catch efficiency (red) and increased catch efficiency (green) where both confidence intervals are under and above the 1.0 baseline respectively (red marks).

A length-integrated average value for the catch ratio can also be estimated from the experimental catch data:

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

where the outer summation includes the length classes observed during the experiments. The results of $CR_{average}$ are specific for the population structure encountered during the experimental trials; therefore, these results cannot be applied to other situations where the population structure can be different due to, for example, other areas or fishing seasons (Cerbule et al., 2021).

7.1.2. Unpaired length-dependent relative catch efficiency estimation

In case of an unpaired length-dependent relative catch efficiency estimation, the collected data from the fishing trials are not collected in pairs and therefore within the individual deployment it cannot be assumed that gear A and gear B is fishing on identical populations, nor they do not necessarily have the same total number of deployments (Fig. 9) due to, for example, practical considerations when handling the gear during the sea trials.

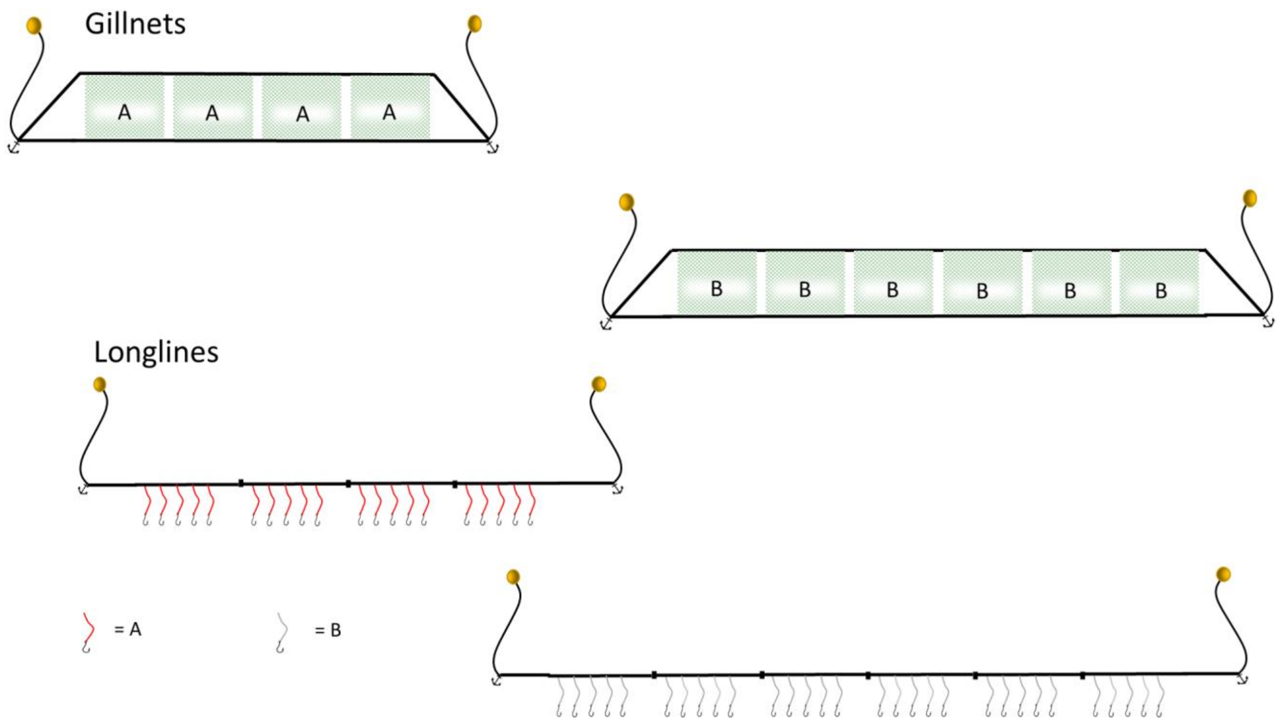

Figure 9. A schematic representation of an example of fishing gear deployment during fishing trials for unpaired length-dependent relative catch efficiency estimation. In the upper drawing, the gillnet example the data is not collected in pairs and do not have the same number of deployments with the compared A and B gillnet designs. In the lower drawing, the data for longline mainlines containing A and B snood types are also not collected in pairs.

This deployment pattern leads to differences in estimations of the unpaired catch ratio compared to the description given above (Chapter 7.1.1.). Specifically, the differences in catch efficiency estimations described here implies that the method does not require that such data are collected in pairs or that equal number of deployments with each of the compared fishing gear types are conducted as described in Chapter 7.1.1. Thus, to estimate the functional form of the catch comparison rate between gear types A and B, the catch data from the deployments of A are summed and compared with the summed data of the deployments conducted with gear type B. In such case, the experimental length-dependent catch comparison rate (CC_l) is expressed as follows:

$$CC_l = \frac{\sum_{i=1}^{Aq} nA_{li}}{\sum_{i=1}^{Aq} nA_{li} + \sum_{i=1}^{Bq} nB_{li}} \qquad (6)$$

In Equation (6), nA_{li} and nB_{li} are the numbers of animals measured in each length class l for gears A and B, respectively. Aq and Bq are the numbers of deployments conducted with each of the compared gears. When the catch efficiency of gears A and B and the number of their deployments are equal (i.e., $Aq=Bq$), the expected value for the summed catch comparison rate, similar as with paired analysis, would be 0.5. However, in case of unequal number of deployments such as in the gillnet example shown in Fig. 9, $Aq/(Aq+Bq)$ would be the baseline to judge whether there is a significant difference in catch efficiency between gears A and B. The functional form for the catch comparison rate $CC(l, \boldsymbol{v})$ is then obtained using the expression:

$$-\sum_l \left\{ \sum_{i=1}^{Aq} \left\{ nA_{li} \times \ln\left(CC(l,\ \boldsymbol{v})\right) \right\} + \sum_{i=1}^{Bq} \left\{ nB_{li} \times \ln\left(1.0 - CC(l,\ \boldsymbol{v})\right) \right\} \right\} \qquad (7)$$

which, compared to the Expression (2) accounts for the number of deployments conducted with gears A and B, respectively. The inner summation in the Expression (7) accounts for the summations of the data from the deployments. Further, the experimental CC_l is modeled by $CC(l, \boldsymbol{v})$ as described for the paired analysis (Equation (3)), and the confidence intervals are estimated using the nested bootstrapping approach (Herrmann et al., 2017). The procedure accounts for between deployment variation in the availability of the animals and catch efficiency by selecting Aq deployments with replacement from the pool of A type deployments and Bq deployments with replacement from the pool of B type deployments during each bootstrap repetition. Within-deployment uncertainty in the size structure of the catch data is accounted for by randomly selecting animals with replacement from each of the selected deployments separately. The number of animals selected from each deployment is the same as the number of them caught within that deployment. These data are then combined as described above, and the catch comparison curve is estimated.

1000 bootstrap repetitions are usually performed (i.e., Herrmann et al., 2017), and the Efron 95% percentile (Efron, 1982) confidence intervals estimated for the catch comparison curve. To identify lengths of observed animals with significant difference in catch efficiency, length classes in which the confidence limits for the combined catch comparison curve do not contain *Aq*/(*Aq*+*Bq*) are observed (Herrmann et al., 2017).

For unpaired analysis, the functional form for catch ratio *CR*(*l*, $\boldsymbol{v}$) is estimated using the following equation as described in Herrmann et al. (2017):

$$CR(l,\boldsymbol{v}) = \frac{Bq \times CC(l,\boldsymbol{v})}{Aq \times (1-CC(l,\boldsymbol{v}))} \qquad (8)$$

The catch ratio then provides a value that is independent of the number of deployments carried out with gear types A and B. For example, if the catch efficiency of A and B is equal, *CR*(*l*, $\boldsymbol{v}$) would be equal to 1.0. The bootstrap approach is applied similarly to estimate the confidence intervals for the catch ratio.

Finally, the length-integrated average value for the catch ratio is estimated with some differences from the paired estimation described by Equation (5). Thus, for unpaired analysis, this is estimated accounting for the number of deployments with gears A and B, respectively, as follows:

$$CR_{average} = \frac{Bq \times \sum_l \sum_{i=1}^{Aq} nA_{li}}{Aq \times \sum_l \sum_{i=1}^{Bq} nB_{li}} \qquad (9)$$

Similarly, as for the estimation of uncertainties for paired length-integrated catch ratio estimation, the uncertainties for unpaired estimations can be obtained by the double bootstrap method as described above.

7.2. Size dependent capture mode estimation for gillnets

During the capture process in gillnets, fish are commonly caught in this gear type in different capture modes. In scientific literature, some descriptions of the most common capture modes for roundfish are mentioned (for example, Potter and Pawson, 1991; Reis and Pawson, 1999; He et al., 2006; Savina et al., 2022). For example, four major categories of roundfish capture in gillnets that are commonly discussed are gilling (caught with the netting behind gill cover), wedging/largest part of the body, snagging (being captured by mouth, teeth, or other part of the head), and entangling (caught by spines or fins depending on the morphology of the fish species considered) (He, 2006; Savina et al., 2022) (Fig. 10).

Figure 10. Capture modes of Atlantic cod (*Gadus morhua*) observed in gillnets in study by Savina et al. (2022). Source: Savina et al. (2022).

Quantifying the most common length-dependent capture modes in a gillnet fishery can provide with a valuable information, for example, when gear capture efficiency is considered as some modes are more efficient at retaining fish than others (Potter and Pawson, 1991; Savina et al., 2022). Therefore, they can be affected by gear properties such as mesh size or hanging ratio but also potentially including the gillnet material type. Savina et al. (2022) developed a method to estimate the length-dependent capture mode probability for fish in gillnets. Specifically, the method uses the data on fish length and corresponding capture modes in gillnets to model the capture mode probability using the catch comparison setup as described in Chapter 7.1. A nested bootstrap approach is used to estimate the Efron 95% percentile (Efron, 1982) confidence intervals for the relevant length values and to account for potential uncertainties from model selection (Savina et al., 2022). However, the data are analyzed independently for each gear type. Specifically, data are grouped according to capture mode with one particular mode compared to the rest. The data collection for such analysis is based on visually assessing the mode how fish are captured in the gillnet netting upon gear recovery by examining the position and tension of the netting around the fish and measuring the corresponding length of each individual. A fish can be assigned one or several capture modes (Savina et al., 2022).

Further, the data are analyzed to determine, conditioned capture, the length-dependent capture mode probability by:

$$CPq_l = \frac{\sum_{j=1}^{m} n_{qlj}}{\sum_{j=1}^{m}\sum_{i=1}^{Q} n_{ilj}} \qquad (10)$$

In Equation (10), n_{qlj} is the number n of fish caught in a length class l with capture mode q in deployment j. Q is the total number of capture modes considered. In Savina et al. (2022), the capture mode probability was observed over deployment days m. Similar as for catch comparison analysis, the functional form of the capture mode probability $CPq(l, \boldsymbol{v})$ was obtained using maximum likelihood estimation by minimizing the Expression (11):

$$-\sum_l \sum_{j=1}^{m} \left\{ n_{qlj} \times \ln\left(CPq(l,\ \boldsymbol{v})\right) + \left(-\, n_{qlj} + \ \sum_{i=1}^{Q} n_{ilj}\right) \times \ln\left(1.0 - CC(l, \boldsymbol{v})\right) \right\} \ (11)$$

where $\boldsymbol{v}$ represents the parameters describing capture mode probability defined by $CPq(l, \boldsymbol{v})$ in value range from 0.0-1.0. Further, similarly to the catch comparison rate estimation (Chapter 7.1.), the experimental CPq_l is modelled by:

$$CPq(l, \boldsymbol{v}) = \frac{exp\left(f(l, v_0, \ldots, v_k)\right)}{1 + exp\left(f(l, v_0, \ldots, v_k)\right)} \qquad (12)$$

The capture mode probability is then estimated by using multimodel inference as in Herrmann et al. (2017). Similarly, fit statistics for the combined model to describe the experimental data sufficiently well should include a p-value which is > 0.05. Further, the nested bootstrapping approach applied for paired catch comparison (Chapter 7.1) is used to estimate the 95% confidence intervals for the capture mode probability.

Finally, a length integrated average value for the capture mode probability can be estimated directly from the experimental catch data based on similar approach as the estimation for length-integrated average value for the catch ratio as follows (Savina et al., 2022):

$$CPq_{average} = \frac{\sum_l \sum_{j=1}^{m} n_{qlj}}{\sum_l \sum_{j=1}^{m} \sum_{i=1}^{Q} n_{ilj}} \qquad (13)$$

However, in comparison to the capture mode probability *CPq*(*l*, $\boldsymbol{v}$), the $CPq_{average}$ values are specific for the population structure encountered at the time and place the experiments are conducted, and thus these results cannot be extrapolated to other situations where the size structure of the fish may be different (Savina et al., 2022).

7.3. Further research needs to evaluate fishing gear performance when using biodegradable materials

Chapters 7.1. and 7.2. of this thesis aimed at providing an overview of some of the available methods for comparing the fishing gear performance when changing some of the fishing gear characteristics such as the material type, i.e., the catch efficiency estimation and the length-dependent capture mode probability estimation used in gillnet fisheries. However, some aspects regarding fishing gear performance are currently not being covered by using the existing methodology.

The approach of estimating the catch efficiency of the target species often can only account for a limited fraction of the catch. Specifically, this can often be the case in multi-species fisheries where several species are captured by the specific fishing gear type. In such fisheries, estimations of the catch efficiency of the main target species or few species of special concern would result in ignoring a fraction of the total species composition in the catches when evaluating the effect the fishing gear and its modifications have on the species community. Therefore, assessments of the whole catch composition would be relevant to provide a more holistic assessment of the impact of changing the fishing gear design.

Further, the fishing gear performance in longline fishery for quantifying the snood losses is not covered by the existing methodology. Specifically, some overall estimates of snood losses are available in the literature (i.e., Richardson et al., 2022); however, this extent has not been scientifically quantified for specific fisheries. This is especially important since the snood loss rate can vary between different fisheries due to varying fishing grounds, target species and gear construction (for instance breaking strength of snoods).

Therefore, these aspects constitute further research needs in methodology regarding how to assess the fishing gear performance, including when changing the material type from commonly used nylon to biodegradable plastic material. This thesis aims to address those aspects and the approach to address this is further described in Chapter 9.

8. Research questions

Based on the objective of this thesis described in Chapter 4, the review of current research on the use of biodegradable plastic materials to reduce marine plastic pollution and ghost fishing in Chapter 5, for the specific fisheries defined in Chapter 6, and the overview on methods to assess the fishing gear performance described in Chapter 7, the specific research questions for this thesis are:

1. How to quantify and compare the total species composition and what is the effect of changing gillnet material in a multispecies fishery?
2. Can biodegradable materials be used in gillnet fisheries without negatively affecting catch efficiency?
3. Can capture modes explain the differences in catch efficiency between the gillnets made of biodegradable and nylon materials?
4. Can effects of manufacturing, physical strain due to gear operation, and biodegradation on tensile properties explain differences in capture modes and catch efficiency of biodegradable and nylon gillnets?
5. How to quantify the snood loss rate in coastal longline fisheries using nylon material?
6. Are there any differences in snood loss rate when changing the snood material from commonly used nylon material to biodegradable plastics?
7. Can the snood material be replaced by biodegradable plastic material in longline fisheries without negatively affecting the catch efficiency?
8. How does change in material affect total species composition in longline catches in a multispecies longline fishery?

9. Studies evaluating performance of biodegradable materials in gillnet and longline fisheries

In this chapter, studies testing the use of biodegradable plastic materials in the four described fisheries (Chapter 6) are presented. Articles I-III present the results from testing biodegradable PBSAT material in gillnet fisheries in Norway and Denmark regarding catch composition, catch efficiency and capture mode probability and material properties. Articles IV and V presents the results from estimating snood loss rates in coastal longline fisheries in Norway and Croatia and results comparing the snood loss rate, catch efficiency and catch composition when biodegradable PBSAT and nylon materials are compared.

9.1. Quantification of catch composition in fisheries: A methodology and its application to compare biodegradable and nylon gillnets (Article I)

The research presented in Article I reports the results of testing the biodegradable plastic material in Danish coastal gillnet fishery. In this fishery, the primary target species are European plaice and cod. However, many other species are often captured (Fig. 11). Some of these contribute to the wanted catches (i.e., species with a commercial value) while some others are unwanted bycatch species. Therefore, the total catch composition normally consists of several species. Use of different material in gillnet netting could affect the catch rates of wanted and unwanted species differently due to different material properties. The aim of this article was to develop and apply a method to quantify and compare the catch composition when using nylon and biodegradable PBSAT gillnets.

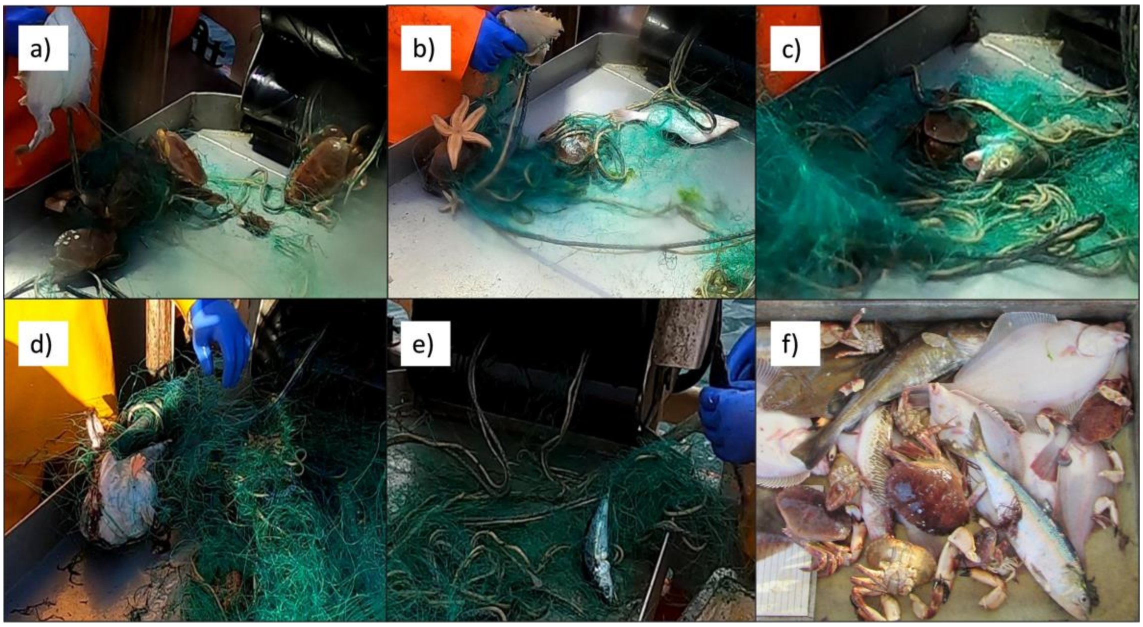

Figure 11. Examples of species observed in gillnet catches during the experiments conducted for Article I. (a) European plaice (wanted catch) and brown crab (large individuals – wanted catch); (b) brown crab, European plaice and common starfish (unwanted catch); (c) cod (wanted catch) and brown crab; (d) monkfish (wanted catch); (e) mackerel (unwanted catch); (f) European plaice, brown crab, herring (unwanted catch), swimming crab (unwanted catch), common dab, greater weever and cod.

The study described in Article I addresses research question 1 of this thesis (Chapter 8). Specifically, it aims to answer the question whether the changes in gillnet material affect the total species composition in a multispecies fishery. To answer this research question, this study developed a method for quantifying the catch composition in fishing gear catches and estimated the catch composition of this gillnet fishery when using nylon material in gillnets. Further, it compared whether there is any significant effect on the catch composition when changing the gillnet material from nylon to biodegradable plastics (PBSAT).

The data for this study were collected during September 2021 in Denmark (Skagerrak area off the coast of Hirtshals) by deploying 8 nylon and 8 biodegradable PBSAT gillnet sheets in an alternated order from a small-scale commercial gillnet vessel. The biodegradable and nylon gillnets in this experiment had the same parameters with the only difference being material type. After each deployment, the catch was sorted according to the gillnet material type, and all fish and invertebrate mega-fauna were sorted by species. The number of individuals were counted for total catch and further sorted into wanted catch (primary and secondary target species) and unwanted bycatch. The catch composition quantified in Article I was estimated by adapting the method used in biodiversity estimations: species richness (Daly et al., 2018), Pielou index (Pielou, 1996) and Shannon diversity index (Shannon, 1948). While species richness accounts for the number of species observed in the sample and Pielou index accounts for evenness in species distributions, Shannon index is accounting for a combination of both richness and evenness of the species distribution. Further, this study assessed species dominance patterns and cumulative dominance patterns in total, wanted and unwanted catch compositions to examine whether one or few species are more abundant in the catches compared to the others (Maurer & McGill, 2011). This approach was applied to estimate whether there are any significant differences when the nylon material is changed to PBSAT in gillnets in this fishery. The uncertainties (i.e., between and within gillnet deployments) were accounted for based on approach in Herrmann et al. (2022). Further, the pairwise difference in cumulative dominance curves for biodegradable versus nylon gillnets were estimated using the delta approach (Herrmann et al., 2022) where the 95% confidence intervals were obtained based on the two bootstrap population of results (Herrmann et al., 2022).

The species dominance patterns in this study were represented using cumulative species dominance curves as often used in studies quantifying species compositions (i.e., Warwick et al., 2008). When using this approach in Article I, the species ranking was kept fixed in all catches for all species observed (Table 1).

Table 1. List of the fixed species ranking sampled during the experiments described in Article I for wanted (green) and unwanted (red) species, respectively.

Wanted species			Unwanted species		
Species ID	Species name	Common name	Species ID	Species name	Common name
1	*Pleuronectes platessa*	European plaice	13	*Merlangius merlangius*	Whiting
2	*Solea solea*	Sole	14	*Asterias rubens*	Common starfish
3	*Gadus morhua*	Cod	15	*Pollachius pollachius*	Pollock
4	*Limanda limanda*	Common dab	16	*Trachinus draco*	Weeverfish
5	*Scopthalmus maximus*	Turbot	17	*Portunus*	Swimming crab
6	*Platichtyes flesus*	Flounder	18	*Hyas araneas*	Spider crab
7	*Cancer pagurus*	Brown crab	19	*Carcinus maenas*	Shore crab
8	*Molva molva*	Common ling	20	*Anguilla anguilla*	Eel
9	*Lophius piscatorius*	Monkfish	21	*Pagurus bernhardus*	Hermit crab
10	*Zeugopterus punctatus*	Topknot	22	*Syngnathus*	Pipefish
11	*Scomber scombrus*	Mackerel	23	*Raja clavata*	Thornback ray
12	*Microstomus kitt*	Lemon sole	24	*Aurelia aurita*	Common jellyfish
			25	*Myoxocephalis scorpius*	Shorthorn sculpin
			26	*Clupea harengus*	Herring
			27	*Eutrigla gurnardus*	Grey gurnard
			28	*Raniceps raninus*	Tadpole fish

The resulting cumulative dominance plots show cumulative proportional abundances plotted against the species rank (Fig. 12). The approach of a fixed species ranking allowed comparison of the steepness of the cumulative dominance curves to obtain an overview on how many species are dominant and the distribution of their relative dominance in total, wanted and unwanted catch compositions in nylon and biodegradable gillnets, respectively.

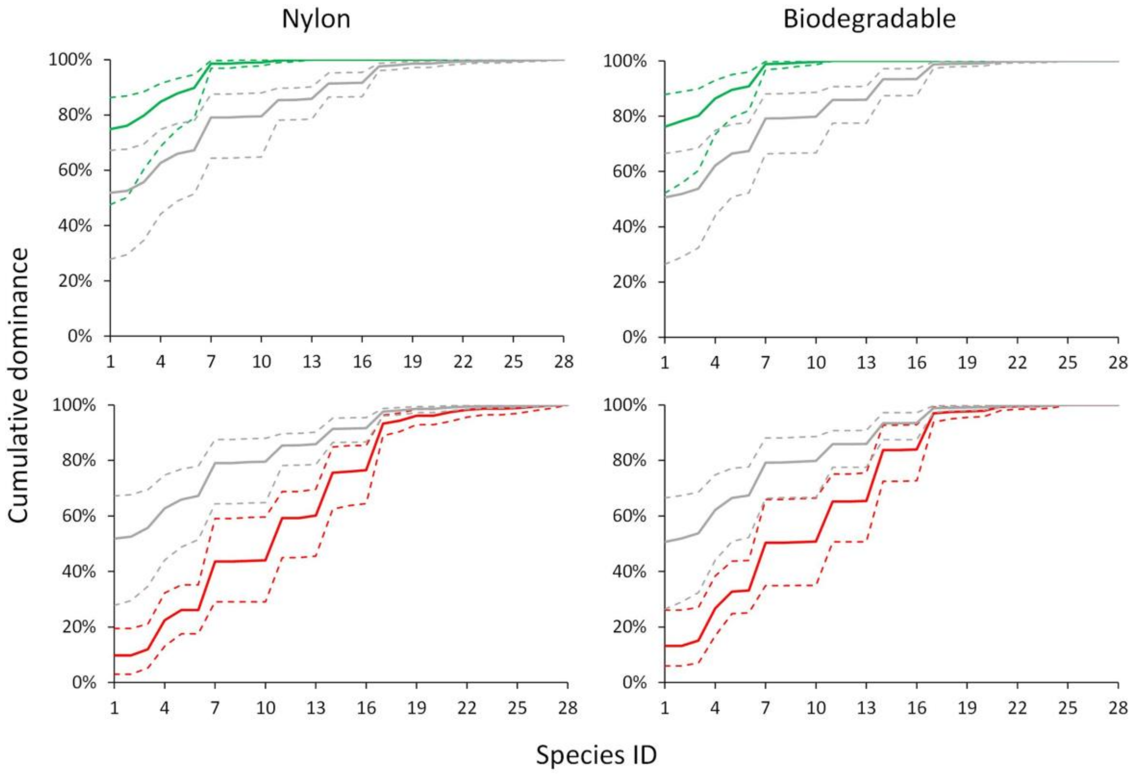

Figure 12. Cumulative dominance results presented in Article I for nylon gillnets (left) and biodegradable gillnets (right). Grey curve represents dominance curve for total catch composition by the particular gear material while green and red line – species that were classified as wanted and unwanted catch, respectively. Dashed lines are 95% confidence intervals estimated based on approach by Herrmann et al. (2022).

In cumulative dominance curves (Fig. 12), according to the applied approach when keeping the species ranking fixed, the steep parts show the species that dominate the catches while horizontal parts show species that are not abundant or not present in the catch compositions.

In this study, biodegradable and nylon gillnets demonstrated a similar catch composition, showing that use of PBSAT material in gillnets would not increase vulnerability of species captured by biodegradable compared to nylon gillnets. Specifically, in the plots showing the pairwise difference in cumulative species dominance for biodegradable versus nylon gillnets (delta), the results included the baseline showing no difference between the gears within the 95% confidence intervals when considering either total, wanted, or unwanted catch compositions (Fig. 13). Therefore, this study showed that changing the material type in the netting to PBSAT would not affect the catch composition and thus does not represent a barrier for implementing biodegradable materials in this commercial gillnet fishery.

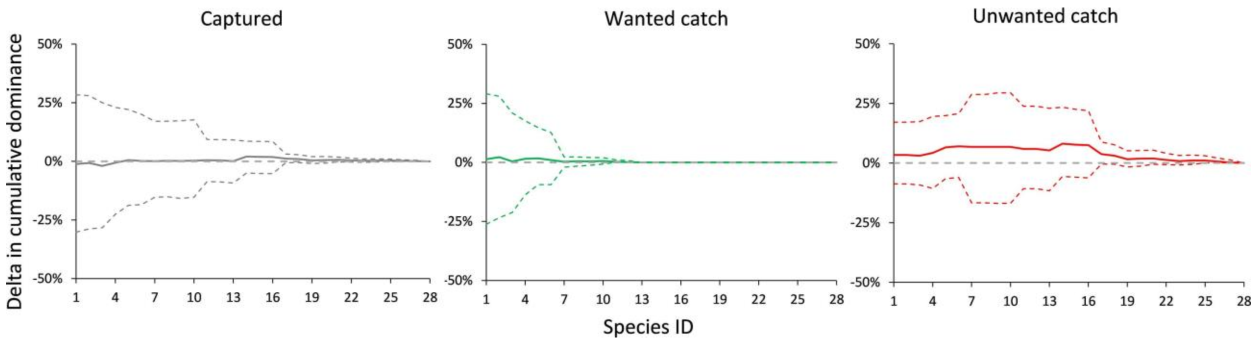

Figure 13. Pairwise difference (delta) in cumulative dominance curves for biodegradable versus nylon gillnets for total captured (left), wanted (middle) and unwanted (right) catch species. Stippled likes are 95% confidence intervals and stippled horizontal line at 0% shows the baseline for no significant difference.

The results of this study showed that there were significant differences in catch composition between total and wanted gillnet catches (Fig. 13). Therefore, this study demonstrated the importance of using a more holistic approach when assessing the effect of changing fishing gear design on entire catch composition. Specifically, the results showed that although the main target species, European plaice, dominated the total catch composition, a large part of the total catch composition, expressed as number of individuals, was consisting of different unwanted species (20.00% (CI: 16.40-23.49%) species for biodegradable and 22.00% (CI: 15.61-25.61%) species for nylon gillnets). The usually applied approach by considering only the target species in this fishery would ignore the other species that could potentially be affected by the changes in fishing gear design. Thus, using this more holistic approach as first presented in Article I has a potential of moving the field beyond focusing on a few commercial species in multispecies fisheries which is typically the case when analyzing the catch efficiency and selectivity of different fishing gears.

9.2. Comparison of the efficiency and modes of capture of biodegradable versus nylon gillnets in the Northeast Atlantic cod (Gadus morhua) fishery (Article II)

Earlier research testing biodegradable PBSAT gillnets have shown lower length-dependent catch efficiency of the target species for biodegradable compared to nylon gillnets (Grimaldo et al., 2018a; 2018b; 2019; 2020a; 2020b) with a decreasing efficiency when used for longer time, as discussed in Chapter 5. To understand these observed differences in catch efficiency and how the material properties of biodegradable and nylon gillnets can affect the catch efficiency over time, the underlying mechanisms of how fish of different sizes are captured in gillnets should be understood and quantified. This would contribute to identifying which improvements have to be made regarding the material properties of the biodegradable gillnets to reduce the observed decrease in catch efficiency.

Article II addressed the objective of this thesis by research questions 2 and 3 in Chapter 8. Specifically, it compared the catch efficiency between new and used biodegradable and nylon gillnets in cod fishery in northern Norway. Further, this study evaluated whether the assessment of capture modes in biodegradable and nylon gillnets based on the approach in Savina et al. (2022) could explain the differences in catch efficiency between the two materials.

The fishing trials were performed in March 2021 under commercial fishing conditions deploying 10 new and 10 used nylon and biodegradable gillnets, respectively, in an alternated order where two biodegradable gillnet sheets were followed by two nylon netting sheets (Fig. 14). The gillnets were deployed in two separate fleets where Fleet 1 contained new biodegradable and nylon gillnets while Fleet 2 consisted of used biodegradable and nylon gillnets, i.e., previously subjected to 12 deployments during the fishing season in 2020.

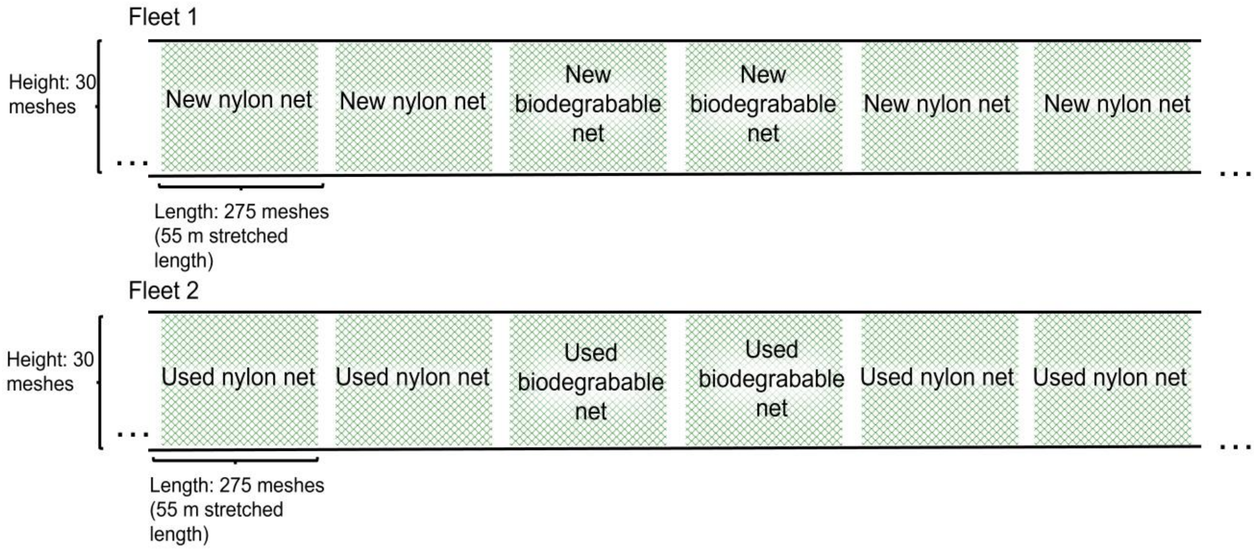

Figure 14. Experimental setup used during the trials described in Article II showing a segment of gillnets used during the fishing trials for each fleet. Fleet 1 contained new nylon and biodegradable gillnets. Fleet 2 contained used nylon and biodegradable gillnets. Fleets were deployed simultaneously and in the same fishing area.

When the nets were hauled on board, the catch was sorted by type of gillnet, and capture mode and length of each cod was observed. Four different capture modes were classified: tip (mouth or maxillary), gills, largest part of the body and entangled in the netting (Fig. 15). In the case of multiple modes, a primary capture mode was assumed according to the principle of likely sequence by Savina et al. (2022).

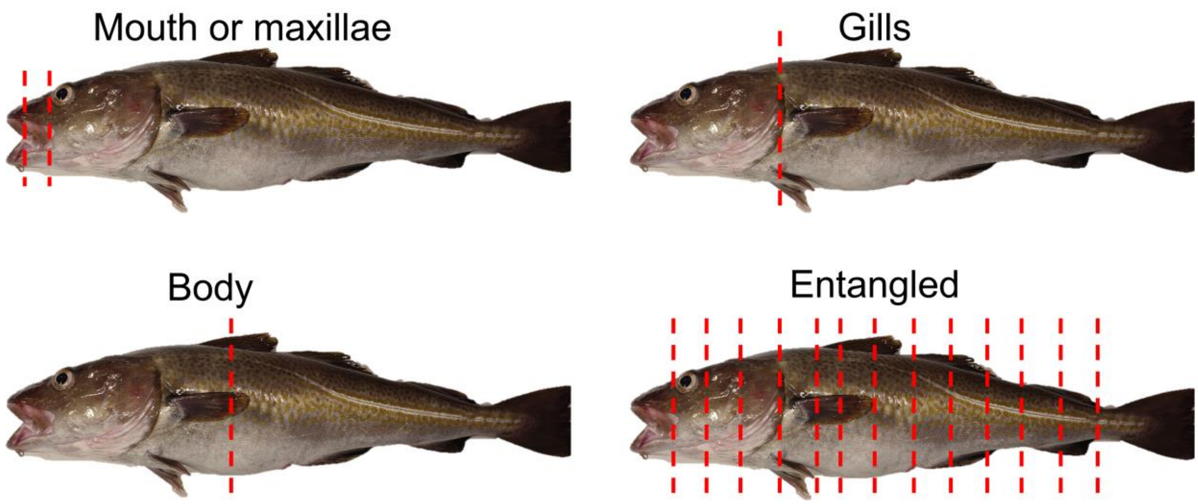

Figure 15. Schematic drawing showing the classification of capture modes for cod during the trials for Article II (tip (mouth or maxillary), gills, largest part of the body and entangled in the netting).

Comparison of catch efficiency between gillnet types was estimated as the paired catch comparison rate and catch ratio (Grimaldo et al., 2019; 2020a) as described in Chapter 7.1 which provided estimates for relative length-dependent catch efficiency between biodegradable and nylon gillnets for the two fleets. Further, to determine conditioned capture, the length-dependent probability of capturing fish in each of the four capture modes (Fig. 16), the approach by Savina et al. (2022) was used as described in Chapter 7.2. Further, the probability of capture in specific gillnet type (new or used biodegradable or nylon gillnet, respectively) and corresponding mode of capture was estimated.

The results of Article II were in accordance with the previous studies (i.e., Grimaldo et al., 2019; 2020a) showing lower catch efficiency of gillnets made of biodegradable material compared to nylon gillnets; especially in case of used biodegradable compared to nylon gillnets for cod larger than 95 cm (Fig. 16).

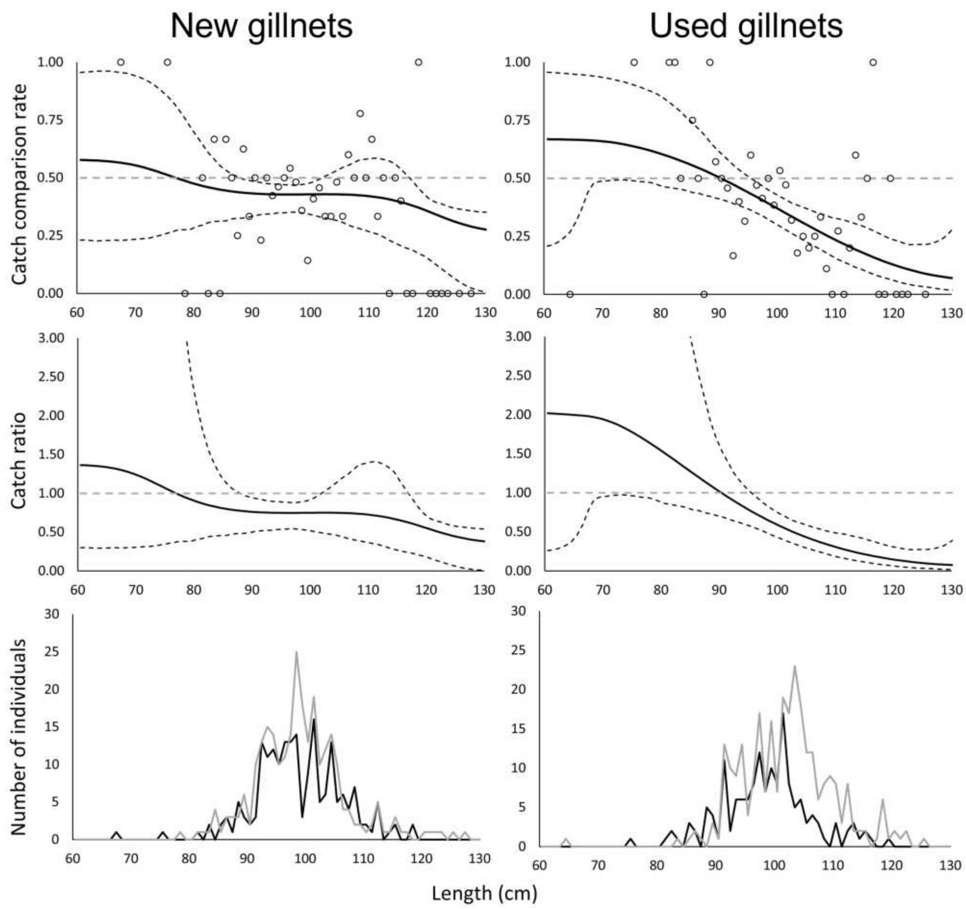

Figure 16. Catch comparison and catch ratio analysis for new (left) and used (right) biodegradable against nylon gillnets. Upper graph: the modelled catch comparison rate (black solid curve) with 95% confidence intervals (stippled curves). Circles represent the experimental catch comparison rate. Middle: the estimated catch ratio curve (black solid curve) with 95% confidence intervals (stippled curves). Bottom: the length frequency distribution of cod captured by the biodegradable gillnets (black) and nylon gillnets (grey). Stippled horizontal lines at 0.5 and 1.0 represent the baseline at which both types of gillnets fish equally.

The results showed that the capture by gills was the most common way of cod being caught in the gillnets. However, the probability of cod being caught by gills in both used and new biodegradable gillnets was lower when compared to both types of nylon nets (Table 2).

Table 2. Length-integrated average value ($CPq_{average}$ (%)) for the probability of being captured in a particular gillnet (new or used biodegradable or nylon gillnet, respectively) conditioned capture by one of the four capture modes observed (tip, gills, body, or entangled). Numbers in parentheses are 95% confidence intervals.

Gillnet type	Tip	Gills	Body	Entangled
New biodegradable	22.11 (15.93–25.13)	18.14 (11.86–21.19)	27.75 (18.55–32.51)	40.00 (23.12–52.99)
New nylon	29.15 (23.88–32.02)	29.30 (23.77–33.17)	30.61 (20.94–38.43)	20.00 (05.58–33.36)
Used biodegradable	17.59 (12.76–23.70)	20.23 (16.56–24.55)	13.47 (10.41–16.27)	12.00 (00.20–35.92)
Used nylon	31.16 (26.67–39.86)	28.16 (22.76–41.34)	28.16 (23.15–40.94)	28.00 (10.44–45.74)

These results of the capture mode observation suggested that the differences in catch efficiency between gillnets of both materials may be due to combination of differences in tensile strength and elasticity which can affect when the gillnet meshes break at the point of tension when cod is caught by gills or largest part of the body. Furthermore, since larger fish are more likely to be caught by the gills than the largest part of the body, these results can explain the reduced catch efficiency especially for larger individuals (> 95 cm total length) in this and previous studies (Grimaldo et al., 2019).

Article II was the first study reporting results of capture mode probability to explain the differences in catch efficiency between biodegradable and nylon gillnets. The results of this study showed that differences in catch efficiency between gillnets were related to specific capture modes which in turn may be related to different material properties. Therefore, it is highlighting the need for and importance of systematic studies of the mechanical properties of the biodegradable material to improve the catch efficiency of future biodegradable gillnets. The use of capture modes can provide useful information for explaining the catch efficiency for gillnets with different material properties, twine diameters and mesh sizes, among others. Therefore, this method can have a potential to be further applied when estimating the gear characteristics aiming to improve the catch efficiency of biodegradable gillnets.

9.3. Weaker tensile properties of biodegradable gillnets reduces catch efficiency much faster than biodegradation (Article III)

Article III of this thesis is adding to the results described in Articles I and II. Specifically, this study aimed at discriminating between the effects of manufacturing, physical strain due to gear operation, and biodegradation on tensile properties, capture modes and catch efficiency of biodegradable and nylon gillnets. The catch efficiency of biodegradable and nylon gillnets were compared during the fishing trials in Danish coastal gillnet fishery targeting European plaice and cod. The results of Article I showed no significant difference between the two materials regarding the catch composition in this fishery, suggesting that biodegradable materials can replace nylon in this fishery when the captured species composition is considered. However, results from previous studies have shown reduced catch efficiency for target species as described in Chapter 5 of this thesis which was in line with the results reported in Article II. Since the catch efficiency of biodegradable gillnets is an important factor that determines their use in commercial fishery, it is necessary to estimate it for this gillnet fishery. Furthermore, Article II showed that differences in catch efficiency can be explained by capture modes of fish in gillnets. The capture modes in the available studies have been examined for roundfish species such as cod; however, information on how flatfish species such as European plaice are captured in gillnets is limited.

Article III of this thesis addressed research questions 2 - 4 (Chapter 8). Specifically, it aimed to:

(1) discriminate between the effects of manufacturing, physical strain due to gear operation and biodegradation on the differences of biodegradable and nylon gillnet tensile properties,
(2) estimate the catch efficiency between new and used biodegradable and nylon gillnets in a Danish coastal gillnet fishery targeting European plaice and cod, and
(3) investigate whether length- and species-dependent capture modes can explain the observed catch efficiency results.

In this study, the material testing was performed to determine and compare the mechanical properties, tensile strength and stiffness, of biodegradable and nylon gillnets at three different timepoints throughout the fishing season. The timepoints for material sampling were selected by, first, sampling the new material at the start of the fishing season, second, at the end of the first fishing trials (10 deployments), and third, at the end of the experiments after second sea trials (additional 14 deployments and 4 months use of the gillnets). For each material sampling, two different netting samples were obtained, one being a sample from the gillnet netting subjected to wear and tear during the fishing process and another being a protected netting sample from a small-meshed bag that was subjected to deployments but protected from the effects of fishing operations. This was done to discriminate between the effects of manufacturing (new gillnets), physical strain due to gear operation (for gillnet samples exposed to fishing operations) and biodegradation (protected samples).

The sea trials comparing 8 biodegradable and 8 nylon nets were conducted in May and September 2021 (new and used gillnets, respectively). During each trial, 10 deployments of the gillnets were conducted. The experiments were carried out using a commercial coastal gillnet vessel and deploying the gillnets in an alternated order to account for the possible variations in spatial availability of fish. After each deployment, the fish were observed for each gillnet sheet (biodegradable and nylon) separately. The mode of capture and corresponding total length of each European plaice and cod were recorded. Based on literature (i.e., Hovgård et al., 1999, Holst et al., 2002; Savina et al., 2022) and observations during a pilot experiment, seven capture modes for European plaice and cod were determined for each species separately due to different morphology of both species considered (Fig. 17).

