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Gear technical contributions to an Ecosystem Approach in the Danish bottom set nets fisheries

PhD Thesis

Written by Esther Savina
Defended 8 Juni 2017

DTU Aqua
National Institute of Aquatic Resources

Gear technical contributions to an Ecosystem Approach in the Danish bottom set nets fisheries

Ph.D. thesis by Esther Savina

December 2013 - April 2017

National Institute of Aquatic Resources (DTU-Aqua), Technical University of Denmark

Section for ecosystem based marine management, fisheries technology group, Hirtshals, Denmark

'So, after tens of thousands of years developing better techniques to catch fish, centuries of concern that such techniques may be causing significant damage to stocks and ecosystems, and half a century of realising that such impacts were occurring, the last two decades have seen a major change in focus in the field of fishing technology. This has occurred as scientists and fishers tried to develop techniques that permit the exploitation of fish stocks in a more sustainable manner.'

Kennelly and Broadhurst, 2002

PREFACE

The present thesis was submitted in partial fulfilment of the requirements for obtaining a Doctor of Philosophy (Ph.D.) degree. The thesis consists of a synopsis and four supporting papers. When submitted, one paper was published, two were in revision and one was a manuscript. The present version was updated on February 2018.

The work took place at DTU-Aqua in the section for Ecosystem based marine management in the fisheries technology group based in Hirtshals from December 2013 to April 2017 under the supervision of Ludvig Ahm Krag (initially Niels Madsen) and co-supervision of Finn Larsen (initially Rikke P. Frandsen and Ludvig Ahm Krag).

The thesis was defended on June 8th 2014, and examined by Ole Ritzau Eigaard (DTU-Aqua), Marie-Joëlle Rochet (IFREMER) and Barry O'Neill (Marine Scotland Science).

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Status: published in Fisheries Research (in revision when the thesis was submitted and defended)

Savina, E., Krag, L.A., Frandsen, R.P., Madsen, N., 2017. Effect of fisher's soak tactic on catch pattern in the Danish gillnet plaice fishery. Fisheries Research, 196, 56-65.

Paper II

Discard of regulated species under the landing obligation in the Danish bottom set nets fisheries for cod, sole and plaice in the North Sea

Status: manuscript

Paper III

Testing the effect of soak time on catch damage in a coastal gillnetter and the consequences on processed fish quality

Status: published in Food Control

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

Paper IV

Developing and testing a computer vision method to quantify 3D movements of bottom-set gillnets on the seabed

Status: published in ICES Journal of Marine Research (in revision when the thesis was submitted and defended)

Savina, E., Krag, L.A., Madsen, N. Developing and testing a computer vision method to quantify 3D movements of bottom-set gillnets on the seabed. ICES Journal of Marine Research, 2017, fsx194, https://doi.org/10.1093/icesjms/fsx194

RESUMÉ (Dansk)

EU er i gang med at implementere rammer for bæredygtig fiskeriforvaltning indenfor Økosystem Baseret Fiskeri med hovedvægt på målene i havstrategi rammedirektivet og den fælles fiskeripolitik (landings forpligtelsen). Da fiskeri kan påvirke andre komponenter og ikke kun målarter, med eksempelvis fysiske skader på fiskehabitater eller udsmid af uønskede fiskearter, skal økosystemet som helhed vurderes. Selve fiskeriflåden er blevet reduceret siden midten af 1990'erne, men garn og toggegarn repræsenterer stadig omkring 80 % af den danske fiskeriflåde i antal fartøjer. Garn og toggegarn har den fordel, at energiforbruget er ret lavt og der opnås god selektivitet. Imidlertid **er der begrænset viden om påvirkningen af bundsatte garn på økosystemet**. Fokus blev lagt på metodeudvikling (Artikel **IV**), **fangstmønstre** (Artikel **I, II** og **III**) og **habitatpåvirkninger** (Artikel **IV**). Hvad angår fangstmønstre kan man have til hensigt at minimere den uønskede fangst (artikel **I** og **II**), eller maksimere den ønskede fangst, f.eks. ved at justere **fiskeritaktik** (Artikel **I**) eller ved at forbedre **fangstkvaliteten** på målarterne (Artikel **III**).

De begrænsede oplysninger om passive redskaber skyldes til dels historisk fokus på aktive redskaber, men også fordi dataindsamling og dataanalyse kræver **udvikling af passende, innovative metoder** til at vurdere den nye informationstype, der skal indsamles som led i en økosystembaseret tilgang til fiskeriet. En stereo billeddannelsesmetode til in situ vurdering af den dynamiske bevægelse af passive redskaber (Artikel **IV**) blev identificeret, tilpasset, testet og anvendt. At sammenligne fiskerier med bundsatte garn kan være en udfordring, da målingen af fiskeriindsatsen afhænger af forskellige faktorer, såsom kombinationen af fiskenettets egenskaber, netlængde, eller garnets sættetid i havet. Statistiske metoder, der for nylig er blevet udviklet, blev identificeret og anvendt til estimering af den relative fangsteffektivitet mellem to forskellige design af et passivt fiskeredskab (Artikel **I**), eller til at standardisere data til en bred vifte af indsatsvariabler ved at inkludere den landede del af fiskeriet med anvendelse af udsmidsandel (Artikel **II**).

Fiskeriteknologer kan spille en central rolle i at søge efter win-win løsninger, så fiskeriet kan fortsætte på en økologisk bæredygtig måde, nemlig at undgå uønsket fangst og at undgå at påføre skader på habitater. Garns selektive egenskaber kan forbedres ved at ændre redskabets karakteristikker, f.eks. maskestørrelse eller garnmateriale, men i mange tilfælde spiller fiskernes operationelle taktik en dominerende rolle, da nye selektive teknologier som involverer mere komplekse redskaber sædvanligvis er begrænset i passivt fiskeri. Fiskeriteknologiske overvejelser, dvs. redskabsdesign og operationel taktik, kan være med til at implementere en økosystembaseret tilgang til det danske bundsatte garnfiskeri. Virkningerne af redskabsdesign, f.eks. lette eller tunge net, på habitat (Artikel **IV**), og fiskernes taktik, dvs. ståtid eller valg af ønskede fiskearter, på fangstmønstre og kvalitet blev undersøgt (Artiklerne **I**, **II** og **III**).

I **Artikel I** blev effekten af fiskernes ståtidstaktik på fangstmønstre i det danske garnfiskeri efter rødspætter undersøgt ved at estimere den længdebaserede fangsteffektivitet, eller relativ størrelsesselektivitet på tre forskellige ståtidsmønstre, dvs. 12 timer om dagen, 12 timer om natten og 24 timer. Ved at justere fiskernes ståtidstaktik, f.eks. til 12 timer om dagen, kan fiskere, der deltager i det kystnære sommerfiskeri efter rødspætter, maksimere deres fangst ved at fange flere rødspætter på kommerciel størrelse, når de er mere tilgængelige for redskabet, og begrænse håndteringstiden ved at fange færre isinger og krabber, når de er mindre tilgængelige for redskabet.

I **Artikel II** blev discard mængden mellem regulerede fiskearter i henhold til landings forpligtelser indenfor dansk bundsat garnfiskeri efter torsk, rødspætte og tunge i Nordsøen beskrevet ud fra de discard data, der er indhentet af observatører på havet, samt effekten af garnets sættetid, dybde, bredde- og længdegrad blev undersøgt ved anvendelse af en betafordeling. Discard mængden varierede mellem 1.10 og 100 % med høj variabilitet mellem fiskeri, arter og fiskepladser. Discard af undermålsfisk, hvor der er anvendt små maskestørrelser ved tungefiskeri er den vigtigst identificerede udfordring. I torskefiskeriet i Nordsøen der var en reduceret sandsynlighed for discard af torsk med øget dybde, med størst effekt i de senere år.

I **Artikel III** blev en stereo billeddannelsesmetode identificeret, tilpasset, testet og anvendt til in situ kvantificering af bevægelsen af blylinen til lette og tunge garn, indsat på bunden på sandede habitater ved at bruge det danske kystnære garnfiskeri som case study. Den direkte fysiske forstyrrelse af havbunden af garn var minimal, da blylinens bevægelse ikke trængte ned i havbunden. Den generelle opfattelse er at tungt fiskeudstyr er mere ødelæggende for habitater, men det blev påvist her, at lette garn bevæger sig signifikant mere end tunge.

I **Artikel IV** blev effekten af ståtid (12 og 24 timer) på fangstkvalitet undersøgt, samt om de registrerede skader på hele fisk har en effekt på forarbejdede produkter såsom fileter, undersøgt om bord på et kystnært garnfiskerfartøj og på en specialiseret forarbejdningsfabrik. Det var signifikant mere sandsynligt at få skader på hele fisk end på fileterede fisk, og signifikant mere sandsynlig længere ståtider. Med den optimale ståtid kan garn levere fisk af en god kvalitet.

ABSTRACT (English)

The European Union is implementing a sustainable fisheries management framework called the Ecosystem Approach to Fisheries, with the main basis provided in the objectives of the Marine Strategy Framework Directive and the Common Fishery Policy (landing obligation). As fishing can affect other components and not just targeted species, with for example physical damage to habitats or discarding of non-target species, the ecosystem as a whole must be considered. Although the fleet has reduced since the mid-1990s, gill- and trammel nets still represent about 80% of the Danish fleet in number of vessels. Gill- and trammel nets have the advantage of low energy consumption and good size selectivity. However, there is **limited knowledge about the ecosystem effects of bottom set nets**. Focus was given to methodological development (Paper **IV**), **catch pattern** (Papers **I**, **II** and **III**) and **habitat effects** (Paper **IV**). Regarding catch pattern, one can intend to minimize the catch that is unwanted (Papers **I** and **II**), or to maximize the part of the catch that is wanted, e.g., by adjusting the **fishing tactic** (Paper **I**) or by improving **catch quality** of the target species (Paper **III**).

The limited information on passive gears is partly due to historical focus on active gears, but also because data collection and analysis calls for the **development of appropriate innovative assessment methodologies** to properly assess the new type of information which has to be gathered as part of an Ecosystem Approach to Fisheries. A stereo imaging method to assess in-situ the dynamic behavior of passive gears was identified, adapted, tested and used (Paper **IV**). Comparing bottom set nets fishing operations can be challenging as the measure of fishing effort depends on various factors such as the combination of netting characteristics, net length, or soak time. Statistical methods that have recently been developed were identified and used for estimating the relative catch efficiency between two different designs of a passive fishing gear (Paper **I**) or to standardize data to a wide range of effort variables by including the landed portion of the fishing operation with the use of discard ratios (Paper **II**).

Gear technologists can play a key role in searching for win-win solutions so that fishing can continue in an ecologically sustainable manner, i.e., avoiding unwanted catch and habitat damage. The selection properties of gillnets may be improved by changing the gear characteristics, e.g., mesh size or netting material, but in many cases the fisher's operational tactic plays a preponderant role, as new selective technologies involving more complex gear are usually limited in passive fisheries. Gear technological considerations, i.e., **gear design and operational tactics**, can help to implement an Ecosystem Approach to the Danish bottom set nets fisheries. The effects of gear design, i.e., light and heavy nets, on habitat effects (Paper **IV**) and fisher's tactic, i.e., soak duration or choice of target species, on catch pattern and quality (Papers **I**, **II** and **III**) were explored.

In **Paper I**, the effect of fisher's soak tactic on catch pattern in the Danish gillnet plaice fishery was investigated by estimating the length-dependent catch efficiency, or relative size selectivity, of three different soak patterns, i.e., 12h at day, 12h at night and 24h. By adjusting their soak tactic, i.e., 12h at day, fishers participating in the costal summer fishery for plaice can maximize their catch by catching more plaice at commercial size when they are more available to the gear, and limit handling time by catching less dab and crabs when they are less available to the gear.

In **Paper II**, discard ratios of regulated fish species under the landing obligation in the Danish bottom set nets fisheries for cod, plaice and sole in the North Sea were described using the discard data from observers at sea, and the effects of soak duration, depth, latitude and longitude on discards were investigated by the use of a beta distribution. Discard ratios ranged from 1.10 to 100%, with high variability between fishing operations, species and fisheries, discard of undersized individuals due to the use of small mesh sizes in the sole fishery being the main challenge identified. In the North Sea cod fishery, there was a decreased probability of cod discard with depth, with greater effect in the more recent years.

In **Paper III**, the effect of soak time (12 and 24h) on catch quality, as well as if the registered damages on whole fish have an effect on processed products such as fillets, were investigated aboard a coastal gillnetter and at a specialized processing factory. Damage in fish was significantly more likely for whole than filleted fish, and significantly more likely for longer soak times. With the optimum soak time, gillnets can deliver good quality fish.