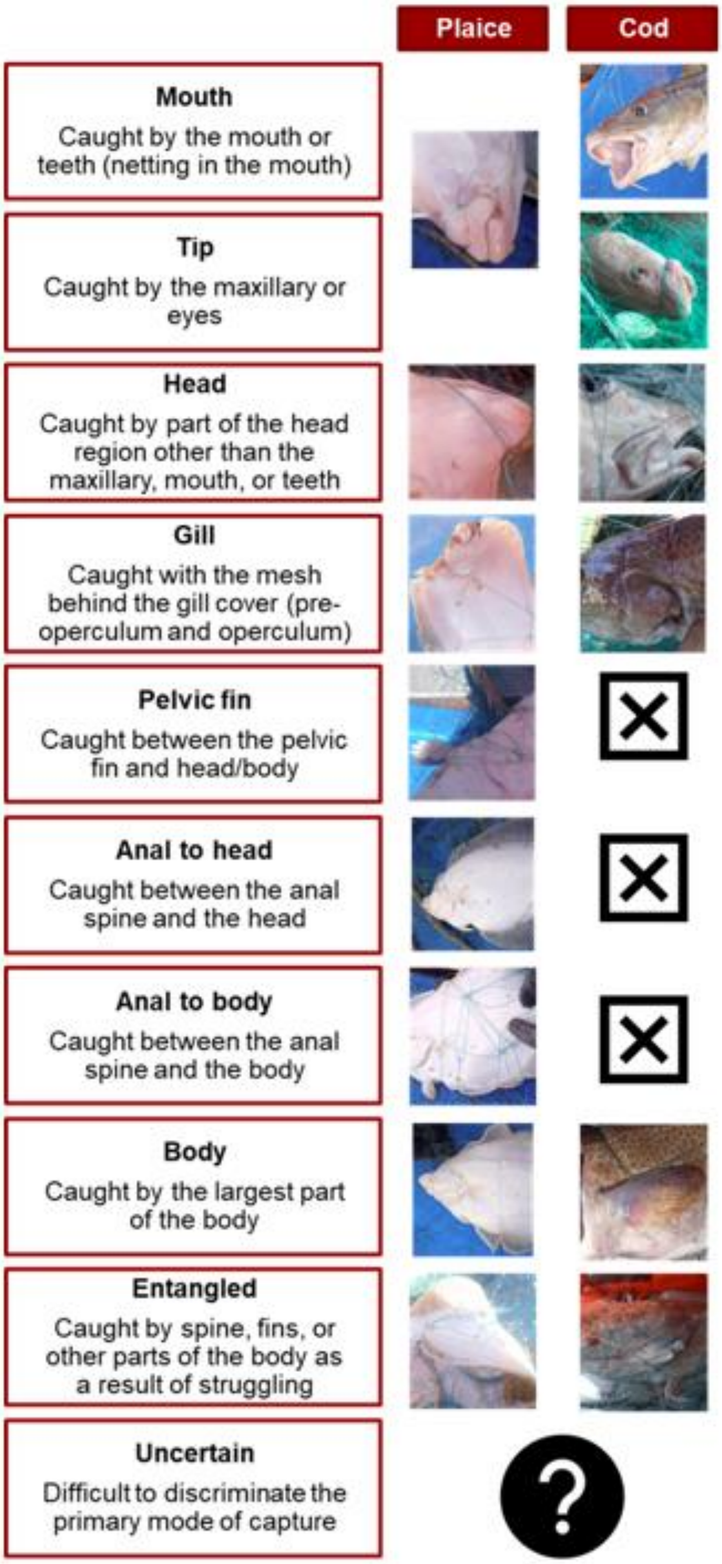

Figure 17. Categories of the capture modes used during the experiments (Article III) for European plaice and cod.

During the study, in case of multiple observed capture modes, the primary capture mode was assumed according to the principle of likely sequence (Savina et al., 2022).

To assess the relative catch performance of biodegradable and nylon gillnets in both trials with new and used gillnets, paired length-dependent catch comparison and catch ratio analysis (described in Chapter 7.1) was used as done in Article II (i.e., Herrmann et al., 2017; Grimaldo et al., 2019; 2020a). Further, the length-dependent probability for European plaice and cod being caught with each of the capture modes and for each gillnet type was determined according to Savina et al. (2022). Tensile testing was performed to test differences between the mechanical properties of the two materials at several timepoints throughout the study.

Results of Article III showed that biodegradable material was weaker and showed a higher elongation at break compared to nylon material of the same twine diameter already for a new material before being exposed to fishing operations. Furthermore, the biodegradable material showed a significant reduction in mechanical properties over time. These differences in material properties could then have affected the catch efficiency of biodegradable compared to nylon gillnets. It could be potentially explained by the weaker biodegradable netting breaking easier, and the associated damages to the net leading to reduction in catch efficiency. Furthermore, due to initially observed weaker tensile properties of biodegradable gillnets, these results showed that the catch efficiency of biodegradable gillnets can be reduced before the biodegradation of the material.

During the sea trials, no significant difference in catch efficiency of European plaice between the two materials was observed during initial trials with new gillnets. However, a significant difference in catch efficiency was detected during trials with used gillnets where biodegradable gillnets captured significantly less European plaice compared to the nylon nets (Fig. 18). Specifically biodegradable gillnets captured 76.96% (CI: 65.51-89.76%) of the target sized European plaice captured in nylon gillnets. For cod, this difference was significant already for the initial testing (79.95% (CI: 62.29-95.56%) for target sized cod) and the reduction in catch efficiency compared to the nylon gillnets increased further for the used gillnets (58.06% (CI: 36.36-81.48% for target sized individuals).

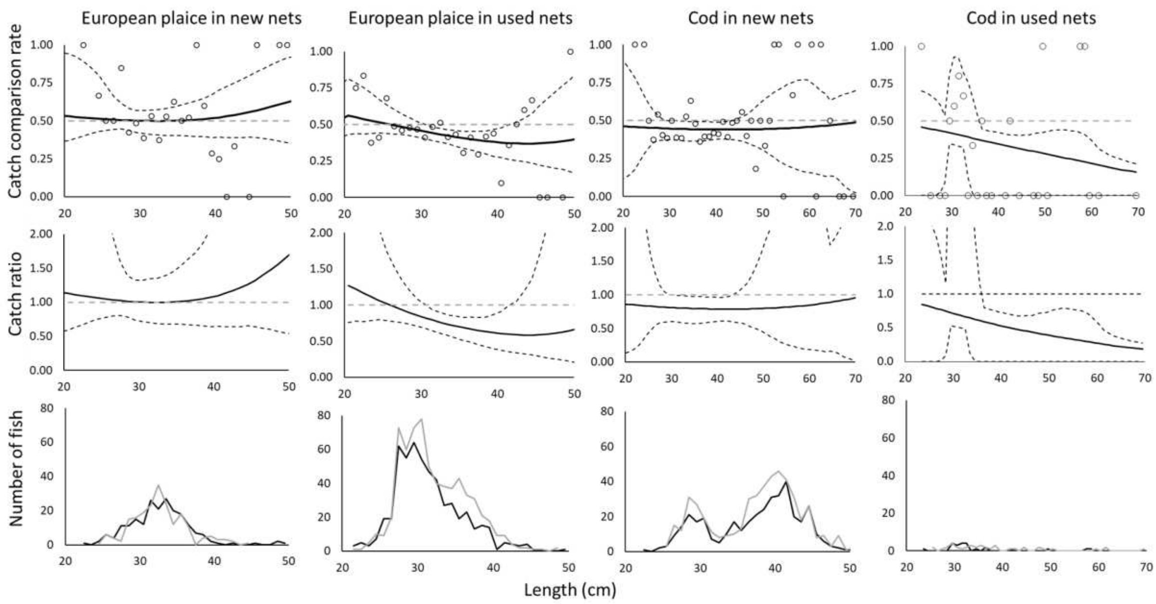

Figure 18. Catch comparison rate, catch ratio and number of European plaice and cod in new and used gillnets, respectively. Upper graphs: the modelled catch comparison rate (black solid line) with 95% confidence intervals (stippled curves). The stippled line at 0.5 represents the baseline at which biodegradable and nylon gillnets have an equal catch rate. Circles represent the experimental rate. Middle graphs: the estimated catch ratio curves (black solid line) with 95% confidence intervals (stippled curves). The stippled line at 1.0 represents the baseline at which both types of gillnets fish equally. Bottom graphs: the length frequency distribution of European plaice and cod captured by the biodegradable (black) and nylon (grey) gillnets.

Most European plaice got captured in gillnets with netting stretching from the anal fin and around the body of the fish (Fig. 17). Due to the specific morphology of flatfish species, this capture mode has not been observed in other trials regarding fish capture modes of gillnets. The new biodegradable gillnets showed a significantly higher probability of capturing European plaice in this capture mode when compared to the used biodegradable gillnets which could contribute to explaining the observed differences between the trials with new and used gillnets regarding the catch efficiency (Fig. 19A).

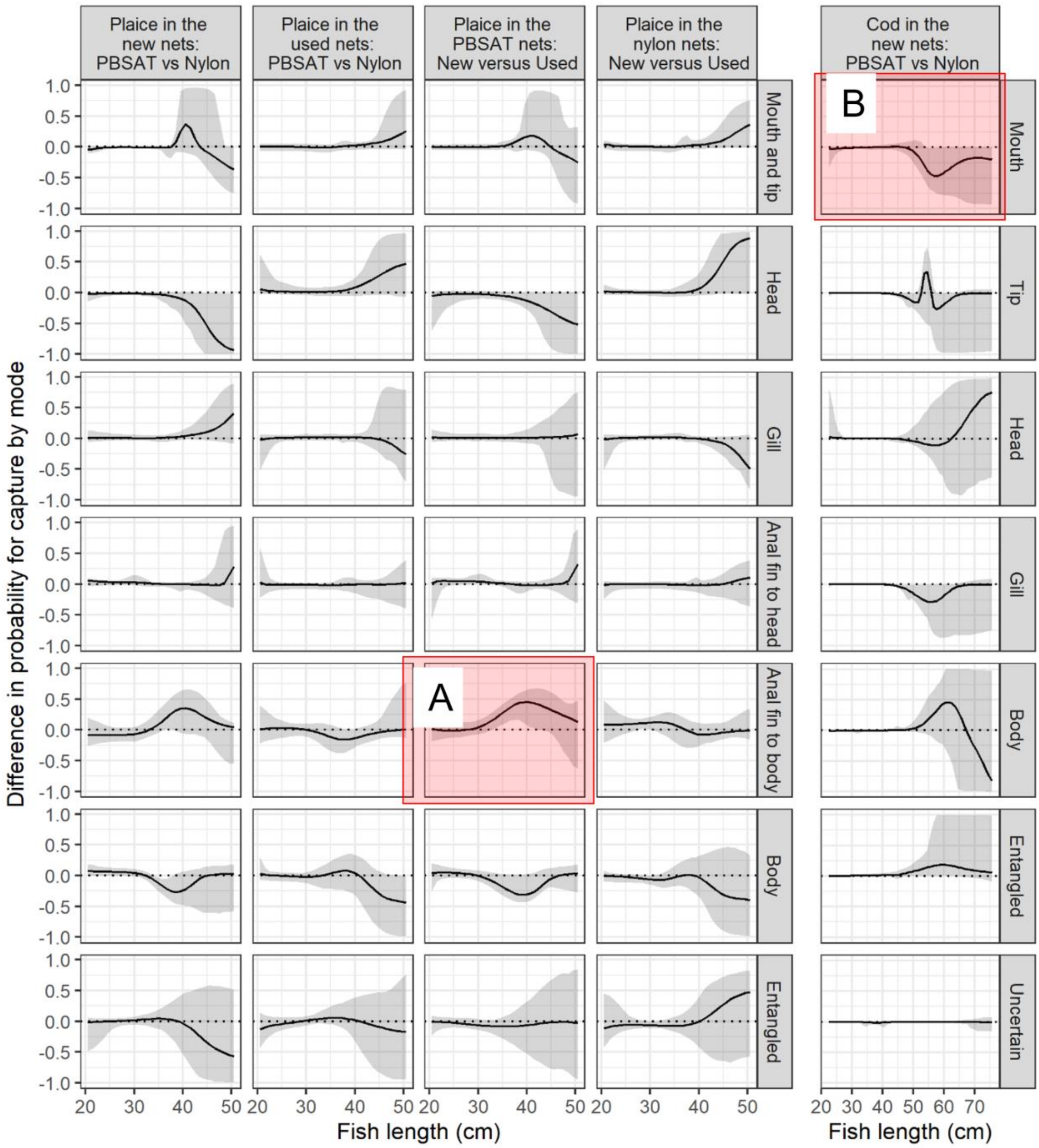

Figure 19. Pairwise difference in capture mode probability (black line) with 95% confidence intervals (grey area) for European plaice captured in new and used biodegradable (PBSAT) and nylon gillnets, respectively, and cod in the new biodegradable and nylon gillnets. The stippled line at 0.0 represent the baseline for no significant difference between the new and used or biodegradable and nylon gillnets. The red area highlights the difference for most common capture mode for (A) European plaice (anal fin to body) and (B) cod (mouth), and the difference between the gillnets.

For cod, the main capture mode was by mouth (Fig. 17) which was in line with earlier study showing that small cod (< 55 cm) are often captured by mouth in gillnets (Savina et al., 2022). The pairwise difference in capture mode probability showed an indication of lower capture probability by mouth in biodegradable compared to nylon gillnets in this study (Fig. 19B). Although this result was not statistically significant, this trend would be in accordance with the catch comparison results showing statistically significant lower catches of cod in biodegradable gillnets.

The results of this study showed that the initial trials using new biodegradable PBSAT gillnet had no significant difference in catch efficiency of European plaice when compared to commonly used nylon gillnets. However, to be accepted in the commercial fishery, the biodegradable gillnets need to provide a comparable catch efficiency not only for the initial tests but also over longer time of being used and stored between the fishing seasons. In our study, the results showed a decreasing catch efficiency for used biodegradable compared to used nylon gillnets. Furthermore, the catch efficiency for cod was reduced already during the initial tests. These observed differences in catch efficiency and capture mode probability between gillnets for both species may be further explained by changes in mechanical properties of the gillnets, and the results showed that the tensile strength for the biodegradable gillnets is lower compared to the nylon gillnets. Specifically, the differences in the gillnet material properties could affect when the gillnet meshes break caused by tension of the enmeshed fish. Therefore, this study showed that the estimation of capture modes can provide relevant information to explain observed catch efficiency results that further can be linked to specific material properties such as the tensile strength. Furthermore, this is the first study quantifying the length-dependent capture modes of a flatfish species in gillnet fishery.

9.4. Can biodegradable materials reduce plastic pollution without decreasing catch efficiency in longline fishery? (Article IV)

Article IV focuses on a set longline fishery in northern Norway and addresses research questions 5-7 of this thesis (Chapter 8). Specifically, Article IV aims at estimating the snood loss rate in the coastal longline fishery targeting haddock and cod to quantify the extent of the resulting marine plastic pollution since this extent has not been previously scientifically quantified for the longline fisheries. Further, it is the first study examining the potential of using biodegradable materials in snoods in longline fisheries for reducing the plastic pollution resulting from loss of nylon snoods as described in Chapter 2.2. This study tested the biodegradable PBSAT snoods of two twine diameters to assess whether using the biodegradable snoods with similar or increased twine diameter compared to nylon could have an effect on the snood loss rate and catch efficiency during initial trials as a result of differences in tensile strength.

Thus, Article IV focused on answering the following specific questions:

- What is the snood loss risk in a coastal longline fishery targeting haddock and cod?
- Are there any differences in snood loss risk between nylon and biodegradable PBSAT materials?
- Is there any difference in length-dependent catch efficiency for both species if the snood material is changed from nylon to biodegradable plastic?
- Would the catch efficiency change if an increased material diameter is used for biodegradable snoods?

The sea trials for data collection for Article IV were conducted onboard a commercial coastal longline vessel during November 2021 in northern Norway. The trials consisted of two series deployed simultaneously. Series one consisted of nylon and biodegradable snoods of the same twine diameter while Series two deployed nylon snoods together with biodegradable snoods of increased twine diameter. In each series, six mainlines of 415 snoods with baited hooks each were deployed. The mainlines with nylon and biodegradable snoods were deployed in an alternated order where each biodegradable snood mainline followed a mainline with nylon snoods (Fig. 20).

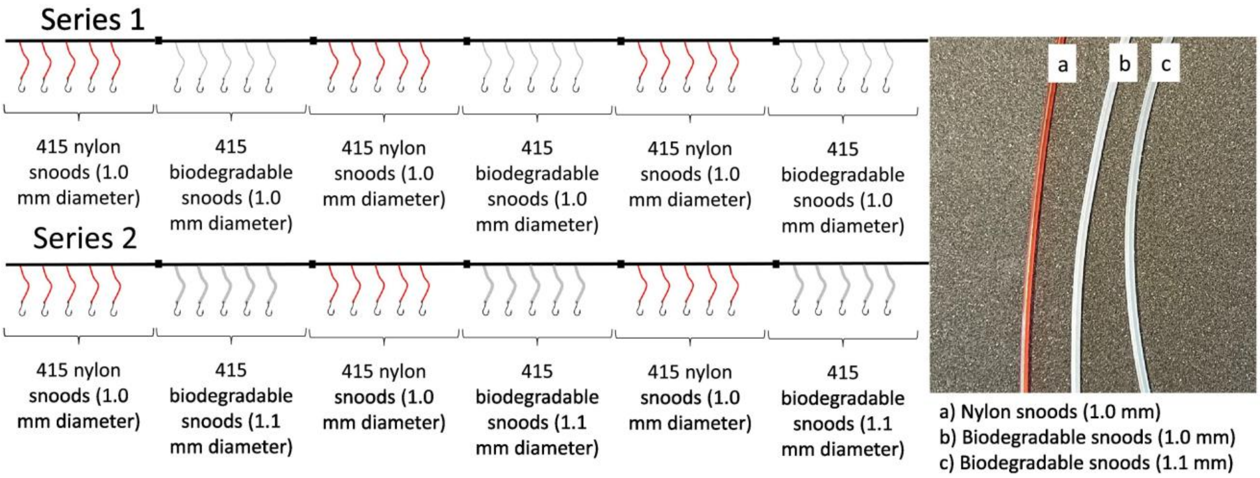

Figure 20. Experimental setup used during the fishing trials described in Article IV. Series 1 consisted of nylon (a) and biodegradable PBSAT (b) snoods of 1.0 mm diameter. Series 2 consisted of biodegradable PBSAT snoods of 1.1 mm diameter (c) and nylon snoods of 1.9 mm diameter.

During retrieval of the gear, all haddock and cod were sorted according to the snood type (nylon or biodegradable material in each of the two series) and measured for the total length. Further, between the deployments during longline rebaiting, the number of lost or damaged snoods were recorded. Specifically, situations when a snood together with a hook was missing on a mainline or when snood lines were broken were recorded separately. New snoods were attached before each deployment to replace lost or damaged ones, so that the total number of hooks and snoods were identical for each following deployment.

Article IV described the application of a new method to estimate the risk of snood line loss or need for snood line replacement. Specifically, this approach allowed to quantify the probability of snood loss as a risk for losing a snood (P_{loss}) during one deployment of it averaged over deployments and snood of the specific type (i.e., biodegradable or nylon) as follows:

$$P_{loss} = \frac{1}{m}\sum_{i}^{m}\left\{\frac{1}{ns_i}\sum_{j=1}^{ns_i} g(s_{ij})\right\} \quad with \quad g(s) = \begin{cases} 1 & \forall \quad s = lost \\ 0 & \forall \quad s \neq lost \end{cases} \tag{14}$$

where ns_i is the number of snoods on the mainline in deployment i and s_{ij} is the status (lost or retained) of snood number j after the mainline deployment i. m is the number of deployments.

To account for uncertainties in the estimations due to within- and between-deployment variability, the use of double bootstrap method was adapted. This method is often used in fishing gear catch efficiency and selectivity studies due to similar structure of uncertainties (i.e., Herrmann et al., 2017). 1000 bootstrap repetitions were performed, and the Efron 95% percentile confidence intervals (Efron, 1982) calculated for the estimated probabilities. Further, the approach described in Larsen et al. (2018) and Herrmann et al. (2018) to infer the difference ΔP_{loss} between nylon and biodegradable snoods in each series was adapted to this study. Based on the bootstrap population, Efron 95% percentile CIs were obtained for ΔP_{loss}. The same approach was used for estimation of snood line replacement between the longline deployments.

Further, the comparison of catch efficiency between the mainlines with different snood materials in both series was estimated as catch comparison rate and catch ratio (Chapter 7.1) (Herrmann et al., 2017).

The results described in Article IV showed that the estimated probability of snood loss in this coastal longline fishery using nylon snoods was 4.66% (CI: 3.84-5.46%) during a longline deployment. Such fishery normally uses longline sets with 10.000-30.000 snood lines (Mustad autoline, 2021). Therefore, the new method allowed estimation of nylon snood line loss in this longline fishery for haddock and cod based on this information. Specifically, this loss rate would vary between 466 (384-546) to 1380 (1152-1638) nylon snoods for each deployment. When estimating the snood loss rate for biodegradable snoods with both twine diameters, no significant increase was found in biodegradable snood loss during initial trials when compared to the nylon snoods. Furthermore, no significant differences in replacement of snoods were shown between the materials. However, an indication of increase in biodegradable snood loss of 1.0 mm diameter compared to biodegradable snoods of 1.1 mm diameter and nylon snoods was estimated. This observation corresponded to the results of material testing where the biodegradable snoods of 1.0 mm twine diameter had the lowest tensile strength compared to the other materials. Further, the results showed no initial significant difference in catch efficiency of haddock and cod between the tested materials (Fig. 21).

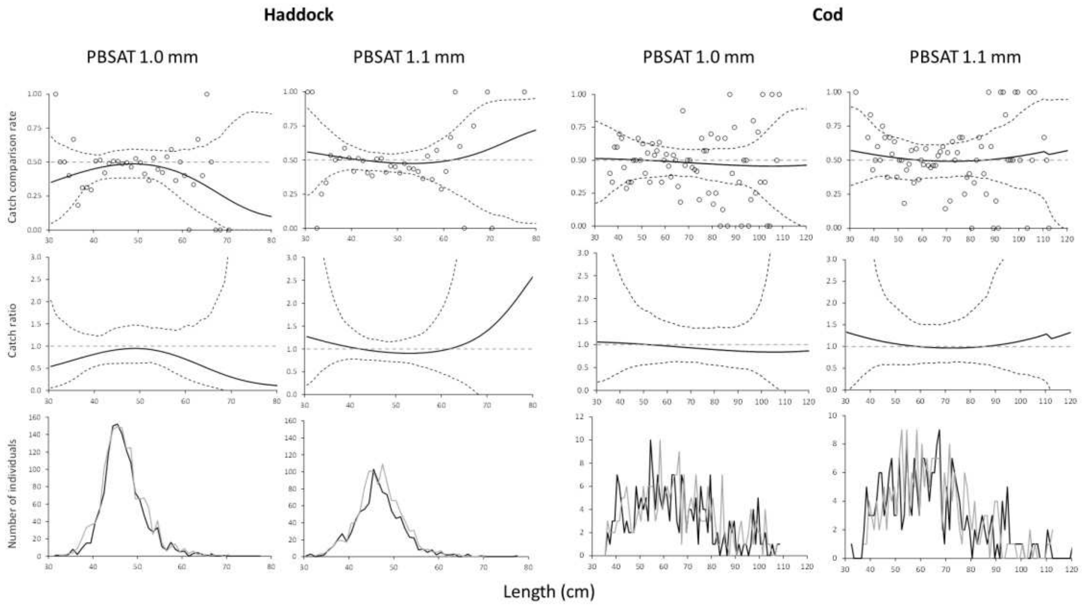

Figure 21. Catch comparison and catch ratio analysis for haddock (left) and cod (right) for testing biodegradable (PBSAT) snoods of 1.0 mm and 1.1 mm twine diameter against nylon snoods of 1.0 mm twine diameter. Upper graphs: the modelled catch comparison rate (black solid line) with 95% confidence intervals (stippled curves). The stippled line at 0.5 represents the baseline at which biodegradable and nylon gillnets have an equal catch rate. Circles represent the experimental rate. Middle graphs: the estimated catch ratio curves (black solid line) with 95% confidence intervals (stippled curves). The stippled line at 1.0 represents the baseline at which both types of gillnets fish equally. Bottom graphs: the length frequency distribution of haddock and cod captured by the biodegradable (black) and nylon (grey) gillnets.

Therefore, the results of this study showed that the biodegradable PBSAT material can have the potential to be used for snoods in this longline fishery to reduce the marine plastic pollution caused by losses of nylon snoods during the longline deployments. The results of Article IV provide a relevant preliminary estimation for this longline fishery showing no initial significant difference in either snood line loss, need for replacement or catch efficiency for both species for the snood materials considered. Therefore, this study should be followed up by tests of prolonged snood use in the fishery (i.e., over a full fishing season or longer). Furthermore, the similar approach for quantifying the snood loss rate in longline fisheries as demonstrated in this study can be applied to fisheries in other areas targeting different fish species since this snood loss rate can vary between them and has not yet been scientifically quantified.

9.5. Use of biodegradable materials to reduce marine plastic pollution in small scale coastal longline fisheries (Article V)

Article V of this thesis added on the results of Article IV. Specifically, it aimed to further develop the method for quantifying the snood loss in Adriatic coastal longline fishery targeting Sparidae species and estimated differences in snood loss rates and replacement. Further, it estimated the initial differences in catch efficiency and catch composition (applying similar approach as presented in Article I) when using new biodegradable materials compared to nylon in snoods in this multispecies longline fishery. Thus, Article V in the thesis addressed research questions 5-8 in Chapter 8.

In the Adriatic Sea, pollution from fisheries, including longline gear, constitute a significant part of marine debris. However, the rate of the snood loss has not been scientifically quantified in this fishery similarly to other longline fisheries. Therefore, a similar approach as outlined in Article IV was used to quantify the snood loss rate when using the nylon snoods and estimate the difference in snood loss between nylon and biodegradable materials.

Further, this study estimated the fishing gear performance regarding the catch efficiency (Chapter 7.1) of common target species in this fishery, common pandora (*Pagellus erythrinus*), two-banded seabream (*Diplodus vulgaris*) and axillary seabream (*Pagellus acarne*), between the two snood line types. However, since in this fishery capture of several other species is often common, the effect of changing the snood line type on the entire catch composition was investigated using the method described in Article I (Chapter 9.1).

Sea trials for study described in Article V were conducted in Croatia in October 2022 using a small-scale fishing vessel. During each deployment, eight mainlines with 25 snoods each were deployed simultaneously where biodegradable and nylon snood were alternated on each of the mainlines (Fig. 22).

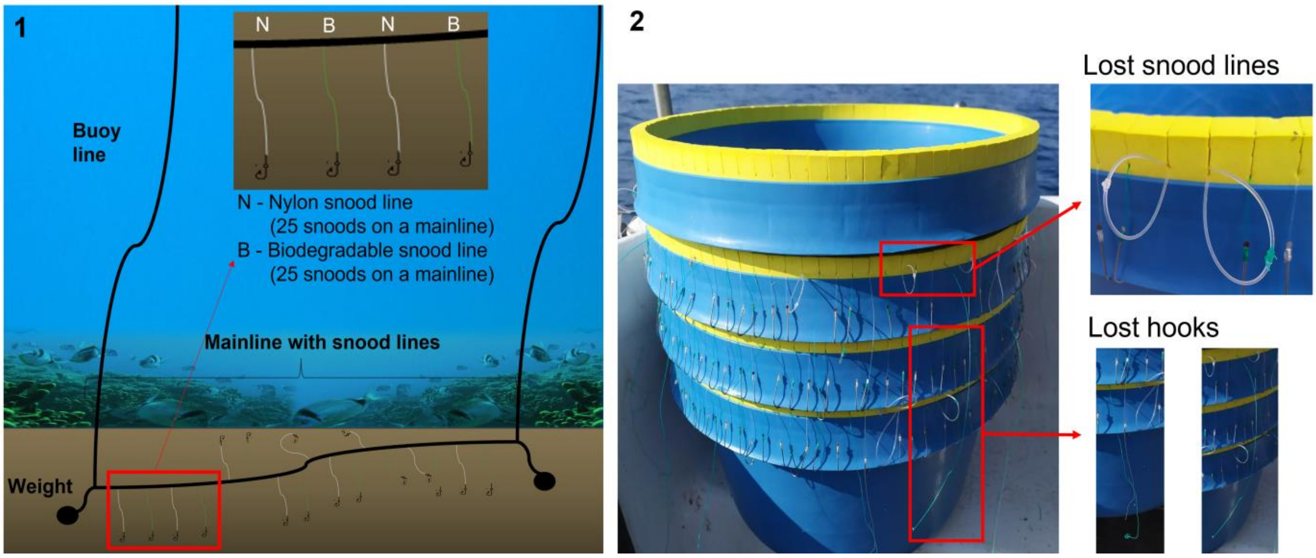

Figure 22. (1) Illustration of experimental setup during the study described in Article V. During the deployment each of the eight longlines was using 25 biodegradable (B) and 25 nylon (N) snoods in an alternated order on each mainline. (2) Examples of observed cases with snood and hook loss after longline retrieval.

After each deployment, the catch was sorted by snood material (biodegradable or nylon) and individuals for each species were counted for catch composition analysis. Further, the individuals of the three species used for the catch comparison analysis were measured for their total length. Similarly, as for Article IV, the snood loss was recorded between the deployments. This study distinguished between two situations, first, loss of hooks and, second, loss of hooks together with the snood line (Fig. 22). In the first situation, the snood line was broken close to the hook resulting in an attachment of a new hook on an existing snood for the next longline deployment. In the second situation, attachment of both, new hook and a new snood line was necessary. This further implies that the plastic material of lost snoods stays in marine environment increasing the plastic pollution. When estimating the hook and hook and snood losses in this study, the approach presented in Article IV was further developed considering that during each experimental fishing day, the mainlines were deployed in slightly different areas with some similarities in the conditions the fishing took place. Therefore, in Article V, it was relevant also to quantify the mean values for hook and hook and snood loss probabilities based on the results for individual mainlines (Fig. 23a) deployed during the same deployment day (Fig. 23b), as well as quantifying the mean probabilities for the complete fishing trials (Fig.

23c). Similarly, as in Article IV, delta approach was used for inferring the effect on probability for hook loss or hook and snood loss by changing the snood material (Fig. 23).

The results of Article V showed that the estimated mean snood loss for the whole fishing trials reached 3.00% (CI: 1.00-5.92%) during a longline deployment when using nylon material (Fig. 23c). Taking into consideration that there are several vessels operating in a small area with regular longline deployments, this amount implies considerable plastic pollution. The results showed that the estimated loss of snood and hooks when using the biodegradable material did not differ significantly when compared to nylon snoods. Furthermore, the estimated loss of hooks also did not have any significant differences when using the biodegradable material compared to the nylon snoods.

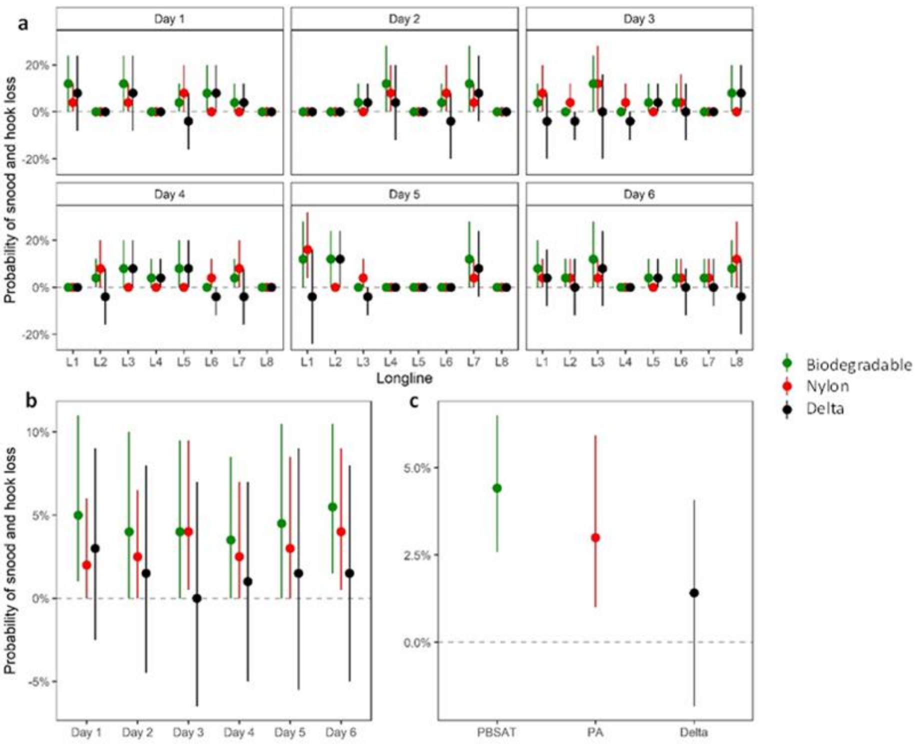

Figure 23. Probabilities (in %) for losing a snood together with the hook of biodegradable (green) and nylon (red) material. a: Probabilities estimated for each longline deployment (L 1-8). b: Probabilities estimated for each deployment day (Day 1-6). c: Mean probabilities for hook loss for the complete fishing trials for the two snood materials separately. Black points are pairwise difference inferring the effect on probability for hook loss by changing the snood materials.

For the three most frequently captured species (common pandora, two-banded seabream and axillary seabream), no significant differences in catch efficiency were observed (Fig. 24) when comparing the two snood materials for initial use.

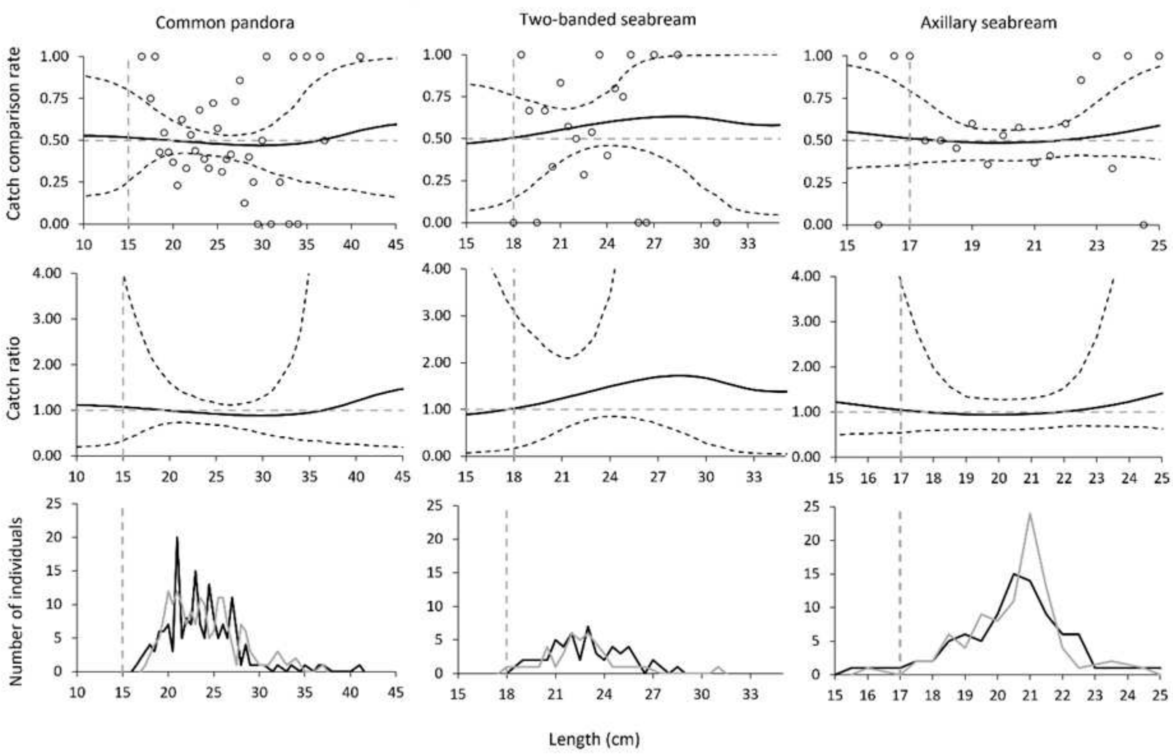

Figure 24. Catch comparison and catch ratio analysis for common pandora, two-banded seabream and axillary seabream. Upper graphs: the modelled catch comparison rates (black curves) with 95% confidence intervals (black stippled curves). Circles represent experimental rate. Middle graphs: the estimated catch ratio curves (black curves) with 95% confidence intervals (black stippled curves). The grey stippled lines at 0.5 and 1.0 represent the point at which both gears have an equal catch rate. Lower graphs: the length frequency distribution of fish captured with the biodegradable snoods (black line) and nylon snoods (gray line). Vertical stippled lines show the minimum conservation reference size for each species.

Further, the results showed no significant difference regarding the catch composition observed between the two snood types and are in line with the initial results in the Norwegian longline fishery described in Article IV. The assessment of the whole composition of the catch, captured with both nylon and biodegradable snoods, allowed making a more holistic evaluation of the performance of the longlines in this fishery. Furthermore, it demonstrated the application of the proposed method (Article I) in catch performance estimation when using other fishing gear type. Thus, the obtained results in Article V showed no initial significant differences in performance between biodegradable and nylon snoods which is in line with the results of Article IV, which is showing a potential for the biodegradable materials to be used to reduce the marine plastic pollution from the longline fishery.

10. Discussion

This thesis presented the research testing the use of recently developed biodegradable plastic (PBSAT) material in bottom set gillnet and longline fisheries to reduce negative effects associated to ALDFG, particularly marine plastic pollution and ghost fishing. Considering the limited number of studies assessing the performance of fishing gear made from biodegradable plastic materials and the global need to reduce fisheries-related plastic pollution, this work provides relevant information for understanding and quantifying the fishing gear performance. Furthermore, it contributes with highlighting the research needs for further development of biodegradable gillnets and longlines that would provide a comparable catch efficiency to the gear made of commonly used non-biodegradable materials, and thus could be accepted by the fishing industry.

Articles I-III included in this thesis presented the results from testing the biodegradable PBSAT material in coastal bottom set gillnet fisheries in Norway (Barents Sea) and Denmark (North Sea) and compared the fishing gear performance to that of commonly used nylon material. In both fisheries, gillnetting is a commonly used fishing method which contributes to the overall catches. The associated sustainability challenges in fisheries using gillnets are related to the risk of ghost fishing and subsequent plastic pollution when the fishing gear material is degrading after being exposed to the marine environment for long periods after being abandoned, lost, or otherwise discarded. Therefore, potential use of biodegradable materials to replace nylon in gillnet netting is relevant for different gillnet fisheries, including the fisheries described in this thesis. Due to differences in material properties of biodegradable plastic compared to nylon netting, the performance of the biodegradable gillnets should be examined in various fisheries. Specifically, the material performance should be assessed when exposing the material to, first, different environmental conditions such as water temperature and salinity, and second, observing the performance of the material when targeting various species with different morphologies and swimming abilities. In case of biodegradable gillnets, different environmental conditions could affect the degradation and material performance at different rates. For example, Kim et al. (2016) observed that the degradation rate of biodegradable plastic material (blend of 82% polybutylene succinate (PBS) and 18% polybutylene adipate-co-terephthalate (PBAT)) was higher with higher water temperatures. In addition, the salinity is also a factor that can affect the biodegradation potential (Hakvåg et al., 2023). Furthermore, fisheries use gillnets with different properties that are adjusted to the specific target species, such as mesh size, twine thickness and hanging ratio, among others. In fisheries targeting smaller fish with poor swimming abilities, the requirements for optimal material properties could, for example, require less tensile strength and elasticity compared to other fisheries targeting large individuals with high swimming capacity and ability to break the netting meshes. Therefore, due to these variations in the conditions the fishing takes place, the observed results when comparing biodegradable and nylon gillnets can, potentially, differ. Articles I and III described the biodegradable gillnet performance in the Danish coastal bottom set gillnet fishery targeting European plaice while Article II reported the results from the Norwegian coastal gillnet fishery targeting cod.

Article I addressed the first research question of this thesis (*How to quantify and compare the total species composition and what is the effect of changing gillnet material in a multispecies fishery?*). The quantification of the whole species community affected by the fishing gear as discussed in Chapter 9.1 was necessary to estimate the effect the fishing gear has on all species instead of few target species, thus providing a more holistic approach. Therefore, this study developed a quantitative method to estimate the species composition in fishing gear catches. Based on the results obtained in this research, there were no significant differences in the species composition in the catches when using biodegradable and nylon gillnets in a multi-species gillnet fishery. This result suggested that the use of biodegradable material in the gillnet netting would not represent a barrier when the catch composition is considered. Furthermore, this approach of quantifying and comparing the catch compositions as first presented in this study contributes to further studies applying similar approach when estimating different fishing gear performance (i.e., Madhu et al., 2023; Petetta et al., 2023; Grimaldo et al., 2023; Yu et al., 2023; 2024).

However, to be applied in a commercial fishery, biodegradable gillnets should also show a comparable fishing efficiency of the target species as the nylon nets. Therefore, Articles II and III evaluated research question 2 of this thesis: *Can biodegradable materials be used in gillnet fisheries without negatively affecting catch efficiency?*. Furthermore, both Articles aimed at explaining the observed differences in catch efficiency by quantifying fish capture modes in both gillnet fisheries by answering research question 3: *Can capture modes explain the differences in catch efficiency between the gillnets made of biodegradable and nylon materials?.* The results in both fisheries demonstrated a reduced catch efficiency of biodegradable compared to nylon gillnets for the main target species. This efficiency was further reduced when the biodegradable gillnets were used in long-term experiments compared to initial tests comparing new biodegradable and nylon gillnets, respectively. These results were in line with those from earlier trials testing biodegradable PBSAT gillnets in Barents Sea (Grimaldo et al., 2018a; 2018b; 2019; 2020a; 2020b). Furthermore, significant reduction in catch efficiency was observed in both fisheries, in Denmark and Norway. However, in the study conducted in Denmark, the results showed that the catch efficiency for European plaice was not significantly different between biodegradable and nylon gillnets for initial trials for European plaice, possibly due to sufficient initial properties of the biodegradable material to capture fish of this size and swimming ability. Despite this, significantly less European plaice was captured during the following trials with used gillnets. In commercial fisheries, gillnets are used for several deployments, therefore this result shows that the reduction in catch efficiency compared to nylon gillnets would not provide an optimal performance of the gear. Furthermore, catch efficiency of cod in the Danish fishery was already reduced for the initial trials.

Assessment of capture modes in both Article II and Article III contributed to explaining these observed reductions in catch efficiency. Specifically, for the most common capture mode of both species in gillnets in each fishery, the probability of capture in biodegradable gillnets was lower compared to the nylon nets. The most common capture mode for cod in the Norwegian fishery was by gills while in the trials conducted in Denmark the most common capture mode for cod was mouth. This observed difference in capture mode could be explained by the different sizes of fish captured in the two areas. The most common mode of capture for European plaice was by netting stretching from anal spine over the body of the fish. In this fishery, used gillnets compared to the new gillnets captured significantly less fish in this capture mode. These results presented in Articles II and III suggested that the changes in material properties such as tensile strength and elongation can affect when the gillnet netting brakes due to the tension applied when the fish is captured. Furthermore, results in Article III showed that the tensile properties of biodegradable material are weaker already for a new material when compared with nylon netting which can reduce catch efficiency before biodegradation of the material. Both studies used the capture mode quantification for the first time to compare gillnets of different materials. Use of the same approach could be beneficial in further studies when developing the future biodegradable gillnets and assessing what are the optimal gillnet parameters for a comparable catch efficiency in the specific gillnet fishery. Furthermore, this approach by comparing the fishing gear performance with assessing the capture modes in the gear can further be applied in different fishing gears, such as longline fisheries (Lomeli et al., 2023).

Articles IV and V compared the fishing gear performance in longline fisheries when nylon material in snood lines is replaced with biodegradable PBSAT material. The trials were conducted in two fisheries with Article IV focusing on coastal set longline fishery in northern Norway (Barents Sea) and Article V describing the results of the trials in coastal set longline fishery in Croatia (Adriatic Sea). Both fisheries were conducted in different fishing areas and conditions and targeted different fish species, thus providing an overview of material performance in fishing gear in two longline fisheries. In longline fisheries, including the two case fisheries described in this thesis, loss of snood lines are common during the fishing process, which contributes to the marine plastic pollution since the snood lines in coastal longline fisheries are often made of nylon. However, the snood loss and resulting pollution extent in often not scientifically quantified for specific longline fisheries and can vary between them. Therefore, Articles IV and V address the research question 5 of this thesis, specifically, *How to quantify the snood loss rate in coastal longline fisheries using nylon material?* To answer this research question, this thesis identified limitations in the existing methodology and developed a new approach for quantifying and comparing the snood loss when using nylon and biodegradable materials as demonstrated in Article IV. Thus, it introduced a method to answer the research question 6 of this thesis: *Are there any differences in snood loss rate when changing the snood material from commonly used nylon material to biodegradable plastics?* Article V further developed this method and applied it in Croatian longline fisheries. The results showed that the snood loss rate and the resulting plastic pollution in both fisheries is considerable, highlighting the need for using more environmentally friendly materials to reduce the marine plastic pollution.

When testing snoods made from biodegradable PBSAT material, no significant differences in snood loss were found in both fisheries regarding the initial testing phase, therefore, showing a promising result for being used in coastal longline fisheries. Further, both studies also addressed the catch efficiency between the two materials when used in longline fishery, specifically research question 7 (*Can the snood line material be replaced to biodegradable plastic material in longline fisheries without negatively affecting the catch efficiency?*). Results in both, Article IV and V, demonstrated that there are no difference in initial catch efficiency for the main target species when comparing new biodegradable and nylon snood line materials. The Croatian longline fishery is a multi-species fishery where, along with few most common target species, the gear is capturing several other species. Therefore, in addition to estimating the catch efficiency for the most common target species, this study further demonstrated the application of catch composition estimation as first demonstrated in Article I of this thesis. Thus, Article V addressed the research question 8 regarding whether *the changes in material affect the total species composition in longline catches in a multispecies longline fishery?* Since no significant differences in the catch composition was found between the two materials, the Article V concluded that neither catch efficiency nor catch composition would represent a barrier for biodegradable snoods being used in Croatian longline fishery. Thus, Articles IV and V provide a valuable information on initial results of testing biodegradable materials in longline fisheries, and a method that can be further applied to estimate the snood loss rates in different longline fisheries and during subsequent experimental trials testing the material performance over longer periods.

10.1. Future research directions

Following the results presented in this thesis (Articles I-V), the follow-up future research should aim at further investigating the optimal biodegradable materials for use in gillnet and longline fisheries. Specifically, the results of this thesis demonstrated that in a gillnet fishery more research is needed for developing biodegradable gillnets that would demonstrate a comparable catch efficiency and thus would have a potential to be accepted by the corresponding fishing industries.

The objective of this thesis was to focus on recently developed biodegradable plastic (PBSAT) material for testing in gillnet and longline fisheries regarding the gear performance. In the future, following the development in biodegradable plastics, different biodegradable materials could further be considered as an alternative to be tested in different fisheries. Furthermore, different parameters that would allow compensating for differences in catch efficiency in gillnets as observed in Article II and III in this thesis could also be considered.

In longline fisheries, no earlier studies have been conducted for assessing the performance of biodegradable plastic materials in snood lines nor their potential to replace currently used non-biodegradable plastic materials. Therefore, this thesis aimed at estimating the initial performance when testing new biodegradable material against new nylon material for the snood lines as reported in Articles IV and V. Performing and reporting results from such initial studies (or so-called pilot studies) are important for investigating the potential of biodegradable plastic material to be developed for use in commercial longline fisheries. Such approach allows avoiding unsuccessful research attempts in further comprehensive research as would be the case in long-term experiments (Thabane et al., 2016). Specifically, this allows to select the materials that can have the potential to be used to such further experiments. Since the results reported in Article IV and V demonstrated that there are no significant initial differences between biodegradable and nylon snoods in either coastal longline fisheries in Barents Sea or Adriatic Sea, these positive results should be further followed up by long-term studies estimating material performance in these fisheries. Furthermore, since the snood loss rate can differ between fisheries, fishing conditions and target species, further studies applying similar approach as presented in this thesis would provide a broader overview on both, the corresponding plastic pollution extent and the potential use of biodegradable materials.

Furthermore, several other aspects outside the scope of this thesis should be evaluated in future research to provide biodegradable plastic materials that could be effective at reducing fisheries related environmental challenges. Specifically, it includes evaluation of biodegradability and toxicity testing of the new materials. Furthermore, currently biodegradable PBSAT plastic is more expensive compared to nylon (Standal et al., 2020) which can be caused by currently limited production. However, increased costs can negatively affect acceptance by the fishing industry, thus becoming a barrier for replacement of conventional to biodegradable materials in fisheries. Therefore, these economic and social aspects would also need further assessments.

10.2. Final remarks

In summary, this thesis presented results on recent research using biodegradable plastic materials in gillnet and longline fisheries. The research presented in Articles I-V contribute to assessing the potential of replacing commonly used nylon materials to reduce ghost fishing and plastic pollution. Therefore, this thesis has achieved the overall objective to *investigate whether recently developed biodegradable plastic materials (PBSAT) can be used in gillnet and longline fisheries to reduce marine plastic pollution and ghost fishing by lost, abandoned, or otherwise discarded fishing gear*. Lastly, from the methodological perspective, this thesis proposed methods for assessing the gear performance in gillnets and longlines when changing the fishing gear material type. Although the studies presented in Articles I-V focus and apply proposed methods in particular gillnet and longline fisheries, potential applications in other fisheries should be considered.

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Articles I – V

Article I

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Quantification of catch composition in fisheries: A methodology and its application to compare biodegradable and nylon gillnets

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ABSTRACT

When evaluating fishing gear catches, the focus is often on a few species as opposed to the entire catch. In some fisheries this can lead to ignoring major part of catch composition. Thus, there is a need for a more holistic approach when evaluating the ecological impact of using a specific fishing gear and when comparing two or more gears. In this context, it is relevant to have a method that describes the total catch and quantifies proportions of the catch being wanted and unwanted. In this study, we outline such a method and demonstrate its applicability to catch data from a small-scale coastal gillnet fishery targeting European plaice (*Pleuronectes platessa,* Linnaeus, 1758) by comparing catch composition when using nylon and biodegradable gillnets. The results showed no significant differences in catch composition between gillnets made of the two materials. Therefore, the catch composition obtained using the more environmentally friendly biodegradable materials does not represent a barrier in this specific gillnet fishery. However, species selectivity of gillnets is still of concern as the primary target species constituted only half of the total catch composition in numbers while the rest was unwanted catch. The presented approach for quantifying and inferring the differences in catch composition can be further applied for assessing the performance of different fishing gears and their modifications.

1. Introduction

The incidental capture of unwanted species and sizes in fishing gear is widely recognised as a threat to nature conservation (i.e., Shester & Micheli, 2011; Northridge et al., 2015; Duarte et al., 2020) and can be considered as a major source of uncertainty in fisheries assessments (Gray et al., 2005a; Fauconnet et al., 2015). Consequently, many countries have established sampling programmes (e.g. Borges et al., 2005; Feekings et al., 2012) and numerous studies have looked into describing and understanding discarding practices (e.g. Borges et al., 2005; Feekings et al., 2012; Uhlmann et al., 2014; Ceylan et al., 2013; Fernandes et al., 2015; Kennelly, 2020). However, relatively few studies have examined total species composition of the entire catch, rather focusing on a few target species or few species of special concern. Such is also the case when assessing the species selectivity of fishing gears (Shester & Micheli, 2011). This can result in ignoring major part of species in the catch composition when evaluating the effects fishing gears have on the full community. Ignoring such species could lead to further declines in species richness, since fishing is known to negatively affect species of limited or no commercial value (Coleman & Williams, 2002). Hence, knowledge of total catch composition caught in fishing gears, including wanted catches consisting of primary and secondary target species, and composition of organisms of non-target species or sizes (unwanted catch) could provide information for identifying potential impacts that the fishery has on different marine species and ecosystems (Gray et al., 2005a; Senko et al., 2022).

Several examples in the literature describe different indices for quantifying species composition and species biodiversity in marine ecosystems (i.e., Whittaker, 1972; Chao, 2005; Gamfeldt et al., 2014). Such studies use these indices for quantifying changes in the environment due to, for example, increasing seawater temperatures due to climate change (i.e., Hiddink & Coleby, 2012; Bilous et al., 2022). They usually apply a combination of different measures to assess the species biodiversity. Since biodiversity is a multidimensional concept, such

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estimates include assessments of species richness, evenness and dominance (Maurer & McGill, 2011; Daly et al., 2018). Herrmann et al. (2022) used species biodiversity indices and applied a nested bootstrapping technique to account for uncertainty in the estimation and infer changes in the species composition in mesopelagic biodiversity (i.e., species richness, Shannon and Pielou indices and indices of species dominance). A similar approach of assessing the species diversity can be adapted to quantify the species composition in fishing gear catches and infer changes in catch composition when changing different parameters of the fishing gear (e.g. material type, mesh size, twine thickness etc.). Furthermore, by adapting the method used in Herrmann et al. (2022), it is possible to obtain confidence intervals and infer changes for the catch composition between different fishing gears. The aim of this study is to establish a method that allows to estimate and compare the catch composition in fisheries by adapting biodiversity indices to assess species diversity, evenness, and species dominance in fishing gear catches. Specifically, we demonstrate the application of such an approach using a case study from a gillnet fishery where the catch composition from gillnets with two different netting materials (nylon and biodegradable plastic) are compared.

Gillnets represent a particular concern due to their relatively low species selectivity if fished in areas with multiple species (Suuronen et al., 2012). This fishing gear is commonly used to harvest many different species of fish (He, 2006a; FAO, 2016). Low species selectivity in gillnets implies that in some fisheries many different species can get captured by the gear. However, relatively few studies have examined the gillnet catch rates by assessing the total catch composition (Shester & Micheli, 2011). Therefore, detailed information on catch composition in gillnets would improve the understanding of the impact of using this fishing gear on different species.

Gillnets consist of a netting wall, usually made of nylon, which is deployed vertically in the water column by having weights along the bottom and floats along the top (He, 2006a). During fishing, gillnets are soaked for varying periods of time to catch animals that swim into netting and get caught. Gillnets are usually made of nylon as this material provides good mechanical properties such as high breaking strength, elasticity and durability. Although such characteristics are desirable, they also create a concern from an environmental perspective. Globally, a significant proportion of gillnets are lost, abandoned, or discarded at sea (Deshpande et al., 2020; Gilman et al., 2021) and their degradation is slow in the marine environment (Grimaldo et al., 2019; Brakstad et al., 2022). Moreover, nylon netting contributes to macro- and microplastic pollution when it is degraded into smaller particles over time (Moore, 2008). In addition, gillnets can continue capturing marine animals when lost in the ocean (so-called "ghost fishing"). (He, 2006a; Deshpande et al., 2020). To limit the pollution caused by lost fishing gear, new biodegradable materials are being developed such as biodegradable plastics made of polybutylene succinate co-adipate-*co*-terephthalate (PBSAT) resin. Such biodegradable material aims to degrade in a shorter time compared to nylon gillnets (Brakstad et al., 2022), thus limiting the potential ghost fishing time. Furthermore, the material degrades into components that are not harmful to the marine environment (Kim et al., 2014a,b).

Gillnets made of biodegradable PBSAT material have different material properties such as lower elasticity and tensile strength compared to nylon gillnets (Grimaldo et al., 2019; Grimaldo et al., 2020). These differences in material properties have resulted in changes in catch efficiency for target species (Grimaldo et al., 2018a, b, 2019, 2020; Cerbule et al., 2022) due to different patterns regarding fishes' mode of capture in gillnets (Cerbule et al., 2022) for biodegradable compared to nylon gillnets. The effect of changing from nylon to biodegradable materials has only been investigated for a few target species; however, the results of these studies suggest that it could possibly also affect the catch composition of species that are not being targeted. To demonstrate our method, we collected catch data from a costal Danish gillnet fishery in Skagerrak targeting European plaice (*Pleuronectes platessa*, Linnaeus, 1758) as the primary target species as a case study.

The gillnet fishery for European plaice constitutes one of the most important small-scale commercial fisheries in Denmark (Savina et al., 2017). Although European plaice is the main target species in this fishery, catches of secondary target species (i.e., other species with a commercial value) such as sole (*Solea solea,* Linnaeus, 1758), lemon sole (*Microstomus kitt*, Walbaum, 1792), common dab (*Limanda limanda,* Linnaeus, 1758) or brown crab (*Cancer pagurus,* Linnaeus, 1758), are also caught. However, wanted catches represent only part of the total catch composition as the catch normally contains several species (Fig. 1), part of which has no commercial value. Further, some commercial species are subjected to minimum conservation reference sizes (MCRS), where the sale of catches below the MCRS are prohibited and, therefore, this part of the catch composition is not considered commercial (European Commission, 2020), representing a challenge regarding size selection for these species. The present study demonstrates the application of the proposed method to compare e.g. different operational strategies, compare different fishing grounds, seasons or to compare different gears such as in this case, material properties of gillnets by quantifying and comparing catch composition in nylon and biodegradable gillnets in total catches, as well as in the wanted and unwanted catches.

2. Materials and methods

2.1. Experimental design and sea trials

The catch composition in gillnets for this study were quantified by recording the number of species in gillnet catches as well as the number of individuals within each species for nylon and biodegradable gillnets, separately. The catch composition of 8 nylon and 8 biodegradable gillnets were investigated during fishing trials conducted onboard a small-scale gillnet vessel targeting European plaice. The experiments were conducted over a total of 10 fishing trips during September 2021 in the Skagerrak area off the coast of Hirtshals. The fishing grounds were located between 57°36.436–57°38.012 N and 09°56.927–10°14.608E (Fig. 2; Table 1).

All biodegradable gillnets were made of PBSAT resin (Kim et al., 2017, patent EP3214133). Nylon and biodegradable gillnets were manufactured by S-ENPOL (Gangwon-do, South Korea). The nets were assembled by Hvalpsund Net AS (Denmark) for the Danish commercial plaice fishery. The nylon and biodegradable gillnet sheets were made of double knotted 0.40 mm monofilament twine. Both types of gillnets had 75 mm half-mesh size (150 mm full mesh) and were 15.5 meshes deep. Each gillnet sheet was 55 m long and they were attached to 18.0 m long float- and leadline to give a hanging ratio (E) of 0.3. The netting was sewn (fastened) to the float- and leadline every-five meshes.

The two different nets were mounted into one fleet where each nylon gillnet (N) was followed by a biodegradable gillnet (B) in an alternated order so that each material type is exposed to the same spatial variability in fish availability within gillnets: ***N***-B-***N***-B-***N***-B-***N***-B-***N***-B-***N***-B-***N***-B-***N***-B. The distance between single gillnet sheets in the fleet was approximately 1 m. Consequently, all gillnets had identical soak patterns during all fishing activity (Table 1).

When the gillnets were hauled and fish unmeshed, the catch was sorted by type of gillnet (i.e., biodegradable or nylon). All fish and invertebrate mega-fauna were sorted by species during the hauling operation and number of individuals for each species counted as "total catch". Further, the catch was sorted into wanted catch (primary and secondary target species) and unwanted catch separately.

2.2. Quantification of catch composition

To quantify catch composition in gillnets, we adapted the following biodiversity estimates: richness (Daly et al., 2018), Pielou index measuring species evenness (Pielou, 1966) and Shannon index

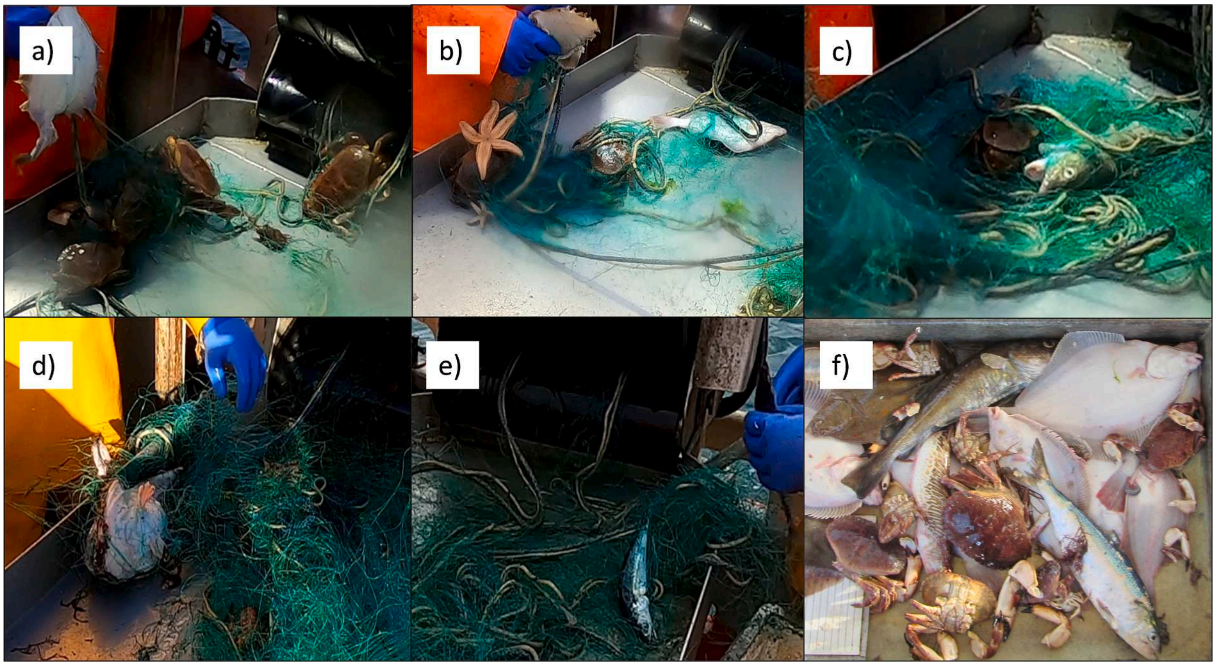

Fig. 1. Examples of species observed during gillnet retrieval process. (a) European plaice (wanted catch) and brown crab (large individuals – wanted catch); (b) brown crab, European plaice and common starfish (unwanted catch); (c) cod (wanted catch) and brown crab; (d) monkfish (wanted catch); (e) mackerel (unwanted catch); (f) European plaice, brown crab, herring (unwanted catch); swimming crab (unwanted catch), common dab, greater weever and cod.

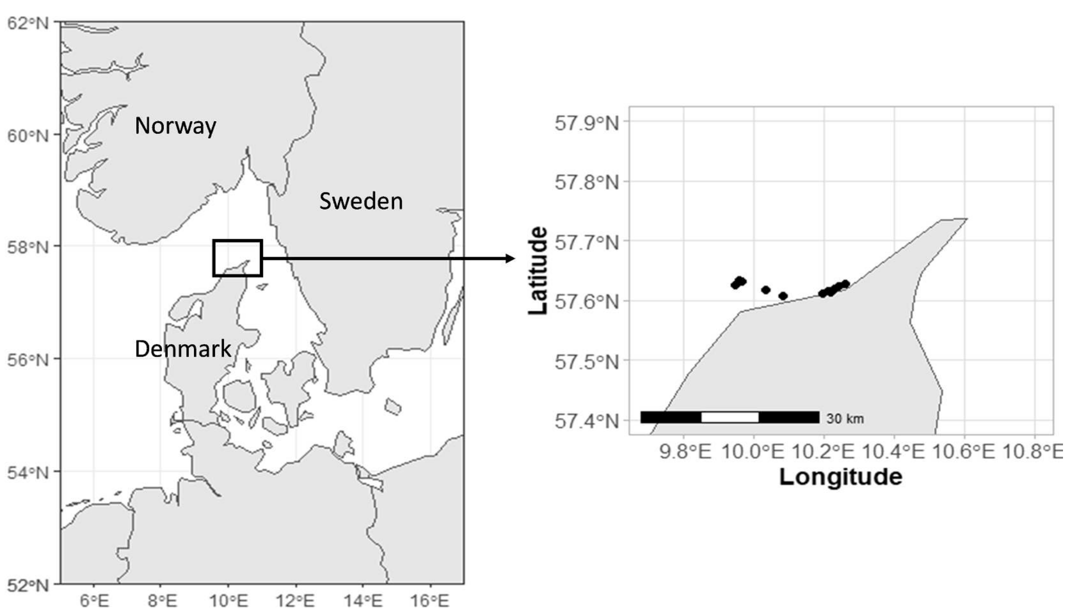

Fig. 2. Map of the positions where the gillnets were deployed.

accounting for a combination of richness and evenness of the species distribution (Shannon, 1948). Such biodiversity measures quantify aspects regarding species composition and dominance of individual species (Herrmann et al., 2022), and, therefore, can be applied to estimate the catch composition (total, wanted and unwanted catch) for each type of gillnet. We assessed the catch composition in nylon and biodegradable gillnet catches by estimating the number of species encountered in our samples and their distribution between total, wanted and unwanted catch.

The value for each of the biodiversity indices was estimated for both gillnet types separately. Further, we used cumulative dominance plots to assess cumulative proportional abundances of the species (i.e., species dominance) (Warwick et al., 2008). We determined the catch composition by calculating values of the indices averaged over all gillnet deployments contrary to using catch composition in individual netting sheets.

The different indices were estimated as described below. The value for each of the indices was estimated for nylon and biodegradable gillnets from count numbers n_{ij} for each species S_i where i is the predefined species ID and j is the gillnet deployment. Q represents the total number of species in the list.

2.2.1. *Species richness*

The richness index accounts for the absolute number of species in the

Table 1
Gillnet deployment date and time and hauling time for following day with the resulting soak time. Depth and the position where the gillnets were deployed during the trials.

Deployment	Date	Deployment time (hh:mm)	Soak time (hh:mm)	Position (start)	Depth (m)
1	10.09.2021	09:15	21:45	57°36.658N 10°11.800E	6
2	11.09.2021	08:35	21:50	57°36.988N 10°01.199E	6
3	15.09.2021	08:00	23:35	57°37.150N 10°13.826E	4
4	19.09.2021	08:35	22:50	57°36.913N 10°12.781E	4
5	20.09.2021	08:00	27:05	57°37.671N 10°15.570E	3
6	21.09.2021	12:00	23:40	57°36.436N 10°04.902E	3
7	27.09.2021	12:30	20:55	57°37.498N 09°56.927E	18
8	28.09.2021	10:30	21:00	57°37.940N 09°57.969E	18
9	29.09.2021	09:25	22:05	57°38.012N 09°57.591E	18
10	30.09.2021	11:30	21:00	57°38.006N 09°57.589E	18

catches (Maurer & McGill, 2011), and was calculated for the total as well as the wanted and unwanted catch composition in nylon or biodegradable gillnets, respectively. According to the estimation of richness (Eq. 1), all species in the sample have equal weight regardless of species abundance encountered (Daly et al., 2018). The richness was estimated as follows (Herrmann et al., 2022):

$$R_j = \sum_{i=1}^{Q} e(n_{ij}) \quad \text{where} \quad e(n) = \begin{cases} 0 & \forall \quad n < 1 \\ 1 & \forall \quad n \geq 1 \end{cases} \tag{1}$$

2.2.2. Shannon index

The Shannon diversity index is one of the most commonly used measures in species biodiversity (Maurer & McGill, 2011). By calculating the Shannon index, we considered both richness and evenness of the species abundance within each gillnet type within the total catch composition and wanted and unwanted catch. The Shannon index increases with the number of species sampled and with a more even distribution of species within the sample. Thus, the value of the Shannon index is zero in cases when only one species in a sample is observed (Daly et al., 2018). Therefore, a low value of the Shannon index implies low species diversity in the catch. The Shannon index was estimated by (Herrmann et al., 2022):

$$H_j = -\sum_{i=1}^{Q} ln\left(\left(\frac{n_{ij}}{n_j}\right)^{\frac{n_{ij}}{n_j}}\right) \quad \text{where} \quad n_j = \sum_{i=1}^{Q} n_{ij} \tag{2}$$

2.2.3. Species evenness

Pielou's evenness index measures how evenly the number of individuals are distributed among the species in the catches (Maurer & McGill, 2011; Daly et al., 2018) in total as well as the wanted and unwanted catch compositions. Therefore, it expresses the degree of equality in species abundance (Bandeira et al., 2013). The index is calculated as follows (Eq. 3) (Herrmann et al., 2022):

$$J_j = \frac{-H_j}{ln(R_j)} \tag{3}$$

The resulting value of Pielou's evenness index will range from 0.0 to 1.0. If the value reaches 1.0, this shows that all species in the sample are equally abundant (Kanieski et al., 2018).

2.2.4. Species dominance pattern

Further, we examined the species dominance patterns in total, wanted and unwanted catch compositions determining whether one or few species are more abundant compared to all the species in the sample (Maurer & McGill, 2011). We quantified the information about the catch composition of relative species abundances for nylon and biodegradable gillnets. Specifically, we estimated the species dominance patterns as follows:

$$d_{ij} = \frac{n_{ij}}{\sum_{i=1}^{Q} n_{ij}} \tag{4}$$

To represent species dominance patterns, cumulative dominance curves are often used. Such cumulative ranked species dominance curves show the cumulative proportional abundances plotted against the species rank. Cumulative dominance is estimated as follows (Eq. 5):

$$D_{Ij} = \frac{\sum_{i=1}^{I} n_{ij}}{\sum_{i=1}^{Q} n_{ij}} \quad \text{with} \quad 1 \leq I \leq Q \tag{5}$$

where I is the species ID summed up in the nominator (Herrmann et al., 2022).

In our study, we kept a fixed species ranking for species in all catches in the dominance curves, starting with wanted species followed by the unwanted species. This allows comparison of the steepness of the cumulative dominance curves to obtain an overview on how many species are dominant and the distribution of their relative dominance in total, wanted and unwanted catch compositions in nylon and biodegradable gillnets, respectively. The steeper the curve, the more dominated by few species is the sample, thus implying a lower diversity. Further, since dominance of some species can be low and they may not be present for some catch compositions (either wanted or unwanted catch composition), this would be shown by resulting horizontal parts in corresponding dominance curves.

2.3. Estimating uncertainty for observed catch composition

The estimation of uncertainty for the observed catch composition was based on Herrmann et al. (2022). The number of individuals of all species identified in the sample from a gillnet deployment j was defined as n_j:

$$n_j = \sum_{i=1}^{Q} n_{ij} \tag{6}$$

Because n_j is a finite number, a resampling method with replacement was used to estimate the uncertainties for the individual species counts. The resulting count numbers n_{ij} varied from one such resampling to another. By performing resamplings, we could obtain a population of data for each n_{ij}. After applying equations (1)–(5), we could generate a bootstrap population of values for each indicator measure, which we could use to obtain Efron percentile 95 % confidence intervals (CIs) (Efron, 1982) for each indicator measure and gillnet deployment j (Herrmann et al., 2022). However, to estimate the total value for the biodiversity indices for all gillnet deployments, n_{ij} in equations (1)–(5) was replaced with n_i which is given by:

$$n_i = \sum_{j=1}^{K} n_{ij} \tag{7}$$

where the summation was considered over a group of K gillnet deployments.

To account for variation between deployments when estimating the uncertainties, another resampling loop was applied (Herrmann et al., 2022). This outer resampling loop resampled with replacement K deployments over the K deployments considered. For each deployment selected, the inner resampling was conducted accounting for the finite sample size for the specific deployment. This nested resampling technique was applied 1000 times, leading to 1000 sets of n_i data. We applied equations (1)–(5) to these data to obtain a population of results for the indicators to estimate Efron 95 % percentile CIs for this estimation based on the group of stations within the area considered. The analysis was conducted using the software tool SELNET (Herrmann et al., 2012), which implements the described method.

2.4. Inferring difference in species dominance and diversity index values

To estimate differences in diversity index values for total, wanted and unwanted catch compositions in nylon and biodegradable gillnets, respectively, and to infer potential effects of changing gillnet material on the indices (Eq. 1–3), we used the ratio between values:

$$r_{y/x} = \frac{r_y}{r_x} \tag{7}$$

where r is one of the indices given by Eq. (1), (2) or (3) and x and y represent the index value for the total, wanted or unwanted catch compositions, respectively, if the comparison is within the same gillnet type. If the comparison is done between the two gillnet types, x and y are index values for the same catch composition (total, wanted or unwanted catch) for the two different gillnet types, respectively. The 95 % CIs for $r_{y/x}$ were obtained based on the two bootstrap population results for r_x and r_y, respectively (Eq. 8). As they were obtained independently of each other, a new bootstrap population of results was created using:

$$r_{y/xl} = \frac{r_{yl}}{r_{xl}} l \in [1 \cdots 1000] \tag{8}$$

In Eq. (8), l denotes the bootstrap repetition index. Based on the bootstrap population of results for $r_{y/x}$, we were able to obtain Efron percentile 95 % CIs (Efron, 1982). To determine whether the difference between the values of the indices is significant, we inspected if the 1.0 value was included in the CI for the ratio $r_{y/x}$. If the value 1.0 (or 100 % if the value is expressed in percentage) was not within the obtained CIs, then the indicator values for nylon and biodegradable gillnets differed significantly. On the contrary, when 1.0 was included in the CIs, no significant difference was detected.

Further, the difference Δd in species dominance d in the nylon (x) and biodegradable (y) gillnets was estimated by (Herrmann et al., 2022):

$$\Delta d = d_y - d_x \tag{9}$$

CIs for Eq. (9) were obtained based on separate bootstrap populations for d_x and d_y by applying the same technique as described above for $r_{y/x}$. However, when inferring for significance, we inspected if the CIs for the difference contained the value 0.0. If 0.0 value was within the CIs, no significant difference was detected (Herrmann et al., 2022).

3. Results

In total, 1280 and 1062 individuals belonging to 28 species were captured in nylon and biodegradable gillnets, respectively, during the sea trials (Table 1). From those, 12 species (821 individuals) and 11 species (631 individuals) was classified as wanted catch (primary and secondary target species) for nylon and biodegradable gillnets, respectively. The rest of the species contributed to unwanted catch (Table 2).

3.1. Estimated catch compositions for nylon and biodegradable gillnets

3.1.1. Species richness

The total, wanted and unwanted catch compositions were estimated for both, biodegradable and nylon, gillnets. Both types of gillnets showed similar catch composition (Tables 3–5). Specifically, no significant differences between the two gillnet types were observed when applying the different biodiversity index estimations (richness, Pielou and Shannon index).

The quantified species richness for the catch composition (i.e., species in the total catch composition) was 25.00 (CI: 19.40–28.40) and 22.00 (CI: 18.85–24.85) for nylon and biodegradable gillnets, respectively. The total catch composition was significantly more diverse compared to the wanted catch species for both gillnet types when the pairwise difference between them was compared (i.e., ratios of richness, Shannon and Pielou values between both gillnet types; Table 4).

3.1.2. Shannon index

There was a significant difference in diversity between unwanted and wanted catch compositions regarding species richness and Shannon index in both gillnets. Specifically, the results of the estimated indices showed significant differences between wanted and unwanted catch compositions for both nylon and biodegradable gillnets (Table 4). Species richness was significantly lower for wanted compared to unwanted catch in nylon (i.e., 55 % (CI: 41–78 %)) and biodegradable (i.e., 55 % (CI: 36–81 %)) gillnets. This showed a higher species diversity in unwanted catch compared to wanted catches in the fishery. A similar result was also reflected in the Shannon index values which for both gillnet types were significantly higher for unwanted catch compared to wanted catches (Table 4).

3.1.3. Pielou evenness index

Additionally, species across the unwanted catch composition of the catch showed higher evenness in species distribution (based on values of Pielou index) compared to wanted catches in both gillnet types. This implies that the individuals of unwanted catch are more evenly distributed among the different species compared to wanted catch where one or few species dominated. Specifically, half of the wanted catch composition in numbers was constituted by catches of the primary target species European plaice. This, therefore, implies that the catch composition for the wanted catch were characterized by higher dominance of limited number of species.

3.2. Dominance patterns

The species cumulative dominance patterns (Fig. 3) and species dominance values (Supplementary material 1) were in line with the results described above regarding species distribution in wanted and unwanted catches in both gillnet types. Fig. 3 shows dominance curves for the cumulative dominance values as estimated by Equation (5). The horizontal parts of the cumulative dominance curve (Fig. 3) show specific species that were not represented in the sample of total (grey lines), wanted catch (green lines) or unwanted catch (red lines) species, respectively.

3.2.1. Species dominance pattern in catch compositions

In both types of gillnets, fewer species contributed to the wanted catches compared to unwanted catch of all captured individuals. In the wanted catch composition, species abundance was dominated by few species. Specifically, European plaice dominated wanted catches with 74.88 % (CI: 47.59–86.36 %) in nylon gillnets and 76.23 % (CI: 52.19–87.84 %) in biodegradable gillnets. Indeed, European plaice contributed to half of the total catch composition individuals (Fig. 3)

Table 2
List of species and number of individuals sampled during the experiments. MCRS = minimum conservation reference size (Fiskeristyrelsen, 2022). Species names marked with * denote species of wanted catch.

				Number of individuals					
				Nylon gillnets			Biodegradable gillnets		
Species ID	Species name	Common name	MCRS (cm)	Total	Wanted	Unwanted	Total	Wanted	Unwanted
1	*Pleuronectes platessa* (Linnaeus, 1758)*	European plaice	27	671	626	45	538	481	57
2	*Solea solea* (Linnaeus, 1758)*	Sole	24	10	10	0	13	13	0
3	*Gadus morhua* (Linnaeus, 1758)*	Cod	30	26	16	10	20	12	8
4	*Limanda limanda* (Linnaeus, 1758)*	Common dab	–	90	42	48	89	39	50
5	*Scopthalmus maximus* (Linnaeus, 1758)*	Turbot	–	42	25	17	46	20	26
6	*Platichtyes flesus* (Linnaeus, 1758)*	Flounder	–	17	17	0	10	8	2
7	*Cancer pagurus* (Linnaeus, 1758)*	Brown crab	–	153	73	80	125	51	74
8	*Molva molva* (Linnaeus, 1758)*	Common ling	–	0	0	0	1	1	0
9	*Lophius piscatorius* (Linnaeus, 1758)*	Monkfish	–	4	3	1	3	2	1
10	*Zeugopterus punctatus* (Bloch, 1787)*	Topknot	–	2	1	1	3	2	1
11	*Scomber scombrus* (Linnaeus, 1758)*	Mackerel	20	76	6	70	64	2	62
12	*Microstomus kitt* (Walbaum, 1792)*	Lemon sole	–	1	1	0	0	0	0
13	*Merlangius merlangius* (Linnaeus, 1758)*	Whiting	23	5	1	4	1	0	1
14	*Asterias rubens* (Linnaeus, 1758)	Common starfish	–	71	–	71	79	–	79
15	*Pollachius pollachius* (Linnaeus, 1758)	Pollock	30	2	–	2	0	–	0
16	*Trachinus draco* (Linnaeus, 1758)	Weeverfish	–	2	–	2	1	–	1
17	*Portunus* (Weber, 1795)	Swimming crab	–	77	–	77	56	–	56
18	*Hyas araneas* (Linnaeus, 1758)	Spider crab	–	5	–	5	2	–	2
19	*Carcinus maenas* (Linnaeus, 1758)	Shore crab	–	8	–	8	1	–	1
20	*Anguilla anguilla* (Linnaeus, 1758)	Eel	40	0	–	0	1	–	1
21	*Pagurus bernhardus* (Linnaeus, 1758)	Hermit crab	–	6	–	6	6	–	6
22	*Syngnathus* (Linnaeus, 1758)	Pipefish	–	4	–	4	1	–	1
23	*Raja clavata* (Linnaeus, 1758)	Thornback ray	–	2	–	2	0	–	0
24	*Aurelia aurita* (Linnaeus, 1758)	Common jellyfish	–	0	–	0	1	–	1
25	*Myoxocephalys scorpius* (Linnaeus, 1758)	Shorthorn sculpin	–	1	–	1	1	–	1
26	*Clupea harengus* (Linnaeus, 1758)	Herring	18	2	–	2	0	–	0
27	*Eutrigla gurnardus* (Linnaeus, 1758)	Grey gurnard	–	2	–	2	0	–	0
28	*Raniceps raninus* (Linnaeus, 1758)	Tadpole fish	–	1	–	1	0	–	0

Table 3
Values of different biodiversity indices estimated for nylon and biodegradable gillnets and divided into species as total, wanted and unwanted catch.

	Nylon gillnets			Biodegradable gillnets		
Index	Total	Wanted	Unwanted	Total	Wanted	Unwanted
Richness	25.00 (19.40–28.40)	12.00 (09.69–13.69)	22.00 (15.61–25.61)	22.00 (18.85–24.85)	11.00 (08.41–12.41)	20.00 (16.40–23.40)
Shannon	01.80 (01.40–02.22)	01.02 (00.64–01.64)	02.28 (02.01–02.47)	01.76 (01.35–02.16)	00.97 (00.60–01.55)	02.15 (01.94–02.29)
Pielou	00.56 (00.43–00.72)	00.41 (00.26–00.65)	00.74 (00.68–00.79)	00.57 (00.43–00.71)	00.40 (00.24–00.67)	00.72 (00.66–00.78)

Table 4
Ratios (%) between values of different biodiversity indices estimated for nylon and biodegradable gillnets and divided into species as total, wanted and unwanted catch. Values in parentheses represent 95% confidence intervals.

	Nylon gillnets			Biodegradable gillnets		
Index	Wanted / total	Wanted / unwanted	Unwanted / total	Wanted / total	Wanted / unwanted	Unwanted / total
Richness	48.00 (39.33–60.20)	54.55 (41.28–78.42)	88.00 (76.72–94.70)	50.00 (37.01–67.49)	55.00 (36.50–81.11)	90.91 (78.79–99.00)
Pielou	73.39 (59.06–91.74)	55.59 (35.85–86.80)	132.02 (103.42–169.40)	70.96 (55.18–93.82)	56.09 (34.98–90.62)	126.51 (102.92–160.88)
Shannon	56.66 (44.76–75.31)	44.69 (27.29–77.74)	126.77 (96.78–164.01)	55.05 (42.81–74.15)	44.90 (26.93–75.88)	122.61 (98.36–156.28)

Table 5
Ratio for index values for biodegradable vs nylon gillnets (%). Values in parentheses represent 95% confidence intervals.

	Biodegradable vs nylon gillnets		
Index	Total	Wanted	Unwanted
Richness	88.00 (67.46–117.70)	91.67 (66.83–121.83)	90.91 (65.68–131.61)
Pielou	101.76 (68.61–146.66)	98.39 (46.37–185.01)	97.51 (86.51–109.44)
Shannon	97.72 (67.51-138.47)	94.94 (42.44-178.84)	94.51 (82.08-108.75)

with 51.81 % (CI: 27.80–67.23 %) and 50.66 % (CI: 26.46–66.55 %) captured in nylon and biodegradable gillnets, respectively. The rest of the total catch composition was dominated by brown crab (11.81 % (CI: 05.78–22.42 %) and 11.77 % (CI: 06.67–20.92 %), for nylon and biodegradable gillnets, respectively) and other secondary target species such as common dab and mackerel among others. Thus, there were less species contributing to the wanted catch composition in nylon and biodegradable gillnets compared to the total catch composition. There was a large variation of species regarding the unwanted catch composition in both nylon and biodegradable gillnets (Fig. 3). Some species were recorded in only a few gillnet deployments.

3.2.2. Pairwise difference in species dominance in biodegradable versus nylon gillnets

The pairwise difference in cumulative dominance (delta) curves (Fig. 4) shows the differences in species dominance for total, wanted and unwanted catch compositions in biodegradable versus nylon gillnets. No significant differences between gillnets using the two materials were

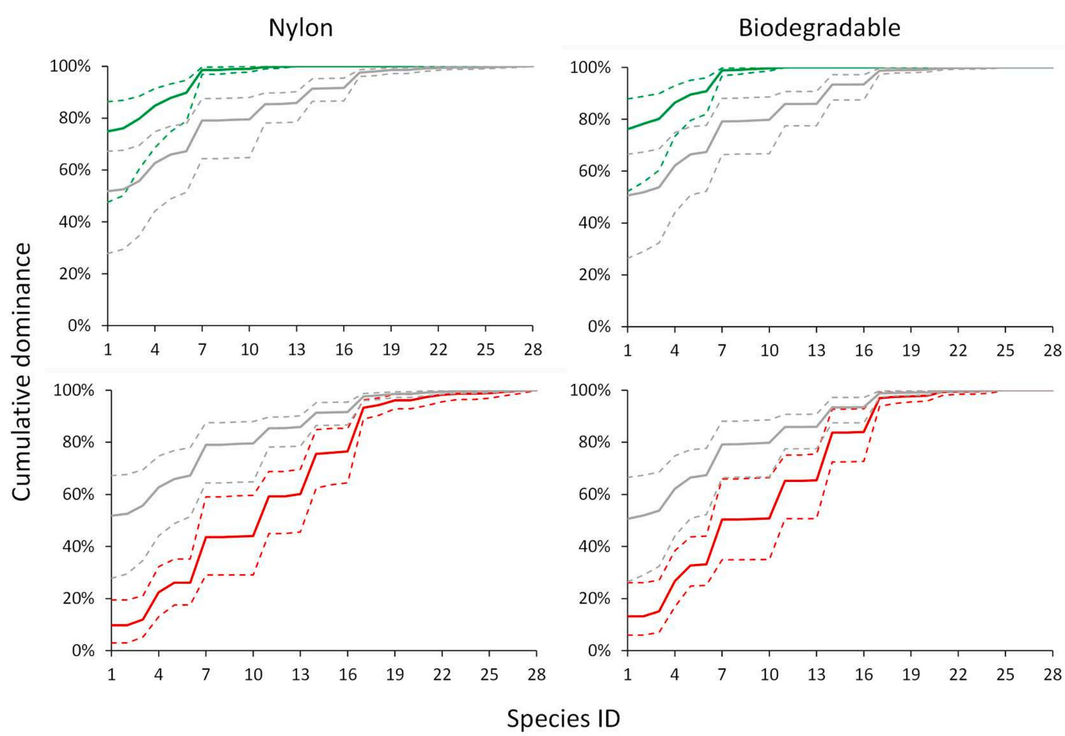

Fig. 3. Cumulative dominance curves for nylon gillnets (left) and biodegradable gillnets (right). Grey curve represents dominance curve for total catch composition by particular gear material while green and red line – species that were classified as wanted and unwanted catch, respectively. Dashed lines are 95% confidence intervals. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

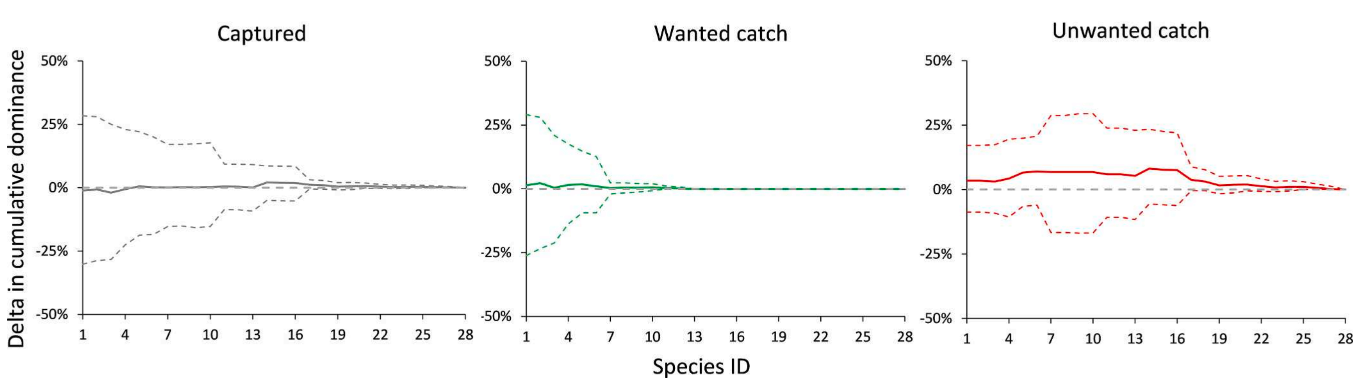

Fig. 4. Pairwise difference in cumulative dominance curves for biodegradable versus nylon gillnets for total (left), wanted (middle) and unwanted (right) catch species. Dashed lines are 95% confidence intervals.

detected regarding catch composition in species dominance as the results included 0.0 within the obtained CIs.

4. Discussion

In this study, we used data from a Danish coastal gillnet fishery directed at European plaice to quantify and compare the catch composition in biodegradable and nylon gillnets. The comparison was done by estimating the ratios between the diversity index values and by using the delta approach (Herrmann et al., 2022) to cumulative dominance plots. Furthermore, the application of the nested bootstrapping (Herrmann et al., 2022) made it possible to infer changes in catch composition between the fishing gear types. Both biodegradable and nylon gillnets showed similar catch composition regarding species recorded as total, wanted and unwanted catch. The primary target species, European plaice, dominated the wanted catch for both types of gillnets, with other species in the wanted catch consisting of several secondary target species. However, our results showed significant differences in composition regarding wanted and unwanted catches in this fishery, with European plaice constituting half of the total catch composition for nylon and biodegradable gillnets. This showed that a large part of the total catch composition, expressed as number of individuals, in this fishery is made up by different unwanted species (20.00 (CI: 16.40–23.40) for biodegradable and 22.00 (CI: 15.61–25.61) for nylon gillnets).

Since European plaice only constituted half of the total catch composition, considering only the target species in this fishery would ignore the other half of the species (in numbers) affected by the particular fishery since 28 different species were captured during this study. Thus, the diversity of the total catch composition was higher compared to what ended up in the wanted catch composition (i.e., 11 and 12 species). The remaining species only contributed to unwanted catch in this fishery. In future studies, this approach can be supplemented by accounting for these patterns expressed not only as number of individuals for each species but also in weight which was not done in this study due to time constraints during the trial.

The results in this case study should be interpreted with caution as they are based on a limited number of gillnet deployments during one fishing season and using one fishing vessel. Further, the trials were performed by slightly changing the fishing area in order to capture cod in sufficient numbers. However, we believe that the collected data are well suited for demonstrating our concept of making a more holistic evaluation of the gillnet performance in the particular fishery. The difference between biodegradable and nylon gillnets did not show any statistical significance regarding the catch composition in wanted and unwanted catch compositions, and the two gillnet types were subjected to the same conditions regarding the factors that could affect the catch composition (i.e., the fishing area, fishing depth, time of deployment, vessel, and gillnet soaking time).

In our study, biodegradable and nylon gillnets showed similar catch composition. These results show that use of new biodegradable gillnets would not increase vulnerability of species being affected by the biodegradable gillnets compared to traditionally used nylon nets. Since no differences were detected by changing gillnet material from traditionally used nylon to biodegradable plastics, the catch composition would not represent a barrier for implementing biodegradable materials in this commercial gillnet fishery. However, the differences in the material properties between biodegradable and nylon nets are expected to increase with the use of the gear (Grimaldo et al., 2020; Cerbule et al., 2022) due to a faster degradation of the biodegradable netting (Brakstad et al., 2022). Therefore, further experiments using the developed method involving repeated deployments would be necessary for determining the effect of long-term use of the biodegradable and nylon gillnets on the catch composition.

In this study, we quantified species richness, evenness and species dominance, as well as cumulative dominance within fishing gear catches. Such an approach can move the field beyond focusing on a few commercial species, which is typically the case when analysing the selectivity of fishing gears, to one that provides a more detailed overview of the entire catch. The presented approach has some similarities when compared to Fauconnet et al. (2015) who aimed at assessing how fishing pressure is distributed across the species community using estimates of species richness and evenness. However, the method described in this study can provide a direct comparison, and it considers the hierarchical structure in uncertainties (i.e., between and within gillnet deployments) and uses a nested bootstrapping approach when estimating biodiversity indices. This further allowed inferring differences between the gears using the delta approach (Herrmann et al., 2022).

The approach developed here for estimating and comparing catch composition for all species caught, both wanted and unwanted, was applying indices that are used for analysing species biodiversity (i.e., Greenstreet et al., 2012; Farriols et al., 2017; Taylor et al., 2017). This approach can provide additional information that can be useful when assessing the impact fishing gears have on the marine ecosystem, since only focusing on the wanted species may not reflect the actual species composition that is caught in a fishery (Eliasen et al., 2019). Furthermore, this approach can be used when analysing data collected during larger data collection programmes for catch and discard sampling (Feekings et al., 2012; Suuronen & Gilman, 2020). These data collections are often based on extensive time series covering all seasons since the targeting behaviour and species composition can have temporal variations (Feekings et al., 2012). The methods developed here would provide an additional way for monitoring changes and allow comparisons between fishing gear types and assess catch compositions in different areas and between different seasons. Specifically, since the abundance and composition of species varies by fishing area and/or period of time, it is, therefore, affecting catch composition of both wanted and unwanted catch. This can result in obligations for fishing vessels to change the fishing grounds and area closures. Therefore, assessing catch composition has the potential to identify fisheries that in different fishing areas, seasons or under different operational patterns may result in desired or undesired levels of environmental impact.

The presented method can be applied in other studies for quantifying and inferring the differences in catch composition in various fisheries and using different fishing gear configurations. Further, the method could be used when grouping the observed species in the total catch composition into functional groups when assessing fisheries impacts on endangered, threatened and vulnerable species. Normally in a fishery, there is an interest in reducing catches of both undersized individuals of target species and catches of non-target species, even if the exact effect on the ecosystem is unknown (Bellido et al., 2011) and to reduce the sorting time during the gear retrieval. In gillnets, the species selectivity can be changed by, for example, different properties of the gear such as hanging ratio (Gray et al., 2005b), gillnet height (He, 2006b), mesh size (Fonseca et al., 2005, Lucchetti et al., 2020; Soe et al., 2022) or netting material (Gray et al., 2005b), or by changing fishing depth (Soe et al., 2022) and soaking time (Savina et al., 2017). However, changes in such properties could also affect the catch rates of wanted and unwanted species differently. Therefore, an assessment of suitable gear properties by quantifying catch composition is necessary. Further, this method could also be applied in studies assessing not only gillnets but also the catch composition of other fishing gears such as trawls, especially when targeting multiple species or in fisheries with high levels of unwanted catches such as in Norwegian lobster (*Nephrops norvegicus,* (Linnaeus, 1758) fishery (Melli et al., 2018). Specifically, this approach can have the potential to be utilized when analysing data collected in large data collection programmes such as discard sampling programmes. The proposed method can involve challenges regarding the data collection process because of the need to identify each species captured by the gear which can be challenging during commercial fishing. However, this process can in the future be optimized by the use of, for example, electronic monitoring to assess compositions of wanted and unwanted species (i.e., Suuronen & Gilman, 2020; Khokher et al., 2022) and to detect and count the species during data collection using e.g. artificial intelligence and machine learning (French et al., 2020; Sokolova et al., 2021). Therefore, there is a potential that the developed method can be used to describe catch composition for fisheries and monitor spatial and temporal developments in species richness, diversity and dominance to guide the development of more sustainable fisheries providing we are able to link catch composition to ecosystem effects.