In **Paper VI**, a stereo imaging method was identified, adapted, tested and used to quantify in-situ the movement of the leadline of light and heavy gillnets, deployed on the bottom in sandy habitats, using the Danish gillnet coastal plaice fishery as a case study. The direct physical disruption of the seabed of gillnets was minimal as the leadline was moving but not penetrating into the seabed. Whereas the general perception is that heavy gears are more destructive to the habitat, it was demonstrated here that light nets were moving significantly more than heavy ones.

ABBREVIATIONS

CCTV	Closed Circuit TV
CDi	Catch-damage-index
CFP	Common Fisheries Policy
EAF	Ecosystem Approach to Fisheries
EC	European Commission
EU	European Union
FO	Fishing Operation
GES	Good Environmental Status
ICES	International Council for the Exploration of the Sea
ITQ	Individual Transferable Quota
MCRS	Minimum Conservation Reference Size
MLS	Minimum Landing Size
MSFD	Marine Strategy Framework Directive
STECF	Scientific, Technical and Economic Committee for Fisheries
TAC	Total Allowable Catch

SPECIES SCIENTIFIC NAMES

Cod	*Gadus morhua*	Pollack	*Pollachius pollachius*
Dab	*Limanda limanda*	Monkfish	*Lophius piscatorius*
Edible crab	*Cancer pagarus*	Northern prawn	*Pandalus borealis*
Flounder	*Platichthys flesus*	Norway lobster	*Nephrops norvegicus*
Haddock	*Melanogrammus aeglefinus*	Saithe	*Pollachius virens*
Hake	*Merluccius merluccius*	Sole	*Solea solea*
Harbour porpoise	*Phocoena Phocoena*	Turbot	*Psetta maximus*
Plaice	*Pleuronectes platessa*	Whiting	*Merlangius merlangus*

I. INTRODUCTION

A. Ecosystem Approach to Fisheries

1. Definition

Fisheries have traditionally been managed with focus on single target species (Pikitch *et al.*, 2004; Godø, 2009; Bellido *et al.*, 2011; Ramírez-Monsalve *et al.*, 2016). But with the collapse of some fish stocks, the need for a better understanding of ecosystem functioning has emerged (Pikitch *et al.*, 2004; Ramírez-Monsalve *et al.*, 2016). The idea that target species should be managed in the context of the overall state of the system, including habitat, non-target species and the human dimensions of fisheries, has led to a change in the paradigm of fisheries management (Pikitch *et al.*, 2004; Bellido *et al.*, 2011). The ecosystem approach promotes a management regime that maintains the health of the ecosystem together with appropriate human use of the environment for the benefit of current and future generations (Garcia and Cochrane, 2005). The application of the ecosystem approach to fisheries has been given various names and definitions, including Ecosystem Based Fisheries Management (EBFM), Ecosystem Approach to Fisheries Management (EAFM) and Ecosystem Approach to Fisheries (EAF). These terminologies refer to approaches with overlapping objectives, but reflect the relative importance given respectively to fisheries objectives and to ecosystem conservation in their interpretation (Garcia, 2003).

The Reykjavik FAO Expert Consultation held in 2003 agreed to define the EAF as follow: “an ecosystem approach to fisheries strives to balance diverse societal objectives, by taking account of the knowledge and uncertainties about biotic, abiotic and human components of ecosystems and their interactions and applying an integrated approach to fisheries within ecologically meaningful boundaries” (Garcia, 2003).

The 2013 revision of the European Union (EU) Common Fishery Policy (CFP) explicitly defines the ecosystem-based approach to fisheries management as “an integrated approach to managing fisheries within ecologically meaningful boundaries which seeks to manage the use of natural resources, taking account of fishing and other human activities, while preserving both the biological wealth and the biological processes necessary to safeguard the composition, structure and functioning of the habitats of the ecosystem affected, by taking into account the knowledge and uncertainties regarding biotic, abiotic and human components of ecosystems” (E.U., 2013).

2. Implementation in the European Union

Few explicit objectives for biodiversity exist, mainly focusing on the protection of rare and vulnerable species and habitats (Greenstreet, 2008; Rochet *et al.*, 2011). At the EU level, the main basis for an EAF is provided in the objectives of the Marine Strategy Framework Directive (MSFD) and the CFP.

i. The Marine Strategy Framework Directive (MSFD)

The MSFD focuses on the implementation of an ecosystem approach to the management of human activities taking place in the marine environment, and aims at achieving Good Environmental Status (GES) for European waters by 2020 (E.C., 2008a; Ramírez-Monsalve *et al.*, 2016). The MSFD has introduced eleven qualitative descriptors which describe what the environment would look like after achieving GES. Some of these descriptors represent the ecosystem features of concern. Regarding the effect of fisheries, the descriptors of interest are biodiversity (D1), non-indigenous species (D2), commercial fish species (D3), food webs (D4) and sea floor (D6) (E.C., 2008; Berg *et al.*, 2015). The other descriptors represent human drivers that put pressures on the ecosystem, including fishing activities contained within the previously mentioned D3 (E.C., 2008; Berg *et al.*, 2015).

ii. The Common Fishery Policy (CFP)

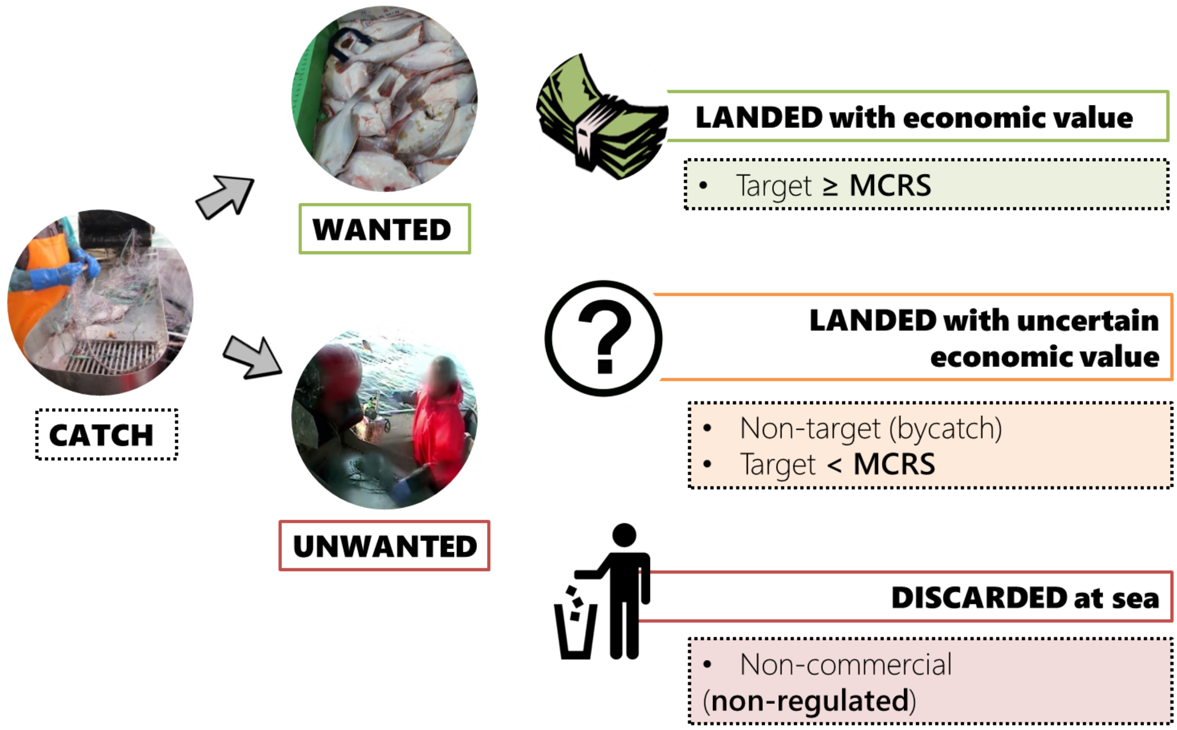
The CFP focuses on the implementation of an ecosystem approach to the management of fisheries activities (Ramírez-Monsalve *et al.*, 2016). For example, the 2013 reform has brought in multiannual plans including several stocks if exploited together. Besides, the new CFP has introduced an obligation to land species subject to catch limits, i.e., managed through Total Allowable Catches (TAC) and quotas (E.U., 2013). A Minimum Conservation Reference Size (MCRS) was established for those species, based on the previous legal Minimum Landing Size (MLS), below which the sale of catches is restricted to non-human consumption products such as fish meal or pet food (E.U., 2013) (*Fig. 1*). Previously, catches below MLS, with insufficient quota, poor condition and limited or no market could deliberately be thrown at sea. Bycatch and discards have, to some extent, similar ecological consequences to the target part of the catch, but, as they do not hold any economic benefit to fishers, represent additional unnecessary mortality (Bellido *et al.*, 2011). The landing obligation aims at encouraging more selective fishing practices in order to reduce bycatch and discards, which have been identified as a threat to the ecosystem's structure and functioning (E.U., 2013).

iii. Current status

Regarding the MSFD, EU countries reported in 2012 their initial assessment, definition of GES and determination of targets and indicators. Each EU country assessed the environmental status of its marine waters, and developed a monitoring programme of measures to reach or maintain GES by 2020. The marine strategies are to be reviewed every six years.

The landing obligation has been gradually implemented since January 2015 fisheries by fisheries (E.U., 2013). Plan for each group of fisheries and area are being established based on joint recommendations from regional groups of member states, and evaluated by the Scientific, Technical and Economic Committee for Fisheries (STECF) of the European Commission (EC). Discard plans last 3 years, and will eventually be incorporated into the previously mentioned multiannual plans. The landing obligation entered into force for demersal fisheries in the North Sea (ICES area IV), Skagerrak and Kattegat (ICES area IIIa) in January 2017 (E.U., 2016). All catches of cod, haddock, sole, whiting, Northern prawn and Norway lobster caught by gillnets and trammel nets are therefore to be landed.

Figure 1. Fate of catch under the landing obligation.



3. Gear technical contributions

The implementation of the EAF in EU entails a limitation in environmental impacts of fishing activities. The combination of gear technical characteristics, i.e., gear design and operational tactics, and conditions of the fishing operation, e.g., meteorological conditions, determine the species and size composition of the catch, as well as the gear dynamic behavior and therefore its potential habitat damage. Gear technological considerations are therefore necessary to better understand ecosystem effects of fishing, and to fully implement an EAF.

Scientific advice in an ecosystem context may lead to short-term economic costs before achieving long-term ecological, social and economic benefits (Jennings and Revill, 2007). The solutions suggested usually involve stopping fishing in sensitive areas and periods (Kennelly and Broadhurst, 2002). However, gear technologists can play a central role in searching for win-win solutions so that fishing can continue in an ecologically sustainable manner (Kennelly and Broadhurst, 2002; Jennings and Revill, 2007).

B. The Danish bottom-set net fisheries

1. General description

i. The fleet

Gillnets stand as the fourth most important general gear type (out of 8) contributing to the global marine catches in weight (based on data from 1950 to 2001, Watson *et al.*, 2006). In 2016, there were 733 registered vessels for bottom set nets in the Danish fleet, among which 69%, i.e., 506 vessels, were professional (NaturErhvervstyrelsens, 2017a). In 2016, about 30% of the registered professional Danish vessels belonged to the bottom set nets fleet (NaturErhvervstyrelsens, 2017). The bottom set netters participate in the mixed human consumption demersal fisheries harvesting round and flatfish in the North Sea, Skagerrak and Kattegat (Vestergaard *et al.*, 2003; Andersen *et al.*, 2012). Although the fleet has reduced in number since the mid-1990s (*Fig. 2*, based on vessel registered in the EU fleet register database, including those with fishing as a subsidiary activity), by landing annually about 7720 t (*Fig. 3)*, the Danish bottom set netters still contribute on average to 17% of the total annual Danish landings of flat and round fish for human consumption (2011-2015, landings data from the AgriFish Agency, processed by DTU Aqua) (NaturErhvervstyrelsens, 2017b).

Figure 2. Number of vessels registered with gillnet or trammel net as main gear in the EU fleet register database, i.e., including those with fishing as a subsidiary activity (E.C., 2016) by year and length class.