CRediT authorship contribution statement

Kristine Cerbule: Conceptualization, Investigation, Formal analysis, Visualization, Writing – original draft. **Esther Savina:** Funding acquisition, Writing – original draft, Supervision. **Bent Herrmann:** Conceptualization, Software, Writing – original draft, Supervision. **Roger B. Larsen:** Writing – original draft, Supervision. **Jordan Paul Feekings:** Conceptualization, Writing – original draft. **Ludvig Ahm Krag:** Conceptualization, Writing – original draft. **Alina Pellegrinelli:** Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Comparison of the efficiency and modes of capture of biodegradable versus nylon gillnets in the Northeast Atlantic cod (*Gadus morhua*) fishery

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ABSTRACT

Modern gillnets are usually made of nylon with high breaking strength, suitable elasticity and durability making them an efficient fishing gear. Lost, abandoned, or discarded gillnets at sea cause plastic pollution and can continue capturing marine animals over long periods of time. Biodegradable materials are being developed to replace nylon in gillnets. However, biodegradable gillnets have shown reduced catch efficiency compared to the nylon gillnets which challenges their acceptance by the fishing sector. This study investigated catch efficiency and modes of capture between biodegradable and nylon gillnets in commercial cod (*Gadus morhua*) fishery. On average, new biodegradable gillnets caught 25% fewer cod compared to new nylon gillnets. The main capture modes were by the gills and by the body in used and new biodegradable gillnets, respectively. Differences in catch efficiency are related to specific modes of capture that may be related to differences in material properties.

1. Introduction

Gillnets, which are efficient and relatively inexpensive, are one of the most commonly used fishing gears in the world (FAO, 2016). Synthetic plastic material (nylon) has high elasticity and breaking strength, and its use as the material for gillnets has increased their fishing capacity and, therefore, the profitability of the industry (He, 2006). However, these same characteristics have a negative effect on the marine environment. Because of the durability of the nylon material, the gear has the potential to continue fishing for years when lost, abandoned and/or discarded at sea (a process known as ghost fishing) (He, 2006). Previous studies have documented large amounts of fish and benthic organisms in lost gillnets upon retrieval (Puente et al., 2001; Humborstad et al., 2003; Good et al., 2010; Beneli et al., 2020). Moreover, nylon does not disappear completely even after long exposure to the conditions at sea. Instead, it is broken down into smaller plastic particles (macro- and microplastics) and toxic substances that continue to impact the marine environment (Moore, 2008). Although gillnets are considered to be a sustainable fishing gear because of, for example, their limited negative effects on juvenile fish and the benthic environment compared to other fishing methods such as, for instance, bottom trawling, the plastic pollution and potential ghost fishing impact by the lost gear is an increasing concern to the sustainability (FAO, 2016; Standal et al., 2020).

The Northeast Atlantic cod (*Gadus morhua*) fishery is the most economically important single species fishery in Norway. In the coastal gillnet fishery for cod, gillnets account for 21% of the total national allowable catch, which was 331,553 t in 2020 (Norwegian Directorate of Fisheries, 2021). However, incidental losses of fishing gear is relatively high in some of the Norwegian gillnet fisheries (Norwegian Directorate of Fisheries, 2019). Deshpande et al. (2020) estimated the annual loss rates of six types of fishing gear in Norway and identified gillnets as the primary source of lost, abandoned, and/or discarded fishing gears.

The feasibility of using new biodegradable materials to replace nylon in gillnets has been tested in South Korea (Park et al., 2007a, 2007b, 2010; Park and Bae, 2008; Bae et al., 2012; An and Bae, 2013; Kim et al., 2013, 2014a, 2014b, 2016) and Norway (Grimaldo et al., 2018, 2019,

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2020). The aim is for the new biodegradable material to have mechanical properties similar to those of nylon during the operation. However, naturally occurring microorganisms should be able to degrade lost nets into substances that are harmless to the marine environment after a specific amount of time in the water, thereby reducing plastic pollution (Kim et al., 2014a, 2014b) and limiting ghost fishing. However, for the new biodegradable material to be used commercially, the nets should have similar catch efficiency as nylon nets to maintain the profitability of the industry, and, therefore, to be ready to be adopted by the industry.

Previous experimental trials conducted in Norway showed that gillnets made from resin of the biodegradable polymer polybutylene succinate *co*-adipate-co-terephthalate (PBSAT) had lower catch efficiency than nylon (polyamide) gillnets (Grimaldo et al., 2018, 2019). Furthermore, the catch efficiency of biodegradable gillnets progressively declined over their lifetime as a consequence of degradation (Grimaldo et al., 2019, 2020). The mechanical properties of the biodegradable material, such as suboptimal tensile strength, elongation at break, and elasticity may explain the differences in catch efficiency between biodegradable and nylon nets as well as the differences between new gillnets and those subjected to repeated use (Grimaldo et al., 2020). Specifically, it was found that the breaking strength decreased more for the biodegradable PBSAT material compared to nylon after 200 h aging test with an initial value that was 23% lower compared to nylon (Grimaldo et al., 2020). Thickness of the twine used and stiffness of the mesh can also affect catch rates (Grimaldo et al., 2020).

To understand how these material properties affect the catch efficiency over time, the underlying mechanisms of how fish are caught in gillnets should be understood. Such information could help identifying the causes of problems regarding the catch efficiency of biodegradable gillnets and, thereby, guide which improvements have to be made regarding the properties of the biodegradable gillnets. Incorporating these modifications would likely increase the use of biodegradable material in commercial gillnet fishery and help to reduce the marine plastic pollution caused by using nylon material in gillnets. Material properties can affect how the fish are caught in the net, with gillnet design parameters expressed as mesh size, hanging ratio, twine thickness, twine construction and material type affecting both catch efficiency and the selectivity of the gear (He, 2006; Sala, 2016; Sala et al., 2018). In the literature, the following capture modes for roundfish have been observed in gillnets: snagging (captured in nets by the mouth, teeth, or maxillae), gilling (captured behind the gill cover by the netting), wedging (stuck in the net by the largest part of the body), or entangling (Hovgard, 2000; He, 2006; Grati et al., 2015). Previous studies reported that the capture mode of fish in gillnets could provide valuable information about how the fish were caught in the netting and how the catch process affected the catchability of the gear (Grati et al., 2015; Savina et al., 2021). The capture mode can also affect whether the fish are retained or released, as some modes of capture are more effective at retaining fish than others (e.g., fish captured by the mouth/maxillae have a greater chance of escaping the netting) (Grati et al., 2015; Savina et al., 2021). Recently, Savina et al. (2021) formally related capture mode to fish size, and the application of this method was relevant to evaluate differences in gear characteristics and to explain catch efficiency.

In the present study, we evaluated whether the assessment of capture modes in gillnets could explain the capture patterns observed for different gillnet materials (PBSAT and nylon) and for the same material over repeated use. We compared the catch efficiency between new and used biodegradable and nylon gillnets used in the cod fishery in northern Norway. We examined whether there were significant differences in capture modes between the two materials and whether they could explain the differences in catch efficiency between the different gillnets.

2. Materials and methods

2.1. Sea trials and data collection

The fishing performance of 10 new and 10 used nylon and biodegradable gillnetswere compared during fishing trials conducted onboard the coastal fishing vessel “Karoline” (10.9 m LOA) under commercial conditions in March 2021 during the most important fishing season for cod. The fishing grounds were located off the coast of Troms (Northern Norway) between 70°21.26–70°21.55 N and 19°40.82–19°42.04 E. The fishing depths varied between 55 and 145 m.

All biodegradable gillnets were made of PBSAT resin (Kim et al., 2017, patent EP3214133). Biodegradable and nylon gillnets were manufactured by S-ENPOL (Gangwon-do, South Korea). Two sets of gillnets were tested in this experiment on separate fleets (Fleet 1 and Fleet 2, respectively):

Fleet 1: New nylon versus new biodegradable gillnets. Both gillnets were made of 0.70 mm monofilament, 210 mm stretched mesh size, and were 30 meshes high and 275 meshes long (stretched length 55 m).

Fleet 2: Used nylon versus used biodegradable gillnets. Nylon and biodegradable gillnets were made of 0.70 and 0.75 mm monofilament, respectively. Both types of nets had 210 mm stretched mesh size and were 30 meshes high and 275 meshes long (stretched length 55 m).

By using this experimental design, we were able to evaluate the effect of catch efficiency from changing from nylon to biodegradable gillnet material for both, new and used gillnets separately. Each fleet consisted of 10 biodegradable and 10 nylon nets that were attached in an alternated order in which two biodegradable net sheets followed two nylon sheets. The distance between individual gillnets was 1 m (Fig. 1). This design provided information that could be used for catch comparison analysis accounting for spatial and temporal variation in the availability of the fish (Herrmann et al., 2017). Here it is important that the two types of gillnets being compared are on average exposed to the same population of fish regarding numbers and size distribution. In order to achieve this, the nets in each fleet was set in a regular pattern. This could in principle be achieved by alternating between the two types of gillnets on the mainline in the following order: B-N-B-N-B-N-B-N-B-N-B-N-B-N-B-N. However, for easing of registration of cod in relation to the type of gillnets, the alternation in gillnet types were only applied after each second net sheet following Grimaldo et al. (2019). Therefore, to make conditions as equal as possible between the gillnets, they were arranged as follows: N-BB-NN-BB-NN-BB-NN-BB-NN-BB-N and set 2 as B-NN-BB-NN-BB-NN-BB-NN-BB-NN-B (Fig. 1).

The used nylon and biodegradable nets had been subjected to fishing during the fishing season in 2020 during a total of 12 deployments. Storing of gillnets from one season to the other follow standard procedures; the nets were washed with fresh water, dried, and stored in dry conditions inside a warehouse. The new set of gillnets were new at the start of these trials. The hanging ratio (i.e., ratio of floatline and leadline length to the stretched net length) was similar for all nets and was 0.5. The gillnets were sewn to 26 mm diameter SCANFLYT-800 floatlines with a buoyancy of 150 g m^{-1} and 16 mm diameter DANLINE line with a weight of 360 g m^{-1} (lead inside the braided line).

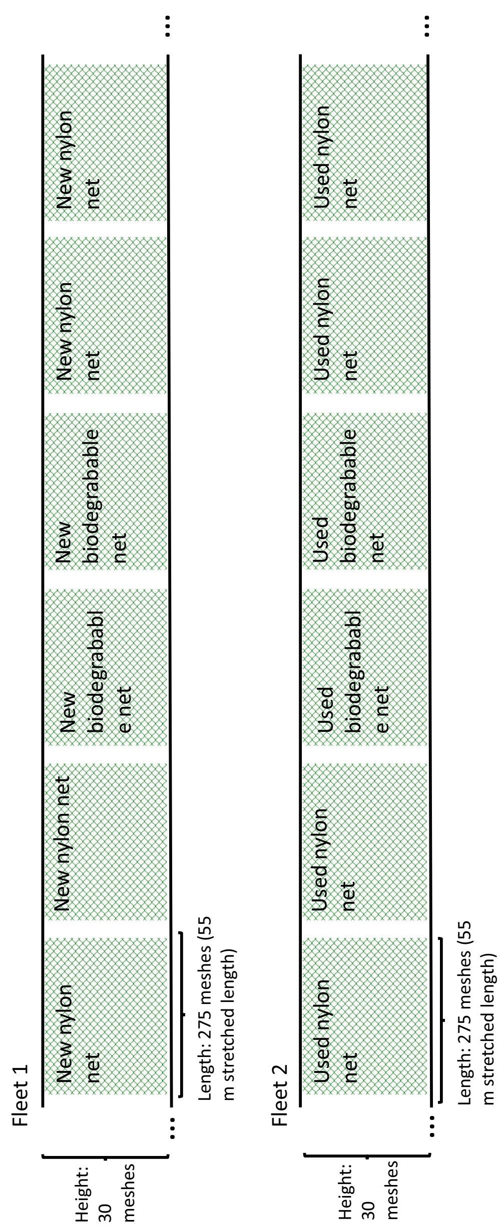

Fig. 1. Experimental setup showing a segment of gillnets used during the fishing trials for each fleet. Fleet 1 contained new nylon and biodegradable gillnets. Fleet 2 contained used nylon and biodegradable gillnets. Fleets were deployed simultaneously and in the same fishing area.

When the nets of Fleet 1 and Fleet 2 were hauled on board, the catch was sorted by type of gillnet. The capture mode of each individual cod was observed and recorded during the hauling operation. We classified the cod into four different modes of capture: tip (mouth and maxillary), gills, largest part of the body, or entangled in the netting. To record capture mode, once onboard each fish was observed one by one, and the mode of capture was determined by the netting tension (i.e., the tightest meshes) around the fish. One or several capture modes was recorded for each individual. In case of multiple modes for an individual cod, we assumed a primary mode according to the principle of likely sequence according to Savina et al. (2021). According to this principle, the primary mode of capture corresponds to the part of the fish that touches the netting last. For example, if a fish was captured by the tip (mouth or maxillary) and gills, the primary capture mode would be recorded as gills. If a fish was captured by the gills and the largest part of the body, the assumed mode of capture would be body (Savina et al., 2021). Finally, the corresponding total length of each cod was measured to the closest cm below. All captured cod were measured for both length and mode of capture.

2.2. Modelling the length-dependent catch efficiency between gillnet types

Comparison of catch efficiency between gillnet types was estimated as the catch comparison rate and catch ratio (Herrmann et al., 2017; Grimaldo et al., 2019, 2020). We analysed relative catch efficiency between nylon and biodegradable gillnets using the statistical software SELNET (Herrmann et al., 2012). Specifically, using the data from Fleet 1 and Fleet 2 (Fig. 1) separately, we were able quantify the effect on catch efficiency by changing from nylon to biodegradable material for new and used gillnets, respectively. We used the catch information (numbers and lengths of cod caught in each gillnet panel deployment) to determine whether there was a significant difference in the catch efficiency averaged over deployments between nylon and biodegradable gillnets and between used and new gillnets. We also tested whether a potential difference between the gillnet types could be attributed to the size (total length) of the cod. We used the method described in Herrmann et al. (2017) and Grimaldo et al. (2019, 2020) to assess the change in relative length-dependent catch efficiency when changing from a nylon gillnet to a biodegradable gillnet, and we compared the catch data for the two gillnet types. We applied the same method to assess the change in relative length-dependent catch efficiency between used and new gillnets. This method models the length-dependent (l) catch comparison rate ($CC(l, \boldsymbol{v})$) and catch ratio ($CR(l, \boldsymbol{v})$) summed over gillnet deployments for the full deployment period. The functional form for the $CC(l,\boldsymbol{v})$ was obtained using maximum likelihood estimation, where $\boldsymbol{v}$ represents the parameters describing the catch comparison curve defined by $CC(l, \boldsymbol{v})$. The length-integrated average catch ratio ($CR_{average}$) value was estimated directly from the experimental catch data. Details about the estimation of $CC(l, \boldsymbol{v})$, $CR(l, \boldsymbol{v})$, and $CR_{average}$ are provided in the supplementary material of Grimaldo et al. (2020).

2.3. Modelling the length-dependent capture mode probability

To determine, conditioned capture, the length-dependent probability of capturing fish with each of the four modes of capture, we followed the method outlined in Savina et al. (2021). Specifically, we used numbers of cod that were captured by each of the capture modes and the corresponding length measurements in each of the gillnet types separately. We considered all gillnets of the same material (nylon or biodegradable material) from each fleet deployment to constitute a unit for the analysis. The analysis was carried out for each mode of capture independently. Conditioned capture (the expected probability for the capture mode q for fish length l) is written as (Savina et al., 2021):

$$CPq_l = \frac{\sum_{j=1}^{h} n_{qlj}}{\sum_{j=1}^{h}\sum_{i=1}^{Q} n_{ilj}} \tag{1}$$

where n_{qlj} is the number n of fish caught per length class l with capture mode q in haul j; Q is the number of capture modes considered; and h is the total number of gillnet deployments. The functional description of the capture mode probability $CPq(l, \boldsymbol{v})$ was obtained using maximum likelihood estimation by minimizing the Expression (2) (Savina et al., 2021):

$$-\sum_{j=1}^{h}\sum_{l}\left\{n_{qlj}\times ln\left[CPq(l,\boldsymbol{v})\right]+\left[-n_{qlj}+\sum_{i=1}^{Q}n_{ilj}\right]\times ln[1.0-CPq(l,\boldsymbol{v})]\right\} \tag{2}$$

where $\boldsymbol{v}$ represents the parameters describing the capture mode probability curve defined by $CPq(l, \boldsymbol{v})$. Eq. (1) and Expression (2) are similar in form to what is often used for modelling and estimating the length-dependent catch comparison rate between two fishing gears (Krag et al., 2014). We adapted the same approach for modelling $CPq(l, \boldsymbol{v})$ as is often applied for catch comparison studies based on binominal count data (Herrmann et al., 2017):

$$CPq(l,\boldsymbol{v}) = \frac{exp[f(l, v_0, \ldots, v_k)]}{1 + exp[f(l, v_0, \ldots, v_k)]} \tag{3}$$

In Eq. (3), f is a polynomial of order k with coefficients v_0 to v_k, such that $\boldsymbol{v} = (v_0, \ldots v_k)$. The values of the parameter v describing $CPq(l, \boldsymbol{v})$ are estimated by minimizing the Expression (2). We considered f of up to an order of 4 using multimodel inference (Herrmann et al., 2017) . Leaving out 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 $CPq(l, \boldsymbol{v})$. Among these models, the capture mode probability was estimated using multimodel inference to obtain a combined model (Burnham and Anderson, 2002). The ability of the combined model to describe the experimental data was based on the p-value, which was calculated based on the model deviance and degrees of freedom (DOF) (Wileman et al., 1996). The combined model described the experimental data sufficiently well at $p > 0.05$.

We used a double bootstrapping method with 1000 bootstrap repetitions to estimate 95% confidence intervals (CIs) (Efron, 1982) for the capture mode probability curve (Savina et al., 2021). We presented the length distribution of the sampled population as the modelled mean number of cod caught for the four capture modes.

The length-integrated average value for the capture mode probability ($CPq_{average}$) was directly estimated from the experimental data using the following equation (Savina et al., 2021):

$$CPq_{average} = \frac{\sum_l \sum_{j=1}^{h} n_{qlj}}{\sum_l \sum_{j=1}^{h}\sum_{i=1}^{Q} n_{qlj}} \tag{4}$$

where the outer summations include the size classes in the catch during the experimental fishing period. In contrast to the length-dependent evaluation of the capture mode probability $CPq(l, \boldsymbol{v})$, $CPq_{average}$ is specific for the population structure encountered during the experimental trials. Therefore, this information cannot be extrapolated to other scenarios in which the size structure of the fish species may be different.

2.4. Probability of capture in a specific gillnet type and mode conditioned capture

For each capture mode q separately, we wanted to investigate whether capture efficiency differed for any of the four gillnets compared to all the other gillnets on average. Experimentally we can describe this by the expected probability $CPkq_l$ of being captured in gillnet type k conditioned it is captured with mode q in one of the four gillnets (1 = new biodegradable gillnets, 2 = new nylon gillnets, 3 = used biodegradable gillnets, 4 = used nylon gillnets):

$$CPkq_l = \frac{\sum_{j=1}^{h} n_{kqlj}}{\sum_{j=1}^{h}\sum_{i=1}^{4} n_{kqlj}} \tag{5}$$

The inner summation in the denominator of Eq. (5) is over the four different gear types. n_{kqlj} represents the number of fish in length class l captured in set j of gear type k with capture mode q.

The functional description $CPkq\ (l,\boldsymbol{v})$ for $CPkq_l$ is obtained by minimizing the following expression:

$$-\sum_{j=1}^{h}\sum_{l}\left\{n_{kqlj}\times ln\left[CPkq(l,\boldsymbol{v})\right]+\left[-n_{kqlj}+\sum_{i=1}^{4}n_{iqlj}\right]\times ln[1.0-CPkq(l,\boldsymbol{v})]\right\} \tag{6}$$

The model applied for $CPkq\ (l,\boldsymbol{v})$ is similar in structure and estimation to that applied for $CPq\ (l,\boldsymbol{v})$ (Section 2.3) except from being based on minimizing (6) instead of (2).

If one of the gears for some sizes of cod catches more than the average for the four gears, then $CPkq\ (l,\boldsymbol{v})$ would be significantly larger than 0.25. In contrast, a $CPkq\ (l,\boldsymbol{v})$ value significantly lower than 0.25 would show that the specific gillnet type captures significantly less cod compared the other gillnets on average regarding capture with mode q.

3. Results

3.1. Catch efficiency of biodegradable versus nylon gillnets

In total, 899 cod were captured and included in the analysis of this study, with 355 and 544 cod captured in biodegradable and nylon gillnets, respectively (Table 1). The fit statistics of the catch comparison analysis showed that the deviation between the experimental data and the modelled data fitted well when new gillnet sets were compared ($p > 0.05$) (Wileman et al., 1996). For used sets of gillnets, the p-value was smaller than 0.05 (p-value = 0.0436) (Table 1). However, the catch comparison curve represented the trends in experimental data well (Fig. 2), therefore, the low p-value was assumed to be due to overdispersion in the data.

Table 1
Fit statistics, catch comparison results, and number of cod observed. Results for nylon and biodegradable gillnets (comparisons between new (left column) and used (right column) sets of gillnets). Values in parentheses represent 95% CIs.

	New gillnet sets	Used gillnet sets
p-value	0.2349	0.0436
Deviance	48.25	55.29
DOF	42	39
$CR_{average}$	74.53 (54.40–89.91)	56.11 (44.19–71.43)
Number in biodegradable nets	199	156
Number in nylon nets	267	277

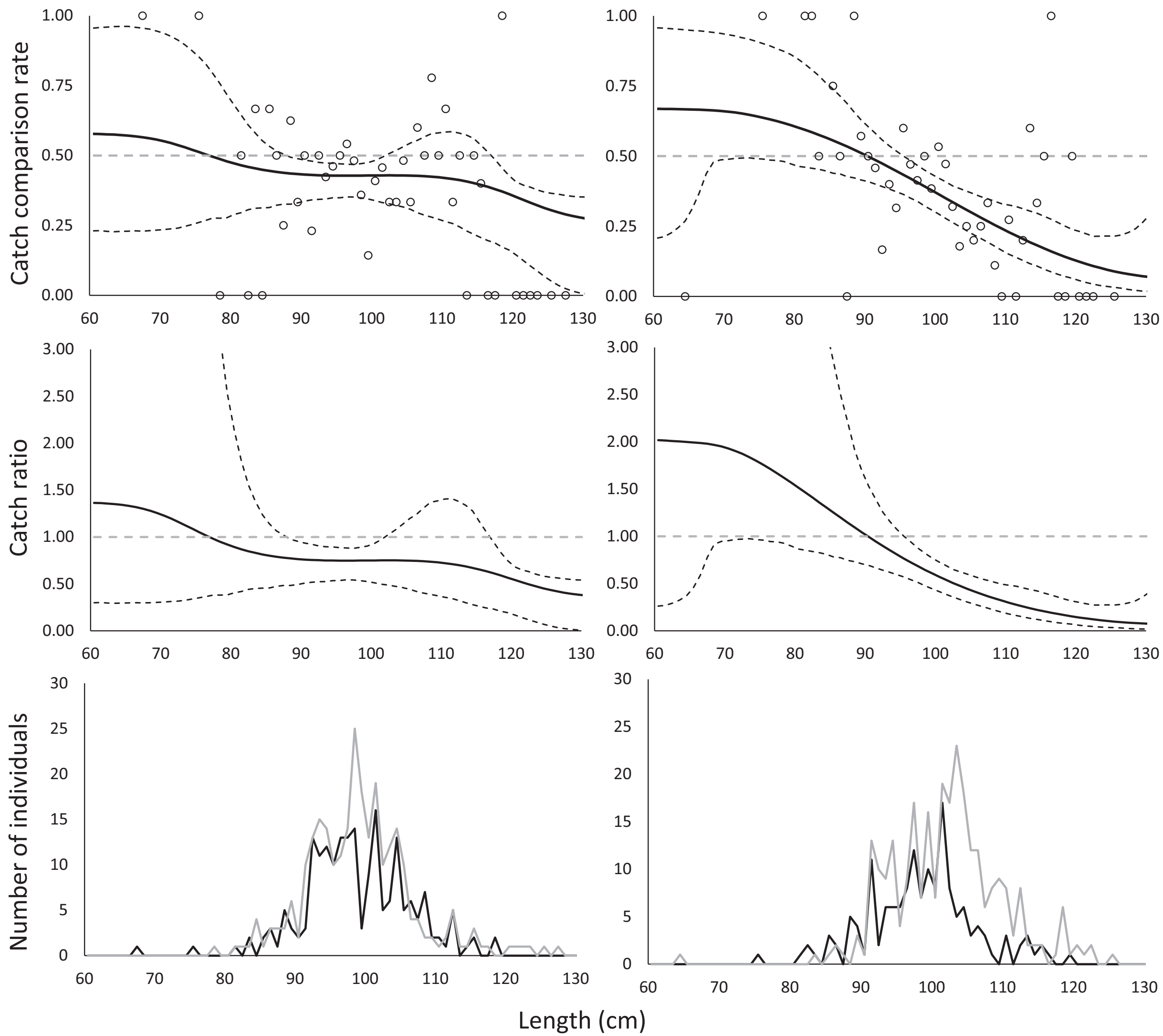

Fig. 2. Catch comparison and catch ratio analysis for biodegradable against nylon gillnets in fishery targeting cod. Left: new biodegradable gillnets versus new nylon gillnets. Right: used biodegradable gillnets versus used nylon gillnets. Upper graph: the modelled catch comparison rate based on all deployments (black curve) with 95% CIs (black stippled curves). Circles represent the experimental catch comparison rate. Middle: the estimated catch ratio curve based on all deployments (black curve) with 95% CIs (black stippled curves). Bottom: the length frequency distribution of cod captured by the biodegradable nets (black line) and nylon nets (grey line). The grey stippled lines at 0.5 and 1.0 represent the baseline at which both types of gillnets fish equally.

Table 2
Fit statistics, catch comparison results, and number of cod observed. Results for used and new biodegradable gillnets (left column) and used and new nylon gillnets (right column).

	Biodegradable gillnets	Nylon gillnets
p-value	0.0223	0.2108
Deviance	52.50	49.07
DOF	34	42
$CR_{average}$	78.39 (61.86–125.00)	103.74 (80.31–159.289)
Number in used nets	156	277
Number in new nets	199	267

Both types of gillnets had a similar tendency of capturing cod between 80 and 125 cm total length. However, for both new and especially for used nets, the biodegradable gillnets had a much clearer length-dependent catch efficiency compared to the nylon gillnets, as they retained significantly fewer cod of larger length classes (Fig. 2). The catch efficiency for fish ≥95 cm was significantly lower in the used biodegradable gillnets compared to the used nylon gillnets, and the efficiency continued to decrease with increasing fish length. This trend was less pronounced when new nets were used. The $CR_{average}$ was 75% (CI: 54.40–89.91) for the comparison between new nylon and biodegradable gillnets and it was further reduced to 56% (CI: 44.19–74.43) for the comparison between used biodegradable and nylon nets (Table 1). Therefore, $CR_{average}$ shows a significant tendency for the biodegradable gillnets to catch fewer cod over time compared to the nylon gillnets.

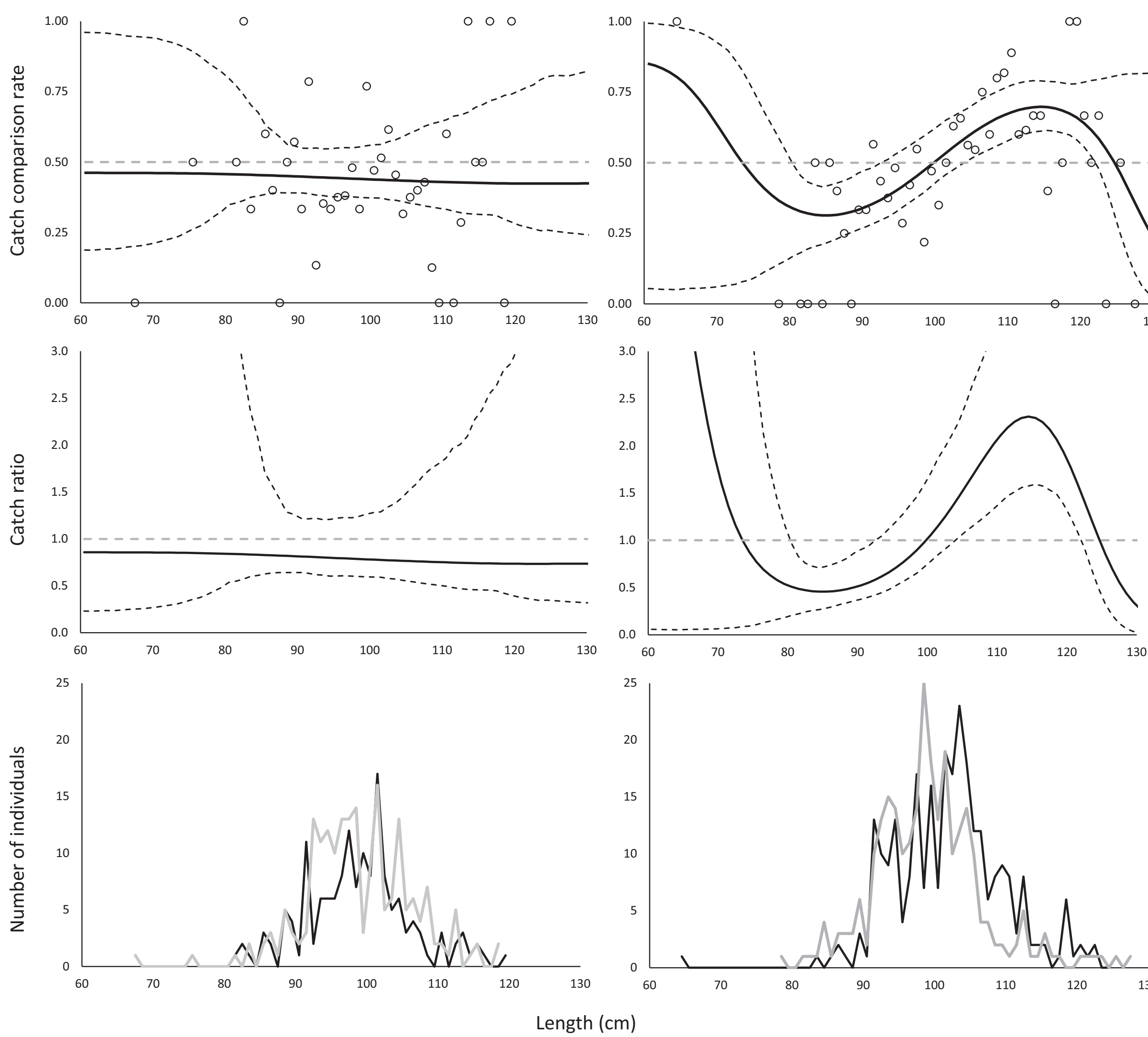

Fig. 3. Catch comparison and catch ratio analysis for used against new gillnets in fishery targeting cod. Left: used biodegradable gillnets versus new biodegradable gillnets. Right: used nylon gillnets versus new nylon gillnets. Upper graph: The modelled catch comparison rate based on all deployments (black curve) with 95% CIs (black stippled curves). Circles represent the experimental catch comparison rate. Middle: the estimated catch ratio curve based on all deployments (black curve) with 95% CIs (black stippled curves). Bottom: the length frequency distribution of cod captured by the used gillnets (black line) and new gillnets (grey line). The grey stippled lines at 0.5 and 1.0 represent the baseline at which both types of gillnets fish equally.

Table 3
Number of cod observed for each capture mode.

Capture mode	New biodegradable	New nylon	Used biodegradable	Used nylon	Total
Tip	36	44	33	59	172
Gills	69	104	83	127	383
Body	74	84	37	84	279
Entangled	20	35	3	7	65
Total	199	267	156	277	899

3.2. Catch efficiency of new versus used gillnets

The comparison of catch efficiency between the two biodegradable and between the two nylon gillnet sets allowed us to estimate the effect of wear on each of the materials. The fit statistics of the catch comparison analysis between new and used nylon gillnets showed that the deviation between the experimental data and the modelled data fitted well ($p > 0.05$) (Table 2). The p-value was 0.0223 (i.e., < 0.05) for the comparison between new and used biodegradable gillnets, so we assessed the deviance and the DOF to determine whether the result was due to structural problems when modelling the experimental data or to overdispersion in the data (Wileman et al., 1996). No clear patterns in deviations between the experimental rate and modelled rate were observed; therefore, we considered the low p-value to be due to overdispersion in the data.

For biodegradable gillnets, the results indicated a reduction in catch efficiency in used compared to new gillnets.

Compared to new nylon nets, used nylon nets showed a significant reduction in capture of smaller cod between 80 and 95 cm length but a significant increase in captured cod between 105 and 125 cm length (Fig. 3) compared to the new nylon gillnets. In total, the $CR_{average}$ for nylon gillnets showed an equal catch efficiency ($CR_{average} = 103.74$ (CI: 80.31–159.29)).

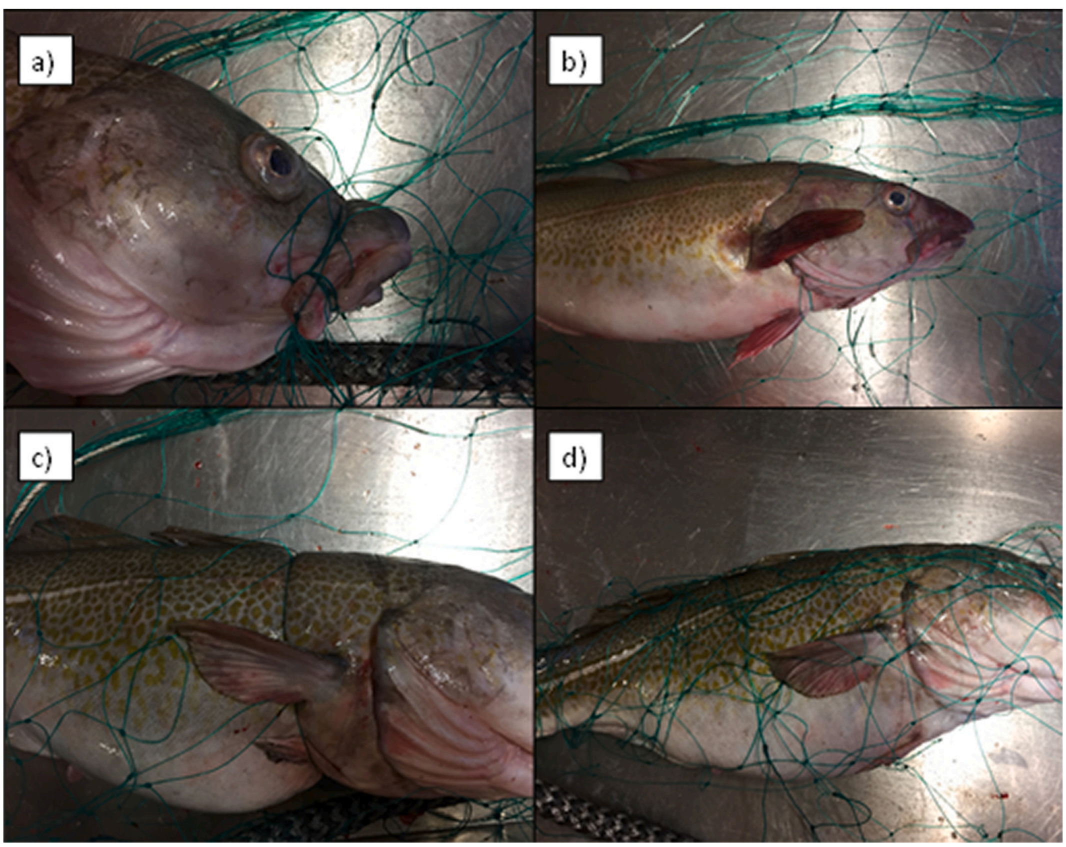

Fig. 4. Examples of capture modes observed. a) Capture by tip (mouth and maxillary); b) gills; c) largest part of the body; d) entangled.

Table 4
Fit statistics for length-dependent capture mode probability: p-value, deviance, degrees of freedom (DOF).

	p-Value				Deviance				DOF			
Capture mode	New biodegradable	New nylon	Used biodegradable	Used nylon	New biodegradable	New nylon	Used biodegradable	Used nylon	New biodegradable	New nylon	Used biodegradable	Used nylon
Tip	0.0856	0.7309	0.1937	0.5151	41.08	32.27	36.45	33.03	30	38	30	34
Gills	0.2758	0.0759	0.2086	0.1025	34.13	51.11	35.98	44.77	30	38	30	34
Body	0.6228	0.9652	0.2533	0.3309	27.01	23.79	34.71	37.03	30	38	30	34
Entangled	0.6228	0.5013	0.9939	0.9723	27.01	37.31	14.12	20.06	30	38	30	34

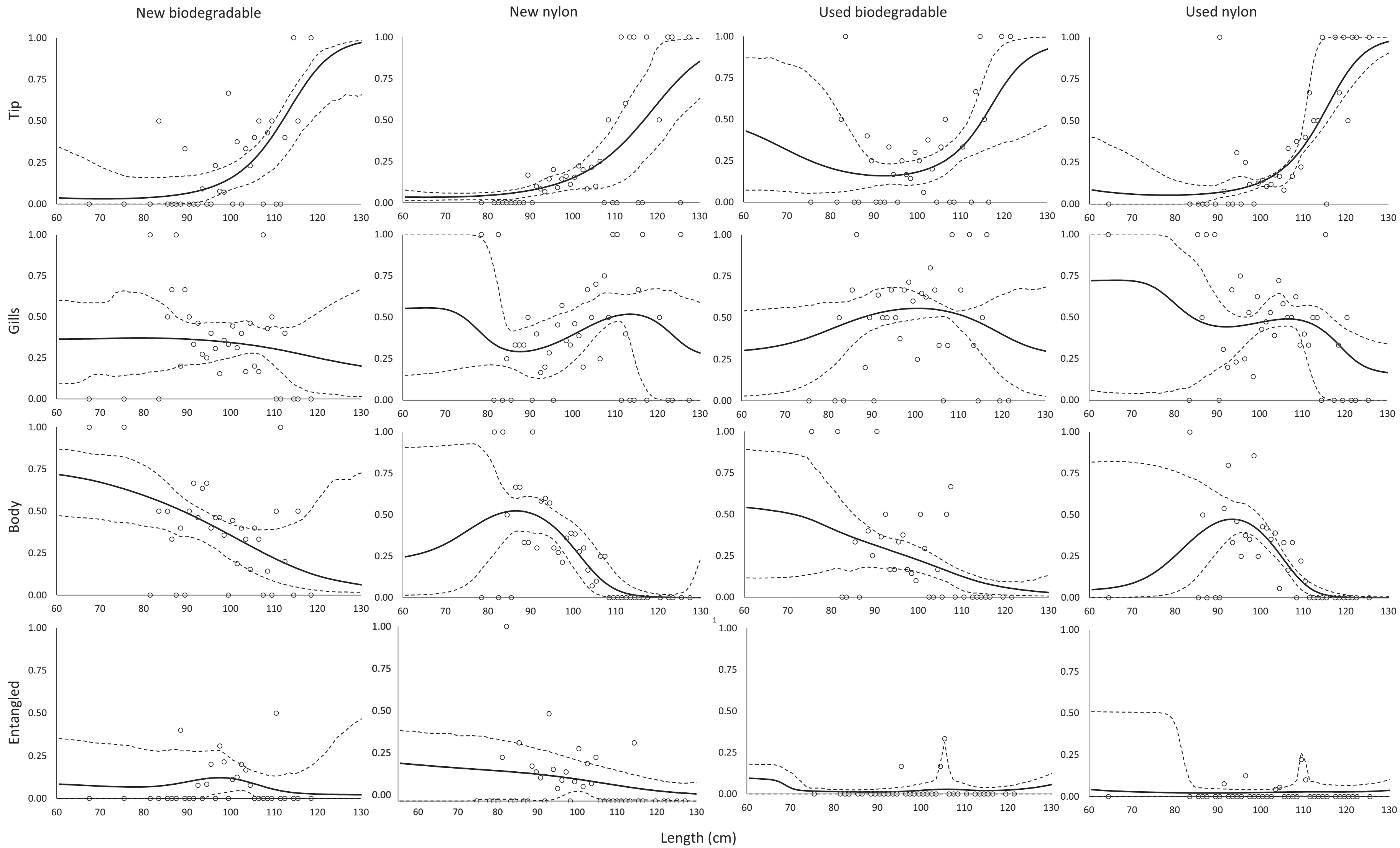

Fig. 5. Probability for capture modes in gillnets (from left to right: new biodegradable, new nylon, used biodegradable and used nylon gillnets). The solid line represents the modelled capture mode probability as bias-corrected mean with Efron percentile bootstrap 95% confidence intervals (stippled lines) fitted to the experimental rate (circle marks).

Table 5
Length-integrated average value for the capture mode probability as bias-corrected means with 95% CIs.

	$CPq_{average}$ (%)			
Capture mode	New biodegradable	New nylon	Used biodegradable	Used nylon
Tip	18.09 (09.55–25.35)	16.60 (08.77–23.58)	21.02 (16.45–25.69)	21.15 (19.81–22.97)
Gills	34.17 (25.41–43.04)	38.49 (25.47–50.75)	53.50 (48.17–60.67)	46.24 (39.08–51.29)
Body	37.19 (25.40–44.37)	31.70 (24.00–40.91)	23.57 (16.00–28.92)	30.11 (26.35–35.35)
Entangled	10.05 (04.00–22.22)	13.21 (03.22–25.95)	01.91 (00.00–04.84)	02.51 (00.76–04.47)

3.3. Length-dependent capture mode probability by gillnet type

The mode of all captured cod was recorded, resulting in 899 capture mode measurements for new and used nylon and biodegradable gillnets distributed over the four modes of fish capture (Table 3; Fig. 4). In most instances, we were able to determine a single mode of capture. For less than 5% of cases (43 cod), we observed more than a single mode of capture. In those cases, a primary mode of capture was determined based on the principle of likely sequence (Savina et al., 2021). Multiple modes of capture were associated mostly with fish being captured by the gills and largest part of the body (33 fish) or tip (mouth or maxillary) and gills (10 fish).

The capture mode probability curves and fit statistics results showed that the model described the experimental data points well. For both biodegradable and nylon gillnets for all four modes of capture, the *p*-value was >0.05 (Table 4; Fig. 5).

In all nets, the main probability of capture of cod was by the gills or the largest part of the body. However, the main probability of capture for the largest fish (> 110 cm total length) was by the tip (mouth or maxillary) (Fig. 5 and Supplementary material 1), whereas individuals under this size were captured by the gills or the largest part of the body. Very few individuals were captured by becoming entangled.

The length-integrated average value for the capture mode probability confirmed that the dominant mode of capture was by the gills in all nets except new biodegradable gillnets (Table 5). The capture mode probability of being caught by the gills was 54% (CI: 48.15–60.67) for used biodegradable nets, 38% (CI: 25.47–50.75) for new nylon nets, and 46% (CI: 39.08–51.29) for used nylon nets (Table 5). For new biodegradable gillnets, the dominant mode of capture was shared between the gills and the largest part of the body ($CPq_{average}$ = 37.19% (25.40–44.37) since this probability did not differ significantly from that of capture by the gills because of the overlapping CIs. This was not the case for used biodegradable gillnets, as the main capture mode (gills) in those nets contained a significantly greater number of cod compared to the body capture mode in the new biodegradable nets (Table 5). The capture by the largest part of the body showed a similar contribution as by the gills in the nylon gillnets as shown by the overlapping confidence intervals (Table 5).

3.4. Probability of being captured in specific gillnets conditioned capture by specific mode

We evaluated capture probability by gillnet type (new or used biodegradable or nylon gillnets, respectively) and examined conditioned capture by a specific mode (tip, gills, body, or entangled) to determine in which fishing gear type the fish had the greatest length-dependent probability of being captured (Table 6). The fit statistics showed that the model described the experimental data points well in all cases except for two. However, for those cases we assumed that the discrepancy was caused by overdispersion in the experimental data.

For the main modes of capture (i.e., gills and body), new nylon gillnets had the greatest probability of retaining fish compared with the other types of gillnets (i.e., 29% (CI: 23.77–33.17) for gills and 31% (CI: 20.94–38.43) for body). Used nylon gillnets had the next highest probability, but the differences were not statistically significant (Table 7).

The probability of capture by the gills for nylon nets was significantly higher than that of used or new biodegradable gillnets. The probability of capture by the largest part of the body in used biodegradable gillnets was significantly lower than that of the other gillnet types, with length-integrated average probability of 13% (CI: 10.41–16.27). Overall, the used biodegradable nets had the lowest length-integrated average probability of capturing fish by all four modes of capture (Fig. 6 and Supplementary material 2). Because only a few individuals were entangled in the nets, it was not possible to draw conclusions about this mode of capture (Fig. 6).

Table 6
Fit statistics for length-dependent probability analysis of being captured in a particular gillnet type conditioned capture by a specific capture mode (tip, gills, body, or entangled). *p*-value, deviance, degrees of freedom (DOF).

	p-value				Deviance				DOF			
Gillnet type	Tip	Gills	Body	Entangled	Tip	Gills	Body	Entangled	Tip	Gills	Body	Entangled
New biodegradable	0.7520	0.0589	0.1772	0.3015	29.93	46.57	34.75	12.88	36	33	28	11
New nylon	0.6478	0.1041	0.5512	0.6422	32.25	43.52	26.40	08.78	36	33	28	11
Used biodegradable	0.1497	0.1699	0.1075	0.4674	44.78	40.62	37.53	10.72	36	33	28	11
Used nylon	0.5659	0.0422	0.1597	0.0444	33.96	40.89	35.36	20.07	36	27	28	11

Table 7
Length-integrated average value for the probability of being captured in a particular gillnet conditioned capture by specific mode (tip, gills, body, or entangled). Data are bias-corrected means with 95% CIs.

	$CPq_{average}$ (%)			
Gillnet type	Tip	Gills	Body	Entangled
New biodegradable	22.11 (15.93–25.13)	18.14 (11.86–21.19)	27.75 (18.55–32.51)	40.00 (23.12–52.99)
New nylon	29.15 (23.88–32.02)	29.30 (23.77–33.17)	30.61 (20.94–38.43)	20.00 (05.58–33.36)
Used biodegradable	17.59 (12.76–23.70)	20.23 (16.56–24.55)	13.47 (10.41–16.27)	12.00 (00.20–35.92)
Used nylon	31.16 (26.67–39.86)	28.16 (22.76–41.34)	28.16 (23.15–40.94)	28.00 (10.44–45.74)

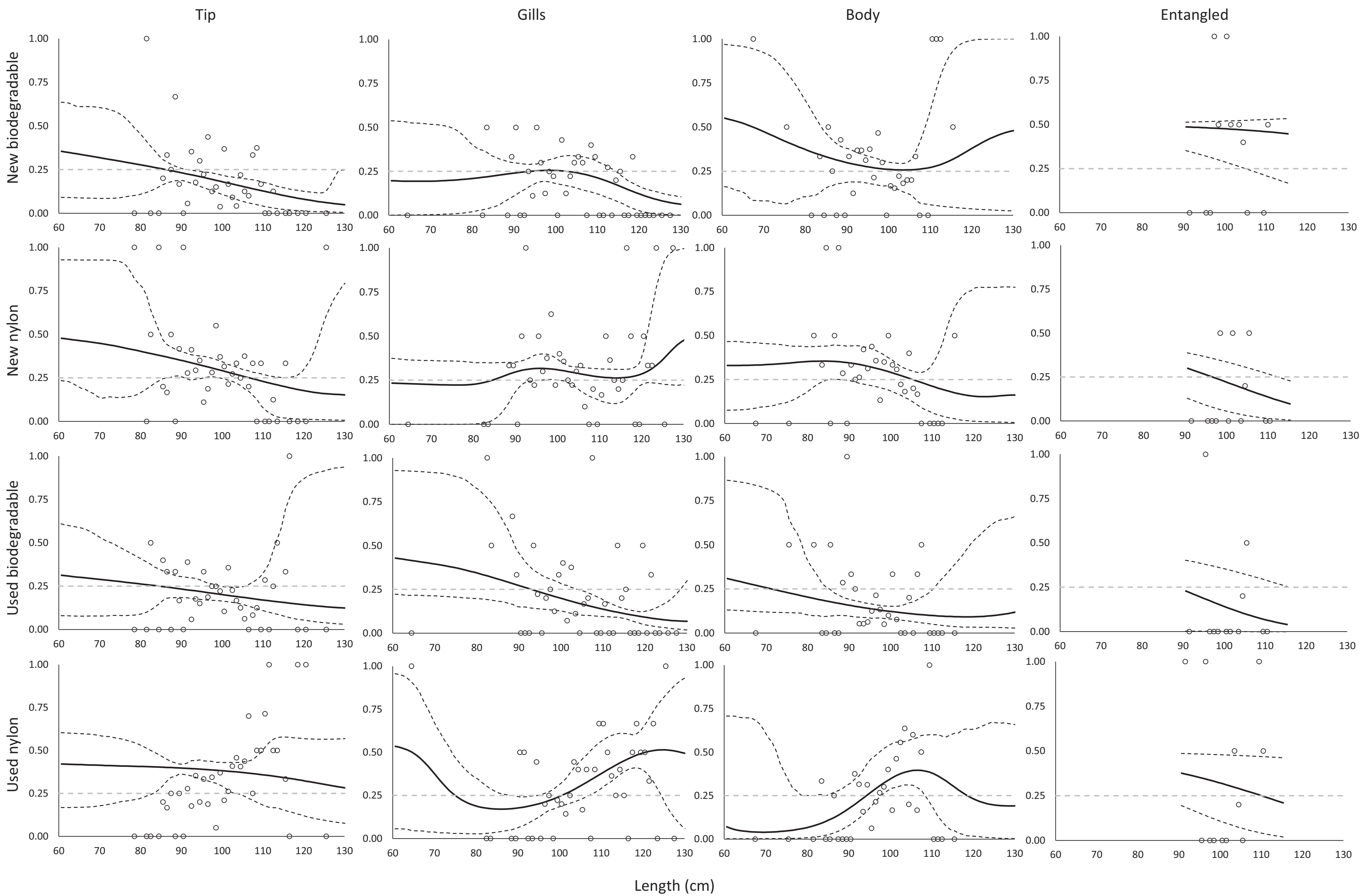

Fig. 6. Probability of capture in a particular gillnet type by a specific capture mode (from left to right: tip, gills, body or entangled). The solid line represents the modelled capture probability as bias-corrected means with Efron percentile bootstrap 95% confidence intervals (stippled lines) fitted to the experimental rate (circle marks). The horizontal grey line represents baseline for no difference in capture efficiency over the gears.

4. Discussion

The results of this study confirmed those demonstrated in earlier trials regarding lower catch efficiency of gillnets made of biodegradable material compared to those made of nylon (Grimaldo et al., 2018, 2019, 2020). We found that on average, new biodegradable gillnets caught 25% fewer cod compared to new nylon gillnets. Similarly, loss of catch efficiency of the biodegradable gillnets after repeated use was indicated, although the difference was not statistically significant: used biodegradable gillnets on average caught 22% fewer cod than used nylon gillnets ($CR_{average}$ = 78.39 (CI: 61.86–125.00)).

The observed difference in catch efficiency between biodegradable and nylon gillnets may be due to differences in breaking strength and elasticity affecting when the netting breaks at the point of tension due to the presence of fish caught by the gills or body. Indeed, capture by gills was the most common way of cod being caught in gillnets, but the probability of being retained in biodegradable gillnets for cod captured by the gills was lower compared to that of nylon nets. Since larger fish are more likely to be caught by the gills than the body, this would explain the reduced catch efficiency of larger fish in the biodegradable nets reported by Grimaldo et al. (2019) and observed also in this study.

In this study, we found that the catch efficiency was reduced for used versus new biodegradable nets for cod of the largest length classes (approximately >95 cm length). Grimaldo et al. (2019, 2020) previously documented loss of catch efficiency of biodegradable compared to nylon gillnets. The main mode of capture for new biodegradable gillnets was by the gills, whereas fish caught in used biodegradable nets were mostly captured by the largest part of the body.

Since larger fish are more likely to be caught by the gills than the body, the results of this study helped explaining the reduced catch efficiency of biodegradable gillnets in relation to particular modes of capture where the gillnets lose the capture efficiency for specific capture modes. This loss may be due to changes in different mechanical properties of the netting. Specifically, reduction in elasticity of the material and reduction in the breaking strength can affect the material when the netting is used (Grimaldo et al., 2020). Used nylon nets caught significantly less smaller cod and more larger cod compared to new nylon nets, which we could relate to a higher tendency for capture of large fish by the tip in used compared to new nylon nets, and a higher tendency for entanglement of small fish in new compared to used nylon nets.

Effect of properties such as breaking strength and elasticity require further studies in order to improve the performance (i.e., catch efficiency) of the biodegradable material used in gillnets. Biodegradable gillnets should preferably have catch efficiency similar to that of nylon gillnets in order to be accepted by the industry. Currently, the use of biodegradable material in gillnets is optional in Norway, and it has not been adopted by the commercial fishery because of its lower catch efficiency and higher production costs (Standal et al., 2020).

The results of this study showed that differences in catch efficiency between gillnet types were related to specific capture modes of fish, which in turn may be related to specific differences in material properties. We are the first to use capture mode probability to explain the differences in catch efficiency between biodegradable and nylon gillnets. The differences we observed may be related to different properties of the material. Therefore, systematic studies of the mechanical properties of the biodegradable material and how these properties change with changing mesh size and twine diameter are needed to improve the catch efficiency of future biodegradable gillnets. More catch efficient biodegradable gillnets will gradually lead to the replacement of nylon gillnets and to the reduction of marine plastic pollution and ghost fishing as biodegradable gillnets, compared to nylon, are degraded into substances that do not have any negative effect on the marine environment such as carbon dioxide, methane and water (Kim et al., 2014a, 2014b).

In our study, the modes of capture might depend on the specific gillnet design tested and, specifically, on factors such as hanging ratio, mesh size, monofilament diameters, and material type. However, the use of capture modes can provide valuable information to explain the catch efficiency for any given hanging ratio, thus this method can be further applied in studies of different gillnet characteristics in order to improve catch efficiency of biodegradable gillnets.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2022.113618.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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CRediT authorship contribution statement

Kristine Cerbule: Conceptualization, investigation, formal analysis, visualization, writing – original draft, writing – review and editing.

Bent Herrmann: Conceptualization, software, writing – original draft, writing – review and editing, supervision.

Eduardo Grimaldo: Conceptualization, writing – original draft, supervision.

Roger Larsen: Conceptualization, writing – original draft, supervision.

Esther Savina: Writing – original draft, supervision.

Jørgen Vollstad: Data gathering and investigation.

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Article III

(manuscript presented in a type-set format)

Weaker tensile properties of biodegradable gillnets reduces catch efficiency much faster than biodegradation

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Abstract

Biodegradable gillnets aim at reducing marine plastic pollution and ghost fishing, but they have shown reduced catch efficiency compared to nylon, challenging their commercial adaptation. This study aimed at discriminating between the effects of manufacturing, physical strain due to gear operation, and biodegradation on tensile properties, capture modes and catch efficiency of biodegradable (PBSAT) and nylon gillnets for roundfish, Atlantic cod (*Gadus morhua*), and flatfish, European plaice (*Pleuronectes platessa*) in the Danish coastal gillnet fishery. The PBSAT gillnet meshes were much weaker than nylon already when new (min-max load and stiffness at break of 49.7-64.5 and 189.6-212.4 N for PBSAT compared to 70.5-79.5 and 298.8-406.3 N for nylon). Differences in mechanical properties already with the new PBSAT material resulted in faster wear and degradation directly affecting catch efficiency, resulting in 32% (CI: 17-49%) less plaice and 57.50% (CI: 37.93-79.49%) less cod captured in the PBSAT gillnets.

Keywords: ALDFG, Biodegradable, Capture mode, Material stiffness, Tensile strength, Material wear

1. Introduction

Gillnets are used throughout the world to target different fish species by capturing individuals swimming without noticing into the gear which is deployed at sea as a wall of netting (He, 2006; He et al., 2021). Gillnets are usually made of decay-resistant polyamide material (PA6, also known as nylon) which has replaced traditional degradable materials like cotton or hemp due to its high elasticity and tensile strength (Matsushita et al., 2008; Brakstad et al., 2022). However, the potential for nylon to persist in the marine environment for many years when gillnets are lost, abandoned, or otherwise discarded challenges the sustainability of gillnet fisheries due to potential prolonged unintended capture of marine animals (ghost fishing) and macro- and micro-plastic pollution (Suuronen et al., 2012; Brakstad et al., 2022). Since biodegradable netting degrades faster than nylon by naturally occurring microorganisms if exposed to the marine environment for prolonged periods, it could fundamentally change the green profile of gillnet fisheries (Tokiwa et al., 2009; Kim et al., 2016; Brakstad et al., 2022). To be applied in gillnet fisheries without compromising the profitability of the commercial fishing operations, the biodegradable fishing gear must, however, show a comparable performance during fishing to that of the nylon material.

Biodegradable polyesters (PLA, PBS, PBAT, PBSAT) are promising candidates for replacing nylon in gillnets (Seonghun et al., 2020; Yu et al., 2023). Polybutylene succinate-co-adipate-co-terephthalate (PBSAT, patent EP3214133 A1) (Kim et al., 2017) has shown to be a viable alternative in some tropical gillnet fisheries (Park et al., 2010; An et al., 2013; Kim et al., 2016; Seonghun et al., 2020), and does not seem to affect species composition in gillnet catches in European waters (Cerbule et al., 2022a). However, the experiments conducted for Atlantic cod (*Gadus morhua*), one of the main target species in European waters, showed lower catch efficiency at commercial sizes compared to nylon nets (Grimaldo et al., 2018a, 2019, 2020a, 2020b; Cerbule et al., 2022b).

Such differences in catch efficiency observed between PBSAT and nylon gillnets can be explained by distinctive change in mechanical properties as the result of (1) differences in the manufacturing process, (2) physical strain during the fishing operation and weathering during storage of the nets, and (3) biodegradation (Dahm et al., 1989; Grimaldo et al., 2020a). Bioplastics are more sensitive to moisture content, which cause problems during the extrusion process (Sikora and Majewski, 2021). When manufacturing a gillnet panel from monofilament twines, the lower melting point of the PBSAT limits the temperature used for heat-treating the knots. Since higher heat treatment temperatures result in smaller pore size inside the knot and, therefore, higher binding strength, newly manufactured PBSAT gillnets already present weaker knots. The later are more likely to break when caught individuals push through the meshes, enabling easier escape and, therefore, reduced catch efficiency (i.e., Grimaldo et al., 2020a; Kim et al., 2020). Numerous environmental factors contribute to weathering and degradation of gillnets, resulting in reduced catch efficiency, such as exposure to UV radiation and waves, in addition to biodegradation (Grimaldo et al., 2020a). Previous ageing studies in controlled conditions (laboratory) showed that PBSAT degrades faster than nylon (Kim et al., 2016; Grimaldo et al., 2020a). PBSAT was considerably degraded after 2 years (Ø 0.30mm) (Kim et al., 2016), but both, PBSAT (Ø 0.75mm) and nylon (Ø 0.70mm), began to degrade after just 8 days (Grimaldo et al., 2020a). Whether such degradation would have occurred in the marine environment or within the time needed for microbial activity to degrade the material is difficult to assess. The finding that sterilized sea water resulted in less physical deterioration of the PBSAT gillnets supports the assumption that biofilms accumulating on the gillnet filaments may be associated with surface biodegradation, but there is to date no known bacteria reported to degrade polymers in the PBSAT biofilms (Brakstad et al., 2022). Bacterial and thermal degradation can happen when the nets are deployed at sea, but also when stored between fishing seasons. Physical strain was studied at the seabed (Brakstad et al., 2022), but little is known about the effect of use and wear, e.g., abrasion in the hauling machine, untangling the catch, on the physical degradation of the gillnets.

Ultimately, the changed surface characteristics (cracks and degraded areas) results in decreased elongation and breaking strength of the PBSAT, contrary to the tensile stability of the nylon due to lack of polymer degradation (Brakstad et al., 2022; Le Gué et al., 2023). It was suggested that nylon netting, a stiffer and less elastic material, may catch more fish by gilling, while PBSAT netting, a more flexible and elastic material, may fish more by snagging (Grimaldo et al., 2020b). Indeed, some modes of capture, i.e., how the fish is caught and retained by the meshes, are more effective at catching fish at a given size than others (with a given mesh size) (Hickford and Schiel, 1996; Hovgård et al., 1999; Methven and Schneider, 1998; Hovgård and Lassen, 2000; He, 2006; Grati et al., 2015; Savina et al., 2022). Recent studies showed reduced probability of capture by the gills in the PBSAT compared to the nylon nets for cod (Cerbule et al., 2022b).

The aim of this study was to discriminate between the effects of manufacturing, physical strain due to gear operation, and biodegradation on the differences in tensile properties, capture modes and catch efficiency of PBSAT and nylon gillnet materials. In addition to gear material, capture modes and catch efficiency depends on fish morphology, behaviour, and swimming ability. We, therefore, selected both, a roundfish, cod, and a flatfish, European plaice (*Pleuronectes platessa*), and collected data in one of the most important commercial gillnet fisheries in Denmark targeting these two species, the Danish coastal gillnet fishery (Ulrich and Andersen, 2004; Savina et al., 2017).

2. Material and methods

2.1. Gear design

Netting panels were custom-made by S-EnPol (Korea) according to the commercial requirements for the Danish fisheries. The biodegradable nets were made of PBSAT and the standard nets of nylon.

The nets were mounted by the gear manufacturer Hvalpsund Net (Mørenot, Denmark) for the Danish commercial plaice fishery. Each gillnet sheet had 75 mm half-mesh size (150 mm full mesh), was made of 0.40 mm monofilament twine, 15.5 meshes deep, 4000 knots long and green in color. The netting panel was mounted with a floatline no. 2 with 4 mm hanging wire and a leadline no. 3 with a 4 mm hanging wire. The netting was mounted 5 meshes on 21.5 cm on the floatline and 5 meshes on 23.5 cm on the leadline. Consequently, each mounted gillnet sheet was about 55 m long and had a hanging ratio of 30%. Inner mesh size measurements were taken for gillnet 20 meshes for each PBSAT and nylon gillnets in the dry state before the sea trials by inserting a steel ruler and using light hand force to stretch the mesh.

2.2. Data collection at sea

The initial trials with new PBSAT and nylon gillnets were conducted over 10 days in May-June 2021. The nets were used for 4 additional days in July 2021 and else stored in the fisher's storage unit at the harbour (wooden crates in a small shed) following commercial practices. The trials with used gillnets were conducted over 10 days in September 2021. During both sea trials, all nets were deployed for 20-25 hours from a commercial Danish gillnetter (vessel length 9.44 m and engine power 53 kW) on shallow sandy fishing grounds off the coast of Hirtshals (Skagerrak). A total of eight nylon and eight PBSAT nets were deployed in an alternated order with about 1 m between individual panels to form two fleets (Figure 1). The nets were joined as one long fleet for the last 4 days of the trial to facilitate handling by the commercial fisher.

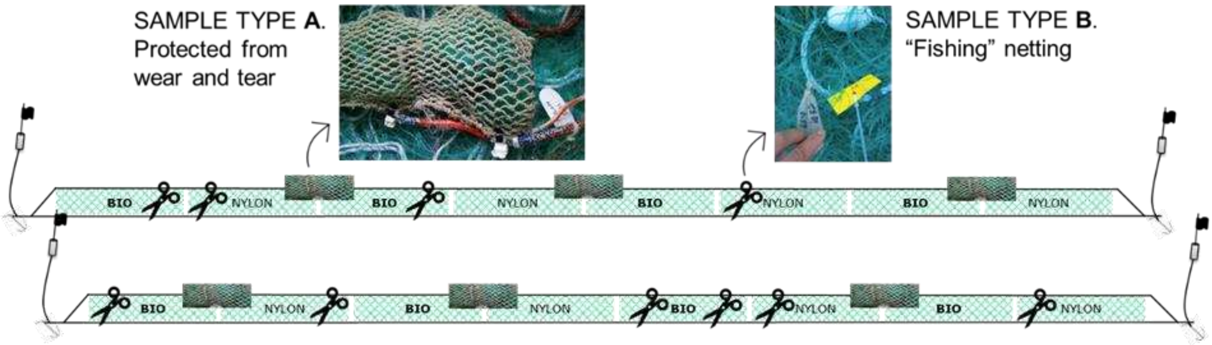

Figure 1. Gear rigging and sampling. A total of eight nylon and eight PBSAT nets were deployed in an alternated order with about 1 m between individual panels to form two fleets. Sample type A consisted of PBSAT and nylon samples put in a meshed net bag on the headline of the gillnet fleets at the beginning of the experiment so that the netting is protected from wear and tear during gear operation. Sample type B consisted of small samples of netting cut directly from the PBSAT and nylon netting panels.

Following each deployment, each fleet was hauled onboard using a net hauler (Netop, Denmark). During the hauling of each individual gillnet sheet (PBSAT or nylon), all cod and plaice were registered for their mode of capture before handling the fish. Specifically, the netting section around each fish was carefully unfolded or stretched out to identify the capture mode as the fish was still held in the netting wall. This was performed to identify the initial capture mode and avoid additional entanglement caused by deck handling. Additionally, all cod and plaice were measured for their total length to the closest cm below.

Mechanism of fish capture was classified in one of ten categories, distinct for flatfish and roundfish (Figure 2). These capture mode categories were adapted from previous work (Hovgård et al., 1999; Hovgård and Lassen, 2000; Wileman et al., 2000; Holst et al., 2002; Savina et al., 2022) and adjusted after observations during a pilot experiment onboard prior to the trials. Specifically, due to the specific morphology of the flatfish, some capture modes had not been observed in previous studies mainly focusing on roundfish species. The primary mode of capture in each instance was defined by the position and tension of the twine. The tightest meshes indicated the primary mode capturing the fish in the netting, or, alternatively, the position of the net mark, i.e., a wound on the fish's body caused by mesh chafing (Yokota et al., 2001). A fish was assigned one or several modes of capture or classified as «uncertain» if it was difficult to determine the primary mode of capture. In total, five observers participated in the two sea trials. All observers were trained for identifying the capture modes similarly, and there were always two observers onboard during the entire data collection.

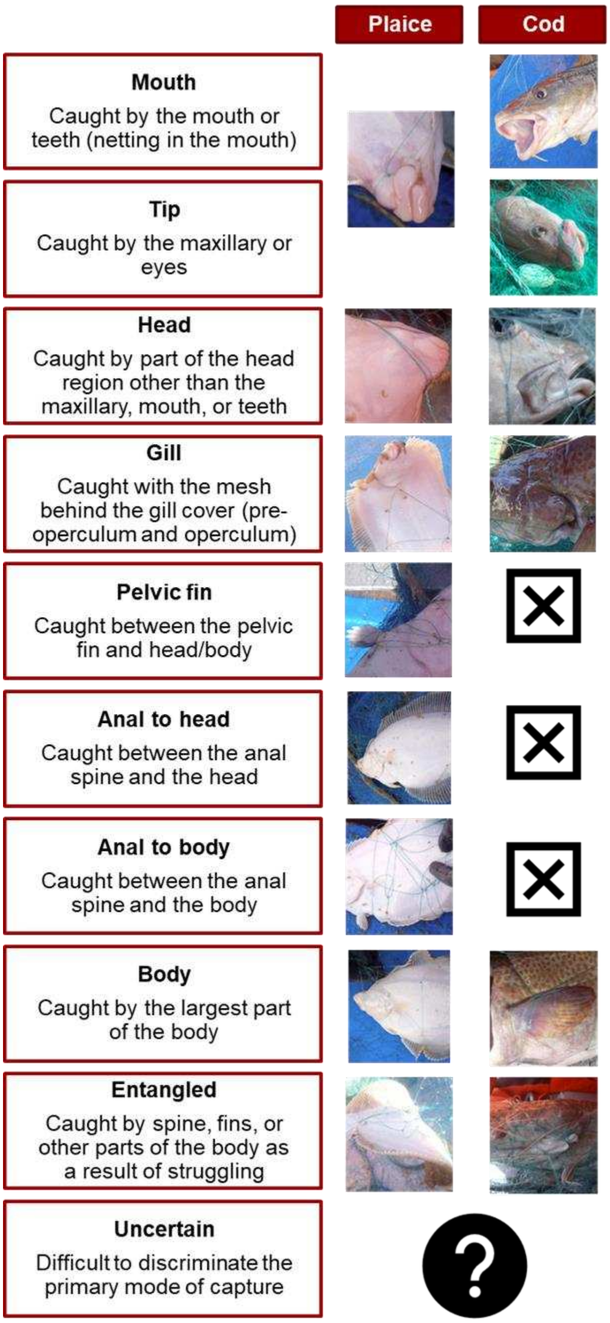

Figure 2. Categories of the capture modes used during the experiments onboard for plaice and cod.

2.3. Tensile testing

Tensile testing was performed to determine and compare the mechanical properties of PBSAT and nylon netting. We tested the monofilament in a mesh (i.e., with the knot). We tested differences between the two netting materials at several timepoints throughout the commercial fishing season: new netting at the start (T0) and end of the first sea trial (after 10 days, T10d), and used netting after 4 months at the end of the second sea trial (T4m). For each netting material, we looked at two sample types to investigate the effect from wear and tear due to fishing, i.e., tension in the netting including when hauling the net and potential damages at the bottom, or during sorting when disentangling the catch. Sample type A consisted of several small samples of netting (both PBSAT and nylon) put in a meshed net bag on the headline of the gillnet fleets at the beginning of the experiment so that the netting was protected. Sample type B consisted of small samples of netting cut directly from the netting panels (both PBSAT and nylon), i.e., the "fishing" netting (Figure 1).

Tensile properties were characterized as tensile strength and stiffness. Tensile strength is how much load the material can withstand without breaking when it is stretched. Stiffness refers to a material's ability to resist strain when subjected to an applied load. All measurements were performed in accordance with ISO 1806:2002 on determination of mesh breaking load of netting in fishing nets, using an electromechanical test machine from Instron equipped with a load cell of 1 kN capacity (Figure 3). Tensile properties of the gillnet samples were found by strength tests. Initial mesh length of gillnets was found as the mesh opening at pretension of 1 N. A displacement-controlled tensile load was applied with a rate of 120 mm/min for both PBSAT and nylon (adjusted according to the mesh size) to have the same test settings for all samples. Tensile properties were measured and found based on at least 18 replicates. Only samples where the break happened at the knot were accepted according to the principle of the ISO standard. The standard also prescribes that failure must happen within 20 ± 3 s. However, this was not possible to achieve for the different net materials, when the rate was kept the same for all samples. Therefore, failures that happened within 20 ± 5 s were considered acceptable. Tensile testing was performed in wet conditions, with samples that had been wetted for 24-72 hours at room-tempered tap water. New samples were also tested in dry conditions to consider the effect of water on tensile properties.

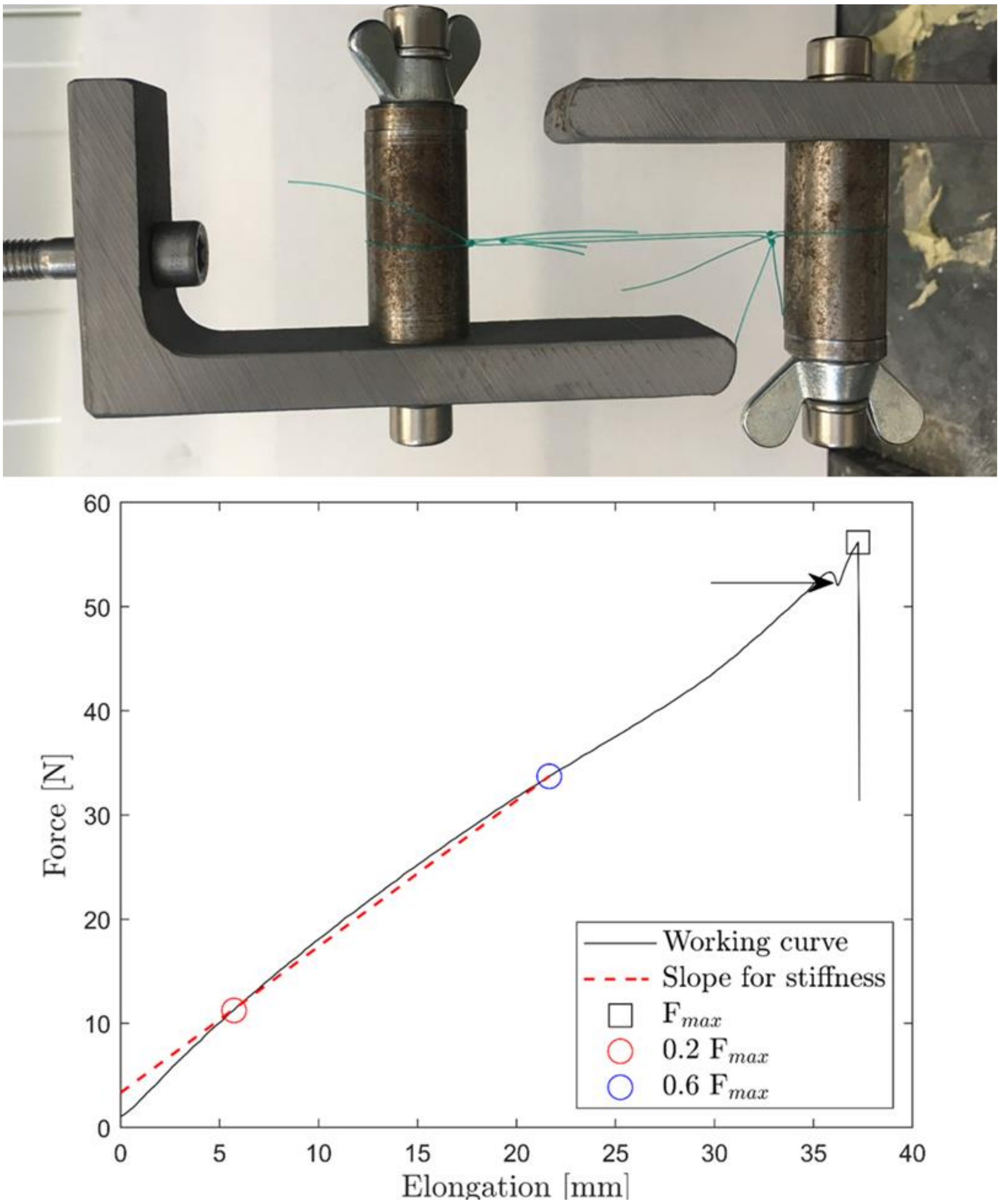

Figure 3. Top: Electromechanical test machine equipped with a load cell used to determine mesh breaking load of the netting. Down: Example of a working curve for tensile test of nets. The tensile strength (Fmax) is determined as the peak of the load-elongation curve (working curve). The corresponding elongation is taken as the elongation at break. The stiffness of the material is determined as the slope of the load-elongation curve from 0.2 x Fmax to 0.6 x Fmax. The arrow shows the slip of the monofilament in the knot, causing a loss of load, then the knot starts to tight again, so the load is increasing.

For each replicate, the tensile strength was determined as the peak of the load-elongation curve, and the corresponding elongation was taken as the elongation at break. For a set of samples, the tensile strength (Fmax) was determined as the average of all tested samples. The stiffness of the mesh was determined as the slope of the load-elongation curve from 0.2 x Fmax to 0.6 x Fmax. An explanation of the calculated properties is shown as an example in Figure 3. The small jump towards the end of the elongation curve indicates that the monofilament slips in the knot, causing a loss of load (Figure 3). It is then observed that the knot starts to tight again (increasing load).

For test of significance difference in material properties, we used difference (delta) in mean results with 95% percentile confidence interval based on bootstrapping (1000 repetitions). There is significant difference if delta does not contain 0.00 within the confidence interval (Efron, 1982; Herrmann et al., 2018).

2.4. Capture mode probability

2.4.1. Assumed primary capture mode

During the data collection, in some instances a fish was registered with several capture modes. In case multiple capture modes were observed for one individual, we assumed a primary capture mode according to the following principles (Savina et al., 2022). In general, we defined the primary mode based on the principle of likely sequence. It is expected that the fish will penetrate the meshes first with the head (swimming forward). If caught further down the body, then in a second time the fish can be snagged further up towards the head. Indeed, it is unlikely that a fish would be caught by the head after being caught by the mouth, or maxillary. Therefore, we assumed that the primary capture mode for the multiple modes, for example, when the fish is registered captured by "mouth", or "maxillary", and "head" would be "head". In line with this principle, we believe that a fish cannot be caught by the gills after being caught by the mouth, maxillary, or head, and similarly cannot be caught by the body after being caught by the mouth, or head, or gills. We always assumed that entanglement happened after the initial capture, and cases with entanglement were considered with the other capture mode as primary, e.g., maxillary or head, or gills. All other multiple occurrences, i.e., not possible to decide (mouth and maxillary) or more than three possible capture modes, were treated as "Uncertain" in a conservative approach (Savina et al., 2022).

2.4.2. Modelling the length-dependent capture mode probability

We used the numbers and length measurements of fish in gillnets in each of the modes to determine, conditioned capture, the length-dependent probability for fish being caught with each of the capture modes and for each net type (Savina et al., 2022). Conditioned capture, the expected probability for capturing a fish of total length *l* in capture mode *q* will be:

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

where n_{ilj} is the number *n* of fish caught per length class *l* with capture mode *i* in deployment *j,* where all fleets from a fishing day constitute a deployment. *Q* is the number of capture modes considered. *h* is the total number of deployments. The functional description of the capture mode probability $CPq(l, \boldsymbol{v})$, experimentally expressed by Equation (1), was obtained using maximum likelihood estimation by minimizing Expression (2):

$$-\sum_{j=1}^{h}\sum_{l}\left\{n_{qlj} \times ln[CPq(l,\boldsymbol{v})] + \left(-n_{qlj} + \sum_{i=1}^{Q} n_{ilj}\right) \times ln[1.0 - CPq(l,\boldsymbol{v})]\right\} \qquad (2)$$

where $\boldsymbol{v}$ represents the parameters describing the capture mode probability curve defined by $CPq(l, \boldsymbol{v})$ that spans the value range [0.0;1.0]. $CPq(l, \boldsymbol{v})$ is modelled as (Krag et al., 2014; Herrmann et al., 2017; Savina et al., 2022):

$$CPq(l,\boldsymbol{v}) = \frac{exp[f(l,v_0,\ldots,v_k)]}{1+exp[f(l,v_0,\ldots,v_k)]} \qquad (3)$$

In Equation 3, *f* is a polynomial of order *k* with coefficients v_0-v_k, such that $\boldsymbol{v} = (v_0,\ldots,v_k)$. The values of the parameters $\boldsymbol{v}$ describing $CPq(l, \boldsymbol{v})$ are estimated by minimizing the Expression (2). We considered *f* of up to an order of 4. Leaving out 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 $CPq(l,\boldsymbol{v})$. Among these models, the mode probability was estimated using the multi-model inference to obtain a combined model (Burnham and Anderson, 2002; Herrmann et al., 2017).

We used a bootstrapping method (1000 bootstrap repetitions) to estimate the 95% percentile confidence intervals to account for uncertainty due to within- and between-deployment variation in the mode of capture (Savina et al., 2022).

2.4.3. Modelling the average (length-integrated) capture mode probability

Length-integrated average value for the capture mode probability ($CPq_{average}$) was estimated directly from the experimental catch data using the following equation:

$$CPq_{average} = \frac{\sum_l \sum_{j=1}^{h} n_{qlj}}{\sum_l \sum_{j=1}^{h} \sum_{i=1}^{Q} n_{ilj}} \quad (4)$$

where the outer summations include the size classes in the catch during the experimental fishing period. In contrast to the length-dependent evaluation of the capture mode probability curve $CPq(l, \boldsymbol{v})$, $CPq_{average}$ are specific for the population structure encountered during the experimental trials and cannot be extrapolated to other scenarios in which the size structure of the fish species may be different (Savina et al., 2022).

2.4.4. Modelling differences in capture mode probabilities

The difference ΔCPq in capture mode probabilities CPq between the PBSAT and nylon nets was estimated by:

$$\Delta CPq = CPq_{PBSAT} - CPq_{Nylon} \quad (5)$$

The 95% confidence intervals for ΔCPq were obtained based on the two bootstrap population results for CPq_{PBSAT} and CPq_{Nylon}, respectively, as described above. As they were obtained independently of each other, a new bootstrap population of results for ΔCPq was created using (Cerbule et al., 2022a):

$$\Delta CPq_i = CPq_{PBSATi} - CPq_{Nyloni} \; i \in [1 \ldots 1000] \quad (6)$$

where i denotes the bootstrap repetition index. As resampling was random and independent between the two bootstrap populations of results, it is valid to generate the bootstrap population of results for ΔCPq based on (6) using the two independently generated bootstrap files (Herrmann et al., 2018). Based on the bootstrap population of results for ΔCPq, we were able to obtain Efron percentile 95% confidence bands (Efron, 1982). If the value 0.0 was not within the obtained confidence bands, then the capture mode probability for PBSAT and nylon differed significantly.

Similar approach was applied to assess the differences in capture mode probabilities between new and used PBSAT and new and used nylon gillnets.

2.5. Catch comparison and catch ratio

To assess the relative catch performance of the PBSAT (test) against the nylon (baseline) netting, length-dependent catch comparison and catch ratio analyses (Herrmann et al., 2017) were performed separatly for cod and plaice. Count data for number of fish in the different length classes l of each species were used to estimate the size-dependent catch comparison rate $CC(l)$ with 95% Efron percentile confidence intervals (Efron, 1982). We considered all fleets from a fishing day to constitute one deployment. The experimental CC_l summed over all gillnet fleet deployments h during the entire study period is expressed by:

$$CC_l = \frac{\sum_{j=1}^{h} nPBSAT_{jl}}{\sum_{j=1}^{h}\{nPBSAT_{jl} + nNylon_{jl}\}} \qquad (7)$$

where $nPBSAT_{jl}$ and $nNylon_{jl}$ are the numbers of individuals of length class l caught by the PBSAT and nylon nets, respectively, in deployment j.

To model the length-dependent catch comparison rate $CC(l)$ averaged over hauls, we used maximum likelihood estimation by minimizing the following expression:

$$-\sum_{j=1}^{h}\sum_{l}\{nPBSAT_{jl} \times ln\big(CC(l,\boldsymbol{v})\big) + nNylon_{jl} \times ln\big(1.0 - CC(l,\boldsymbol{v})\big)\} \qquad (8)$$

where $\boldsymbol{v}$ represents the parameters describing the catch comparison rate $CC(l, \boldsymbol{v})$. We adapted a flexible model for $CC(l, \boldsymbol{v})$ often applied in catch comparison studies (Krag et al., 2014):

$$CC(l,\boldsymbol{v}) = \frac{\exp\big(f(l,v_0,\ldots,v_k)\big)}{1+\exp\big(f(l,v_0,\ldots,v_k)\big)} \qquad (9)$$

where f is a polynomial of order k with coefficients v_0 to v_k so that $\boldsymbol{v} = (v_0,\ldots, v_k)$. To enable sufficient flexibility in the model, f was considered up to an order of 4. Leaving out one or more of the parameters $v_0,\ldots,v_4$ provided 31 additional models that were considered as potential models to describe $CC(l, \boldsymbol{v})$. The selection of the final model was based on multimodel inference (Akaike, 1971; Burnham and Anderson, 2002; Herrmann et al., 2017). The ability of the combined model to describe the experimental data was based on the p-value, which is calculated based on the model deviance and degrees of freedom (Wileman et al., 1996; Herrmann et al., 2017). For the combined model to be a candidate model to describe the experimental data, the p-value should not be < 0.05 and the model deviance and the degrees of freedom should show values within the same order of magnitude unless the experimental data are overdispered (Wileman et al., 1996). We used a nested bootstrapping method (1000 bootstrap repetitions) to estimate the 95% confidence intervals for $CC(l, \boldsymbol{v})$ that accounts for uncertainty due to within- and between-deployment variation in the cath data (Lomeli et al., 2019).

To quantify the differences in catches between the PBSAT and nylon nets, we estimated the catch ratio $CR(l, \boldsymbol{v})$ from the relationship with $CC(l, \boldsymbol{v})$ (Herrmann et al., 2017):

$$CR(l, \boldsymbol{v}) = \frac{CC(l,\boldsymbol{v})}{1-CC(l,\boldsymbol{v})} \quad (10)$$

If the catch efficiency of both nets is equal, i.e., if there is no significant effect of the netting material on the catch efficiency, the $CR(l, \boldsymbol{v})$ would be 1.0. In contrast, $CR(l, \boldsymbol{v})$ = 1.25 and $CR(l, \boldsymbol{v})$ = 0.75 would mean that the PBSAT nets on average catch 25% more and 25% less individuals of length *l* than the nylon nets, respectively.

Catch comparison results are commented with reference to a Minimum Conservation Reference Size (MCRS, threshold for commercial size) of 30 cm for cod and 27 cm for plaice (MCRS in Skagerrak).

2.6. *Software*

We used the statistical software SELNET (Herrmann et al., 2012) to analyse the catch comparison and capture mode data. We used the packages dplyr (Wickham et al., 2020) for data formatting and ggplot2 (Wickham, 2016) for graphical output in R statistical software (R 2021).

3. Results

3.4. Data collected

Measurements of the mesh openings showed that the mean mesh size was 148.0 ± 1.44 mm for the PBSAT and 148.8 ± 0.36 mm for the nylon gillnets (mean ± standard deviation).

We caught a total of 443 and 1208 plaice in the new and used nets, respectively, and 900 and 63 cod in the new and used gillnets, respectively (Table 1). Due to the low abundance of cod during the fishing trials with used nets in September 2021, few observations did not allow estimations of capture mode probability. Therefore, the capture modes were observed for a total of 438 and 1201 plaice in the new and used nets, respectively, and 890 cod in the new nets. When handling the catch, we observed serious damage to the PBSAT netting, building faster over time compared to the nylon.

Table 1. Total number of fish caught in the PBSAT and nylon gillnets with mean (min-max) length in cm for each fishing day (considered as a deployment).

	Date	Number of fish				Fish length (cm)			
		Plaice		Cod		Plaice		Cod	
		PBSAT	Nylon	PBSAT	Nylon	PBSAT	Nylon	PBSAT	Nylon
New nets	2021-05-22	21	13	43	36	34 (27-49)	33 (29-39)	38 (25-75)	39 (25-69)
	2021-05-23	6	6	25	54	32 (29-34)	32 (29-36)	36 (27-46)	37 (25-51)
	2021-05-24	6	14	31	55	33 (29-38)	31 (25-35)	38 (22-44)	38 (26-56)
	2021-05-25	27	35	72	92	32 (24-40)	33 (27-41)	39 (25-64)	38 (26-67)
	2021-05-26	32	40	93	100	32 (27-45)	33 (25-44)	38 (24-56)	38 (25-48)
	2021-05-27	12	8	44	39	31 (25-38)	32 (26-35)	38 (27-56)	38 (26-66)
	2021-05-28	11	14	34	48	33 (25-37)	33 (28-42)	37 (26-57)	36 (26-46)
	2021-05-31	37	31	18	19	31 (25-36)	31 (24-36)	32 (24-43)	33 (26-46)
	2021-06-01	38	23	16	27	33 (26-48)	31 (25-40)	36 (28-43)	37 (27-48)
	2021-06-02	29	40	22	32	32 (22-48)	32 (25-42)	36 (26-50)	36 (26-48)
Used nets	2021-09-10	156	201	0	0	29 (21-42)	30 (23-40)	-	-
	2021-09-11	42	51	0	0	29 (22-38)	29 (21-39)	-	-
	2021-09-15	23	30	0	0	32 (28-37)	33 (24-39)	-	-
	2021-09-19	8	11	0	0	29 (21-32)	33 (29-39)	-	-
	2021-09-20	11	11	0	0	29 (23-37)	34 (22-40)	-	-
	2021-09-21	11	17	0	0	33 (28-49)	28 (25-31)	-	-
	2021-09-27	11	7	12	18	27 (21-35)	29 (24-37)	38 (23-58)	38 (27-69)
	2021-09-28	43	47	2	3	32 (26-44)	33 (25-44)	31 (30-31)	42 (25-59)
	2021-09-29	195	233	2	5	32 (24-44)	33 (24-48)	30 (29-31)	37 (25-61)
	2021-09-30	37	63	7	14	32 (25-43)	34 (25-46)	31 (29-36)	37 (28-50)

Table 2 presents the load, time, displacement at break and strain used to estimate the tensile strength and stiffness from the load-elongation curves presented in Supplementary material 1. We only accounted for break at the knot to follow the ISO standard, but there were many (invalid) occurences where the PBSAT broke at other points of the netting.

Table 2. Total number of samples measured (Total), load (N), time (s), displacement (mm) at break and strain (%) are given as mean (standard deviation) for PBSAT and nylon at three time points (T0 new nets, T10d after 10 days and T4m after 4 months). Sample type A consisted of samples put in a meshed net bag on the headline of the gillnet fleets so that the netting is protected from wear and tear (bag), whereas sample type B consisted of small samples of netting cut directly from the netting panels (fishing). Strain was calculated as the displacement / (2 x mesh opening) with mean mesh size of 148.0 mm for PBSAT and 148.8 mm for nylon.

Time	Type	Material	Total	Load (N)	Time (s)	Displacement (mm)	Strain (%)	Stiffness (N)
T0	Dry	PBSAT	20	61.2 (04.1)	19.9 (0.8)	45.6 (2.5)	15.4 (0.9)	194.3 (07.6)
		Nylon	20	77.9 (07.5)	17.7 (1.3)	32.6 (2.7)	26.2 (2.5)	298.8 (17.2)
	Wet	PBSAT	20	64.5 (04.3)	20.7 (0.9)	47.2 (2.9)	16.0 (1.0)	189.6 (07.2)
		Nylon	20	78.8 (06.1)	17.4 (1.1)	33.1 (2.3)	23.6 (7.0)	312.5 (16.0)
T10d	Bag	PBSAT	18	59.5 (07.8)	19.5 (1.9)	44.9 (4.5)	15.2 (1.5)	198.1 (16.3)
		Nylon	22	78.0 (07.1)	15.7 (1.1)	39.5 (2.4)	13.3 (0.8)	366.2 (16.6)
	Fishing	PBSAT	20	61.7 (08.2)	19.3 (1.8)	44.3 (3.8)	15.0 (1.3)	205.1 (10.7)
		Nylon	22	79.5 (09.7)	15.2 (1.5)	39.0 (2.9)	13.1 (1.0)	406.3 (34.4)
T4m	Bag	PBSAT	22	49.7 (07.7)	17.2 (2.2)	39.7 (4.9)	13.4 (1.6)	212.4 (14.6)
		Nylon	26	78.0 (06.1)	15.6 (1.0)	39.2 (2.4)	13.2 (0.8)	367.3 (14.6)
	Fishing	PBSAT	22	56.2 (14.5)	17.9 (4.4)	42.7 (8.8)	14.4 (3.0)	207.2 (19.4)
		Nylon	22	70.5 (16.4)	14.4 (2.7)	37.0 (5.3)	12.4 (1.8)	342.9 (37.9)

3.5. Tensile testing

Figure 4 shows typical load-strain curves obtained from the mechanical testing of dry and wet meshes made from PBSAT and nylon, with the peak of each curve being the failure. Local loss of load can be explained by the slipping of the monofilament inside the knot, which leads to an overestimation of the mesh strain. This phenomenon is more visible on the working curves for nylon yarns as they are more slippery. The slipping of the nylon knots led to an increase of the mesh strain up to 1.5% (Figure 4). Figure 4 also shows an inflection in the stiffness with mesh strain for PBSAT meshes compared to nylon meshes that have a more linear increase in the stiffness. PBSAT meshes are stiffer than nylon meshes for small strains, but stiffness decreases with increasing load, while nylon meshes have increasing stiffness (Figure 4).