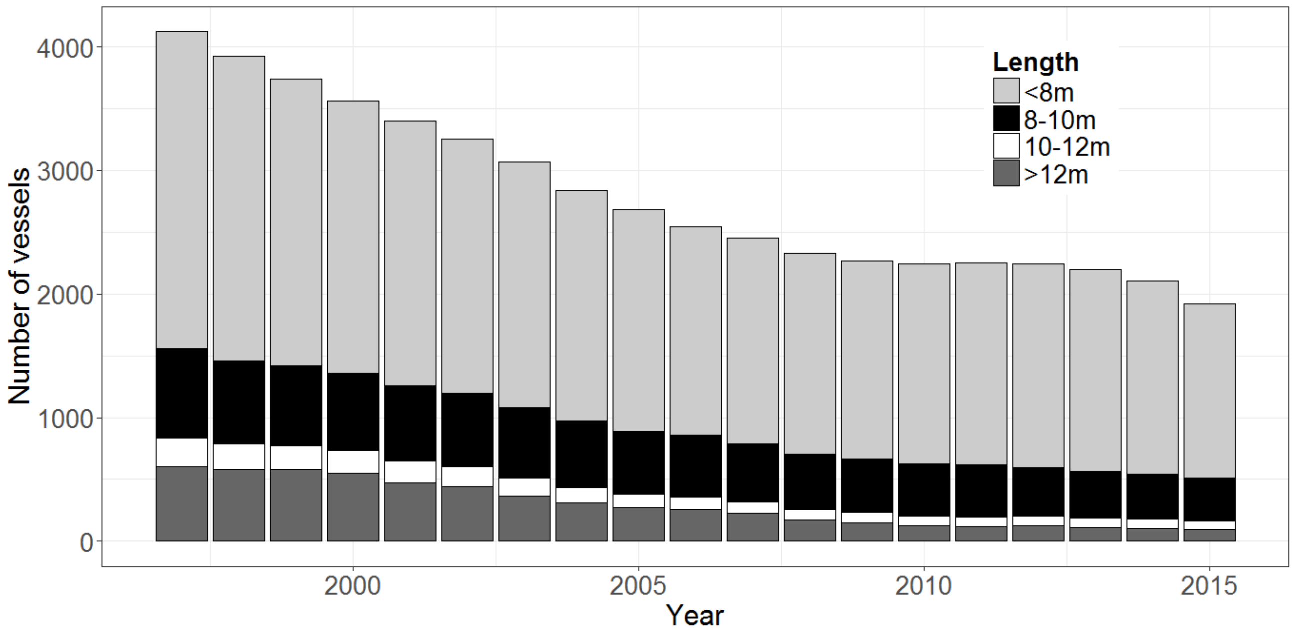
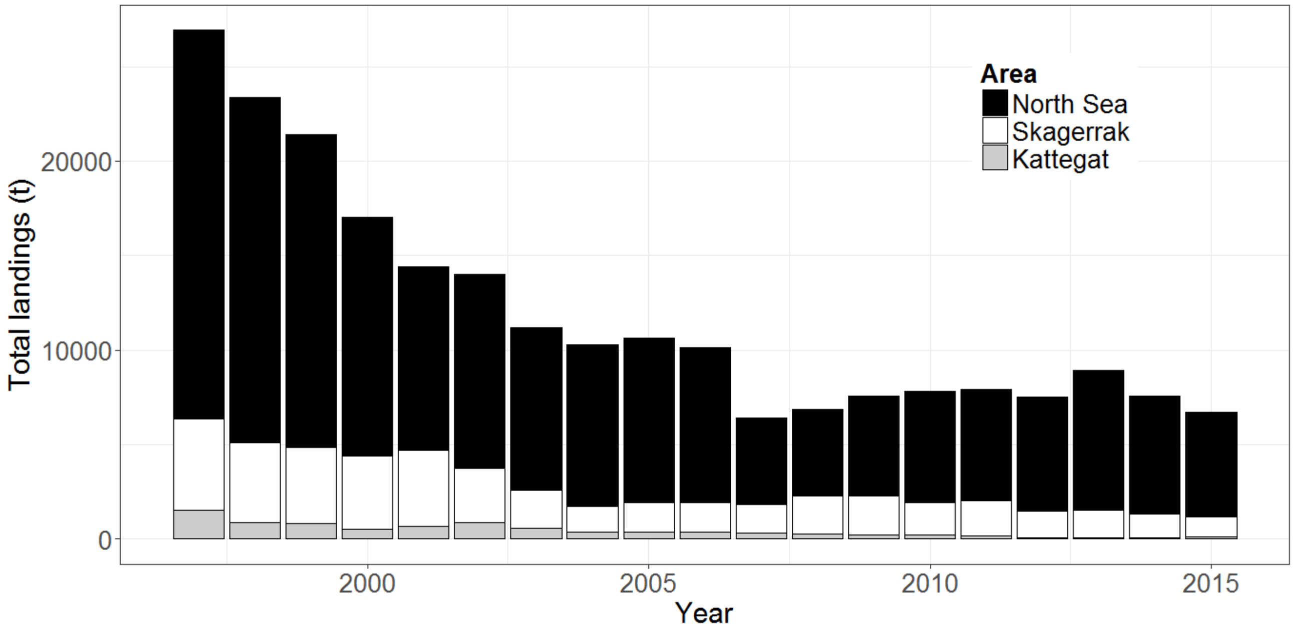


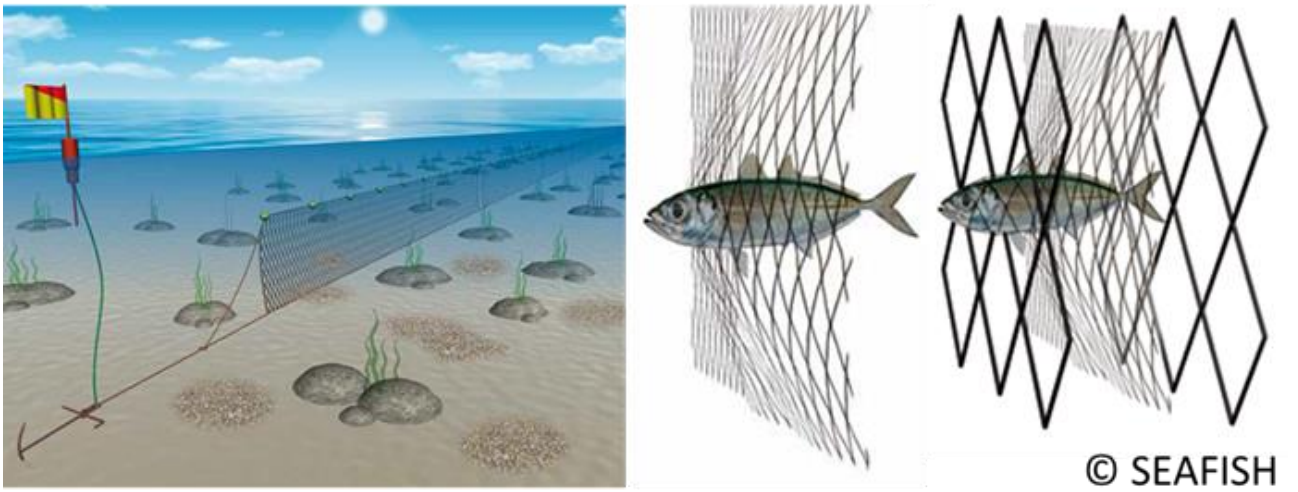
Figure 3. Total landings in tons by the Danish bottom set netters for the North Sea, Skagerrak and Kattegat (landings data from the AgriFish Agency, processed by DTU Aqua).



ii. The gear

Bottom-set nets are designed to stand at the bottom for targeting demersal species such as cod or flatfish (Hovgård and Lasse, 2000). A typical gillnet consists of webbing attached at intervals to the headline and the leadline (He and Pol, 2010) (*Fig. 4*). The net is spread vertically by the buoyancy of floats on the headline and weight in the leadline (Hovgård and Lasse, 2000; Takagi *et al.*, 2007; He and Pol, 2010). The choice of headline buoyancy depends on the target species, but also on the environmental fishing conditions: less buoyancy is required in the Baltic than in the North Sea for example, due to the absence of strong tidal currents.

Figure 4. Bottom set nets (left), gillnet (middle) and trammel net catching method (right).



iii. *Difference between gill and trammel nets*

A gillnet consists of a single netting wall, whereas a trammel net consists of three layers of netting: a slack middle net with a smaller mesh size, and two outer nets with larger mesh sizes (Hovgård and Lassen, 2000; He and Pol, 2010) (*Fig. 4*). The dominant method of capture in gillnet is by gilling, i.e., when a fish is retained by its gills in the net, but individuals can also be caught by the largest part of the body, by the mouth or head region, or by spine and fins as a result of struggling (He and Pol, 2010). The dominant method of capture in trammel nets is by entangling, i.e., when whole or part of the body of the fish is entangled in the pocket of the smaller mesh net (*Fig. 4*). In both gear types, the capture process is based on the fact that the fish does not see the netting and actively swims into the gear.

In the Danish fleet, 3% on average of the vessels with gillnet as main gear also declared using trammel nets as second gear (1997-2015, based on vessel registered in the EU fleet register database, including those with fishing as a subsidiary activity) (E.C., 2016).

2. Fishing operation (FO)

i. Deployment of a fleet on the bottom

Several nets are usually attached together to form a fleet. The fleet is set on the bottom (*Fig. 5*), and usually moored at both ends with weights or anchors (He and Pol, 2010). Nets are anchored to the bottom using 4 to 8 kg anchors on average, ranging from 1 to 2 kg for smaller vessels to up to 14 kg for bigger vessels. In Denmark, fleets are commonly soaked from west to east to avoid gear collision, which is also the main wind – and current – direction in Danish waters.

ii. Soaking

Nets are soaked for various durations, depending on the target species, but also on the fishing ground or season (*Table 1*). Soak duration can be very short, e.g., around an hour in the cod wreck fishery, up to several days in the monkfish fishery.

iii. Hauling

Nets can be hauled by hand in very small vessels, but the use of net hauler is now very common (*Fig. 5*). The fisher manually untangles the catch from the net (*Fig. 5*). Fishing with nets is therefore known to be labour intensive, and handling of the catch plays an important role in fishing effort and tactics (Suuronen *et al.*, 2012).

3. Danish bottom set nets fleet and fisheries

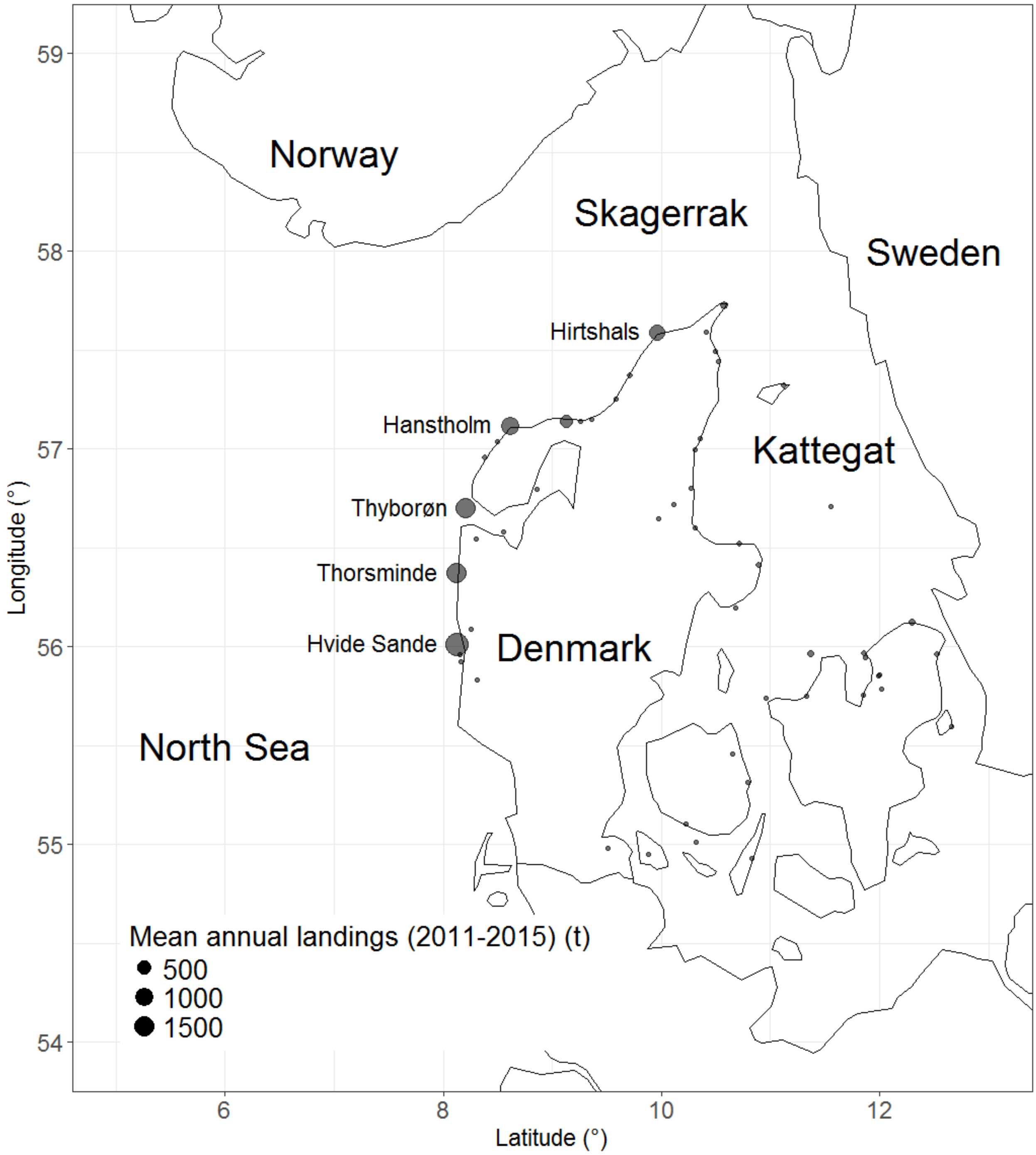
i. Home harbour, fishing area and operational range

Most netters are based in the northern west coast of Jutland, e.g., Hirtshals, Hanstholm and Thyborøn, or in the southern west coast of Jutland, e.g., Thorsminde and Hvide Sande (*Fig. 7*), but

Figure 5. Deployment of a fleet from the back of the vessel (top left), a net fully deployed on the bottom (top right), hauling the fleet with a hauler from the side of the vessel (bottom left) and untangling the catch (bottom right).

Figure 6. Danish netters of different length classes.

Figure 7. Mean annual landings in tons (2011-2015, landings data from the AgriFish Agency, processed by DTU Aqua) by harbours landed by the Danish bottom set netters in Denmark.



some vessels can temporarily change landing harbour for the season of a given fishery (Andersen *et al.*, 2012). Some vessels also land in the Netherlands, Norway and the United Kingdom with on average respectively 512, 129 and 4 tons landed annually (2011-2015, landings data from the AgriFish Agency, processed by DTU Aqua). Most vessels in the Danish bottom set nets fleet participate in the North Sea and Skagerrak fisheries (*Fig. 3*). Most vessels are relatively small (*Fig. 2*) and fish for daily trips in coastal areas.

ii. Target species and seasonality

Bottom set nets tend to be relatively species selective, and often target a single species at a time, changing fishing ground and sometimes gear from one season to the other (Vestergaard *et al.*, 2003; Ulrich and Andersen, 2004; Andersen *et al.*, 2012) (*Table 1*). Danish bottom set nets target a range of bentho-demersal fish (*Table 1*), cod, plaice and sole being the most important ones in weight (*Table 2*). In the context of mixed-species fisheries, there can be a shift in target species driven by the scarcity of the resource, e.g., a switch from cod to plaice was observed in the North Sea (Marchal *et al.*, 2002).

Table 1. Characteristics of the gear and fishing ground of fishing operations sampled by the Danish observers at sea sampling program between 1998 and 2016 in the North Sea, Skagerrak and Kattegat per target species (Target): number of fishing operations (FO) and number of different vessels (Vessel) sampled for gill- (G) and trammel nets (T), quarter (Quarter), range (min-max) of the soak duration in h (Soak), the full mesh size in mm (Mesh size), the total net number (Net nr.), the length of an individual net in m (Net length) and the depth in m (Depth). Information in bold gives the most common occurrence of the different events.

Target	Gear	FO	Vessel	Quarter	Soak	Mesh size	Net nr.	Net length	Depth
North Sea									
Hake	G, T	14	4	3	4-14	125-150	40-200	60	27-83
Turbot	G	22	6	2, 3	2-214	170-270	40-200	70-87	22-75
Plaice	G, T	106	16	**1**, **2**, **3**, 4	2-123	120-180	5-200	50-92	0-56
Lumpfish	G	2	1	2	51-99	220-260	45-85	-	10
Sole	**G**, T	39	6	**2**, 3	9-50	92-124	90-448	47-72	5-42
Cod	**G**, T	490	20	**1**, **2**, **3**, **4**	0-44	130-300	2-240	42-75	8-157
Skagerrak									
Monkfish	T	4	3	3, 4	97-124	250-270	95-200	80-90	55-83
Hake	G	3	2	3, 4	3-17	130	80-220	60-62	50-71
Pollack	G	6	4	1, 2, 4	3-13	120-150	6-260	55-60	19-104
Plaice	G, T	31	11	2, 3, 4	2-48	70-200	10-240	50-100	7-47
Lemon sole	G	2	1	3, 4	24	150	80-120	-	35-50
Sole	**G**, T	8	3	2	6-25	96-124	60-144	45-56	8-19
Cod	G, T	80	14	**1**, **2**, 3, **4**	2-73	115-180	2-218	45-100	10-105
Kattegat									
Turbot	G	1	1	2	64	240	12	62	5
Plaice	T	2	2	3	20-27	120-140	36-90	55	16
Lemon sole	T	1	1	3	18	130	48	50	18
Lumpfish	**G**, T	27	5	1, 2	46-312	120-270	12-100	62-85	18
Sole	G, T	45	13	1, **2**, 3, **4**	5-72	92-150	9-600	45-88	18
Cod	T	10	4	1, 2, 3, 4	10-44	120-130	36-64	50-53	22

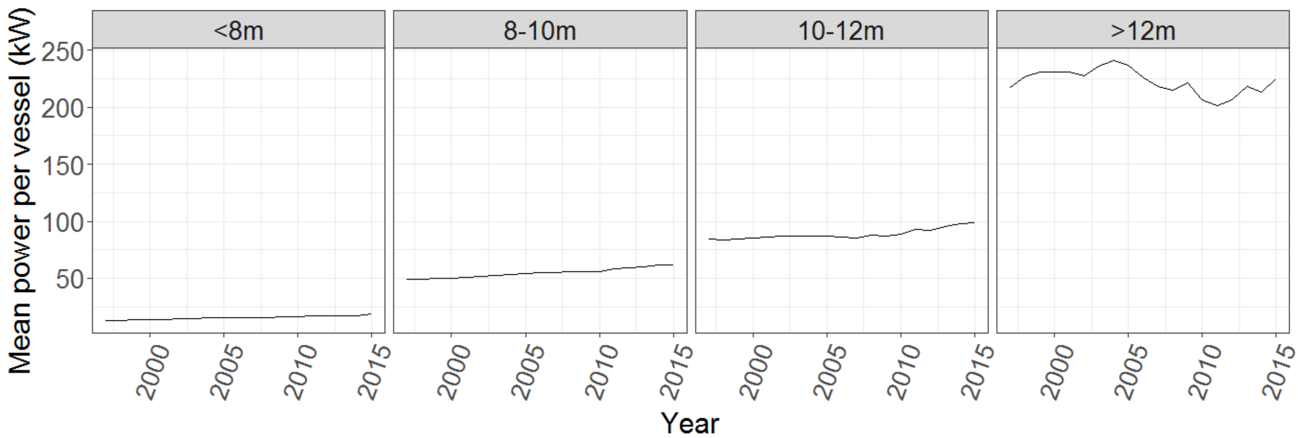
Table 2. Mean annual landings (2011-2015, landings data from the AgriFish Agency, processed by DTU Aqua) by bottom set nets for the first five main species landed in the North Sea, Skagerrak and Kattegat.

North Sea		***Skagerrak***		***Kattegat***	
Species	Annual landings (t)	Species	Annual landings (t)	Species	Annual landings (t)
Plaice	3078	Cod	648	Lumpfish	34
Cod	1477	Plaice	405	Sole	19
Sole	351	Pollack	110	Plaice	12
Hake	339	Monkfish	56	Herring	6
Turbot	283	Saithe	25	Pollack	5

iii. Vessel length, horsepower, tonnage and crew size

Vessel length, horsepower and tonnage are not very good descriptors of effective capacity in fisheries with static gears. Except for few specific fisheries that require bigger vessels, either to handle high nets (6 m), e.g., for saithe and hake, or to allow for a larger and more powerful hauler to fish offshore in deeper waters, e.g., for saithe and monkfish, there is no additional gain in fishing power for bigger vessels that can operate more nets due to the necessity of manually handling the catch. This is reflected in the Danish bottom set net fleet structure where small vessels are still predominant compared to the trawl fleet (*Fig. 2, Fig. 6*) and where the increase in power per vessel has remained relatively stable throughout the years (*Fig. 8*).

Figure 8. Mean power per vessel in kW for Danish vessels registered with gillnet as main gear in the EU fleet register database, i.e., including those with fishing as a subsidiary activity (E.C., 2016) by length class and year.



Most of the very small vessels, i.e., length class less than 8m, are however mostly fishing as a subsidiary activity (*Fig. 2*). If bigger vessels permit the same handling amount per crew member per hour, one has to note that they still provide with the possibility of more days at sea by being able to fish in rough weather, a larger crew and a higher number of nets. The latter can be useful to have different nets for different target species, or as in the sole fishery for example, to be able to let the unwanted dab and plaice rot while fishing with other nets to skip the handling labour.

Usually the vessel is owned by a single man, with one or two crew members, but vessels participating in labour demanding fisheries, e.g., the sole fishery along the Dutch coast, can have larger crews.

iv. Access to and management of the fisheries

Access to the Danish fisheries requires both recognition as a commercial fisherman and a vessel license. Before 2007, the seasonal allocation of the Danish quota for most demersal stocks was through a catch-ration system, the ration size depending on the vessel size for a given stock, but not the gear type (Andersen *et al.*, 2012; Vestergaard *et al.*, 2003). In 2007, Individual Transferable vessel Quotas (ITQ) were implemented in the Danish demersal fishery (Andersen *et al.*, 2012). Few technical regulations apply to bottom set nets in the European waters, except for the hake and monkfish fisheries which are restricted in mesh size, number of nets and soak time (COM, 2016). However, fishermen are restrained in their fishing effort by workload. Disentangling catch from the netting can be time consuming, and as netters usually operate on vessels less than 12m with limited crew, handling time is a major limiting factor for additional fishing power.

4. Gear characteristics

i. Hanging ratio

The hanging ratio measures how tightly the netting is stretched along the headline and the leadline, modifying slackness of the netting (Hovgård and Lassen, 2000; He and Pol, 2010). The hanging ratio vary between 0 with all meshes mounted at the same point on the ropes so the net has no length dimension and 1 with the netting fully stretched out so the net has no height dimension (Hovgård and Lassen, 2000). Hanging ratios are found between 0.25 and 0.65 in commercial fisheries, with lower hanging ratios for flatfish and higher ones for roundfish (Wileman *et al.*, 1999; Hovgård and Lassen, 2000; He and Pol, 2010).

ii. Netting material and colour

The netting can be made of monofilament, multimonofilament or multifilament. Monofilament nets consist of monofile nylon thread, which can also be combined in multimonofilament, whereas multifilament are thin nylon fibres twisted together. The netting material, numbers of filaments in the twine, and twine size affect the visibility of the netting and the mechanism of fish capture (He and Pol, 2010). Nets constructed of thinner twine were found to catch more fish than those made of thicker materials, as they are less visible and softer (Hovgård and Lassen, 2000; He and Pol, 2010). However, thinner twines may also have a poorer size selection due to the netting elongation when a fish pushes into the mesh and a higher tendency for entangling, including invertebrates (Hovgård and Lassen, 2000; He and Pol, 2010). They are also more easily damaged, which may result in increased costs and lost fishing time (Hovgård and Lassen, 2000; He and Pol, 2010). Therefore, choice of netting material and twine thickness implies a trade-off between fishing power and net durability, depending on the type of fisheries. For example, multifilament may provide with strength not required for coastal fisheries.

The most efficient colour, which makes the netting invisible to the fish, depends on the target species, water and seabed colours, and twine thickness (Hovgård and Lassen, 2000). A general trend was observed with preference for grey or green in the North Sea (Hovgård and Lassen, 2000).

iii. Mesh size

Mesh size is likely the most important factor affecting size selectivity (He and Pol, 2010). Thus, mesh size vary with the target species, e.g., small mesh size of less than 120 mm (full mesh) for sole, and more than 220mm for turbot (*Table 1*). Mesh size can also vary throughout the year for the same target species, e.g., larger mesh sizes are used in spring (140-150mm, full mesh) compared to winter (120-130mm) in the Bornholm cod fishery as cod is full of roe.

iv. *Net dimensions*

Net height depends on the target species and fish behavior. Nets are high in the hake (5-6m) or cod wreck (3-5m) fisheries. Lower nets are more likely to tangle up.

Individual nets of a limited length can be used, e.g., 3 nets of about 45 m set in parallel in the cod wreck fishery, or a total net length as long as 100 km such as in the turbot fishery, but about 30 km of nets are usually soaked in a typical bottom-set gillnets fishing operation (Montgomerie, 2015) (*Table 1*). The total net length partly depends on the man power onboard the vessel, e.g., 2.5 to 6 km for a single crew vessel.