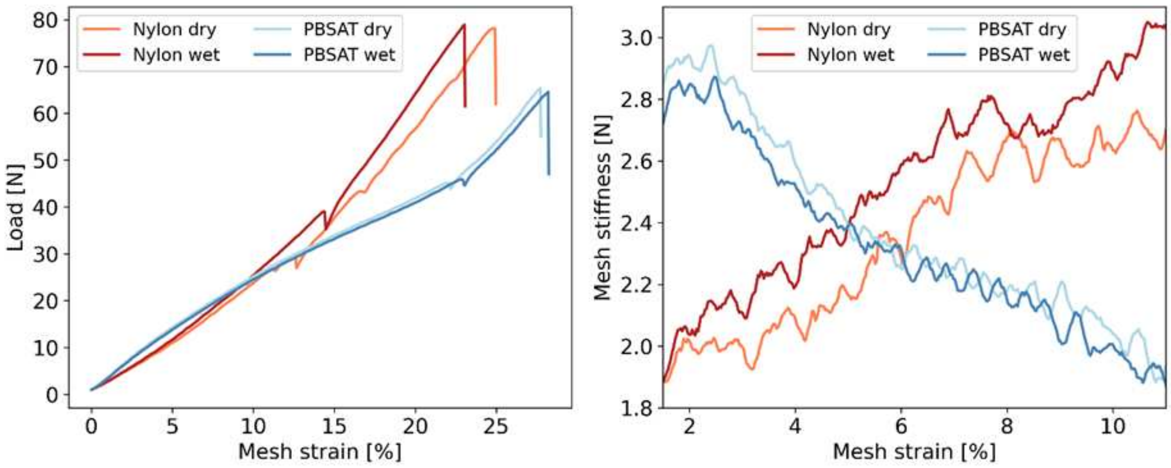

Figure 4. Load (N, left) and stiffness (N, right) as a function of mesh strain (%) obtained from the mechanical testing of meshes made from PBSAT (light blue, dark blue) and nylon (orange, red) at the start (T0) for dry and wet, respectively.

No effect of water (wet verus dry) was observed with similar loads and mesh strains at break for both PBSAT and nylon (Table 2). In all cases, both load and stiffness at break were lower for the PBSAT meshes (min-max: 49.7-64.5 and 189.6-212.4 N, respectively) compared to the nylon nets (min-max: 70.5-79.5 and 298.8-406.3 N, respectively) (Table 2).

The difference in mechanical properties between PBSAT and nylon meshes was significant already for the new netting (T0), with smaller differences for sample type B (fishing) compared to sample type A (bag) (Table 5, Figure 5). The wear and tear effect was only observed to be significant for nylon meshes after 4 months (Table 5, Figure 5). Except for stiffness in sample type A (bag) at T0, all PBSAT meshes showed a significant loss of mechanical properties with time from the beginning (T10d compared to T0 and T4m compared to T10d) (Table 5). There was no significant difference in load at break for nylon meshes between T0 and T10d and between T10d and T4m - other properties (strain, stiffness) were significantly different (Table 5).

Table 5. Fit statistics and results of the comparison in material properties between PBSAT and nylon as bias-corrected mean with Efron percentile bootstrap 95% confidence limits at three time points (T0 new nets, T10d after 10 days and T4m after 4 months). Sample type A consisted of samples put in a meshed net bag on the headline of the gillnet fleets so that the netting is protected from wear and tear (bag), whereas sample type B consisted of small samples of netting cut directly from the netting panels (fishing). Significant differences are highlighted in bold.

Time	Type	Material	F max [N]	Strain max %	Stiffness [N]
			PBSAT – Nylon		
T0	Wet	-	**-14.18 (-17.34; -10.94)**	**4.2 (3.5; 5.1)**	**-122.91 (-130.55; -115.81)**
T10d	Bag	-	**-18.58 (-23.09; -13.82)**	**4.9 (3.7; 6.3)**	**-168.08 (-178.29; -158.97)**
T10d	Fishing	-	**-17.78 (-23.24; -12.10)**	**5.5 (4.1; 6.8)**	**-201.22 (-217.52; -187.11)**
T4m	Bag	-	**-28.31 (-32.19; -24.29)**	**1.9 (0.7; 3.3)**	**-154.92 (-163.00; -147.15)**
T4m	Fishing	-	**-14.34 (-23.34; -6.37)**	**4.6 (1.9; 7.1)**	**-136.12 (-152.59; -119.02)**
			Fishing – Bag		
T10d	-	PBSAT	2.25 (-2.83; 6.74)	-1.9 (-1.7; 1.2)	6.97 (-0.87; 16.33)
T4m	-	PBSAT	6.46 (-0.04; 12.55)	1.0 (-1.6; 3.3)	-5.20 (-14.37; 4.12)
T10d	-	Nylon	1.46 (-3.42; 6.42)	-0.8 (-1.8; 0.3)	**40.10 (24.37; 56.40)**
T4m	-	Nylon	**-7.50 (-14.81; -0.69)**	**-1.6 (-3.2; -0.1)**	**-24.00 (-39.60; -7.44)**
			T10d – T0		
-	Bag	PBSAT	**-5.12 (-8.88; -1.13)**	**-1.6 (-2.8; -0.4)**	8.52 (-0.04; 15.96)
-	Fishing	PBSAT	**-2.86 (-7.08; -0.89)**	**-1.8 (-3.0; -0.7)**	**15.49 (9.88; 21.25)**
-	Bag	Nylon	-0.73 (-4.76; 3.19)	**-2.2 (-3.1; -1.3)**	**53.69 (43.84; 62.72)**
-	Fishing	Nylon	0.73 (-4.54; 5.26)	**-3.0 (-4.0; -2.0)**	**93.79 (78.64; 110.00)**
			T4m – T0		
-	Bag	PBSAT	**-14.86 (-18.22; -11.16)**	**-4.7 (-5.9; -3.4)**	**22.75 (15.62; 28.67)**
-	Fishing	PBSAT	**-8.40 (-14.44; -2.79)**	**-3.7 (-6.1; -1.5)**	**17.55 (10.05; 25.41)**
-	Bag	Nylon	-0.74 (-4.26; 2.75)	**-2.4 (-3.2; -1.6)**	**54.76 (45.78; 63.14)**
-	Fishing	Nylon	**-8.24 (-15.21; -0.77)**	**-4.0 (-5.6; -0.024)**	**30.75 (14.92; 48.09)**

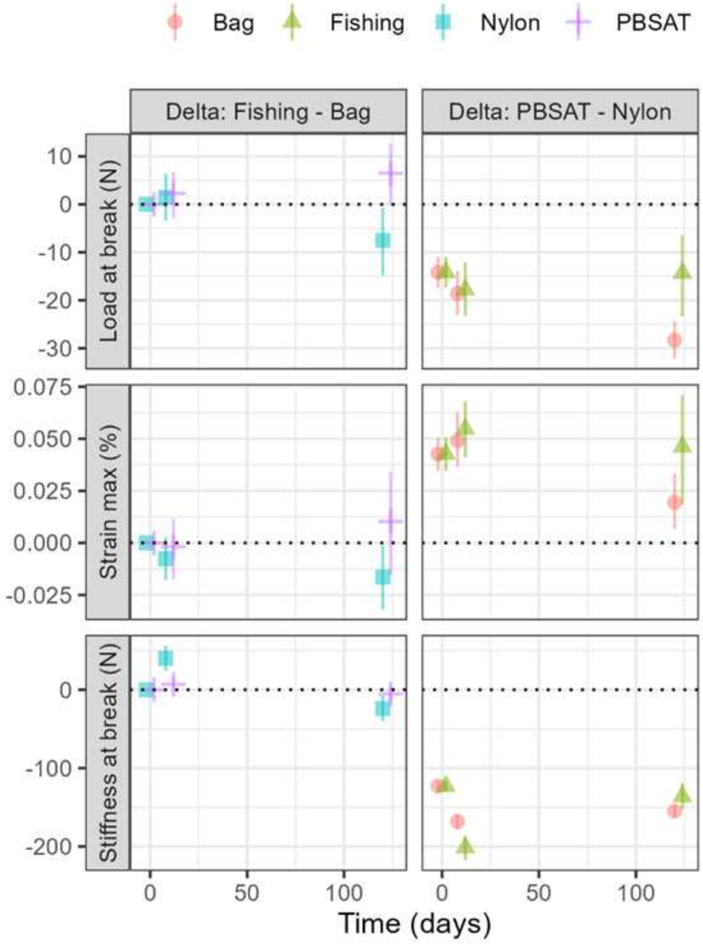

Figure 5. Difference (delta) in load at break (N), strain at break (%) and mesh stiffness at break (N) as a function of deployment time (days) between (left) sample type A put in a meshed net bag on the headline of the gillnet fleets so that the netting is protected from wear and tear (bag), and sample type B cut directly from the netting panels (fishing) for PBSAT (purple) and nylon (blue), and between (right) PBSAT and nylon for sample type A (bag, red) and sample type B (fishing, green). Mean results (points) are presented with 95% percentile confidence intervals (vertical lines). There is a significant difference if delta does not contain 0.00 (black dotted horizontal line) within the confidence interval.

3.6. Length-dependent and length-integrated capture mode probability

We could observe a single mode of capture for 66% of the plaice, mainly captured by the anal spine to the body, and 96% of the cod, mainly captured by the mouth (Supplementary material 2). For 1% of the plaice and 0.3% of the cod, we were able to assume a primary mode based on the principle of likely sequence. Less than 1% of the capture modes for both species were left uncertain. Due to low cod abundance during the second set of trials with used nets, we were not able to estimate the capture mode probability.

The capture mode probability curves described the trend in the experimental data points well for both, plaice and cod, with increasing binomial noise outside the length classes representing the main bulk of the catches (Supplementary material 3). The ability of the capture mode probability curves to describe the experimental data was also verified by the fit statistics (Table 3). In both the PBSAT and nylon nets, the main capture mode for plaice was by the anal fin to body, with 73-75% (CI: 66-84% and 65-79%) in the new nets, and 65% (CI: 55-76% and 53-81%) in the used nets, respectively (Table 3, Supplementary material 3). There was a minor contribution of capture by the body and fish being entangled, with about 10-15% of the fish caught (Table 3, Supplementary material 3). In both the PBSAT and nylon nets, cod was mostly caught by the mouth, with 95-96% (CI: 93-97% and 94-99%) in the new nets, respectively (Table 3, Supplementary material 3). The other captured modes for cod accounted for less than 5% of the fish caught (Table 3, Supplementary material 3).

Table 3. Fit statistics for plaice in the new and used nets, and cod in the new nets for length-dependent capture mode probability analysis: *p*-value, deviance, degrees of freedom (DOF), and length-integrated average value for the capture mode probability as bias-corrected mean with Efron percentile bootstrap 95% confidence limits.

	Capture mode	Number of fish		*p*-value		Deviance		DOF		$CPq_{average}$ (%)	
		Nylon	PBSAT	Nylon	PBSAT	Nylon	PBSAT	Nylon	PBSAT	Nylon	PBSAT
Plaice in the new nets	Mouth, tip	3	4	0.61	0.92	12.0	08.8	14	16	1.38 (00.05-03.65)	1.88 (00.04-04.31)
	Head	7	0	0.41	1.00	14.5	00.0	14	16	3.23 (00.91-06.12)	0.00 (00.00-00.00)
	Gill	6	8	0.94	0.56	06.8	14.5	14	16	2.76 (01.38-04.51)	3.76 (01.06-07.81)
	Anal fin to head	4	8	0.74	0.71	10.3	12.5	14	16	1.84 (00.11-04.55)	3.76 (01.39-06.45)
	Anal fin to body	158	159	0.22	0.64	17.7	13.5	14	16	72.81 (64.54-78.79)	74.65 (66.09-83.94)
	Body	20	11	0.54	0.81	12.8	11.1	14	16	9.22 (04.50-13.91)	5.16 (01.74-09.33)
	Entangled	19	23	0.00	0.79	32.3	11.2	14	16	8.76 (02.89-14.91)	10.80 (02.62-19.64)
Plaice in the used nets	Mouth, tip	5	3	0.99	0.95	05.3	10.7	22	20	0.75 (0.07-02.22)	0.58 (0.00-1.15)
	Head	15	22	0.89	0.23	14.4	24.2	22	20	2.27 (0.11-04.97)	4.25 (0.30-13.07)
	Gill	11	15	0.56	0.29	20.4	22.9	22	20	1.66 (0.66-02.55)	2.90 (1.54-5.35)
	Anal fin to head	16	5	0.62	0.64	19.4	17.2	22	20	2.42 (0.20-08.48)	0.96 (0.04-2.18)
	Anal fin to body	430	336	0.81	0.01	16.2	39.1	22	20	64.95 (52.96-80.53)	64.86 (54.99-75.83)
	Body	88	59	0.01	0.75	39.2	15.4	22	20	13.29 (3.19-22.17)	11.39 (2.96-20.10)
	Entangled	97	78	0.01	0.02	38.9	35.6	22	20	14.65 (7.62-18.14)	15.06 (10.47-20.00)

Cod in the new nets	Mouth	481	374	0.68	0.41	24.0	33.1	28	32	96.39 (94.08-98.51)	95.16 (92.82-97.35)
	Tip	5	1	0.99	1.00	13.3	2.0	28	32	1.02 (0.25-1.97)	0.25 (0.00-0.85)
	Head	4	6	0.96	0.94	16.1	20.7	28	32	0.80 (0.19-1.56)	1.53 (0.00-3.30)
	Gill	0	1	0.99	1.00	13.3	2.8	28	32	1.00 (0.21-1.87)	0.25 (0.00-0.95)
	Body	4	4	0.98	1.00	15.2	9.8	28	32	0.80 (0.00-1.57)	1.02 (0.00-2.45)
	Entangled	1	7	1.00	0.83	1.7	24.4	28	32	0.20 (0.00-0.66)	1.78 (0.00-5.48)
	Uncertain	4	0	1.00	1.00	11.3	0.0	28	32	0.80 (0.00-1.98)	0.00 (0.00-0.00)

There was significantly more plaice between 33 and 42 cm caught by the anal fin to body in the new compared to the used PBSAT nets (Figure 6). There was no difference in probability for capture mode of cod for the main bulk of the data (Figure 6).

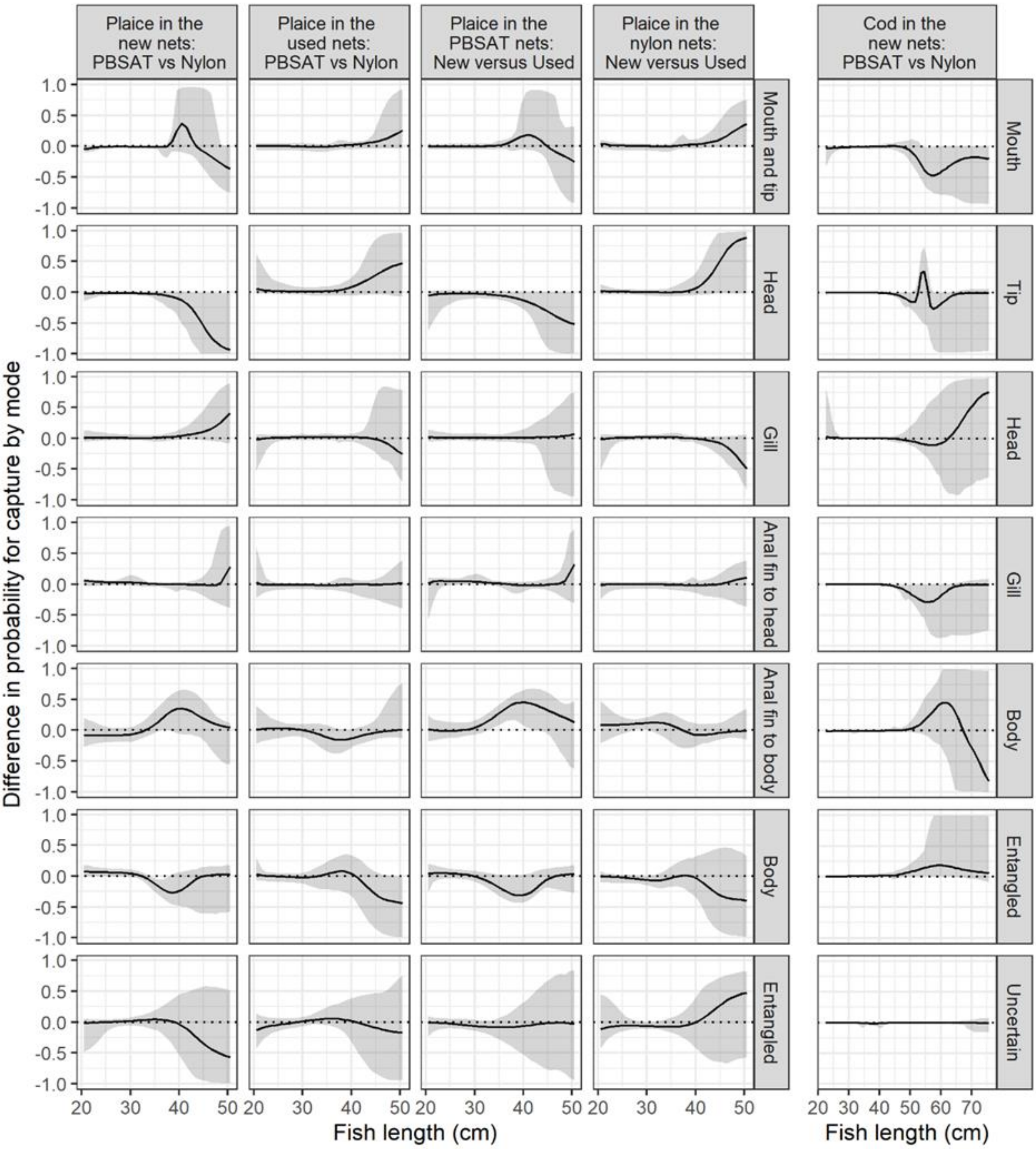

Figure 6. The difference in probability of capture mode (black line, with 95% confidence interval as grey shade) for plaice in the new and used PBSAT and nylon nets, and cod in the new PBSAT and nylon nets. The stippled line at 0.0 represents the point at which there is no significant difference between the new/used or PBSAT/nylon nets.

3.7. *Catch comparison and catch ratio*

Due to low cod abundance during the second set of trials, catch comparison results for cod in used nets needs to be taken with precaution since they are based on a very limited number of observations leading to uncertainty in the estimated catch ratio curve. Uncertainties are, however, reflected in the confidence bands around the catch ratio curves that are provided along with the results.

The ability of the catch comparison curve to describe the experimental data was demonstrated by a *p*-value >0.05 together with residual deviances and degrees of freedom within the same order of magnitude (Table 4). For plaice in new gillnets and cod in used nets, the *p*-value was lower than 0.05 (Table 4). However, the modelled curve followed the main trend in the data (Figure 8); therefore, the low *p*-value was considered to be due to overdispersion in the experimental data.

Table 4. Fit statistics and results of the catch comparison between PBSAT and nylon for plaice in the new and used nets and cod in the new nets. *CR* is the catch ratio in %.

	Plaice in the new nets	Plaice in the used nets	Cod in the new nets	Cod in used nets
p-value	0.0035	0.1297	0.3980	0.0111
Deviance	39.78	30.72	38.58	38.54
DOF	19	23	37	21
CR_{total}	101.47 (75.24-212.50)	80.03 (69.93-90.71)	79.28 (62.80-95.31)	57.50 (37.93-79.49)
$CR_{average-}$	118.18 (31.58-450.00)	121.74 (71.88-193.33)	76.14 (52.25-113.75)	55.56 (14.29-128.57)
$CR_{average+}$	100.52 (73.89-137.91)	76.96 (65.51-89.76)	79.95 (62.29-95.56)	58.06 (36.36-81.48)

There was no significant difference between PBSAT and nylon for capturing plaice in the trials with new nets (Figure 7, Table 4). However, there was a significant difference between PBSAT and nylon for plaice in the used nets for fish between 31 and 41 cm, i.e., above MCRS (Figure 7, Table 4). The catch ratio for plaice showed that the used PBSAT nets caught down to 32% (CI: 17-49%) less individuals than the used nylon nets (lowest value at 35 cm). There was a significant difference between PBSAT and nylon for capturing cod in the new nets for fish between 33 and 42 cm, i.e., above MCRS (Figure 7, Table 4). At its lowest at 37 cm, the catch ratio for cod showed that the new PBSAT nets caught 21% (CI: 3-42%) less individuals than the new nylon nets. The capture efficiency of the PBSAT gillnets was further reduced when comparing the catch efficiency between used PBSAT and nylon gillnets. The used PBSAT gillnets captured on average 57.50% (CI: 37.93-79.49%) cod when compared to the used nylon gillnets.

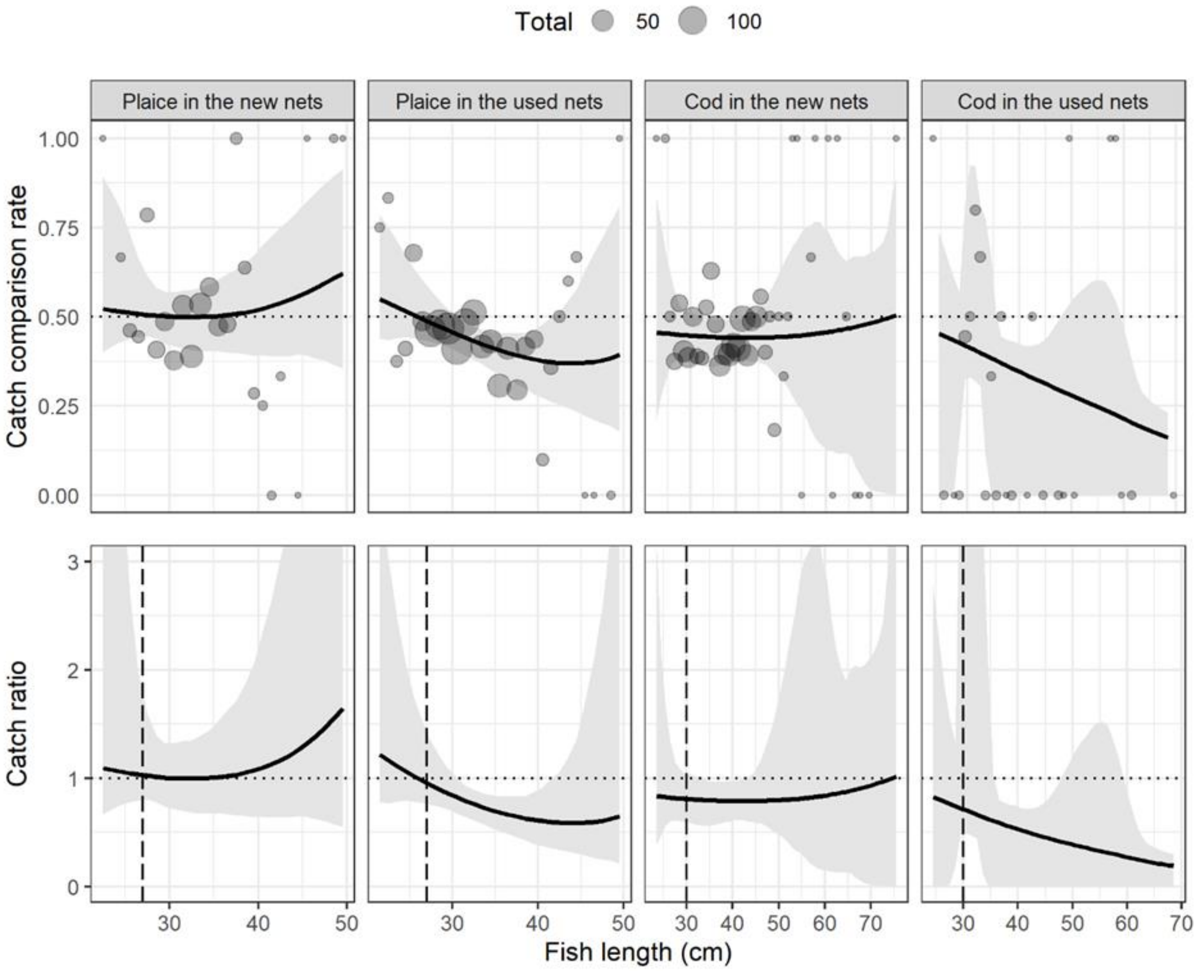

Figure 7. Catch comparison rate, catch ratio and number of individuals for plaice and cod in the new and used nets. The upper panels present the modelled catch comparison rate (black line) with 95 % confidence interval (grey shade). The stippled line at 0.5 represents the point at which PBSAT and nylon have an equal catch rate. Circles represent the experimental rates with size proportional to the number of individuals. The lower panels present the estimated catch ratio curve (black curve) with 95 % confidence interval (grey shade). The stippled line at 1.0 represents the point at which both netting materials have an equal catch ratio.

4. Discussion

In this study, we aimed to discriminate between the effects of manufacturing, physical strain due to gear operation, and biodegradation on the differences in tensile properties, capture modes and catch efficiency over time of the PBSAT and nylon twine.

In line with previous studies, we demonstrated that PBSAT was weaker and elongated more at break than nylon of similar twine diameter (Bae et al., 2013; Kim et al., 2016; Grimaldo et al., 2018b; 2020a). The PBSAT mesh was much weaker compared to the nylon already when new, resulting in faster degradation due to use and wear as well as weathering. When handling the catch, we observed large holes in the PBSAT netting compared to nylon. Such large holes in the netting then directly affects catch efficiency. It is not expected that fish are able to break the netting when trying to escape. Indeed, if we consider that fish muscle breaking strength is less than 1.2 N (observations between 60 and 120 g for different fish species (Ando et al., 1999)), fishes caught in the gillnet meshes would apply a load that is between 10-100 times lower than the loads observed here (60-80 N) for the meshes to break. However, stiffer PBSAT meshes that are harder to open compared to nylon ones could make it more difficult for the fish to be caught and result in lower catch efficiency.

Our results apply only for meshes with knots, and thus it is not possible to compare with previous studies testing the monofilament only (Brakstad et al., 2022; Seonghun et al., 2020). If we consider other studies that reported on breaking strength of PBSAT netting of comparible diameter (since twine diameter affects breaking strength), i.e., 0.55 mm, the breaking strength was on average 109 N (11.1 kg) and 130 N (13.3 kg) for new meshes after 21 deployments and 112 N (11.5 kg) and 93 N (9.5 kg) for used meshes after 92 deployments, respectively (Grimaldo et al., 2018a; 2020b). We also noticed that the PBSAT meshes could easily break at other points of the netting than the knot, which implies that some parts of the PBSAT yarn were at least 50% less resistant (i.e., 2 yarns for one knot).

The estimation of capture mode probability provided valuable information to explain the observed differences in catch efficiency when previously assessing the performance of biodegradable gillnets for cod (Cerbule et al., 2022b). To the best of our knowledge, this study was the first assessing length-dependent capture modes in gillnets for flatfish species. Modes of capture depend on the specific gillnet design and its parameters such as hanging ratio, mesh size or material type (Hansen, 1974; Hamley, 1975; Hovgård, 1996; Samaranayaka et al., 1997; Hovgård et al., 1999; Wileman et al., 2000; Yokota et al., 2001; Holst et al., 2002; He, 2006;

Grati et al., 2015; Cerbule et al., 2022b). In this study, we observed the performance of PBSAT and nylon gillnets, keeping other gillnet parameters similar. There was no difference in capture mode probability between the PBSAT and nylon nets. There was more plaice caught by its main capture mode, i.e., anal fin to body, in the new compared to the used PBSAT nets, which is in line with lower catch efficiency over time for the PBSAT netting. The main capture mode for cod was by mouth, as fish are too small to be caught in other capture modes with respect to the fish size, morphology and mesh geometry (fish up to 55 cm total length; Savina et al., 2022). Fish captured by mouth has a higher probability of escape than if it was captured by other capture modes such as body (Grati et al., 2015; Savina et al., 2022). In addition with a higher swimming ability of roundfish compared to flatfish, this could have resulted in loss of cod already with the new nets.

Lower catch efficiency over time in PBSAT gillnets are in line with the results of earlier studies in the Norwegian cod fishery (Grimaldo et al., 2018b, 2020a; Cerbule et al., 2022b), with a 57.50% (CI: 37.93-79.49%) reduction in catch efficiency for cod between used PBSAT and nylon gillnets after 4 months observed in the current study compared to, e.g., 50% reduction after 3 months (Grimaldo et al., 2018a). Reduction in catch efficiency does not match biodegradation rates observed in controlled systems, and thus has to also result from weaker mechanical properties at production further worsened by wear and tear. As a reference point, changes on Ø 55 mm PBSAT surfaces (i.e., axial cracks) in a natural seawater-sediment microcosm became apparent after 24 months of incubation (Brakstad et al., 2022).

Currently, the use of gillnets made of biodegradable material in the commercial and recreational fisheries is optional. Higher production costs, lower catch efficiency and lower lifespan are serious limits to the commercial use of PBSAT gillnets (Standal et al., 2020). Our trials were run over the course of a few months while in this fishery the gillnets are normally used for longer periods, i.e., up to 1 year if fished constantly; however, they are often used during a season of 3-5 months over several years. PBSAT would thus need to provide a comparable catch efficiency to nylon not only during the first deployments, but also over a few months for several years. Because gillnetters often target several species, one should also consider optimal tensile properties for both, flatfish and roundfish. Systematic mechanical studies of PBSAT and other biodegradable material candidates are needed to provide an optimal catch and degradation profile that would be accepted by the industry. Further studies should compare differences in mechanical properties at the three scales of interest for commercial application: twine, mesh with knots and netting panel. Considering the cost of sea trials and the very poor performance of the PBSAT material, mechanical properties should be properly assesssed before testing at sea. We can only stress the need to propose guidelines suited to testing of alternative new materials. We also observed slips in the knots which will tend to overestimate the load estimations (longer twine sample) and underestimate the stiffness of the tested material (if initial length increase then stiffness decrease). We could suggest to test the central mesh of 3 x 3 meshes to reduce risk of slipage as recommended in the ISO standard.

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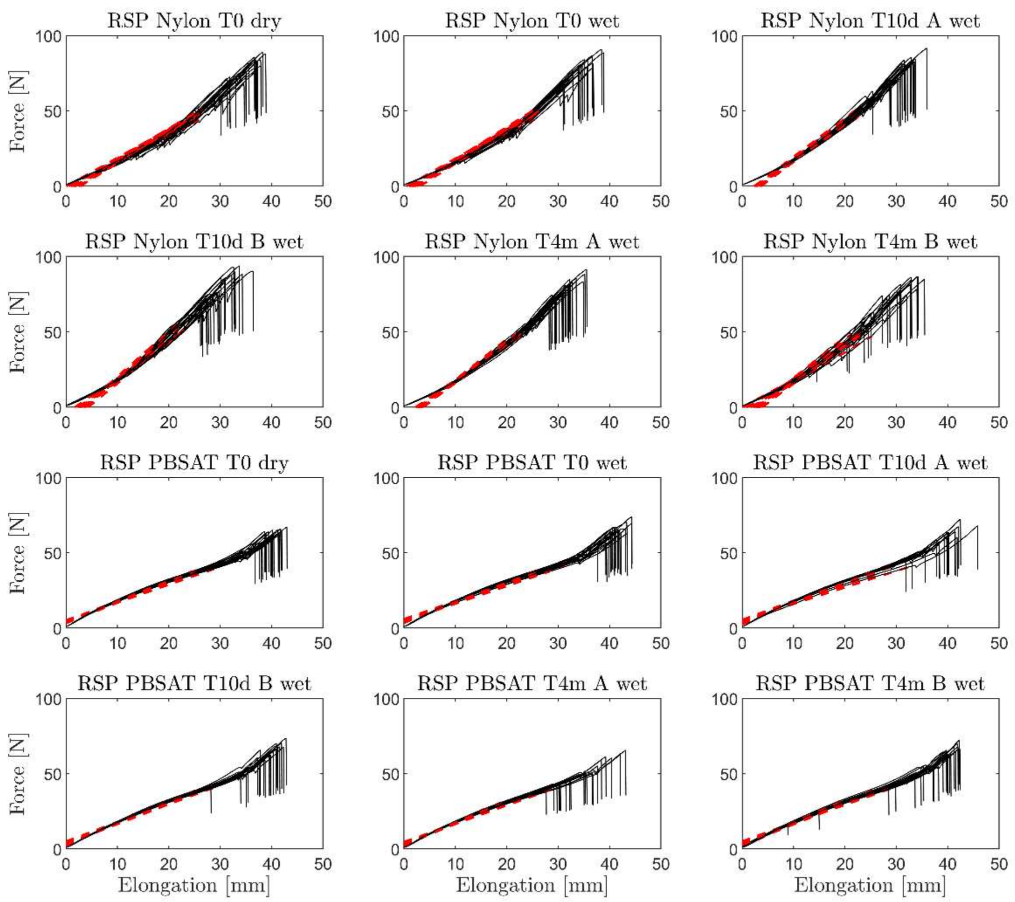
Supplementary materials

Supplementary material 1. Load-elongation curves for the PBSAT and nylon meshes at the start (T0, dry and wet) and end (T10d, wet) of the first sea trial and after 4 months at the end of the second sea trial (T4m, wet). For each netting material, we looked at sample type A put in a meshed net bag on the headline of the gillnet fleets so that the netting is protected from wear and tear, and sample type B cut directly from the netting panels (see material and methods for additional information). RSP stands for plaice.

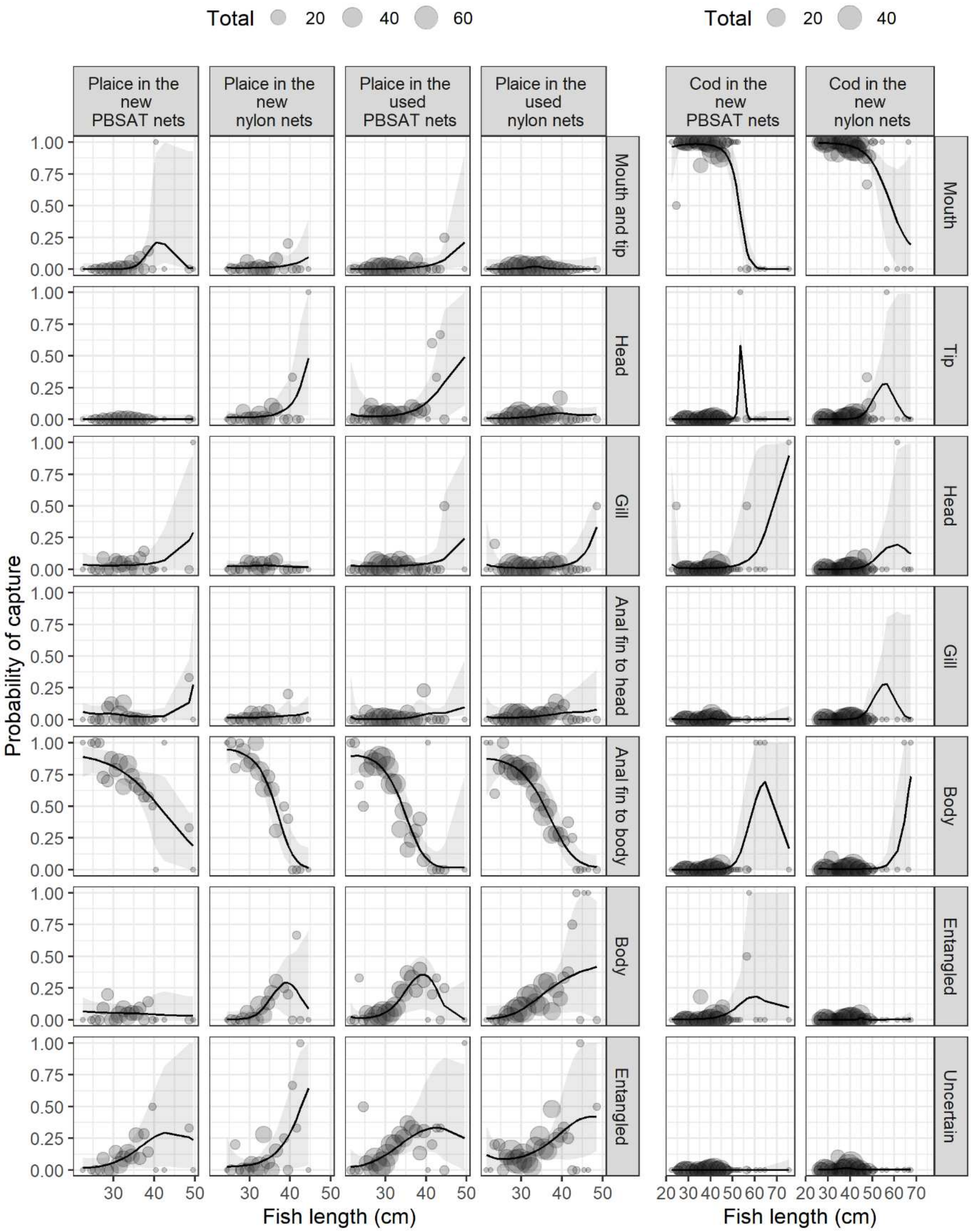


Supplementary material 2. Number of fish (cod and plaice) for the observed and assumed primary capture mode(s) in case of multiple occurrences.

	Observed	Assumed primary	Principle	Number of fish
Plaice	Anal to body	Anal to body	Single mode	1081
	Entangled	Entangled	Single mode	217
	Body	Body	Single mode	172
	Head	Head	Single mode	44
	Gill	Gill	Single mode	39
	Anal to head	Anal to head	Single mode	31
	Uncertain	Uncertain	Single mode	20
	Tip	Tip	Single mode	8
	Mouth	Mouth	Single mode	6
	Gill & Body	Body	Likely sequence	4
	Anal to body & Entangled	Anal to body	Entangled secondary	3
	Pelvic fin	Pelvic fin	Single mode	3
	Gill & Anal to body	Anal to body	Likely sequence	2
	Tip & Anal to body	Anal to body	Likely sequence	2
	Mouth & Anal to head	Anal to head	Likely sequence	1
	Mouth & Anal to body	Anal to body	Likely sequence	1
	Mouth & Gill	Gill	Likely sequence	1
	Mouth & Entangled	Mouth	Entangled secondary	1
	Head & Gill	Head	Likely sequence	1
	Anal to head & Entangled	Anal to head	Entangled secondary	1
	Anal to body & Body	Body	Likely sequence	1
	Body & Entangled	Body	Entangled secondary	1
Cod	Mouth	Mouth	Single mode	855
	Entangled	Entangled	Single mode	8
	Body	Body	Single mode	7
	Head	Head	Single mode	7
	Tip	Tip	Single mode	6

Uncertain	Uncertain	Single mode	5
Mouth & Entangled	Mouth	Entangled secondary	2
Mouth & Head	Head	Likely sequence	2
Mouth & Body	Body	Likely sequence	1
Head & Entangled	Head	Entangled secondary	1
Gill	Gill	Single mode	1

Supplementary material 3. Probability for capture mode and number of individuals for plaice in the new and used PBSAT and nylon nets, and cod in the new PBSAT and nylon nets. The black line represents the modelled mode probability as bias-corrected mean with Efron percentile bootstrap 95% confidence interval (grey shade) fitted to the experimental rate (circle marks with size proportional to the number of individuals).



Article IV

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Can biodegradable materials reduce plastic pollution without decreasing catch efficiency in longline fishery?

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ABSTRACT

Longlining is a widely used fishing method. During longline fishing, some of the snoods connecting the hooks to the mainline are often lost at sea. Since snoods are made of nylon or polyester, lost snoods contribute to marine plastic pollution. Replacing nylon or polyester with a new material made of biodegradable plastics can potentially reduce macro- and microplastic pollution that is caused by lost snoods. In this study, we estimated the risk for snood loss in a longline fishery targeting haddock (*Melanogrammus aeglefinus* (Linnaeus, 1758)) and Atlantic cod (*Gadus morhua* (Linnaeus, 1758)) in Barents Sea. Further, we compared catch efficiency in this fishery for snoods made of biodegradable and nylon materials. No significant differences were found between the two materials. Therefore, catch efficiency does not represent a barrier for using biodegradable materials in snoods.

1. Introduction

Longlining is a widely used fishing method in different fisheries worldwide (Watson et al., 2006; He et al., 2021). All types of longlines consist of three components: a mainline, snoods and hooks (Fig. 1). The snood (also termed gangion) is a short line connecting mainline with the hook at the other end at regular intervals. Each snood is attached at a certain interval along the mainlines either directly with a knot or by using a clip or swivel usually equipped with a spinner (He et al., 2021). Fish are attracted to the longline by bait on the hooks.

In Norway, demersal longlines are widely used to target demersal fish species such as cod (*Gadus morhua* (Linnaeus, 1758)), haddock (*Melanogrammus aeglefinus* (Linnaeus, 1758)) and Greenland halibut (*Reinhardtius hippoglossoides* (Walbaum, 1792)) in coastal/inshore areas. In 2020, line and longline fisheries contributed to 33.8% of haddock, 19.8% of cod and 39.5% of Greenland halibut landings in Norway (Norwegian Directorate of Fisheries, 2021). The coastal fleet uses both, manually and mechanically baited gears and operates between 10.000 and 30.000 hooks per day (Mustad autoline, 2021a). Their operation is based on daytrips and landing of fresh fish (fresh fish on ice/chilled water). The deep-sea longline fleet (called the autoline fleet) operates mechanized baiting systems with up to 60.000 hooks deployed and hauled per day and their capture periods last for weeks (Larsen and Rindahl, 2008; Mustad autoline, 2021b) since processed fish is packed and stored frozen. This fleet targets similar species as the coastal fleet, while such species like tusk (*Brosme brosme* (Ascanius, 1772)), ling (*Molva molva* (Linnaeus, 1758)), redfish (*Sebastes* spp.) and spotted wolffish (*Anarhichas minor* (Olafsen 1772)) are common bycatch species.

The longline fishery mostly uses synthetic materials such as spun polyester or polyamide 6, herein called nylon, monofilament for the main line and monofilament nylon or twisted polyester for snoods. While the Norwegian deep-sea fleets use snoods made from polyesters, the coastal fleets with manually and mechanically baited gears prefer the monofilament nylon snoods. In demersal longline fishery, longlines (or sections of them) are often lost at sea because of being deployed along rough grounds and because of large abrasion of the materials. Similarly, snoods risk being lost at sea because of, for example, being snagged at the seafloor or during the fishing process when the fish break the snood line and escape with the hook and part of snood.

Because snoods are made from petrol-based synthetic plastic material, they will degrade very slowly in seawater in case of being lost. Furthermore, even after long exposures (i.e., decades), the material does

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not degrade completely – instead it is being broken down into smaller plastic particles and increases macro- and microplastic pollution and releases toxic substances into the marine environment (Moore, 2008). This can negatively impact the food web of the marine ecosystem (Lee et al., 2013; Cole and Galloway, 2015; Desforges et al., 2015; Chae and An, 2017; Lusher et al., 2017). Use of biodegradable plastic to replace synthetic plastic materials such as nylon in fishing gear are being tested in other fisheries such as gillnets (Grimaldo et al., 2018a, 2018b, 2019, 2020) by using biodegradable material made of polybutylene succinate *co*-adipate-co-terephthalate (PBSAT) resin. Such biodegradable material has the properties for being fully degraded after specific time in the seawater by naturally occurring microorganisms (Tokiwa et al., 2009).

Experiments with biodegradable PBSAT materials to replace commonly used nylon material, have shown reduced catch efficiency in gillnet fisheries (Grimaldo et al., 2018a, 2018b, 2019, 2020). Biodegradable PBSAT material has a lower tensile strength (Grimaldo et al., 2020) compared to nylon. Therefore, use of biodegradable PBSAT plastic in the snood material could potentially show a reduced catch efficiency because of the loss of snoods during the fishing process as a result of breaking of the material. An increased material thickness (diameter of the snood) may be needed for biodegradable snoods to provide a similar tensile strength to that of the nylon material. However, earlier trials testing increased snood thickness (diameter) in longline fishery targeting hake (*Merluccius merluccius*) have resulted in a reduced catch efficiency (Herrmann et al., 2017). The reasons for this might be related to the visibility of the snoods to the fish (Herrmann et al., 2017). However, the effect of increased snood diameter is not known in other fisheries.

Additionally, the extent of snood loss by using the biodegradable materials should not exceed the loss of snoods made of nylon to be accepted commercially. In case of increased snood loss by changing of the material, more labor would be involved to replace the loss. It would, furthermore, increase the costs by using additional quantity of snood material and hooks and reduce the capture efficiency during fishing. Although some snood loss is common in the fishery (i.e., 5.9% in the Patagonian toothfish fishery (AFMA, 2010)), the extent of such loss per gear deployment has not been scientifically quantified. Further, longlines using the biodegradable material must obtain a similar catch efficiency to that of nylon snoods to be adopted by the industry, and thereby contribute at reducing marine plastic pollution. Initial tests are needed to provide information whether the new material is initially providing a similar catch efficiency to that of nylon before further proceeding with experiments involving repeated deployments for determining the effect of long-term use of the biodegradable snoods on the catch efficiency.

In this study, we estimated the probability of snood loss using nylon and biodegradable PBSAT materials with two different monofilament thicknesses. Further, we tested the effect of using the biodegradable material with a similar and increased snood material thickness on the catch efficiency of haddock and cod targeted in a coastal longline fishery in Northern Norway. Thus, the aims of this study were to address the following research questions:

- What is the risk for snood loss in coastal longline fishery for haddock and cod?
- Is there any difference in risk for snood loss if the snood material is changed from nylon to biodegradable PBSAT plastic material with equal and increased material thickness?
- Is there any difference in catch efficiency of haddock and cod if the snood material is changed from nylon to biodegradable PBSAT plastic material?
- Would the catch efficiency change if an increased material thickness of biodegradable PBSAT snoods is used?

2. Materials and methods

2.1. Sea trials and experimental setup

Sea trials were conducted onboard a commercial coastal longline vessel "Vardøyfisk 2" (12.95 m LOA) during November 2021. The fishing grounds were located in Northeast Norway between 70°00.00–70°07.64 N and 30°19.85–30°43.68 E. The fishing depth varied between 100 and 240 m. The trials consisted of two series of longlines, where each longline was made from 6 mainlines which consisted of 415 snoods and hooks each. The snoods were attached to a three stranded spun polyester mainline with 5.5 mm diameter. The distance between each snood was 1.3 m. Therefore, the total length of each mainline was 540 m. Prior to each fishing trip, all longlines were manually baited using mackerel (*Scomber scombrus* Linnaeus 1758) and stored in tubs. The longlines of each series were deployed and soaked equally long time in the same area.

In each series, the mainlines with biodegradable and nylon snoods were alternated (Fig. 2) as follows:

Series 1: A longline consisting of three mainlines with 415 snoods each made of biodegradable PBSAT material of 1.0 mm diameter alternated with three mainlines with 415 snoods made of nylon with 1.0 mm diameter.

Series 2: A longline consisting of three mainlines with 415 snoods each made of biodegradable PBSAT material with an increased diameter (1.1 mm) alternated with three mainlines with 415 snoods made of nylon with 1.0 mm diameter.

During hauling of the longlines, fish were sorted according to type of the snoods (biodegradable or nylon). All haddock and cod were measured for the total length to the closest cm below. Further, after each fishing trip during the rebaiting, the numbers of lost or damaged snoods for each material type were recorded. New snoods were attached if missing or replaced if damaged where necessary so that the number of

Fig. 1. Illustration of longline components.

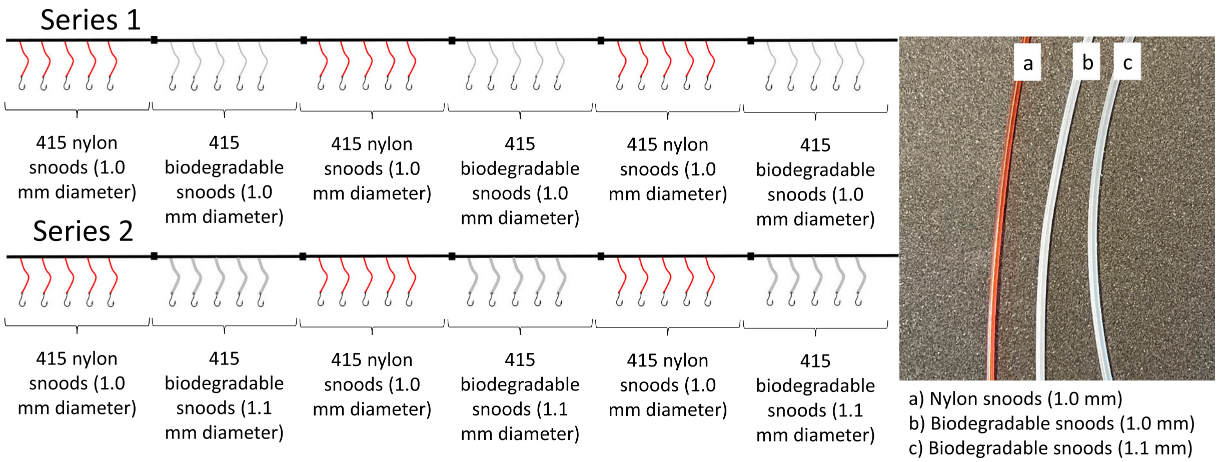

Fig. 2. Experimental setup used during the fishing trials. Series 1 consisted of nylon (a) and biodegradable PBSAT (b) snoods of 1.0 mm diameter. Series 2 consisted of biodegradable PBSAT snoods of 1.1 mm diameter (c) and nylon snoods of 1.0 mm diameter.

snoods was identical for each longline deployment (i.e., 415 snoods per mainline).

2.2. Estimating risk of snood line loss

The risk for losing a snood (P_{loss}) during one deployment of it is quantified by the probability averaged over deployments and snoods of the specific type:

$$P_{loss} = \frac{1}{m}\sum_{i}^{m}\left\{\frac{1}{ns_i}\sum\nolimits_{j=1}^{ns_i} g\left(s_{ij}\right)\right\}$$
$$with \tag{1}$$
$$g(s) = \begin{cases} 1 \ \forall \ s = lost \\ 0 \quad \forall \quad s \neq lost \end{cases}$$

where ns_i is the number of snoods on the mainline in deployment i. s_{ij} is the status (lost or retained) of snood number j after line deployment i. m is the number of deployments.

Estimation of uncertainties for P_{loss} calculated based on Eq. (1) required consideration that the risk may vary between deployments with the same type of snood due to uncontrolled effects in the fishing process. Further, assessing the risk for the individual deployments is subjected to uncertainty (within-deployment variability) because of limited number of snoods being deployed. To account for these uncertainties in the estimations, a double bootstrap method was adapted. This method is well established for evaluating fishing gear selectivity and catch efficiency for fisheries known to be subjected to a similar structure in uncertainties (i.e., Herrmann et al., 2017). The procedure accounts for between-deployment variation in the risk by selecting m deployments with replacement from the pool of deployments of mainlines with the specific snood type (i.e., nylon or biodegradable (1.0 mm or 1.1 mm diameter, respectively)) during each bootstrap repetition. Within-deployment uncertainty in the obtained risk was accounted for by randomly selecting snoods with replacement from the selected mainline. The number of snoods selected from each deployment was the same as the number of snoods used in that deployment (ns_i). The resulting data for each bootstrap were then used to estimate the expected risk for snood loss based on Eq. (1). We performed 1000 bootstrap repetitions and calculated the Efron 95% percentile confidence intervals (Efron, 1982) (CIs) for the estimated probabilities.

To infer the difference ΔP_{loss} between two types of snoods, we used the two populations of bootstrap results obtained by the procedure described above following method described in Larsen et al. (2018) and Herrmann et al. (2018):

$$\Delta P_{loss} = P_{lossB} - P_{lossA} \tag{2}$$

where P_{lossA} represents the value for P_{loss} for snood type A, and P_{lossB} represents the value for P_{loss} for snood type B. Efron 95% percentile confidence limits for ΔP_{loss} was obtained based on the two bootstrap populations of results (1000 bootstrap repetitions in each) for both P_{lossA} and P_{lossB}. As they were obtained independently, a new bootstrap population of results was created for ΔP_{loss} by:

$$\Delta P_{loss\,i} = P_{lossB\,i} - P_{lossA\,i} \; i \in [1\ldots1000] \tag{3}$$

where 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 Eq. (3) using the two independently generated bootstrap files (Herrmann et al., 2018). Based on the bootstrap population, Efron 95% percentile CIs were obtained for ΔP_{loss} as described above. In case ΔP_{loss} does not include the value 0.0 in the CIs for P_{loss}, the loss risk between deploying snoods of type A and B, respectively, will be significantly different.

We used an identical approach for estimation of $P_{replacement}$ for need of snood line replacement between longline deployments and difference $\Delta P_{replacement}$ between different types of snoods. We used the statistical software SELNET (Herrmann et al., 2012) to conduct the analysis described above.

2.3. Estimating the length-dependent catch efficiency between longlines with different snood materials

Comparison of catch efficiency between the mainlines with different snood materials in Series 1 and Series 2 was estimated as catch comparison rate and catch ratio (Herrmann et al., 2017). We used the catch information (numbers and lengths of haddock and cod caught with each of the mainlines with different snood materials and diameters) to determine whether there was a significant difference in the catch efficiency averaged over deployments. We used the statistical software SELNET (Herrmann et al., 2012) to analyze the catch data and conduct length-dependent catch comparison and catch ratio analyses. We also tested whether a potential difference between the snood types could be attributed to the size (total length) of haddock and cod. We used the method described in Herrmann et al. (2017) to assess the change in relative length-dependent catch efficiency when changing the snood material in each series. Further, we applied the same method to assess the change in relative length-dependent catch efficiency between snood material types. The method models the length-dependent (l) catch comparison rate ($CC(l)$) and catch ratio ($CR(l)$) summed over all deployments for the full deployment period. We used the double bootstrapping method (1000 bootstrap repetitions) to estimate the 95% CIs for the catch comparison and catch ratio curves following the description in Herrmann et al. (2017). When the catch efficiency of the two types of snoods is equal, the catch comparison rate is 0.5 and the catch ratio is 1.0. The length-integrated average catch ratio ($CR_{average}$) value was estimated directly from the experimental catch data. Details on the estimation of $CC(l)$, $CR(l)$, and $CR_{average}$ is explained in Herrmann et al. (2017).

Further, to infer the effect of changing biodegradable snood diameter from 1.1 (A) to 1.0 (B) mm on the catch ratio curve $CR(l)$ where both catch ratio curves are obtained against the same baseline (i.e., nylon snoods with 1.0 mm diameter), the length-dependent change $CR_{A/B}(l)$ in the values was estimated by (Jacques et al., 2021):

$$CR_{A/B}(l) = \frac{CR_A(l)}{CR_B(l)} \tag{4}$$

where CR_B (l) is the catch ratio value for biodegradable snoods with 1.0 mm diameter and CR_A (l) is the catch ratio value for biodegradable snoods with 1.1 mm diameter. Efron 95% percentile CIs were obtained based on the two $CR_{A/B}$ (l) bootstrap populations of results (1000 bootstrap repetitions in each) for both CR_A (l) and CR_B (l) (Herrmann et al., 2017). As they were obtained independently, a new bootstrap population of results was created by:

$$CR_{A/B}(l)_i = \frac{CR_A(l)_i}{CR_B(l)_i} \; i \in [1...1000] \tag{5}$$

where i is the bootstrap repetition index. As the bootstrap resampling was random and independent for the two results, it is valid to generate the bootstrap population of results for the difference based on Eq. (5) using the two independently generated bootstrap files (Herrmann et al., 2018).

2.4. Mechanical properties of the snoods

All biodegradable snoods were made of the PBSAT resin (Kim et al., 2017, patent EP3214133). Biodegradable snood line material was produced in South-Korea and manufactured by S-EnPol Ltd. The mean tensile strength of biodegradable (1.0 mm and 1.1 mm diameter separately) and nylon snood material was measured according to ASTM D2256/D2256M-21 (ASTM, 2021). The tensile strength tests were performed on new material samples that have not been used in fishery. The measurement for the mean tensile strength and elongation at break of the samples were recorded for each material type. Tensile strength, given in kilograms, is defined as the stress necessary to break the tested snood material. Elongation at break, given as a percentage relative to the initial snood sample length, is defined as the length of the sample after it has been stretched to the breaking point. The differences in tensile strength between the different materials were estimated using Welch's t-test (Microsoft Excel2007).

3. Results

3.1. Risk of snood line loss

Longlines with 2490 nylon snoods and 1245 biodegradable snoods with 1.0 or 1.1 mm diameter, respectively, were deployed during each fishing trip (Table 1). In total, the gear was deployed over 5 fishing trips. Snoods were considered lost when a snood together with hook was missing on the mainline (Fig. 3a) or when they were broken (Fig. 3b). The snoods were replaced in cases when a part of the hook was missing (Fig. 3c), or the snood was damaged during the fishing process (Fig. 3d).

The risk of the loss of snoods (P_{loss}) varied from 4.66% (CI: 3.84–5.46%) for nylon snoods to 6.10% (CI: 4.59–7.96%) for biodegradable snoods with 1.0 mm diameter thickness, and the rate of lost biodegradable snoods was higher compared to the nylon material (Table 1). The pairwise difference between the rates of snood losses between the material types (ΔP_{loss}) did not show statistical significance (Table 2).

Table 1
Numbers of total lost and replaced snoods over all deployments and mean risk of snood loss or need for replacement for each of the three snood line materials. Values in brackets represent 95% confidence intervals. Lost snoods were registered in cases when the snood with the hook was missing on the mainline while additional replaced snoods were registered in cases when hooks or part of the hooks were missing, or the snood was damaged during the fishing process.

	Nylon (1.0 mm diameter)	Biodegradable (1.0 mm diameter)	Biodegradable (1.1 mm diameter)
Total number of snoods in each deployment	2490	1245	1245
Total number of lost snoods over all deployments	584	378	348
Total number of replaced snoods over all deployments	175	100	88
Probability of loss (P_{loss}) (%)	4.66 (3.84–5.46)	6.10 (4.59–7.96)	5.59 (3.99–7.38)
Probability of replacement ($P_{replacement}$) (%)	1.41 (0.76–2.18)	1.61 (0.59–3.60)	1.43 (0.83–3.60)

Further, the differences in number of replaced snoods by material type and diameter ($P_{replacement}$) were recorded. No significant differences were observed for snood loss between the three snood line types as the pairwise difference ($\Delta P_{replacement}$) included 0.0 (Table 2).

3.2. Catch efficiency of biodegradable versus nylon snoods

In total, 4943 haddock and 936 cod were captured and included in the analysis of this study (Table 3). The fit statistics of the catch comparison analysis showed that the deviation between the experimental data and the modelled data fitted well in both series for both haddock and cod because p-value >0.05 (Wileman et al., 1996). This showed that the deviation between the experimental data and the modelled data could be coincidental and, therefore, the model could be used to describe the trends in the data (Table 3).

Both types of longlines in both series had a similar pattern of capturing haddock and cod regarding the fish length. For haddock, the length ranged between 31 and 78 cm and for cod it was between 31 and 111 cm total length (Figs. 4 and 5). Biodegradable snoods with both material thicknesses (1.0 and 1.1 mm) did not show significant difference in catch efficiency when compared to the nylon snoods of 1.0 mm for either haddock or cod (Figs. 4 and 5). The average catch ratio ($CR_{average}$) for both haddock and cod did not show any significant differences between use of nylon or biodegradable snoods with either 1.0- or 1.1-mm diameter of the snoods (Table 3). There was an indication of reduced capture of haddock when using 1.1 mm biodegradable material ($CR_{average}$ = 84.43 (CI: 76.73–101.95)). However, this difference was not statistically significant. Moreover, the length-dependent change in catch ratio between biodegradable snoods ($CR_{A/B}(l)$) with material thickness of 1.1 mm ($CR_A(l)$) and 1.0 mm ($CR_B(l)$) did not show significant difference in capture of haddock and cod (Fig. 6).

3.3. Mechanical properties of the snood lines

The average tensile strength of the nylon snood material was 47.8 kg while for the biodegradable material it was 32.7 and 37.0 kg for snoods with 1.0 and 1.1 mm thickness, respectively (Table 4). The average elongation at break was 33.1% for nylon snoods and 31.7% and 29.3%

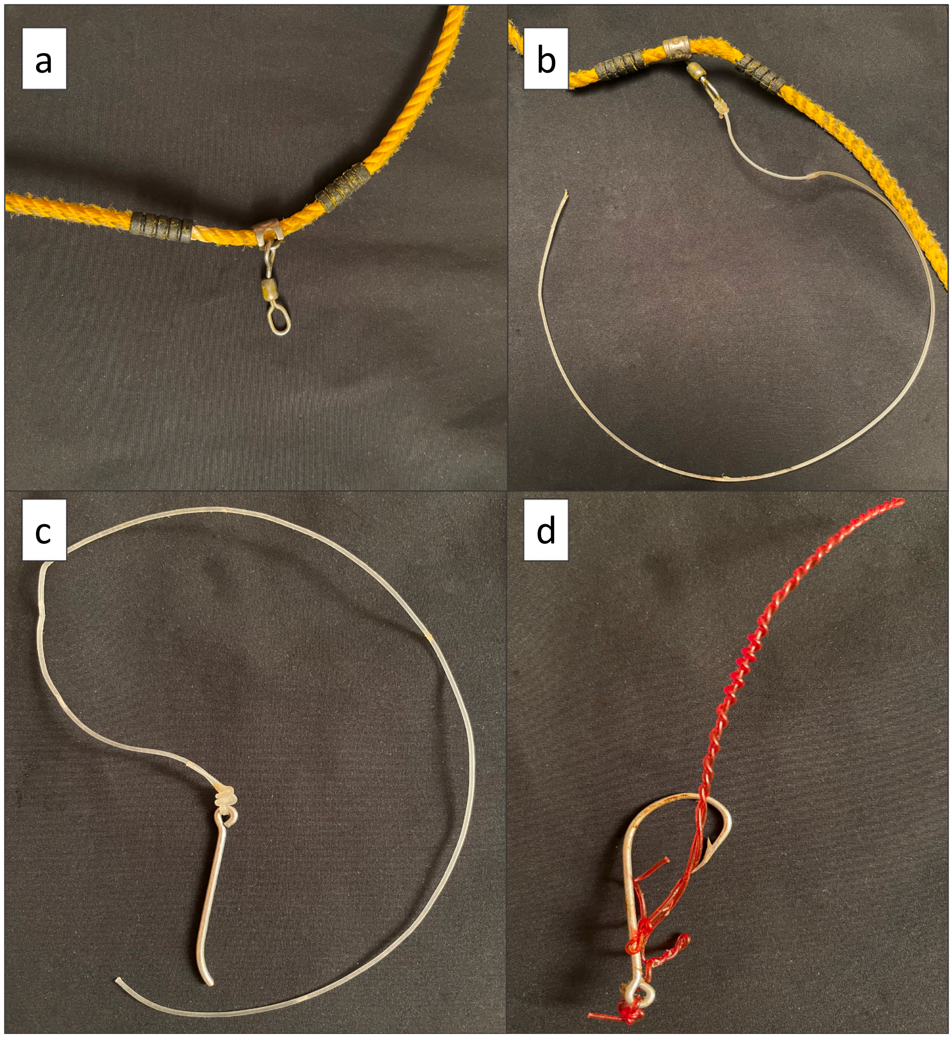

Fig. 3. Examples of cases when snoods were lost (pictures a and b) or needed replacement (pictures c and d) for the next longline deployment during rebaiting. (a) snood missing after deployment; (b) broken snood; (c) removed broken hook; (d) removed damaged snood.

Table 2
Pairwise difference (delta) between snoods of the three materials with corresponding diameters in brackets regarding risk of loss or need for replacement of the snoods. Values in brackets represent 95% confidence intervals.

	Loss (ΔP_{loss}) (%)	Replacement ($\Delta P_{replacement}$) (%)
Biodegradable (1.0 mm) against nylon	1.41 (−0.26–3.57)	0.19 (−1.28–2.27)
Biodegradable (1.1 mm) against nylon	0.26 (−0.18–0.36)	0.02 (0.00–0.04)
Biodegradable (1.1 mm) against biodegradable (1.0 mm)	−0.48 (−3.11–1.86)	−0.18 (−2.14–1.28)

for biodegradable snoods with 1.0 and 1.1 mm thickness, respectively (Table 4). There was a significant difference in the tensile strength between biodegradable snoods of both material thickness compared to nylon material (Welch's *t*-test, *p*-value <0.01). The difference was also significant when the tensile strength was compared between the two biodegradable snoods with different material thicknesses (Welch's test, *p*-value <0.01) (Table 5).

4. Discussion

In this study, we investigated whether biodegradable PBSAT materials can be used to reduce marine plastic pollution caused by lost snood lines. Specifically, we estimated the risk of snood loss, replacement, and catch efficiency when using nylon and biodegradable snood material in a longline fishery for haddock and cod. In addition, we tested whether increased biodegradable snood thickness would show different results compared to biodegradable material of equal thickness to that of nylon snoods. We aimed at estimating the initial differences between the materials, i.e., using new materials for the snoods that have not been subjected to fishing.

The estimated probability of snood loss in the coastal manually baited longline fishery for haddock and cod using nylon snoods was 4.66% (CI: 3.84–5.46%) during a longline deployment. Since the coastal longline fishery usually uses longline sets with 10.000–30.000 snood lines (Mustad autoline, 2021a), the estimated snood line loss in this longline fishery for haddock and cod would vary between 466 (384–546) to 1380 (1152–1638) snoods for each single deployment when using nylon snood lines. We found no significant increase in biodegradable snood loss during initial trials when compared to nylon snoods. The estimated biodegradable snood loss was 6.10% (CI: 4.59–7.96%) and 5.59% (CI: 3.99–7.38%) for 1.0 and 1.1 mm snood thickness, respectively. There were no significant differences regarding the estimated replacement of snoods of nylon and biodegradable material with the different thickness. However, there was an indication of increased 1.0 mm biodegradable snood loss compared to biodegradable snoods of 1.1 mm thickness and nylon snoods. These results correspond

Table 3
Fit statistics, catch comparison results and number of fish observed. Results for biodegradable snoods with 1.0 mm thickness (left column) and 1.1 mm thickness (right column) for haddock and cod. In all cases the nylon snoods with 1.0 mm thickness were used as a baseline. Values in brackets represent 95% Efron confidence limits. DOF denotes degrees of freedom.

	Haddock		Cod	
	1.0 mm diameter	1.1 mm diameter	1.0 mm diameter	1.1 mm diameter
p-value	0.0829	0.1167	0.3097	0.2700
Deviance	47.11	44.02	71.17	74.69
DOF	35	34	66	68
CRaverage (%)	89.44 (63.64–124.65)	84.43 (76.73–101.95)	91.46 (64.41–123.51)	97.53 (70.40–136.52)
Number of individuals (biodegradable snoods)	1355	949	210	237
Number of individuals (nylon snoods)	1515	1124	246	243

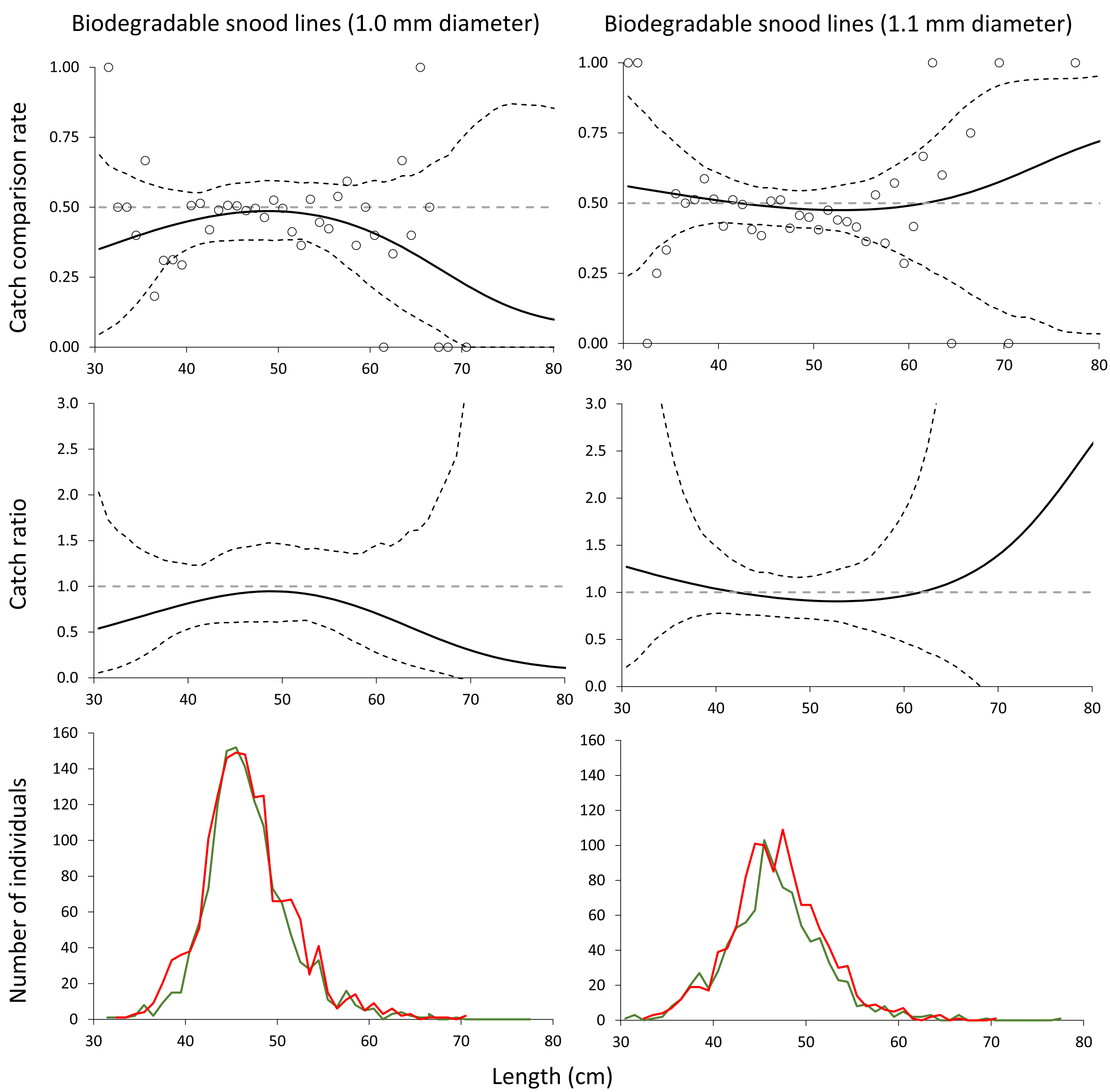

Fig. 4. Catch comparison and catch ratio analysis for haddock. Left: biodegradable snoods with 1.0 mm thickness vs nylon snoods. Right: biodegradable snoods with 1.1 mm thickness vs nylon snoods. Upper graph: the modelled catch comparison rate (black curve) with 95% confidence intervals (black stippled curves). Circles represent experimental rate. Middle: the estimated catch ratio curve (black curve) with 95% confidence intervals (black stippled curves). The grey stippled lines at 0.5 and 1.0 represent the point at which both gears have an equal catch rate. Bottom: the length frequency distribution of fish captured with the biodegradable snoods (green line) and nylon snoods (red line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

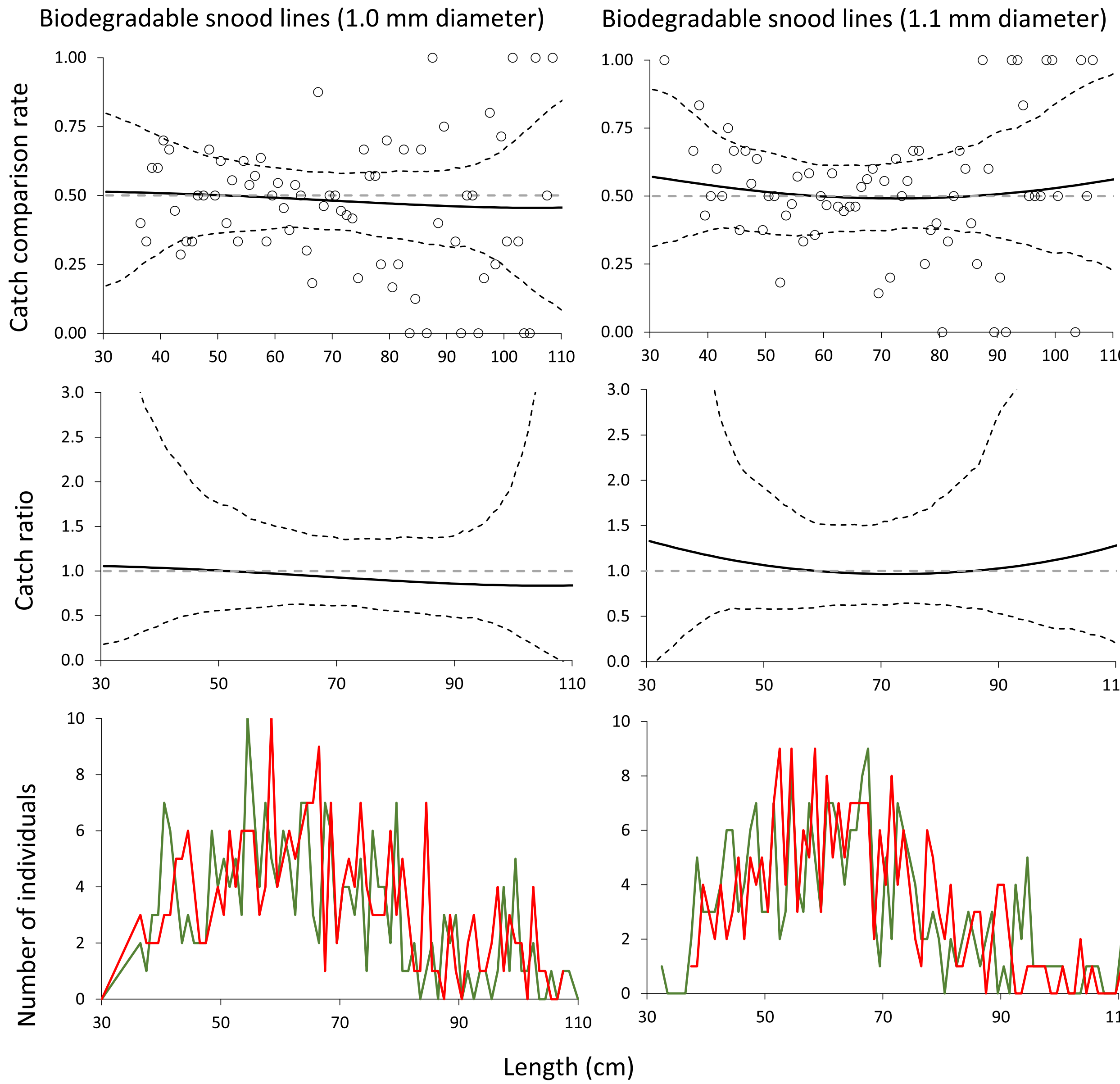

Fig. 5. Catch comparison and catch ratio analysis for cod. Left: biodegradable snoods with 1.0 mm thickness vs nylon snoods. Right: biodegradable snoods with 1.1 mm thickness vs nylon snoods. Upper graph: the modelled catch comparison rate (black curve) with 95% confidence intervals (black stippled curves). Circles represent experimental rate. Middle: the estimated catch ratio curve (black curve) with 95% confidence intervals (black stippled curves). The grey stippled lines at 0.5 and 1.0 represent the point at which both gears have an equal catch rate. Bottom: the length frequency distribution of fish captured with the biodegradable snoods (green line) and nylon snoods (red line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

with the results obtained from the material testing regarding tensile strength of the snoods. Thus, the highest estimated risk of losing the snoods is associated with the material with the lowest tensile strength, i. e., the biodegradable material with 1.0 mm thickness (mean tensile strength was 32.7 kg compared to nylon with mean breaking strength of 47.8 kg). Therefore, although not statistically significant, the results of snood loss and replacement indicate that the materials with higher tensile strength (i.e., nylon followed by biodegradable material of 1.1 mm thickness) has lower estimated risk of snood loss or replacement compared to biodegradable snoods with 1.0 mm thickness.

Further, the results showed no significant difference in catch efficiency of haddock and cod between the tested materials. Both Series 1 and Series 2 were carried out in similar conditions and the catch length dependency was also similar between the two series. No significant differences were found between fishing with snoods made of nylon and biodegradable materials. $CR_{average}$ did not show any significant differences between the snood line materials for either haddock or cod (Table 3). In addition, the results show that fishing with snoods with equal and increased twine thickness did not result in difference in catch efficiency. Specifically, in initial use of the biodegradable snoods, increasing the snood line thickness from 1.0 mm to 1.1. mm did not affect the catch efficiency when compared to conventionally used nylon snoods of 1.0 mm diameter. Moreover, the pairwise difference between biodegradable snoods on catch efficiency of haddock and cod was not significant.

Therefore, the results of this study show that use of biodegradable PBSAT material for snoods in longline fishery has a potential to reduce the marine plastic pollution. Moreover, since there are no significant differences in the estimated loss and replacement of snoods, the use of biodegradable material would not result in an increase of the associated

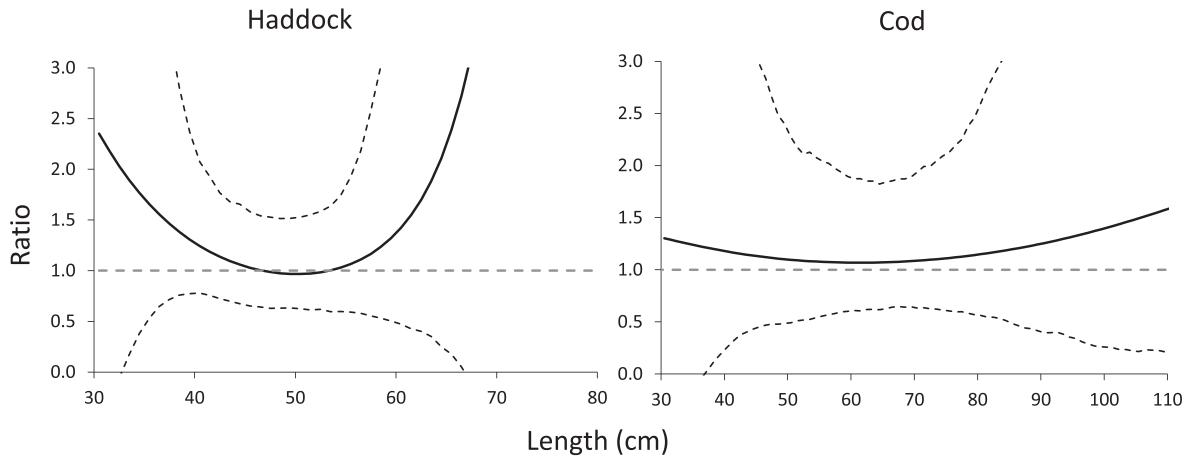

Fig. 6. Difference between biodegradable snoods of 1.0 and 1.1 twine diameters regarding catch efficiency of haddock and cod. Black line represents the estimated catch ratio curve with 95% confidence intervals (black stippled curves). Horizontal stippled line at 1.0 represents the point at which both gears have an equal catch rate.

Table 4
Mechanical properties of the snoods with corresponding diameters (in brackets). Mean values for tensile strength (kg) and elongation at break (%), with range of values (in brackets) and sample size for longlines used in the experiments.

Snood material	Elongation (%)	Tensile strength (kg)	Sample size
Nylon (1.0 mm)	33.1 (30.5–34.9)	47.8 (46.8–48.9)	3
Biodegradable (1.0 mm)	31.7 (30.6–33.1)	32.7 (32.5–32.9)	5
Biodegradable (1.1 mm)	29.3 (28.5–29.9)	37.0 (36.7–37.5)	5

Table 5
Difference in tensile strength compared by material types (Welch's t-test). Values in brackets are diameters of the material.

Compared materials	*p*-value
Biodegradable (1.0 mm) vs nylon (1.0 mm)	1.43E-03
Biodegradable (1.1 mm) vs nylon (1.0 mm)	2.00E-03
Biodegradable (1.0 mm) vs biodegradable (1.1 mm)	3.50E-07

work with replacing the snoods and loss in catch efficiency due to missing snoods and hooks during the fishing.

Because of the properties of the biodegradable PBSAT material, the lost snoods would not affect marine environment negatively even if the snoods are lost at the same quantities as with the nylon material due to biodegradation. Controlled laboratory aging test (Grimaldo et al., 2020) indicated that the chemical structure of the PBSAT polymer changed more than nylon over a 1000 h aging period (Fig. 7). The PBSAT monofilament exhibited changes in the surface in the form of degradation of the amorphous regions and the monofilament's crystalline regions. However, since aging tests are unable to replicate the outdoor conditions of field tests (i.e., temperature, light, bioactivity, and physical conditions), it was not possible to directly correlate the results of the field and laboratory tests. Grimaldo et al. (2020) concluded that it was unclear whether the fragmentation process observed in the aging test would have occurred in the marine environment or within the time needed for microbial activity to degrade the material.

It is also important to show that the new biodegradable materials do not have any negative ecotoxicological effects on the marine environment before the material is used in large scale. Generally, biodegradability is exclusively a function of the polymer structure and does not depend on the origin of the raw materials, whether they are petrochemically based or comes from renewable resources (Witt et al., 1999). Therefore, biodegradable polymers are an active area of investigation, particularly those polymers that can be produced from sustainable, biobased monomers, such as *co*polymers of polybutylene succinate (PBS) and PBS resin blended with polybutylene adipate-co-terephthalate (PBAT/PBSAT) that can be degraded by naturally occurring organisms. PBS-degrading microorganisms are widely distributed in the environment, including both actinomycetes, proteobacteria and fungi (Suyama et al., 1998; Ishii et al., 2008; Tokiwa et al., 2009). The ester linkages may be attacked by esterases and lipases in the environment (Tokiwa et al., 2009; Yamamoto-Tamura et al., 2015). MALDI-TOF analyses indicated fungal hydrolytic degradation of the ester bonds, with 10–30% mineralization during 100 days of incubation (Saadi et al., 2013). Anaerobic polyester degradation have also been reported (Pathak, 2017), while PBS degradation under anoxic conditions have not been reported. PBAT has been reported to be degraded by actinomycetes and fungi (Kijchavengkul et al., 2010; Meyer-Cifuentes et al., 2020). However, most PBAT-degrading microorganisms cannot use the monomer as carbon-source, suggesting bacterial cooperation for complete mineralization (Meyer-Cifuentes et al., 2020). Toxicology tests of aliphatic-aromatic copolyesters (i.e., Ecoflex-type) with *Daphnia magna* and *Photobacterium phosphoreum* under conditions present in a composting system showed no significant toxicological effects, neither for the monomeric intermediates nor for the oligomeric intermediates. This study concluded that there was no indication for an environmental risk when this material were introduced into the composting processes (Witt et al., 2000).

This study was conducted with new snood materials and for a limited period and, therefore, it lacks the time dimension effect on the performance of the materials. Therefore, this study should be followed up by tests of prolonged snood use in the fishery. However, such preliminary results are important to report to investigate which material has potential to be developed to commercial use and to avoid potential replication of unsuccessful research and development work (Thabane et al., 2016). The obtained results in this study showed no initial significant differences between biodegradable and nylon snoods and the two twine thicknesses of the biodegradable material regarding estimated snood loss, need for replacement and catch efficiency. However, this difference must be estimated over repeated use under wearing of the material. Since differences in tensile strength for the biodegradable material compared to nylon are estimated to increase over time and affect the catch efficiency of the material in other fisheries (i.e., Grimaldo et al., 2020), similar processes might take place over prolonged biodegradable snood line use. This could further affect the loss of snood lines and the catch efficiency. Furthermore, currently biodegradable PBSAT materials are more expensive compared to nylon (Standal et al., 2020) which might be related to limited production since the material is still in the

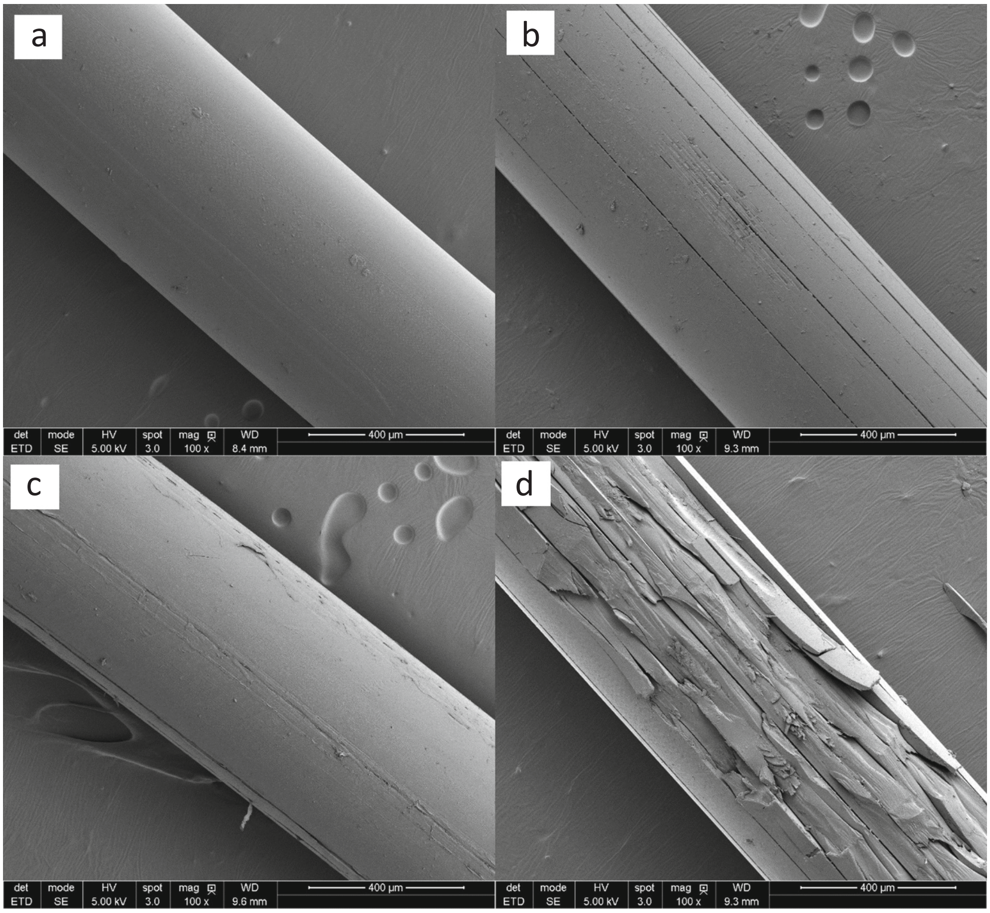

Fig. 7. Scanning electron microscope images of nylon monofilament samples (A and B images) and PBSAT monofilaments (C and D images) before (left) and after 1000 h of aging (right). Source: Grimaldo et al., 2020.

development phase. That is probably a barrier for replacement of nylon to biodegradable PBSAT snoods. However, this challenge might be overcome in time with reduction in costs if the production of the biodegradable material is scaled up and put in mass production.

CRediT authorship contribution statement

Kristine Cerbule: Conceptualization, data gathering and investigation, formal analysis, visualization, writing – original draft, writing – review and editing.

Eduardo Grimaldo: Conceptualization, writing – original draft, writing – review and editing, visualization, supervision.

Bent Herrmann: Conceptualization, software, writing – original draft, writing – review and editing, supervision.

Roger Larsen: Conceptualization, writing – original draft, supervision.

Jure Brčić: Writing – original draft, supervision.

Jørgen Vollstad: Data gathering and investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Use of biodegradable materials to reduce marine plastic pollution in small scale coastal longline fisheries

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ABSTRACT

Pollution from lost, abandoned, or discarded fishing gear is recognized as a global nature conservation concern. Longlining with hooks is a commonly applied fishing method in fisheries around the world. The longline gear consists of a mainline with a number of baited hooks that are attached to it by thinner twine (snoods) which are often made of plastic material such as polyamide (nylon) or polyester that degrades very slowly in the marine environment. During longline fishing, some of the snoods are lost at sea contributing to marine macro- and micro-plastic pollution. The extent of the snood loss is often unknown and can vary between different longline fisheries and fishing grounds. In this study, we estimated and compared the risk for the biodegradable and nylon snood loss in an Adriatic small scale longline fishery. Further, we compared the catch composition and estimated catch efficiency between biodegradable and nylon snoods for capture of common pandora (*Pagellus erythrinus*), two-banded seabream (*Diplodus vulgaris*) and axillary seabream (*Pagellus acarne*). The risk for nylon snood loss in this longline fishery (3 % for each snood for each deployment), demonstrate that the use of more environmentally friendly materials is necessary for nature conservation. No significant differences between the performance of the two materials regarding snood loss rate, hook loss rate, catch efficiency and catch composition were found during short-term usage in the fishery. Based on these results, future long-term testing is encouraged to investigate whether this promising performance of the biodegradable snood material is persistent over longer fishing periods.

1. Introduction

Marine debris comprise of different materials among which plastic is considered as the most represented marine litter category due to its resistance to degradation and thus the persistence in the environment (Strafella, Fabi, Depalatovic, Cvitković, & Fortibuoni, 2019). At a global level, it is estimated that 640 000 tons of fishing gear is lost, abandoned, or discarded each year, contributing to the marine plastic pollution (Macfadyen, Huntington, & Cappell, 2009). Abandoned, lost, or otherwise discarded fishing gear (ALDFG) is recognized as a problem of global concern due to increasing fishing effort and the use of non-degradable materials for the fishing gear, primarily plastics. Such ALDFG has negative ecological impacts on the marine environment due to macro- and microplastic pollution (Gilman, 2015). Therefore, pollution resulting from fishing gear losses is now considered as an important threat to the marine ecosystem (Strafella et al., 2019).

The rate of littering can vary greatly among regional areas depending on the scale of fishing activities at the local level and on the specific hydrological and geomorphological conditions (Pham, Ramirez-Llondra, Alt, & Amaro, 2014; Moschino et al., 2019; Strafella et al., 2019). In the Adriatic Sea, pollution resulting from lost, abandoned, or discarded fishing gear (such as longlines and gillnets) and aquaculture related debris accounts for half of the total plastic litter (Strafella et al., 2019). Specifically, in a study conducted in the western part of the Adriatic Sea, results showed that 78 % of the total marine debris consisted of derelict fishing gear where longlines were the most abundant

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gear identified (61 %) (Consoli, Romeo, Angiolillo, Canese, & Esposito, 2019).

Longlines with hooks are commonly used fishing gears in the world (He, Chopin, Suuronen, Ferro, & Lansley, 2021). One example of such fishery is the small-scale coastal longline fishery in the Adriatic targeting Sparidae species such as common pandora (*Pagellus erythrinus*) and two-banded seabream (*Diplodus vulgaris*). Each longline consists of a mainline and baited hooks that are connected to it by thinner twines called snoods. In demersal longline fisheries, snoods are often lost at sea during fishing because of, for example, snagging at the seafloor during the deployment or when the fish break the snood material (Cerbule et al., 2022). In many longline fisheries, the mainline and snoods are made from monofilament or multifilament polyamide (nylon) or multifilament polyester. Such plastic materials degrade slowly in the seawater in case of being lost. The ALDFG resulting from longlines and snoods do not represent a ghost fishing risk to the same extent as other fishing gear types such as gillnets. However, they can cause considerable long-term negative effects on the marine environment (Consoli et al., 2019) such as macro- and micro-plastic pollution when the material from lost snoods degrades into smaller plastic particles that can be ingested by marine organisms.

To limit the pollution caused by ALDFG, new biodegradable plastic materials are being tested in longline and gillnet fisheries (e.g., Kim et al., 2014a; 2014b; Grimaldo et al., 2019; Grimaldo et al., 2020; Cerbule et al., 2022; Cerbule et al., 2022). The aim of the biodegradable material is to limit marine plastic pollution as the material degrades in a shorter period when lost at sea compared to non-biodegradable materials such as nylon (Brakstad et al., 2022) and is aimed to degrade into components that are not harmful to the marine environment (Lucas et al., 2008).

Use of biodegradable materials such as polybutylene succinate-*co*-adipate-co-terephthalate (PBSAT) to replace non-biodegradable material (nylon) in snoods has earlier been tested in the Barents Sea fishery targeting cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) for reducing the plastic pollution resulting from lost snoods in this longline fishery (Cerbule et al., 2022). The results from these trials showed no differences in the short-term performance between the new and the traditionally used nylon material regarding capture efficiency and the snood loss rate. Therefore, this biodegradable material may be used to reduce the marine pollution resulting from the longline fisheries. However, such experiments could potentially show differences when testing the material performance in different fisheries and in different regions such as the coastal demersal longline fishery in the Eastern Adriatic. Specifically, the differences between environmental factors such as temperature and salinity between the two regions can affect the degradation of the biodegradable material and thus result in lower performance of the material in this fishery.

To be accepted commercially, the biodegradable snood loss should not exceed the loss of snoods made of nylon. Furthermore, the fishing gear performance of the biodegradable gear should be comparable to the traditionally used gear regarding the catch efficiency of the targeted species. Also, since the longline fishery in the Adriatic Sea addressed in the present study targets several fish species, the effect on the entire catch composition has to be investigated rather than focusing only on the primary target species. Specifically, although the commonly captured species are common pandora, two-banded seabream and axillary seabream (*Pagellus acarne*), several other species with a commercial value are caught in this fishery. Thus, the assessment of the whole composition of the species diversity in the catches, captured with both nylon and biodegradable snoods, would allow making a more holistic evaluation of the performance of the longlines in this fishery and of the effect of the gear on the full species community. Specifically, such approach would enable evaluating the effect of the gear changes on the full species community instead of focusing on a few target species.