C. Challenges for an Ecosystem approach to the Danish bottom set nets fisheries

1. Main potential fishing effects on the ecosystem

i. Selectivity of target and non-target species

Selective fishing is the ability of a fishing gear to target specific types of individuals, allowing unwanted sizes and species to avoid capture (Wileman *et al.*, 1996; Breen *et al.*, 2016). Gillnets are, in general, considered as being size selective, with larger mesh sizes catching larger fish (Stergiou and Erzini, 2002; He and Pol, 2010). Retention of fish in gillnets increases with fish size up to a length of maximum catch and decreases afterward (Millar and Fryer, 1999; Fonseca *et al.*, 2002; Fauconnet and Rochet, 2016). However, all species are not equally vulnerable to the gear, and nets can catch various species (Fonseca *et al.*, 2002; Valdemarsen and Suuronen, 2003; He and Pol, 2010; Breen *et al.*, 2016). Compared to gillnets, the selectivity of trammel nets are lower due to the higher variety of capture mechanisms, i.e., gilling, wedging, entangling and pocketing, associated with trammel nets

(Borges *et al.*, 2001; Erzini *et al.*, 2006; Gonçalves *et al.*, 2007; Batista *et al.*, 2009). There is therefore an interest in reducing bycatches of undersized target species and non-target species. As part of the EAF approach, selective fishing is encouraged to reduce bycatch and discards, but there is an important scientific debate regarding whether selective fishing on adult age classes of few commercial species is ecologically preferable than distributing a moderate fishing mortality across the widest possible range of species, stocks and sizes, the latter being known as balanced harvesting (Zhou *et al.*, 2010; Rochet *et al.*, 2011; Garcia *et al.*, 2012; Breen *et al.*, 2016; Ulrich *et al.*, 2016). A conservation perspective can also aim at the trophic level balance of the ecosystem, i.e., removing low and high trophic level classes in percentages higher and lower, respectively, than those found in the ecosystem (Stergiou *et al.*, 2007).

Incidental catch of a number of vulnerable species such as skate and rays, turtles, marine mammals or seabirds, is a matter of growing concern in certain areas, e.g., bycatch of harbour purpoise in the lumpfish fishery in Denmark. Previous research projects focused on the catch of marine mammals in the bottom set nets fisheries for cod in the Baltic Sea (Kindt-Larsen, 2015).

Ghost fishing, i.e., when lost nets continue fishing, is also a serious issue worldwide, but of less concern in shallow areas such as those fished by the Danish netters as lost nets are commonly rapidly rolled up by storm and tide action (Brown and Macfadyen, 2007).

ii. Genetics of exploited populations

Catching fish above a minimum size increases the relative mortality of fast-growing individuals and favours early maturity and slow growth. In set net fisheries, the selectivity curves are already (double) dome-shaped and may encourage favourable genetic selection (Jennings and Revill, 2007).

iii. Food webs

Fishing affects the predator-prey interactions, including predators of conservation interest such as seabirds and mammals. In most fisheries, the understanding of fishing effects on food webs is not sufficient to assess how changes in gear technology might mitigate any unwanted food web effects (Jennings and Revill, 2007). However, gear technology can contribute to better understand the capture pattern of bottom set nets, which are likely to have an effect on food webs, e.g., by discarding at sea unwanted catches not regulated by the landing obligation.

iv. Habitats

Habitat damage is of high interest in an EAF as some fishing gears can remove or damage habitat forming structures, potentially reducing the complexity, diversity and productivity of benthic environments (Jennings and Kaiser, 1998; Kaiser *et al.*, 2000; Kaiser *et al.*, 2002; Hermsen *et al.*, 2003; Grabowski *et al.*, 2014). It is generally assumed that habitat impacts of passive gears are lower than those of active gears, and most likely during retrieval of the gear only (Suuronen *et al.*, 2012;

Grabowski *et al.*, 2014). However, these conclusions are based on few experimental studies. For example, there were only five studies regarding passive gears, i.e., longlines, traps and gillnets, out of 97 used for the latest assessment in New England, US (Grabowski *et al.*, 2014). There is no direct evidence of potential effect for many of the current habitat-gear combinations (Eno *et al.*, 2013). Taking a closer look at bottom gillnets, the lack of studies regarding habitat impact might be attributed to the general assumption of negligible effects (Uhlmann and Broadhurst, 2013). However, after in situ observation at two rocky reefs, Shester and Micheli (2011) identified set gillnets as a priority conservation concern due to their potential to damage habitat-forming species. In the Welsh part of the Irish Sea, Eno *et al.* (2013) assessed nets sensitivity as high to medium for high to low fishing intensities in 8 habitats out of 31, mostly rock with associated branching species such as kelp, seaweeds or maerl beds. The degree to which passive gears drift on the bottom has therefore to be quantified for the different bottom types (Grabowski *et al.*, 2014).

2. Limited information on passive gears

The limited information on passive gears is partly due to historical focus on active gears, but also because data collection and analysis calls for the development of appropriate innovative assessment methodologies to properly assess the new type of information which has to be gathered as part of an EAF. Challenges include (1) the difficulty to find an appropriate quantitative method that can be used in-situ around entangling nets, (2) the need to standardize data before comparing catch from nets of various fishing effort due to the use of different gear types, mesh sizes, net length and/or soak durations, and (3) the prerequisite of having modelling methods and software to properly analyse bottom set net data.

3. Aim of the PhD project

Bottom set nets do not represent the largest number of professional vessels in the Danish fleet, but they account for about 80% of the total number of vessels registered in Danish waters (E.C., 2016) and are passive gears often proposed as a potential alternative to active fishing gears in, e.g., sensitive areas. Bottom set nets have the advantage of low energy consumption, low investment cost and relatively good size selectivity, but they are work intensive and some disadvantages remain, such as poor species selectivity and catch quality, as well as unclear habitat impacts. There is limited knowledge about the ecosystem effects of bottom set nets partly due to historical focus on active gears, but also because data collection and analysis calls for the development of appropriate innovative assessment methodologies. Thus, focus was given to methodological development (Part **II**), catch pattern (Part **III**) and habitat effects (Part **IV**) (*Table 3*).

Table 3. Gear technical parameters looked at for each of the EAF component of focus in the present thesis for different case studies. Each case study included the development or use of an adapted methodology (Method), including Generalized Linear Mixed Model (GLMM), Catch Damage Index (CDi) and Cumulative Linear Mixed Model (CLMM). The corresponding part in the synopsis is given, together with the resultant paper.

		Catch pattern			**Seabed effect**
		Catch pattern	Discard ratio	Catch quality	Seabed effect
Gear technical parameter		Soak	Fishery, soak, depth	Soak	Light/heavy nets
Case study	Gear	Gillnet	Gill- trammel	Gillnet	Gillnet
	Target	Plaice	Cod, plaice, sole	Plaice	Plaice
	Ground (coastal)	Skagerrak	North Sea	Skagerrak	Skagerrak
	Season	Summer	All year	Summer	-
	Data	Experimental	Commercial	Experimental	Experimental
Method		Catch comparison	Discard ratio, betaGLMM	CDi, CLMM	Stereo imaging
Synopsis		II, III-1	II, III-2	II, III-3	II, VI
Paper		Paper **I**	Paper **II**	Paper **III**	Paper **IV**

Even if the exact ecosystem effects are not known, there is an overall interest in reducing bycatches of undersized target species and non-target species. Focus was given to the fish species regulated by the new landing obligation (Paper **II**), but also to the overall species composition (Part III) and one of the most important fish species targeted in the Danish fisheries, plaice (Papers **I** and **III**). Regarding catch pattern, one can intend to minimize the catch that is unwanted (Papers **I** and **II**), or to maximize the part of the catch that is wanted (Paper **I**), e.g., by improving catch quality of the target species (Paper **III**). Regarding habitat effect, focus was given to the estimation of the extent of physical damage by bottom set nets, including the development of an assessment method (Paper **IV**).

Gear technological considerations, i.e., **gear design and operational tactics**, can help to implement an Ecosystem Approach to the Danish bottom set nets fisheries (*Table 4*). The selection properties of nets may be improved to limit bycatch (mesh size, netting material, twine thickness), but due to the nature of the gear, one would most likely also impair the catch rate of the target species. New selective technologies involving more complex gear are limited in passive fisheries, and therefore, in many cases, the fisher's operational tactic plays a preponderant role (Kennelly and Broadhurst, 2002; Andersen *et al.*, 2012; Eliasen *et al.*, 2014; Fauconnet *et al.*, 2015; Breen *et al.*, 2016; Fauconnet and Rochet, 2016). It has the advantage of no additional economic cost, workload or risk (Sigurðardóttir *et al.*, 2015). The effects of gear design, i.e., light and heavy nets, on habitat effects (Paper **IV**) and fisher's tactic, i.e., soak duration or choice of target species, on catch pattern and quality (Papers **I**, **II** and **III**) were explored (*Table 3*).

Table 4. Contribution of fishing gear technology to the EAF in the bottom set nets fisheries.

GEAR design & OPERATIONAL tactics determine:	Objectives in an ECOSYSTEM APPROACH:
✓ Species and size composition of the catch	✓ Limit unwanted catch
✓ Gear dynamic behaviour	✓ Limit seabed effects

Change in gear design and operational tactics aiming at a better environmental sustainability should of course also guarantee socio-economic sustainability and help maximize fisherman profit. The best soak tactic in the fisher's interest was assessed in Papers **I** and **III**. In the new landing obligation system, all catch of regulated species are to occupy space in the vessel's hold and be deduced from the vessel's quotas. The discard ratio of regulated species was therefore used as a proxy for the non-profitable fraction of the landed catch to assess if the landing obligation would have an economic impact on fishers (Paper **II**).

- ✓ Bottom set nets are one of the most widely used fishing gears, but there is limited knowledge about their ecosystem effects.
- ✓ Bottom set nets have the advantage of low energy consumption and good size selectivity. However, some disadvantages remain, such as poor species selectivity and catch quality, as well as unclear habitat impacts.

II. MATERIAL AND METHODS

A. Find an appropriate quantitative method

1. Experimental set-up: stereo-imaging

Several optical or acoustic techniques have been developed as complementary tools to assess the impact of active gears on the seabed (Smith *et al.*, 2003; Humborstad *et al.*, 2004; O'Neill *et al.*, 2009; Lucchetti and Sala, 2012; Depestele *et al.*, 2016). However, not all techniques provide a spatial resolution fine enough to assess the effects of bottom set nets. Others are restrictive in sampling duration. Underwater videos appear as an appealing candidate, with cost efficiency, high precision and less bias than direct visual observation, but their use as informative data also depends on the ability to extract relevant measurements (Struthers *et al.*, 2015; Neuswanger *et al.*, 2016). Eventually, not all techniques can easily and safely be run around bottom set nets, prone to entanglement. We tested for a method to quantitatively assess the dynamic behavior of the leadline of the nets.

i. Experimental set-up

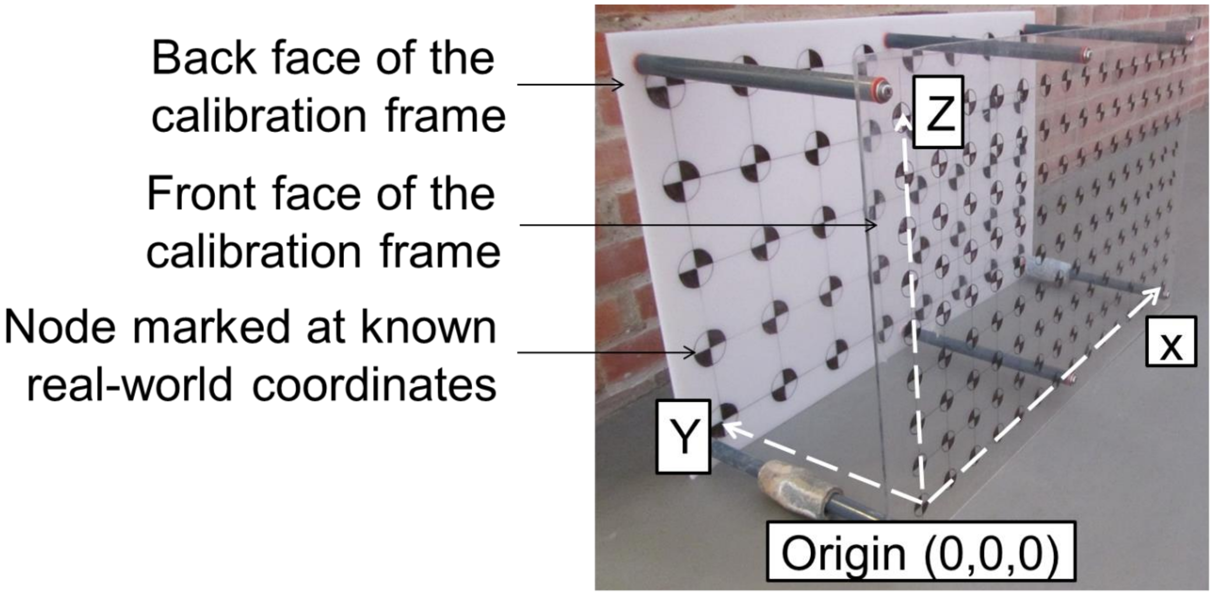
Stereo imaging consists in two cameras taking synchronized images of a scene from slightly different perspectives, which then allow to estimate the distance to an object such as in the human 3D vision. A stereo imaging method, currently used in other fields, e.g., to count fish underwater (Graham *et al.*, 2004) was identified and adapted. A stereo recording unit, composed of a metallic frame on which were attached two cameras, was positioned on the seabed facing the middle length of a fleet (**Paper I**).

ii. Data collection and analysis

If an object is uniquely identified in both images and if the translation and rotation of one camera relative to the second is known, it is then possible to estimate the location of the object in 3D space (Schmidt and Rzhanov, 2012). Nets were marked with different red tape patterns on the leadline to make sure that these marks would easily be uniquely identified. The video clips were processed with the free open-source Mac application VidSync version 1.66 (www.vidsync.org), based on the OpenCV library computer vision algorithms (Neuswanger *et al.*, 2016).

Before the proper calculation of the 3D coordinates of a point, one has to correct for lens distortion and establish the perspective of each camera. Lens distortion is induced by the fisheye lens of the camera, meant to widen its angle of view, but particularly pronounced when the camera records underwater through housing and prone to bias calculations. Correction factors, or distortion parameters, can be found by locating nodes on a chessboard pattern and arranging them into straight lines (*Fig. 9 and 10*). The same chessboard pattern can be used to calculate the projection matrices for each camera by matching the known physical 2D node coordinates on each face of the calibration frame with screen coordinates, which were recorded in VidSync by clicking on the centre of each node on the clips (*Fig. 10*). The position of the calibration frame defined the 3D coordinate system (*Fig. 9*).

Figure 9. 3D calibration frame – partly reproduced from *Savina, E., Krag, L.A., Madsen, N. Developing and testing a computer vision method to quantify 3D movements of bottom-set gillnets on the seabed. ICES Journal of Marine Research, 2017, fsx194, https://doi.org/10.1093/icesjms/fsx194* .



The 3D coordinates of a point were calculated in VidSync by iterative triangulation, aiming at establishing two lines-of-sight that approximately intersect at the point of interest. Screen coordinates are projected onto the two planes in real-world space. The 3D position of the mark is the intersection of the line of sight of both cameras. It consisted in clicking on the point of interest, here different points of the leadline, on each clip.

iii. Limitations and further improvement

The adaptation of stereo-imaging to passive fishing gears proved to be a relevant methodology for quantifying gear dynamic behavior in-situ. The following improvements could, however, be suggested.

The stereo-imaging experimental set-up, i.e., the choice of camera separation and the dimensions and position of the calibration frame, was configured to measure relatively small objects close to the cameras. Accuracy and precision decreased as distance from the cameras increased. The nets were not expected to move in such an order of magnitude, but a larger chessboard, i.e., large enough to fill the screen, could have helped limit the measurement errors. The fish eye effect could be reduced by limiting the field of view.

A variety of challenges were faced when deploying the recording units near the nets at sea, among which water turbidity, also noticed as a limitation for optical methods by Lucchetti and Sala (2012) and Struthers *et al.* (2015) (*Fig. 11*). The ongoing adaptation of a time-of-flight camera to work as range-gated camera, i.e., the camera only capture light reflected from objects further away than a certain distance which can be used to remove the effects of scattered light, as part of the Horizon 2020 programme (http://www.utofia.eu/) could solve the issue of water turbidity. The nets got tangled in the cage (*Fig. 11*), leading to a modification of the distance between each camera on the frame as well as the inclusion of a netting protection (**Paper I**). However, the recording unit should be positioned from above, i.e., hanging from the sea surface, provided that measurements are independent of wave activity.

Calibration and distortion corrections obtained in a tank with the same camera specifications for each recording unit as those at sea were used, but any optical adjustment such as removing a camera from its underwater housing to change a battery or a change of the angle between the cameras during transportation/aboard the vessel may have affected the parameters and therefore the results. Control tests did not show major issues with the data, and the order of magnitude of the results can therefore be relied on, but the cameras should remain fixed throughout the experiment.

2. Onboard observations under commercial conditions: CCTV

In addition to experimental set-up, it is also possible to collect data directly onboard commercial vessels, either with Closed Circuit TV (CCTV), or with onboard observers. We explored the potential of CCTV and onboard observers for documentation of catch pattern, including discards.

i. The data set

The dataset was gathered by DTU-Aqua as part of field trial tests (Dalskov and Kindt-Larsen, 2009; Kindt-Larsen and Dalskov, 2010; Kindt-Larsen *et al.*, 2012). It included 14 gillnetters targeting cod and plaice in the Danish waters (North Sea, Skagerrak, Øresund, Storebælt, around Æro/Langeland). The settings (frame rate and lens resolution) and location of the camera(s) aimed at recording marine mammals and birds, as well as cod for some of the vessels, while limiting the use of space on the hard disk in order to have a longer recording duration.

ii. Data analysis

The assessment possibilities of the recordings regarding species discrimination were tested. It was sometimes possible to spot flora such as seaweed. However, flora came most of the time mixed with other species, it was not possible to quantify, and it was not possible to know whether it was torn form the seabed or simply collected as floating flora during the hauling process. Depending on the position of the camera and the picture quality, it was sometimes possible to discriminate invertebrates to the suborder (e.g. crustacean), class (e.g. starfish) or infraorder (e.g. crab) level but

Figure 10. Undistortion and rectification of the stereo images using VidSync - adapted from Bradski and Kaehler (2008).

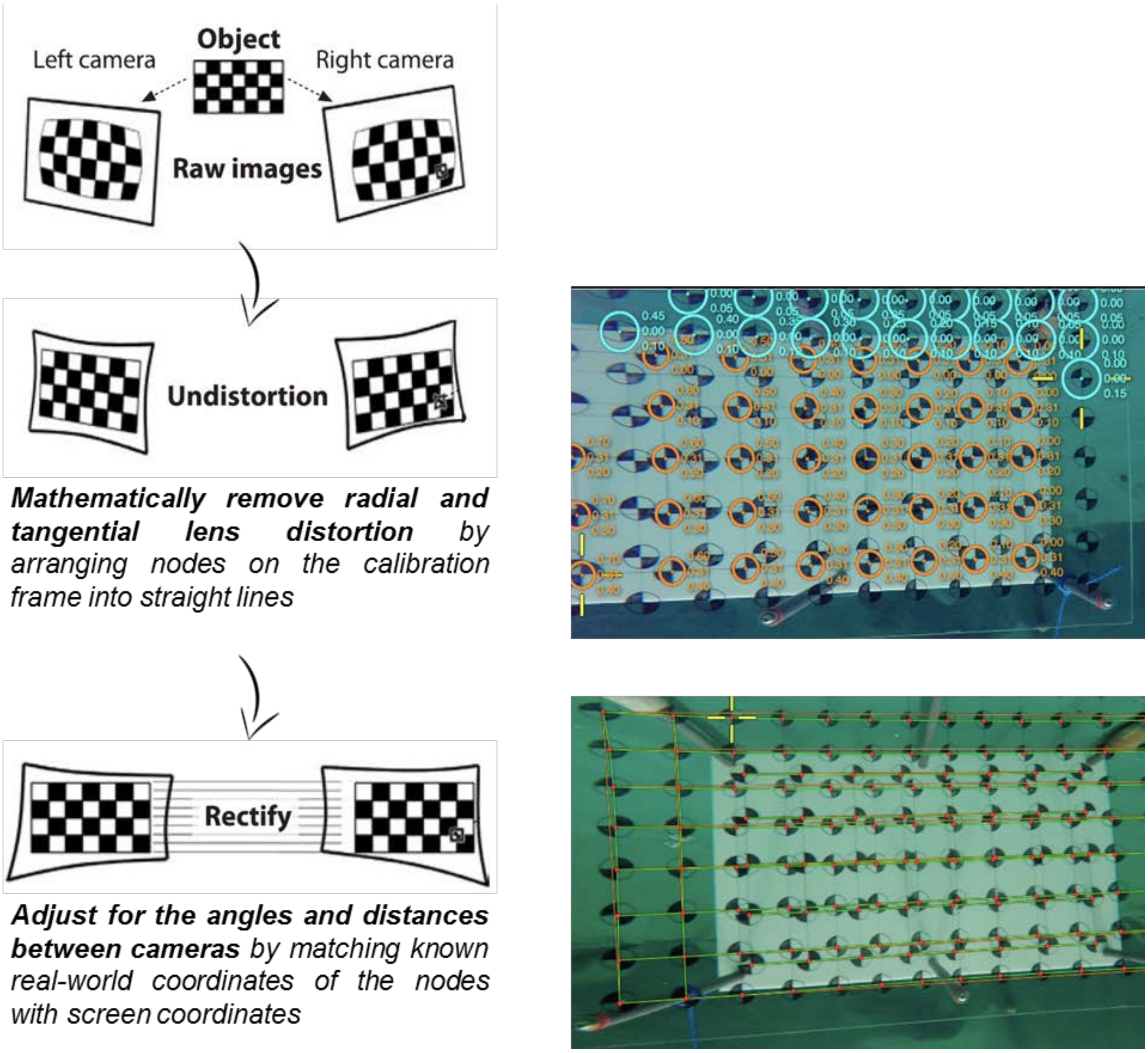


Figure 11. Low visibility (left) and entanglement with the netting (right).

not to the species level. It was sometimes possible to discriminate fish to the species level, or whether it was a round or a flat fish (*Fig. 12*). None of the recordings was suitable for discrimination of all individuals at species level.

The potential use of CCTV for quantifying drop-out, survival/mortality rate, and discard ratio, eventually in relation to fish quality, was assessed. It should have been possible to see individuals falling from the net when hauling, i.e., drop out, on the side camera, but it did not happen in our analysis of the recordings. It was sometimes possible to see if the fish was still moving on the sorting table or, after sorting, in the box on the deck. Depending on the position of the camera and the arrangement of the deck, it was sometimes possible to follow the fate of the catch – kept on board and thrown in a box on deck, or discarded and thrown back to water, or smashed (*Fig. 13*). However, this was not possible on vessels which have one side camera only. None of the recordings was good enough to assess fish quality.

Biological information is also important when looking at gear selectivity. It was sometimes possible to get an idea of the relative length of the individual, in relation to the fisherman size or to the surrounding vessel objects, or in comparison with other caught individuals. However, accurate length measurements were not possible and other biological information such as weight or sex were not available (Dalskov and Kindt-Larsen, 2009). None of the vessel provided with enough data quality for an accurate analysis.

iii. Limitations and further improvement

The number and position of cameras, as well as frame rate and lens resolution, affected the cans and cants of the recordings.

As the trials aimed at evaluating the marine mammals and birds bycatch, it was not necessary to have a complete overview of the vessel activity. Therefore, some vessels only had one camera recording the side of the vessel, whereas others had up to 6 cameras located at various deck locations such as the sorting belt, the boxes where the catch are kept or the hole where discards are thrown. It was obviously easier to get more information with several cameras (*Fig. 14*).

Type and accuracy of the information collected depended on the camera location and how the crew was using the deck. Fishermen might hide the view on the sorting belt if working in front of the camera (*Fig. 15*). An overall view of the deck allowed to spot the fate of catch (discarded or not) but made species discrimination more difficult, contrary to a focus on the sorting belt (*Fig. 15*).

Image quality was highly variable from one vessel to the other, and even sometimes from one FO to the other for the same vessel. Image quality mostly depends on lens resolution and frame rate (Evans and Molony, 2011), but other parameters such as weather conditions or light (day

Figure 12. Starfish (left), cod (middle), unknown round fish (right).

Figure 13. Cod kept (left), flatfish discarded (middle), and crustacean smashed (right).

Figure 14. Four cameras recording side of vessel, sorting belt and sorted catch on deck.

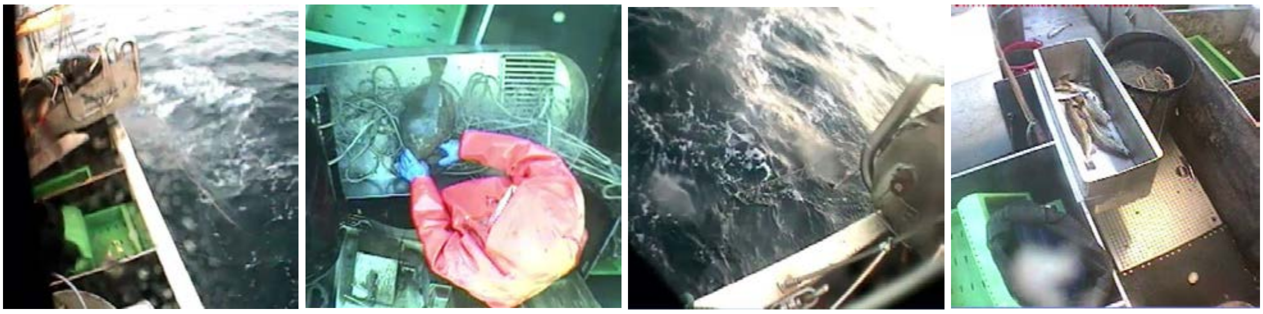


Figure 15. Fisherman hiding view (left), large overview of deck with sorting far from camera (middle), and camera on top of sorting belt (right).

versus night, ray of light) can interfere. The available data did not show enough differences in lens resolution and frame rate to quantify their effects on the image quality.