Thus, the aims of this study were to address the following research questions:

- What is the risk of loss of conventional nylon snoods and snoods constructed of biodegradable PBSAT material in the Adriatic longline fishery?
- Is there any difference in catch efficiency of common pandora, two-banded seabream and axillary seabream if the snood material is changed from nylon to biodegradable PBSAT plastic material?
- What is the catch composition in small-scale longline fisheries in the Eastern Adriatic, and can material properties of PBSAT snoods change the catch composition in this fishery?

2. Materials and methods

2.1. Sea trials and experimental design

Sea trials were conducted with a small-scale fishing vessel (6.6 m LOA, 25.6 kW) during October 2022 in Croatia. The fishing grounds were located between N43°95854-44°12371 and E15°02750-15°18495 (Fig. 1a). The fishing depth varied between 33.0 and 64.7 m (Supplementary material 1).

During each deployment day, eight separate mainlines with snoods were deployed close together on a rocky substrate at the edge of a reef. Therefore, the deployment pattern varied with some of the mainlines being deployed parallel to each other while others were deployed in a consecutive order (in a row) depending on the variations in the seabed conditions. The mainlines were made of monofilament nylon with twine diameter of 1 mm. Each mainline consisted of 25 biodegradable and 25 nylon snoods (50 snoods and hooks in total) with twine diameter of 0.44 mm. We used the same twine thickness in both biodegradable and nylon snoods in this experiment to avoid differences in catch efficiency that can potentially be caused by alternating snood diameter (Herrmann, Sistiaga, Rindahl, & Tatone, 2017).

Biodegradable (B) and nylon (N) snoods were attached in an alternated order on the mainline so that each material type was exposed to the same spatial variability regarding fish availability: N-B-N-B-N-B-N-(..) (Fig. 1b). The distance between each snood was ~ 6.4 m. Therefore, the total length of each mainline was 314 m. In all longlines, same type of hooks was used (J-hooks, VMC 9746S, no. 13). Prior to each deployment, hooks on all longlines were baited manually using squid and stored in tubs.

During retrieval of the longlines, catches were sorted and counted by species and separated according to type of the snoods (biodegradable or nylon). Further, all individuals of common pandora (minimum conservation reference size (MCRS) = 15 cm), axillary seabream (MCRS = 18 cm) and two-banded seabream (MCRS = 17 cm) were measured for the total length to the closest 0.5 cm below.

After each fishing trip, the numbers of lost hooks and lost snoods with hooks were recorded for each snood type (biodegradable and nylon, respectively). Specifically, we separately recorded two situations regarding hook and snood losses. First, the situation where the snood was broken close to the hook resulting in a hook loss and need of attachment of new hook on the existing snood. Second, a situation where the snood was broken closer to the mainline, resulting in need for replacement of snood and attachment of a new hook. Before new deployments with the same mainlines, new hooks or snoods with hooks, respectively, were attached where necessary so that the number of snoods was identical for each longline deployment and consisted of 50 snoods on each mainline.

2.2. Estimating probabilities of hook and snood loss

To estimate probabilities for losing the hook or the hook together with the snood k for mainline i, during deployment j, we recorded the damage status of the specific nylon snood on the specific mainline and specific deployment sN_{ijk} according to:

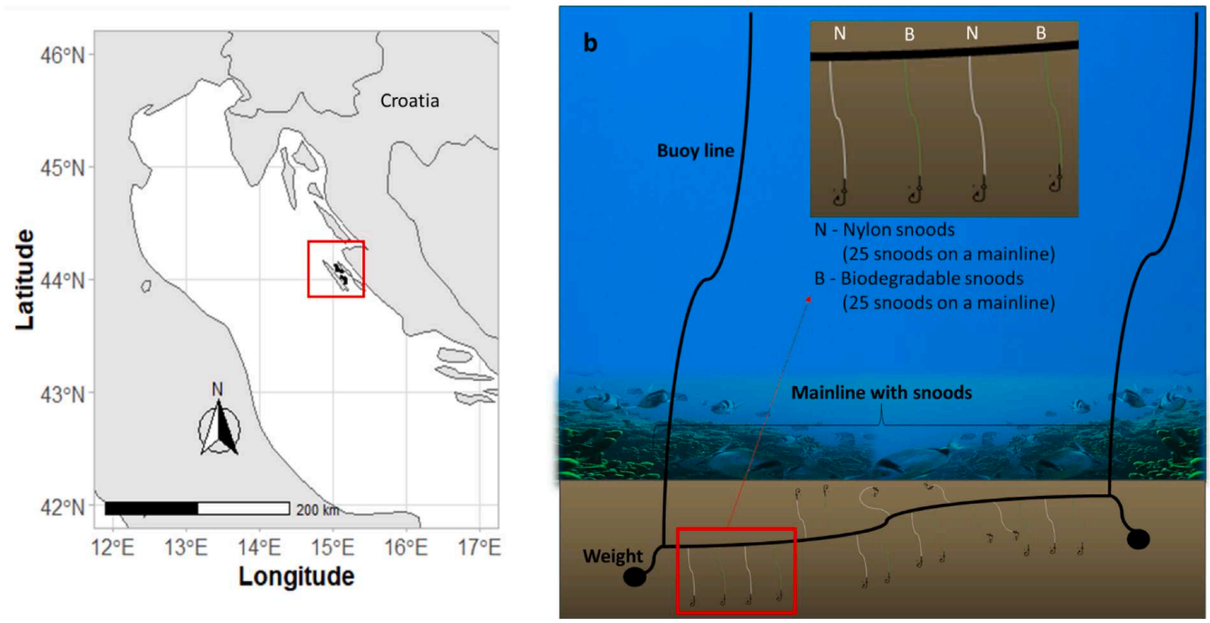

Fig. 1. Map of the location where the experiments were conducted (a) and illustration of experimental setup (b) showing longline components.

$$sN_{ijk} = \begin{cases} 0 & : \textit{snood line and hook intact} \\ 1 & : \textit{hook lost but snood intact} \\ 2 & : \textit{hook and part or entire snood lost} \end{cases} . \tag{1}$$

For the biodegradable snoods, we used the same approach and scored the status sB_{ijk} as for the nylon snoods (Eq. (1)).

The probabilities for losing only the hook for nylon (phN_{ij}) and biodegradable (phB_{ij}) snoods during one specific deployment j of mainline i were estimated by:

$$phN_{ij} = \frac{1}{m}\sum_{k=1}^{m} g\left(sN_{ijk}\right)$$

$$phB_{ij} = \frac{1}{m}\sum_{k=1}^{m} g\left(sB_{ijk}\right) \tag{2}$$

$$\textit{with}$$

$$g(s) = \begin{cases} 0 & \forall \quad s = 0 \\ 1 & \forall \quad s > 0 \end{cases}$$

where m is the number of snoods on the mainline made of nylon or biodegradable materials, respectively ($m = 25$).

For estimating the probability of losing both the hook and the snood for nylon ($pshN_{ij}$) and biodegradable ($pshB_{ij}$) materials, respectively, during one specific deployment j of mainline i, we used:

$$pshN_{ij} = \frac{1}{m}\sum_{k=1}^{m} g\left(sN_{ijk}\right)$$

$$pshB_{ij} = \frac{1}{m}\sum_{k=1}^{m} g\left(sB_{ijk}\right) . \tag{3}$$

$$\textit{with}$$

$$g(s) = \begin{cases} 0 & \forall \quad s < 2 \\ 1 & \forall \quad s = 2 \end{cases}$$

The uncertainties for probabilities of losing the hook or the snood together with the hook during one deployment j for the specific mainline i were estimated by bootstrapping for nylon and biodegradable snoods separately by resampling (1000 bootstrap repetitions) the individual snoods on the mainline and applying Eq. (1)–(3). Uncertainties were given as Efron 95 % confidence intervals (CI) (Efron, 1982) similar as in Cerbule et al. (2022).

For inferring the effect on probability for hook loss or snood and hook loss by changing the snood material for one specific deployment j of specific mainline i, we used:

$$\begin{aligned} \Delta ph_{ij} &= phB_{ij} - phN_{ij} \\ \Delta psh_{ij} &= pshB_{ij} - pshN_{ij} \end{aligned} . \tag{4}$$

The advantage of inferring the difference in probability for hook and snood and hook loss between the two materials for the individual deployments is that the two materials are exposed to the same varying fishing conditions. This increases the power in inferring differences regarding the material type used in snoods.

Efron 95 % percentile CIs for Δph_{ij} and Δpsh_{ij} were obtained based on the two bootstrap populations of results (1000 bootstrap repetitions in each). As they were obtained independently, a new bootstrap population of results was created by (Herrmann, Krag, & Krafft, 2018):

$$\begin{aligned} \Delta ph_{ij_q} &= phB_{ij_q} - phN_{ij_q} q \in [1 \cdots 1000] \\ \Delta psh_{ij_q} &= pshB_{ij_q} - pshN_{ij_q} q \in [1 \cdots 1000] \end{aligned} \tag{5}$$

where q denotes the bootstrap repetition index. As the bootstrap resampling were independent for the two materials, it is valid to generate the bootstrap population of results for the difference based on Eq. (5) using the two independently generated bootstrap files (Herrmann et al., 2018; Cerbule et al., 2022). In case Δph_{ij_q} or Δpsh_{ij_q} do not include the value 0.0 in the CIs, the hook or snood and hook loss probability between biodegradable and nylon material would be significantly different.

During each experimental fishing day j, the mainlines were deployed on slightly different fishing grounds with some similarities in the conditions the fishing took place. Therefore, it is relevant also to quantify the mean values for hook and snood and hook loss probability based on the results for individual mainlines deployed during the same day j. Therefore, we used the following equation:

$$
\begin{aligned}
phN_j &= \frac{1}{a}\sum\nolimits_{i=1}^{a} phN_{ij} \\
pshN_j &= \frac{1}{a}\sum\nolimits_{i=1}^{a} pshN_{ij} \\
phB_j &= \frac{1}{a}\sum\nolimits_{i=1}^{a} phB_{ij} \\
pshB_j &= \frac{1}{a}\sum\nolimits_{i=1}^{a} pshB_{ij} \\
\Delta ph_j &= \frac{1}{a}\sum\nolimits_{i=1}^{a} \Delta ph_{ij} \\
\Delta psh_j &= \frac{1}{a}\sum\nolimits_{i=1}^{a} \Delta psh_{ij}
\end{aligned}
\tag{6}
$$

where a is the number of mainlines fished during the specific deployment day. In Eq. (6), we applied Eq. (2)–(4). Uncertainties for the values estimated by Eq. (6) were obtained by bootstrapping by resampling results for the a mainlines deployed for the specific day j. We used Efron 95 % CIs which were obtained by using 1000 bootstrap repetitions.

Further, to quantify the mean probabilities for hook loss and snood and hook loss, respectively, for the complete fishing trials, we used Eq. (6) in:

$$
\begin{aligned}
phN &= \frac{1}{u}\sum\nolimits_{j=1}^{u} phN_j \\
pshN &= \frac{1}{u}\sum\nolimits_{j=1}^{u} pshN_j \\
phB &= \frac{1}{u}\sum\nolimits_{j=1}^{u} phB_j \\
pshB &= \frac{1}{u}\sum\nolimits_{j=1}^{u} pshB_j \\
\Delta ph &= \frac{1}{u}\sum\nolimits_{j=1}^{u} \Delta ph_j \\
\Delta psh &= \frac{1}{u}\sum\nolimits_{j=1}^{u} \Delta psh_j
\end{aligned}
\tag{7}
$$

where u is the total number of deployment days. Uncertainties for the values estimated by Eq. (7) were obtained by bootstrapping results for the u deployment days. We used Efron 95 % CIs which were obtained by using 1000 bootstrap repetitions.

2.3. *Estimating the length-dependent catch efficiency between longlines with different snood materials*

Comparison of catch efficiency for the three target species (two-banded seabream, axillary seabream and common pandora) between biodegradable and nylon snoods was estimated by analysing the relative catch efficiency between biodegradable and nylon snoods separately for each species following procedure descried below. Specifically, we estimated the length-dependent catch comparison rate $CC(l,\boldsymbol{v})$ and catch ratio $CR(l,\boldsymbol{v})$ for deployment of all mainlines during all deployment days to investigate potential differences in catch efficiency when using biodegradable instead of nylon snoods (Herrmann et al., 2017; Cerbule et al., 2022). We assumed the same fish availability regarding the abundance and size structure for both biodegradable and nylon snoods since they were deployed in an alternated order on each mainline. Therefore, we used paired catch comparison analysis for estimating the catch efficiency (Lomeli et al., 2021). Specifically, we used the count numbers of the three most frequently species caught with biodegradable and nylon snoods, separately) to determine whether there was a significant difference in the catch efficiency between the two snood types.

To assess the relative length dependent catch comparison rate (CC_l) of changing from nylon to biodegradable snoods, we used Eq. (8) (i.e., Lomeli et al., 2021):

$$CC_l = \frac{\sum_{j=1}^{u}\sum_{i=1}^{m} nB_{lij}}{\sum_{j=1}^{u}\sum_{i=1}^{m}\left\{nB_{lij} + nN_{lij}\right\}}. \tag{8}$$

In Eq. (8), $\boldsymbol{nB_{lij}}$ and $\boldsymbol{nN_{lij}}$ are the number (n) of fish of the selected species with length l, caught in deployments j for mainlines i with the biodegradable (B) and nylon (N) snoods, respectively. The functional description of the catch comparison rate $CC(l,\boldsymbol{v})$ that experimentally was expressed by Eq. (8) was attained using maximum likelihood estimation by minimizing the Expression (9) (Lomeli et al., 2021):

$$-\sum_{j=1}^{u}\sum_{i=1}^{m}\sum_{l}\left\{nB_{lij}\times ln[CC(l,\boldsymbol{v})] + nN_{lij} ln[1.0 - CC(l,\boldsymbol{v})]\right\}. \tag{9}$$

In Expression (9), $\boldsymbol{v}$ represents the parameters describing the catch comparison curve defined by $CC(l,\boldsymbol{v})$ (Lomeli et al., 2021). The experimental CC_l was modelled by the function $CC(l,\boldsymbol{v})$ using the following equation (Herrmann et al., 2017):

$$CC(l,\boldsymbol{v}) = \frac{exp[f(l, v_0, \cdots, v_k)]}{1 + exp[f(l, v_0, \cdots, v_k)]}. \tag{10}$$

In Eq. (10), f is a polynomial of order k with coefficients v_0-v_k, such that $\boldsymbol{v} = (v_0,\ldots,v_k)$ (Lomeli et al., 2021). We considered f of up to an order of 4. Leaving out one or more of the parameters $v_0 \ldots v_4$, at a time resulted in 31 additional candidate models for $CC(l,\boldsymbol{v})$. Among these models, the catch comparison rate was estimated using the 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 based on the p-value. The p-value is calculated based on the model deviance and degrees of freedom (DOF) (Wileman, Ferro, Fonteyne, & Millar, 1996; Herrmann et al., 2017). Therefore, suitable fit statistics for the combined model to describe the experimental data sufficiently well should include a p-value > 0.05 (Lomeli et al., 2021). If the p-value exceeded 0.05, the deviance and the DOF were assessed to determine if the result was due to structural problems when modelling the experimental data, or due to overdispersion. Further, to provide a direct relative value of the catch efficiency between the two snood materials, we used the following catch ratio $CR(l,\boldsymbol{v})$ equation (Lomeli et al., 2023):

$$CR(l,\boldsymbol{v}) = \frac{CC(l,\boldsymbol{v})}{[1 - CC(l,\boldsymbol{v})]}. \tag{11}$$

We used a double bootstrapping method with 1000 bootstrap repetitions to estimate the Efron 95 % CIs for the catch comparison and catch ratio (Efron, 1982). If the catch efficiency of the biodegradable and nylon snoods is equal, the catch comparison rate is equal to 0.5 and the catch ratio is 1.0 (Lomeli et al., 2023; Cerbule et al., 2022).

2.4. *Estimation of length-integrated average catch ratio*

Based on the experimental catch data, length-integrated average values for the catch ratio for target sized fish of each species above the MCRS ($CR_{average+}$) were assessed utilizing the following equation (Eq. (12) (Herrmann, Grimaldo, Brčić, & Cerbule, 2021):

$$CR_{average+} = 100 \times \frac{\sum_{j=1}^{u}\sum_{i=1}^{m}\sum_{l\geq MLS} nB_{lij}}{\sum_{j=1}^{u}\sum_{i=1}^{m}\sum_{l\geq MLS} nN_{lij}}. \quad (12)$$

In case the estimated $CR_{average+}$ value includes 100 % within the CIs, this implies no significant differences in the length-integrated average values between biodegradable and nylon snoods, while values significantly higher than 100 % would mean that biodegradable snoods are retaining significantly more target sized fish compared to gear with nylon snoods (Herrmann et al., 2017). Contrary to the length-dependent evaluation of $CR(l,\boldsymbol{v})$, the $CR_{average+}$ is specific for the fish population structure encountered during the fishing trials (Herrmann et al., 2017). Therefore, it cannot be extrapolated to other scenarios in which the size structure of the three fish species may be different.

2.5. Quantification of species composition in longline catches

To quantify the species composition observed in longline catches with biodegradable and nylon snoods, respectively, we used species dominance estimation (Cerbule et al., 2022; Herrmann et al., 2022). This estimate takes into consideration all observed species in the catch and is measuring how much one or few species dominate among the other species in the catches (Maurer & McGill, 2011). In this study, we estimated the catch composition for each snood type (biodegradable and nylon) separately by estimating the dominance patterns of species observed in our samples averaged over snood deployments.

The species dominance patterns in catch composition retained by biodegradable and nylon snoods were estimated separately, by using the following equation (Cerbule et al., 2022; Herrmann et al., 2022):

$$d_e = \frac{\sum_{j=1}^{u}\sum_{i=1}^{m} n_{eij}}{\sum_{e=1}^{t}\sum_{j=1}^{u}\sum_{i=1}^{m} n_{eij}}. \quad (13)$$

In Eq. (13), n_{eij} is the count number of individuals of species e caught in deployment j for mainline i with the specific snood material (biodegradable or nylon). t is the maximum species ID following the approach for species ranking as outlined in Herrmann et al. (2022).

Further, we used cumulative dominance curves to represent species dominance patterns by showing the cumulative proportional abundances of the species plotted against the species rank (Warwick, Clarke, & Somerfield, 2008). Cumulative dominance is estimated as follows (Eq. (14) (Cerbule et al., 2022; Herrmann et al., 2022):

$$D_E = \frac{\sum_{e=1}^{E}\sum_{j=1}^{u}\sum_{i=1}^{m} n_{eij}}{\sum_{e=1}^{t}\sum_{j=1}^{u}\sum_{i=1}^{m} n_{eij}}. \quad \text{with} \quad 1 \leq E \leq t \quad (14)$$

In Eq. (14) E is the species ID summed up in the nominator (Cerbule et al., 2022; Herrmann et al., 2022). Following the approach in Herrmann et al. (2022) and Cerbule et al. (2022), we kept a fixed species IDs for species in all catches in the cumulative dominance curves to allow comparison of the steepness of the cumulative dominance curves. This approach allows obtaining an overview of how many species are dominant and the distribution of their relative dominance in longline catches with biodegradable and nylon snoods, respectively. The steeper the resulting cumulative dominance curve is, the more dominated the particular species is in the sample. On the contrary, the horizontal parts in cumulative dominance curves would show that the particular species are not abundant (Cerbule et al., 2022).

We applied the same approach for uncertainty estimation for the observed catch compositions as in Herrmann et al. (2022) and Cerbule et al. (2022). Specifically, we obtained Efron 95 % CIs (Efron, 1982) for dominance patterns following the procedure described in Herrmann et al. (2022). This procedure enables estimation of the uncertainty around the dominance values induced by limited sample sizes for individual deployments as well as for between deployment variation in species dominance values.

The difference Δd in species dominance d in the nylon (N) and biodegradable (B) snoods was estimated by (Cerbule et al., 2022; Herrmann et al., 2022):

$$\Delta d_e = dB_e - dN_e \quad (15)$$

where dB_e and dN_e are obtained by using Eq. (13). CIs for Eq. (15) were obtained based on separate bootstrap populations for dB_e and dN_e similar as in Cerbule et al. (2022). When inferring for significance, we inspected if the CIs for the difference contained the value 0.0. If 0.0 value was within the CIs, no significant difference was detected (Cerbule et al., 2022; Herrmann et al., 2022). The analyses described above in sections 2.3-2.5 were conducted using the software tool SELNET (Herrmann, Sistiaga, Nielsen, & Larsen, 2012), software version date 27 March 2023.

3. Results

3.1. Risk of hook and snood loss

During the experiments, eight mainlines with 50 snoods each were deployed during six fishing trips, resulting in 48 longline deployments. Each deployment had 200 biodegradable and 200 nylon snoods. During our trials, we observed both situations of loosing snoods together with hooks (Fig. 2a) and loosing hooks without the snoods (Fig. 2b).

The total number of observed lost hooks over all deployments were 95 and 69 for the snoods with biodegradable and nylon material, respectively. Of those, cases where the hook was lost together with part of the snood was 53 for the biodegradable snoods and 36 for the nylon snoods.

The estimated probabilities for losing a hook or a snood together with hook during each deployment separately varied over the deployments. However, the results did not show any significant differences between the two materials (Fig. 3a and 4a) except of one instance during deployment on day 4 where a higher loss of hooks from snoods of biodegradable (phB_{ij}) material compared to nylon (phN_{ij}) was shown (Fig. 3a). However, no other significant differences for hook or snood and hook loss probabilities between the two materials during the deployments were observed. Furthermore, these differences were not significant either when compared for each deployment day based on the results for the individual mainlines deployed (Fig. 3b and 4b), although there was an indication that more snoods of biodegradable materials were lost during each deployment day.

Finally, for the whole fishing trials with biodegradable and nylon snoods, the estimated probabilities for losing a hook attached to the mainline by biodegradable (phB) or nylon (phN) snoods were 7.91 % (CI: 5.17–11.17 %) and 5.75 % (CI: 2.75–9.83 %), respectively. Similarly, as when considering the snood loss for each deployment or deployment day, the pairwise difference between the probabilities for hook losses between the two material types (Δph_{ij}) for the whole fishing trials did not show any statistically significant differences (Fig. 3c). Further, the pairwise difference between the probabilities for loss of snoods together with hooks (Δpsh_{ij}) showed an indication that the probability of snood and hook loss is higher for the biodegradable material. Specifically, the estimated snood and hook loss for the whole fishing trials was 4.42 % (CI: 2.58–6.50 %) for biodegradable snoods and 3.00 % (CI: 1.00–5.92 %) for snoods of nylon material (Fig. 4c).

3.2. Catch efficiency of biodegradable versus nylon snoods

In total, 347 common pandora, 167 axillary seabream and 87 individuals of two-banded seabream, were captured and included in the analysis (Table 1). The fit statistics for the catch comparison analysis showed that the modelled curve fitted the experimental data well for

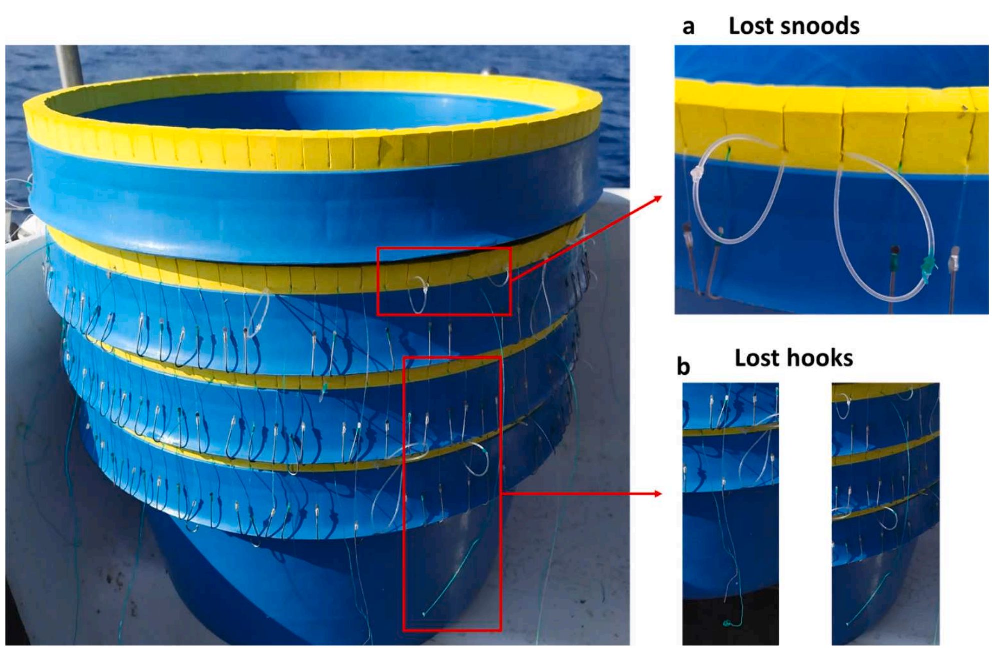

Fig. 2. Examples of cases with snood (a) and hook (b) loss after longline retrieval.

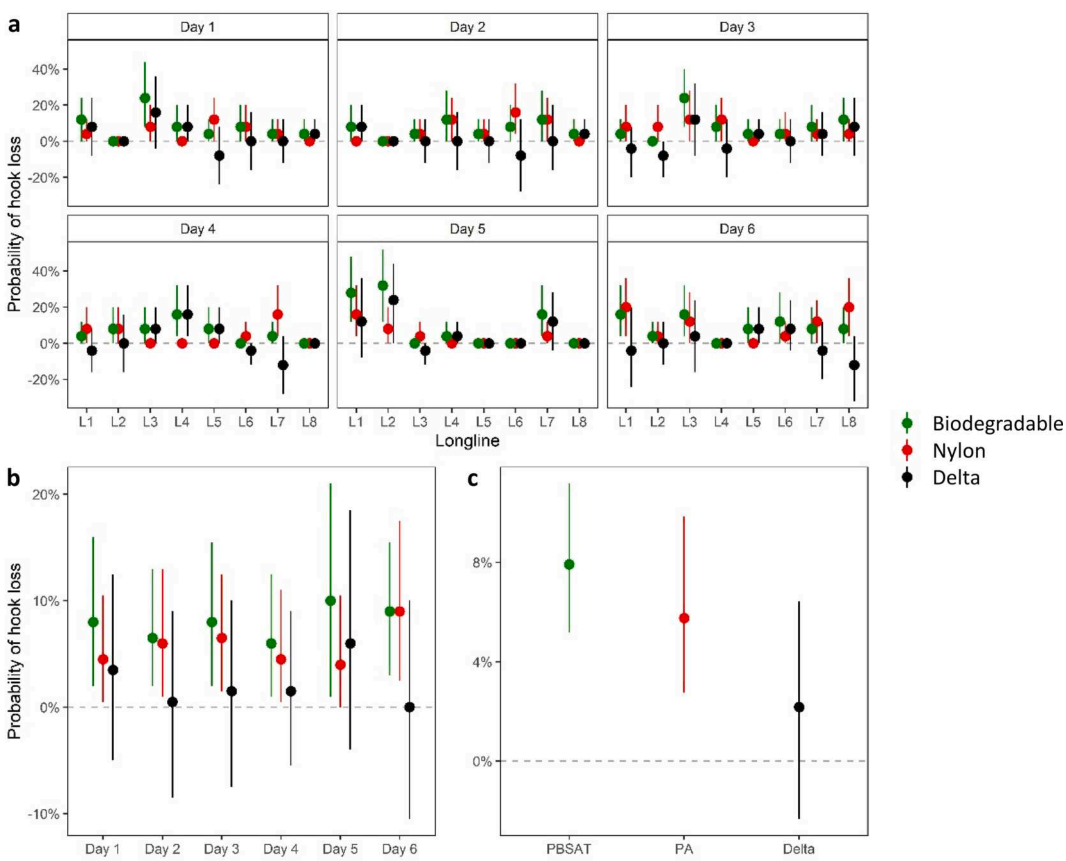

Fig. 3. Probabilities (in %) for losing a hook of biodegradable (green) and nylon (red) material. a: Probabilities estimated for each deployment in each day (L 1–8). b: Probabilities estimated for each deployment day (Day 1–6). c: Mean probabilities for hook loss for the complete fishing trials for the two snood materials separately. Black points are pairwise difference inferring the effect on probability for hook loss by changing the snood materials.

axillary seabream since the *p*-value was > 0.05 (Wileman et al., 1996). For two-banded seabream and common pandora, the *p*-value was < 0.05 (Table 1); however, the catch comparison curves represented the trends in experimental data well (Fig. 5), therefore, the low *p*-value was assumed to be due to overdispersion in the data.

Both snood material types had similar patterns of capturing all three species regarding the fish length, with most individuals being above the MCRS for all species (Fig. 5). Further, biodegradable snoods did not

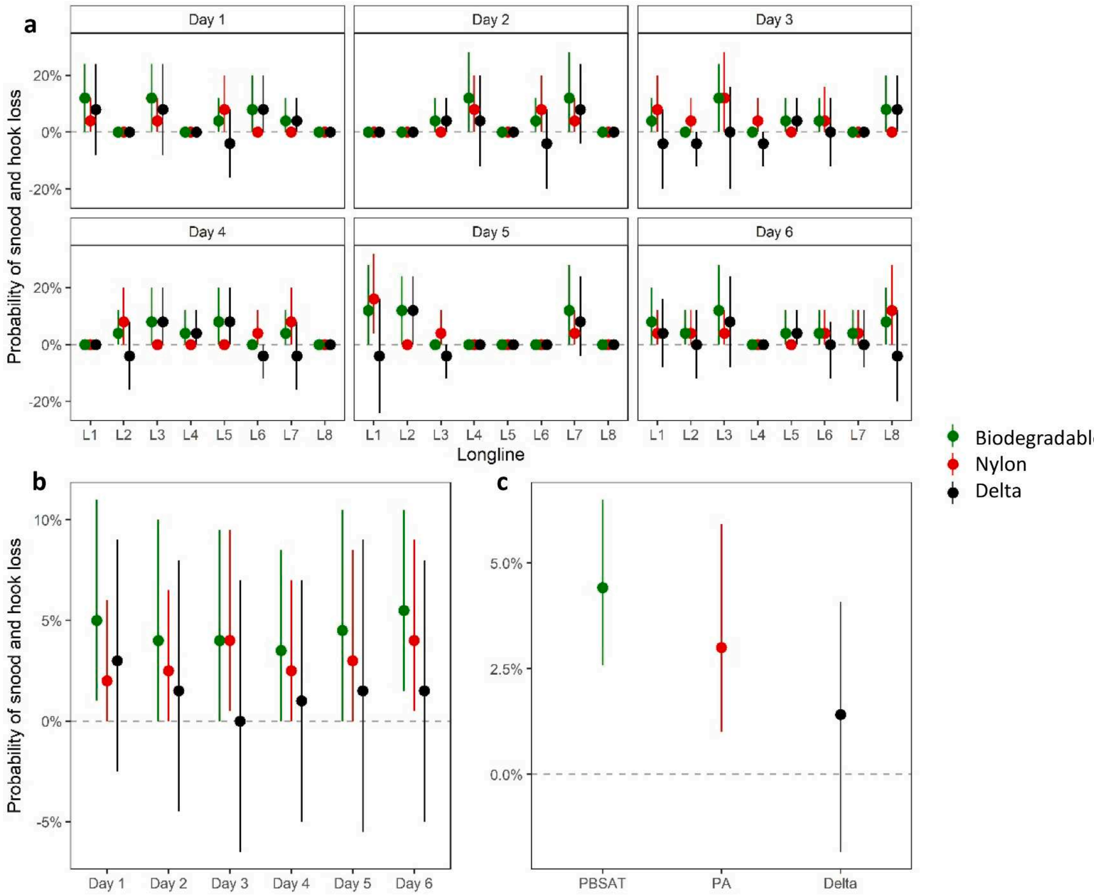

Fig. 4. Probabilities (in %) for losing a snood together with hook of biodegradable (green) and nylon (red) material. a: Probabilities estimated for each deployment (L 1–8). b: Probabilities estimated for each deployment day (Day 1–6). c: Mean probabilities for snood and hook loss for the complete fishing trials for the two snood materials separately. Black points are pairwise difference inferring the effect on probability for snood and hook loss by changing the snood materials.

Table 1
Number of fish observed, fit statistics, and catch comparison results. Values in brackets represent 95 % Efron confidence CIs. DOF denotes degrees of freedom.

	Common pandora	Two-banded seabream	Axillary seabream
Number of individuals; biodegradable snoods	169	50	83
Number of individuals; nylon snoods	178	37	84
p-value	0.0020	0.0290	0.1481
Deviance	59.98	28.32	20.66
DOF	32	16	15
CRaverage+ (%)	96.08 (75.44–117.39)	108.33 (81.81–138.09)	96.08 (72.41–132.56)

show significant differences in catch efficiency for any of the three species when compared to the nylon snoods (Fig. 5). Specifically, the average catch ratio (*CRaverage+*) for target sized individuals (i.e., over MCRS) of the three species did not show any significant differences when using biodegradable instead of nylon snood material (Table 1).

3.3. Species dominance pattern in catch compositions

During the trials in this coastal longline fishery, a total of 338 and 347 individuals belonging to 21 species were captured by biodegradable and nylon snoods, respectively (Table 2).

The species cumulative dominance patterns (Fig. 6) and species dominance values (Supplementary material 2) showed that the longline catch in this fishery is dominated by the three main target species, the two-banded seabream, axillary seabream and common pandora. However, during our experiments, other species contributed to the catches to a small extent as shown by the dominance curves for the cumulative dominance values. Thus, some species were recorded in only few deployments (Table 2). The species cumulative dominance patterns did not differ significantly between catches using biodegradable or nylon snood material (Fig. 6; Supplementary material 2). The pairwise difference in cumulative dominance (delta) curves (Fig. 6) is used for inferring for differences in catch composition between longline catches with snoods of biodegradable and nylon materials. No significant differences between the two materials were detected regarding the catch composition in species dominance as the results included 0.0 within the obtained CIs.

4. Discussion

In this study, we investigated whether biodegradable PBSAT material can be used to reduce marine macro- and micro-plastic pollution caused by lost snoods in the Adriatic small scale longline fishery. Specifically, we investigated the short term differences in performance between the materials by estimating the risk of hook and snood and hook losses, catch efficiency, and catch composition in this fishery.

During this study, we differentiated between hook loss and snood and hook loss probability. The hook loss alone implies an attachment of new hook on an existing snood for the next deployment of the longline which results in additional work and expenses for the fishers regarding use of new hooks. However, the second situation when the hooks are lost

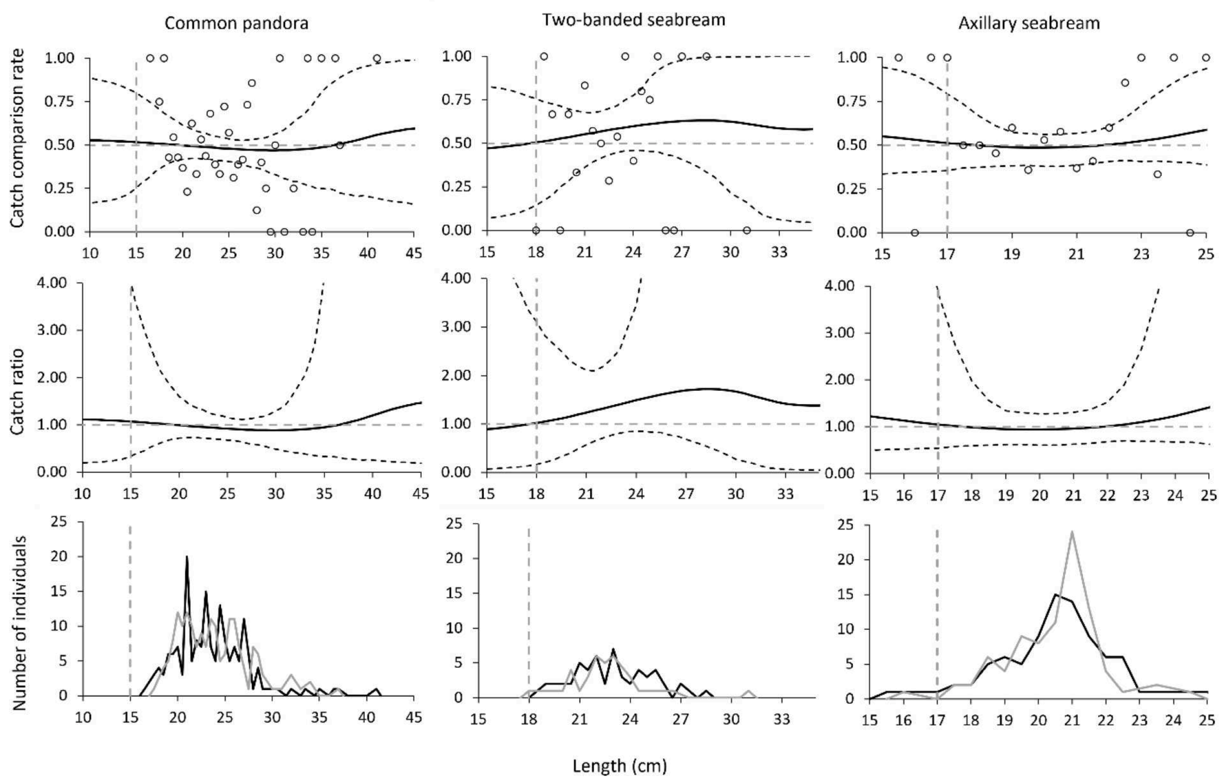

Fig. 5. Catch comparison and catch ratio analysis for common pandora, two-banded seabream and axillary seabream. Upper graphs: the modelled catch comparison rates (black curves) with 95 % CIs (black stippled curves). Circles represent experimental rate. Middle graphs: the estimated catch ratio curves (black curves) with 95 % CIs (black stippled curves). The grey stippled lines at 0.5 and 1.0 represent the point at which both gears have an equal catch rate. Lower graphs: the length frequency distribution of fish captured with the biodegradable snoods (black line) and nylon snoods (gray line). Vertical stippled lines show the minimum conservation reference size for each species.

Table 2
List of species and number of individuals sampled during the experiments with biodegradable and nylon snood.

Species ID	Species name	Common name	Number of individuals	
			Biodegradable	Nylon
1	*Pagellus erythrinus*	Common pandora	173	179
2	*Pagellus acarne*	Axillary seabream	88	90
3	*Diplodus vulgaris*	Common two-banded seabream	50	37
4	*Trachurus trachurus*	Atlantic horse mackerel	3	9
5	*Echelus myrus*	Painted eel	6	3
6	*Sparus aurata*	Gilthead seabream	2	7
7	*Conger conger*	European conger	4	3
8	*Mustelus punctulatus*	Blackspotted smooth-hound	2	4
9	*Boops boops*	Bogue	2	1
10	*Merluccius merluccius*	European hake	2	1
11	*Scorpaena notata*	Small red scorpionfish	1	2
12	*Diplodus annularis*	Annular seabream	0	2
13	*Myliobatis aquila*	Common eagle ray	0	2
14	*Scyliorhinus stellaris*	Nursehound	1	1
15	*Serranus hepatus*	Brown comber	1	1
16	*Spondyliosoma cantharus*	Black seabream	0	2
17	*Squilla mantis*	Spottail mantis squillid	0	2
18	*Pagrus pagrus*	Red porgy	0	1
19	*Raja miraletus*	Brown ray	1	0
20	*Serranus scriba*	Painted comber	1	0
21	*Spicara smaris*	Picarel	1	0

together with whole or part of the snoods, would imply that the plastic material of lost snoods stays in the marine environment. Therefore, in longline fisheries this situation is more critical regarding the increase of plastic pollution. In this longline fishery in the Adriatic Sea, the estimated mean snood loss for the whole fishing trials reached 3.00 % (CI: 1.00–5.92 %) during a longline deployment when using traditional nylon material. Taking into consideration that there are several vessels operating in a relatively small area with regular longline deployments, this amount implies a considerable source of plastic pollution. The Adriatic Sea is one of the areas highly affected by benthic litter (Pasquini, Ronchi, Strafella, Scarcella, & Fortibuoni, 2016). Microplastic pollution in the Adriatic Sea has been demonstrated in the marine environment, including surface waters, sediments, and biota (Schmid, Cozzarini, & Zambello, 2021). In longline fisheries, the amount of snood loss can vary over the fishing grounds and the way how the longlines are being operated. For example, in earlier study estimating the snood loss in a coastal longline fishery in the Barents Sea, the fraction of lost nylon monofilament snoods was close to 5 % during each longline deployment (Cerbule et al., 2022). However, Lomeli et al. (2023), reported an observation of hook damage and snood loss (e.g., due to breaking of snood) to be around 1.3 % in the fishery targeting Pacific halibut (*Hippoglossus stenolepis*) when using hard-lay twine (Powers #72 braided nylon cover with a Dyneema® polyester core).

In this study, the estimated loss of snoods when using the biodegradable material did not differ significantly when compared to nylon and was 4.42 % (CI: 2.58–6.50 %). This difference was neither significant when considered over deployment days or single longline deployments. Furthermore, there were no significant differences between biodegradable and nylon snoods except for only one instance when the hook loss probability for a single mainline in a single deployment between the two materials was significant. However, since no significant

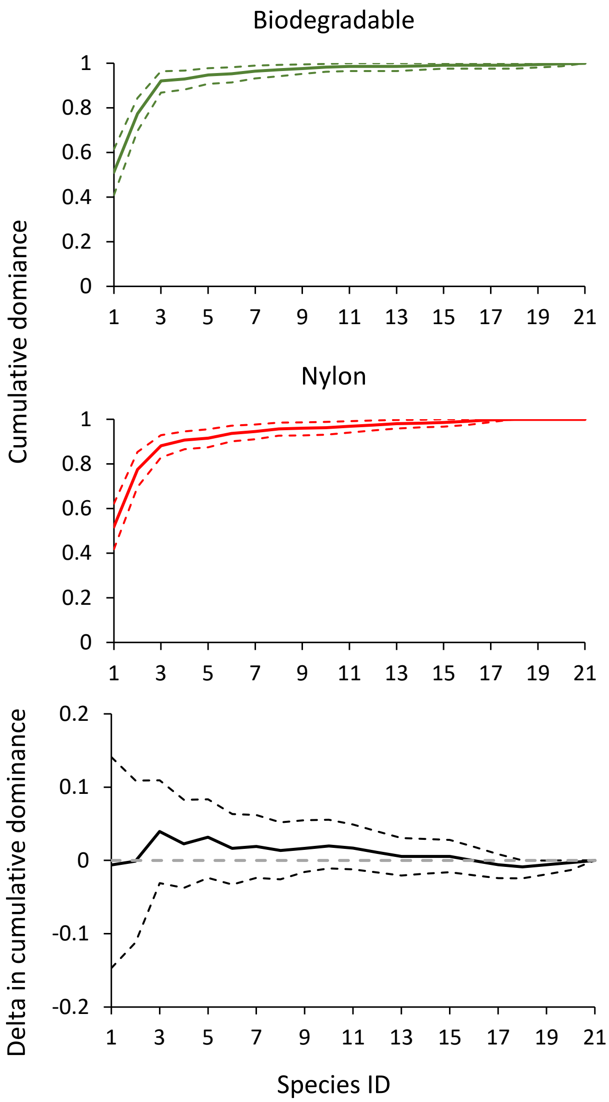

Fig. 6. Cumulative dominance curves for catch composition of biodegradable snoods (green; upper graph) and nylon snoods (red; middle graph) and pairwise difference (delta) in cumulative dominance curves for biodegradable versus nylon snoods (lower graph). Dashed lines are 95 % CIs.

differences in hook loss between snoods of the two materials were observed in any of the remaining 47 longline deployments, this difference can be coincidental. Therefore, the results of this study are in line with the earlier study in the Barents Sea where no significant differences in snood losses were observed in initial trials comparing nylon and biodegradable PBSAT plastic snoods during the initial trials (Cerbule et al., 2022).

For the three most frequently captured species (common pandora, two-banded seabream and axillary seabream), no significant differences in catch efficiency were observed when comparing the two snood materials for initial use. Specifically, snoods of both materials showed similar efficiency at capturing individuals of the three species of all sizes observed. The average catch efficiency for target sized individuals (*CRaverage+*) did not show any significant difference between the snood materials for any of the species.

Our obtained results showed no initial significant differences in performance between biodegradable and nylon snoods in line with results from a Norwegian longline fishery (Cerbule et al., 2022) which showed no significant differences between snoods of nylon and PBSAT materials. The degradation of the PBSAT is taking place faster compared to nylon (Brakstad et al., 2022), which would imply that snoods of such material would degrade faster compared to nylon snoods if exposed to the marine environment in case of being lost. Furthermore, due to biodegradation by naturally occurring microorganisms (Tokiwa, Calabia, Ugwu, & Aiba, 2009), this material is aimed at degrading into substances that would not affect marine environment negatively even if the snoods are lost at similar quantities as when using traditional non-biodegradable materials (Cerbule et al., 2022). However, the production of PBSAT is currently limited due to further material development. Therefore, the costs of it are higher when compared to nylon (Standal et al., 2020). Despite that, a reduction in costs of this material could take place when the production of the biodegradable material is scaled up and put in mass production (Cerbule et al., 2022).

Performing and reporting preliminary results as done in this study are important for investigating whether the biodegradable plastic material has potential to be developed to commercial use thereby avoiding unsuccessful research and development work in further comprehensive studies and select the materials that have the potential to be used in further experiments (Thabane et al., 2016). However, these short-term positive results should further be followed up by studies estimating material performance over long-term use. Differences in material properties such as tensile strength of the biodegradable PBSAT material compared to nylon are estimated to increase over time (i.e., Grimaldo et al., 2020) due to faster material degradation and reduced breaking strength of the biodegradable material (Brakstad et al., 2022). This has previously shown to affect the material performance when used in gillnet fishery (Grimaldo et al., 2020; Cerbule et al., 2022). Therefore, such degradation process might also have an effect on material performance in the longline fishery when tested over several deployments regarding loss of the snoods and the fishing performance of the gear.

The results from the Adriatic Sea showed potential for the biodegradable materials to be used to reduce the marine plastic pollution from the longline fishery and thus contribute to the nature conservation. Therefore, this should further be investigated by a follow-up study assessing long-term performance of the material before a final conclusion can be made regarding whether the biodegradable materials can solve the plastic pollution problem created by the longline fishery.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jnc.2023.126438.

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