3. Onboard observations under commercial conditions: observers at sea

i. The dataset

Data was collected on-board commercial fishing vessels by scientific observers during regular FO as part of the national sea sampling programme initially carried out under a national program before 2002 and then under the EU Data Collection Framework (E.C., 2008b). A limited part of the bottom set net fleet is conducting self-sampling, i.e., fishermen are asked to land their discards on randomly chosen days, which are then handled by the observer as a normal discard trip (Storr-Paulsen *et al.*, 2012). Before 2011, observers were responsible for covering a vessel group and area with fixed days at sea, but could choose the vessels. A new stratified random sampling system was introduced in 2011. For each vessel group and area, vessels are weighted with the number of trips conducted in the same area the year before and randomly selected (Storr-Paulsen *et al.*, 2012).

In the Danish sea sampling program, only the top 90% of the métiers ranked by landing amount, landing value or fishing effort are selected for sampling, or if the discard ratio is larger than 5% in weight (Storr-Paulsen *et al.*, 2012). Regarding bottom set nets (gear unspecified, i.e, either gill or trammel nets) in the North Sea, Skagerrak and Kattegat, 7 métiers are currently sampled, all targeting demersal fish, and characterised by area and mesh size classes (Storr-Paulsen *et al.*, 2012). Derogations have been granted every year since 2008 in the North Sea for two small fisheries targeting respectively sole and turbot, with relatively low landings (less than 300 t annually) and discards (DTU-Aqua *et al.*, 2011).

ii. Data analysis

The discard data from observers at sea was tested as a source of data to describe catch of landed and discarded individuals in the bottom set nets Danish fisheries, investigate the effects of gear and operational tactics on discard ratio and establish the relative contribution of different discarding drivers (**Paper II**).

iii. Limitations and further improvement

Stratification into métiers is a major issue regarding the bottom set nets fisheries: there should be enough groups to illustrate properly the diversity of the practices, but not too many so that there are enough data per strata. There have already been some thoughts about the topic, e.g., merging métiers in Skagerrak and Kattegat, or not merging them in the North Sea, but no proper analysis (DTU-Aqua *et al.*, 2011). For example, three métiers are currently sampled in the North Sea, based on mesh size, i.e., <120mm, 120-220mm and >220mm, but with no distinction between gear, i.e., gill- or trammel nets, and target species (Storr-Paulsen *et al.*, 2012). One could expect differences between gill- and trammel nets due to the higher variety of capture mechanisms associated with trammel nets, but these effects could not be looked at due to a low number of observations after subsetting the data to avoid confounding effects (Rubin, 2008; Nikolic *et al.*, 2015). The low number of observations for some of the strata sampled by the observers at sea for bottom set nets, together with a large variability in the data, provides with small power to investigate fine scale effects of catch pattern and discarding practices.

As the MLS has remained the same through the years of interest for the regulated fish species (1998-2016, Paper **II**), making assumptions on the proportions of discards below MCRS under the landing obligation was rather safe. But regarding quota restriction, the implementation of ITQ have most likely changed fisher tactics with a yearly quota attribution, giving more chance to fishers to optimize their catch on price rather than on quota as before. However, most of the sampling effort for observers on bottom set nets was concentrated in the late 90's, which leave the scientist with the insoluble choice between a less representative case study – also because the natural state has changed - with enough observations, or a more recent and representative case study but with a very low number of observations. Focusing all sampling effort in the next few years on species and/or fisheries with the most concern should be considered instead of a low sampling effort in all initially designated métiers if one needs to explore further the catch pattern and discarding practices under the new landing obligation.

B. Standardize different fishing efforts

1. Experimental set-up representative of commercial conditions

Running an experimental trial allows the scientist to be able to standardize the observations, which can be handy in the bottom set net fisheries to avoid the challenge of having to compare catch from nets of various types, length, soak durations. In **Papers I** and **III** for example, fleets of identical characteristics, with only soak duration as a varying factor, were used. But even with an experimental set-up, great care should be taken to be as representative as possible to commercial conditions, e.g., in the choice of net type and dimensions, or the way the net is soaked. It can therefore be very helpful to run experimental trials onboard a commercial vessel, so that the fisher can participate in the choice of the fishing grounds for example, ensuring optimum catches (Stergiou *et al.*, 2002), or reproduce commercial handling practices, which are of importance in particular regarding catch damage (**Paper III**).

2. Catch comparison analysis

We used a general analysis method that estimates the relative catch efficiency between two different designs of a fishing gear developed by Herrmann *et al.* (2017) (**Paper I**).

3. Discard ratio

Discards can be standardized per target species (Depestele *et al.*, 2012), per net length and soak time (Gonçalves *et al.*, 2007), per net number (Perez *et al.*, 2005), or by using the discard ratio (Rochet and Trenkel, 2005). The discard ratio is the ratio between discard and total catches, and may be computed for individual species or combined groups of species (Kelleher, 2005). Discard ratios, by including the landed portion of the FO, are inherently standardized to a wide range of effort variables, e.g., gear type, mesh size, net length or soak duration (Paradinas *et al.*, 2016) (**Paper II**).

C. Adjust to specificity of the data

Most of the previous studies regarding bottom set nets have been using hypothesis testing which does not allow for the estimation of the size of effects, unlike model-based methods, among which mixed modelling allows to include random effects to tackle the issue of pseudo-replication. Not all response variables have a normal error distribution, especially in our field of interest, with, e.g., count with number of individuals, proportions with discard ratio, or ordinal categories with catch quality, calling for the choice of a suitable distribution for the response variable, to appropriately model the data.

1. Specificity of bottom set nets data

i. Multi-model inference to account for (double) bell shaped selection curve in catch comparison

The method developed by Herrmann *et al.* (2017) and used in **Paper I** accounts for multiple competing models to describe the data using multi-model inference, and let us run catch comparison analysis in bottom set nets, independently of the shape of the selection curve - known to usually show a (double) bell shaped selection curve in bottom set nets(Millar and Fryer, 1999; Burnham and Anderson, 2002).

ii. Catch damage index to assess fresh fish quality

In the coastal fishery, fish is usually landed less than one day after capture and freshness, i.e., age of the raw material, which is usually perceived as the most important attribute of the quality of fish, is not appropriate (Denton, 2003; Esaiassen *et al.*, 2013; Martinsdóttir *et al.*, 2003). Instead, semi-quantitative indices of individual fish condition grouped in an index can be used to evaluate whole or processed fish damage in fishing gears (Depestele *et al.*, 2014; Digre *et al.*, 2010; Digre *et al.*, 2016; Karlsen *et al.*, 2015; Olsen *et al.*, 2013; Rotabakk *et al.*, 2011) (**Paper III**).

2. Specificity of response variable

i. Beta distribution for discard ratio

Discard ratios are measures of proportions which can take any continuous value ranging between 0 and 1, and can appropriately be described by a beta distribution – assuming that a transformation is applied for the two extremes, i.e., 0 and 1. Proportions are commonly used in descriptive studies, but the lack of available software to handle such data has restricted the uptake of the beta distribution for statistical regression. Instead, other response variables have been used, e.g., discard per unit effort, which might not be as appropriate here as discussed previously. Discard ratios have recently been modelled using beta distribution in a Bayesian hierarchical model by Paradinas *et al.* (2016). Instead, a beta distribution in a likelihood based approach was used with the newly developed open-source software R package glmmTMB (Magnusson *et al.*, 2017) (**Paper II**).

ii. Cumulative link mixed modelling for ordinal multi-category responses

The degree of fish damage was assessed using scores for different attributes ranging from 0 for flawless to 2 for most severe, known as an ordinal response. Again, choice of an appropriate distribution for the response variable is important. Cumulative link mixed modelling were used for such ordinal multi-category responses as they have shown to work well for sensometric data (Christensen and Brockhoff, 2013) (**Paper III**).

3. Inclusion of random effects

The random effect of, e.g., fleet or FO or vessel, is added to the model to avoid pseudo-replication by accounting for mechanisms that could generate positive association among clustered observations (Fryer, 1991; Millar and Anderson, 2004). For example, vessel was included as a random effect in **Paper II** to account for potential sources of variation on discards due to differences among vessels such as a skipper effect or unobserved gear characteristics. In addition to the use of random effects to account for within-fleet or FO or vessel correlations, fleet was also used as a random effect in **Paper III** to deal with scoring subjectivity, i.e., there may be differences in the assessment when all fish in a fleet are in similar condition or when they show a broader range of damage severities (Benoît *et al.*, 2010).

In catch comparison analysis, the between and within fleet variation was also accounted for by simulating multiple samples directly from the observed data in a double bootstrapping method. Between-fleet variation in the availability of fish and catch efficiency was accounted for by randomly selecting *aq* and *bq* fleets from the pool of fleets of soak patterns *a* and *b*, respectively (initial resampling). Within-fleet uncertainty in the size structure of the catch data was accounted for by randomly selecting fish from each fleet, with a total number of fish similar to that sampled in the fleet (bootstrapping of the initial resampling) (**Paper I**).

Additionally, one should keep in mind the relatively low number of observations per FO, e.g., compared to a commercial haul in active gear fisheries, due to the capture process of passive gears, which influence the total sample size available for analysis and therefore the number of potential covariates that one can look at.

- ✓ The limited information on passive gears is partly due to historical focus on active gears, but also because data collection and analysis calls for the development of appropriate innovative assessment methodologies to properly assess the new type of information which has to be gathered as part of an EAF.
- ✓ A stereo imaging method to assess in-situ the dynamic behavior of passive gears was identified, adapted, tested and used.
- ✓ Comparing bottom set nets fishing operations can be challenging as the measure of fishing effort depends on gear and fishing operation characteristics. We can work with experimental data in a controlled sampling design, but key information also comes from commercial observations. Statistical methods that have recently been developed were identified and used for estimating the relative catch efficiency between two different designs of a passive fishing gear or to standardize data.

III. CATCH PATTERN

Part 1 - Catch pattern (overview)

A. Species composition

1. Few different species caught by plaice gillnets in the Skagerrak

All species are not equally vulnerable to the gear, and bottom set nets can catch various species (*Fig. 16*). We assessed the species composition of gillnets in the summer plaice fishery in the Skagerrak (**Paper I**).

2. Major findings

In the Danish summer plaice gillnet fishery, there were few different species caught. Plaice, dab and edible crab were the most abundant and the most commonly occurring species (*Fig. 17*).

Figure 17. Species relative abundance per fleet and species occurrence, i.e., very common (≥75%), common (50-75%), uncommon (25-50%) and rare (<25%) species, for bottom set nets soaked 12 hours at day (12hD) in the summer plaice fishery in the Skagerrak.

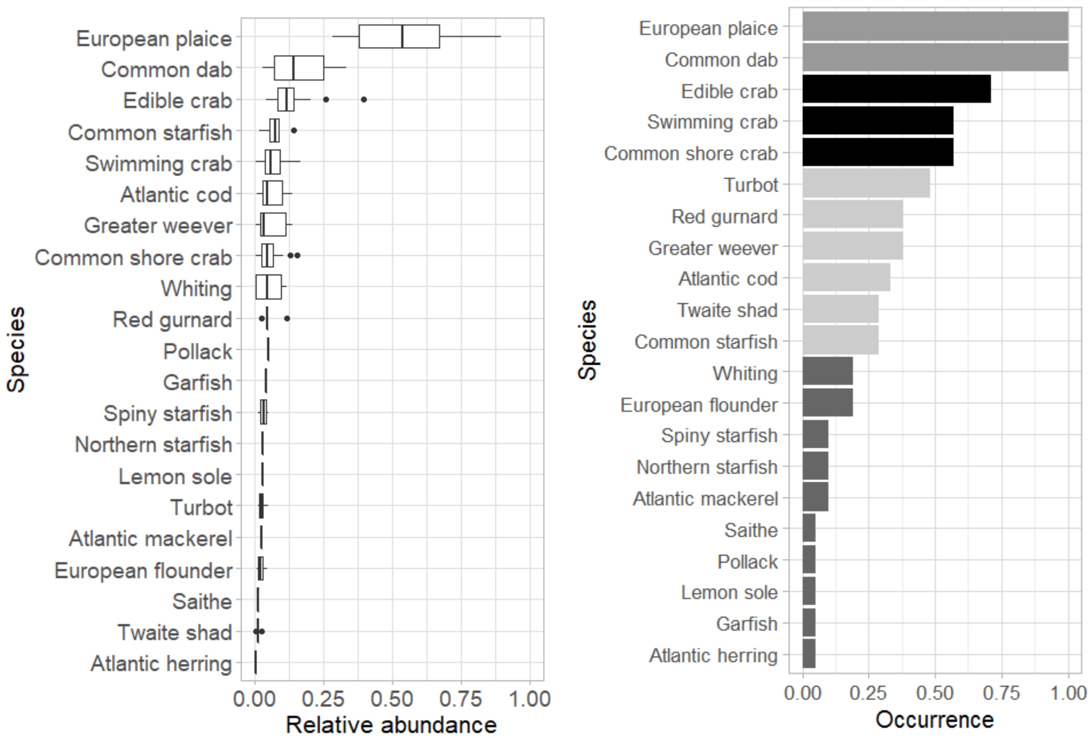


Figure 16. Catch from a gillnet in the Danish summer plaice fishery in the Skagerrak.

Figure 18. Edible crab entangled in the netting after passing through the drum of the hauler (right), individual untangled (middle left) and crushed (middle right), edible crab with shell crushed and missing legs (right)

3. In the perspective of the EAF

Experimental nets in the Danish summer plaice gillnet fishery were catching mainly benthic scavenging invertebrates, benthic feeding flatfish and fish species that eat small fish. The upper predators cod, saithe and pollack were caught in small numbers (*Fig. 17*). As the North Sea is dominated by small- and intermediate-sized species with correspondingly higher growth and reproductive rates (Rochet *et al.*, 2011), one should not expect drastic negative effects on natural populations.

4. Further development

Other gear types or fisheries, e.g., trammel nets or nets targeting the upper predator cod, may show a higher species diversity with a higher relative abundance and occurrence of the round fish.

Ultimately, the current debate on the overall objectives of an EAF, e.g., species selectivity versus balanced harvesting, make it difficult for gear technologists to develop further on the exact ecosystem effects of given fisheries.

B. Effects of gear design and operational tactics

1. Time of day and soak duration as key adjustable factors

Time of day and soak duration are easily adjustable factors and may play a key role in the gillnet fisheries. Previous studies suggested no relationship between soak time and catch size for soak durations longer than 6 hours (Acosta, 1994; Gonçalves *et al.*, 2008; Hickford and Schiel, 1996; Losanes *et al.*, 1992; Minns and Hurley, 1988; Rotherham *et al.*, 2006; Schmalz and Staples, 2014), but others proposed that there could be a decrease in catch rate with longer soaks as the net becomes more noticeable with the struggling of fish trying to escape and a repelling effect due to the smell of spoiled or dead fish, or space limitation in the net (Kennedy, 1951; Gonçalves *et al.*, 2008; Prchalova, 2013). On the other hand, longer soaks may increase the chance of scavengers and predators, and especially invertebrates, to be attracted by spoiled or dead fish in the net (Gonçalves *et al.*, 2008). Some species may be more likely to be present at day or at night regarding their daily rhythm, such as scavengers and predators which are more likely to be active at night (Hickford and Schiel, 1996).

We investigated the selective potential of three different soak patterns, i.e., 12h at day, 12h at night and 24h, in the Danish summer plaice gillnet fishery (**Paper I**).

2. Major findings

On average, there were about 1.5 more catches of the target species plaice with commercial size (above 27cm), and 2 and 4 times less catches of the unwanted dab and edible crab, respectively, for 12h at day compared to the other soak patterns (12h at night and 24h). It is in the gillnetter’s interest to adopt a soak tactic that maximize the catch value by balancing ambient catch levels and handling time for the deployed gillnets. Gillnetters participating in the costal summer fishery for plaice can maximize their catch by catching more plaice at commercial size when they are more available to the gear, and limiting handling time by catching less dab and crabs when they are less available to the gear, i.e., during 12h at day.

3. In the perspective of the EAF

The landing obligation is meant to eliminate discards by promoting more selective fishing, ideally not just for commercial species (E.U., 2013). Avoiding unwanted bycatch, i.e., dab and crabs here, would also benefit the ecosystem approach. This is especially relevant if one question the survivability of discards released at sea – providing that they are not covered by the landing obligation. Dab were observed to be more prone to damage than plaice, and thus more likely to be released dead. Most of the crabs were crushed or had their legs removed by the fishermen to facilitate disentanglement from the net (*Fig. 18*).

Whereas operational challenges are expected for trawlers to avoid large bycatches in the context of the landing obligation, as it is already in the gillnetters' interest to limit unwanted catch, it is not expected that the landing obligation will favour another soak pattern or more generally drastic changes in fishing tactics in the summer plaice fishery.

4. Further development

Our experiment was designed to reproduce commercial practices in the summer plaice gillnet fishery in the shallow Skagerrak fishing grounds, for which the soak tactic is governed by edible crabs. Other patterns may be expected in other fisheries, seasons or areas.

Part 2 - Minimize unwanted catch

A. Discard ratio in North Sea cod, plaice and sole fisheries

1. A high variability in discard ratios for bottom set nets

The high variability found in discard ratios of several passive fisheries (*Table 5*), even using the same gear and in adjacent areas, reflect the versatility of nets and indicate the need to evaluate discards for each fishery (Gonçalves *et al.*, 2007; Batista *et al.*, 2009; Morandeau *et al.*, 2014).

Table 5. Discard ratio in number (DRnr) and weight (DRw) found in different studies across the world for gill (G) and trammel (T) nets, based on commercial (C) or experimental (E) data, with in brackets the number of fishing operations (FO) accounted for. Depth of the FO is given in m. The studies accounted for (Focus) fish (F), and/or mega-invertebrates (I), and/or other components, e.g., habitat formers, birds and mammals (All[1]), or birds and tortoises (All[2]). Discard ratios are given for all individuals, and/or target species [T], non-commercial species [NC], invertebrates [I], crabs [Cr], or others [O]. Variability for the last study was due to a difference in mesh size of the gears used (*).

Gear	Location	Depth	Exp (FO)	Focus	DRnr	DRw	Reference
G	Atlantic, France	-	C (27)	F	30 (0-50)	11	Morandeau *et al.*, 2014
T	Atlantic, France	-	C (27)	F	70 (10-88)	53	Morandeau *et al.*, 2014
G	Pacific, Mexico	-	C (30)	All[1]	45	34.3	Shester and Micheli, 2011
T	Atlantic, Portugal	10-100	C (37)	I, F	52.8	21.9	Batista *et al.*, 2009
T	Atlantic, Portugal	10-90	E (40)	I, F	74 (±8), 48 (±14) [I]	-	Gonçalves *et al.*, 2008
T	Atlantic, Portugal	15-100	E (40)	I, F	49.4	-	Gonçalves *et al.*, 2007
T	Atlantic, Spain	20-80	E (49)	I, F	22.3	-	Gonçalves *et al.*, 2007
T	Atlantic, Spain	10-30	E (60)	I, F	31.4	-	Gonçalves *et al.*, 2007
T	Aegan sea, Greece	10-80	E (41)	I, F	14.7	-	Gonçalves *et al.*, 2007
G	Atlantic, Brazil	132-607	C (14)	I, F	6.1 [T], 22.2 [Cr], >75 [O]	-	Perez and Wahrlich, 2005
G	Tasman Sea, Australia	-	C (265)	All[2]	6.2	3.3	Gray *et al.*, 2005
G	Atlantic, Portugal	500-700	E (20)	I, F	-	42 [T], <3 [NC]	Santos *et al.*, 2002
T	Atlantic, Portugal	<30-200	C (11)	I, F	-	0.13	Borges *et al.*, 2001
G	Aegan sea, Greece	4-90	E (42)	I, F	4.9-8.1*	2.9-7.3 *	Stergiou *et al.*, 2002

Discard ratios of the regulated fish species under the landing obligation, i.e., cod, haddock, sole and whiting, were described for the Danish bottom set nets fisheries targeting cod, plaice and sole in the North Sea (Paper **II**).

Over-quota and undersized discards were shown to be minor in other bottom set nets fisheries, but not all species or quality conditions have commercial value and can therefore also be discarded (Borges *et al.*, 2001; Santos *et al.*, 2002; Kelleher, 2005; Gonçalves *et al.*, 2007; Batista *et al.*, 2009; Morandeau *et al.*, 2014). As different discarding behavior may call for different mitigation measures, the discarding drivers in the Danish North Sea bottom set nets were explored. The relative contribution of different discarding drivers was established for each regulated species in all three fisheries using a hierarchical decision tree (Paper **II**).

2. Major findings

Discard ratios ranged from 1.10% for cod in the cod fishery to 100% for whiting in the sole fishery, with high variability between fishing operations, species and fisheries.

High-grading and catch quality were the main reasons for discarding observed in the cod and plaice fisheries, and catch of undersized individuals due to the use of small mesh sizes was the main challenge identified in the sole fishery.

3. In the perspective of the EAF

If the species is included in the landing obligation, it has to be landed, with no or uncertain economic value for the fisher, and will contribute to the same extent as commercially fit individuals to an EAF, i.e., removal of biomass from the ecosystem.

Bio-economic impact assessments performed on several North Sea mixed-fisheries fleets highlighted the impact of choke species, where the early TAC exhaustion of the least productive stock, e.g., cod, sole, whiting or turbot, or of a stock with limited historical fishing rights, e.g., hake, could lead to fishery closure and under-exploitation of the more productive stocks (Ulrich *et al.*, 2016). Such an effect in the bottom set nets fisheries is however expected to be relatively limited with the yearly quota attribution by the means of ITQ now in use in the Danish demersal fishery, together with the ability for netters to target different fish species throughout the year with limited discards for some of the fisheries.

Estimating discard patterns by fishery is of prime importance for mixed fishery models which are becoming more and more important for the biological advice to the different management authorities.

4. Further development

The low number of observations for some of the strata sampled by the observers at sea for bottom set nets, together with a large variability in the data, provides with small power to investigate fine scale effects of catch pattern and discarding practices. Focusing all sampling effort in the next few years on species and/or fisheries with the most concern should be considered instead of a low sampling effort in all initially designated métiers if one needs to explore further the catch pattern and discarding practices under the new landing obligation.

B. Effects of gear design and operational tactics

1. Choice of target species, fishing ground and soak duration are key to limit discards

Danish bottom set netters in the North Sea target successively plaice, sole and cod throughout the year, depending on the season. If small mesh sizes, i.e., less than 120mm, are used in the sole fishery, identical gear and mesh sizes can be used in the cod and plaice fisheries, yet resulting in the preferred catch of the target species and different discard ratios. Discards are highly variable in time and space, as local species diversity, season, depth or weather conditions are known to affect catch composition (Gray *et al.*, 2005; Stergiou *et al.*, 2002; Gonçalves *et al.*, 2007; Cambiè *et al.*, 2010). It was also suggested to reduce nets soak time in order to minimize the amount of damaged fishes (Acosta, 1994; Borges *et al.*, 2001; Gray *et al.*, 2005; Gonçalves *et al.*, 2007; Batista *et al.*, 2009; Cambiè *et al.*, 2010; Savina *et al.*, 2016). The effect of different explanatory variables on the discards in the Danish North Sea bottom set nets fisheries were explored (Paper **II**).

2. Major findings

Depth, year, soak time and vessel were more important in determining discard ratio for cod in the North Sea cod fishery than latitude and longitude, with an increased probability of cod discard with shallower waters.

3. In the perspective of the EAF

In general under the new landing obligation, the industry has not faced any major issue in fisheries using full mesh sizes between 130 and 200mm, e.g., the cod and plaice fisheries, as there are typically little discard (Chairman of Hirtshals fishermen organization, *Pers. Com.*). It was shown that fishers can adjust their strategy to limit the amount of unwanted catch (Paper **I**). However for fisheries using smaller mesh sizes between 80 and 120mm full mesh, e.g., the sole fishery, fishermen are facing larger bycatch of the round fish cod, haddock, saithe and whiting, and have started to change their tactics with the new landing obligation which could be described as a “real time monitoring” of discards: several fleets are soaked in the same time, one being lifted at regular intervals to check for the amount of unwanted catch (Chairman of Hirtshals fishermen organization, *Pers. Com.*).

4. Further development

The difficulty of reducing discards due to limited size selectivity in the small mesh sizes fisheries without impairing the catch of the target species has been acknowledged in the discard plan by granting to bottom set netters catching sole a minimis exemption up to a maximum of 3% of their total annual catches of sole. Considering a higher sampling effort for species and/or fisheries with higher concern, e.g., the sole fishery, one could also assess potential mitigation measures by testing for the effects of, e.g., fishing grounds or time of the day, on discards. Indeed, as sole is given high value on the markets, one strategy may be to find tactics limiting bycatch of the other species, even if the later would result in lower catch of the target species.

One could consider a modified stratification sampling scheme for the observers programme adapted not only to the mesh size of the FO, but also representative of the other characteristics defining the fisheries, i.e., gear and target species.

Part 3 - Maximize wanted catch

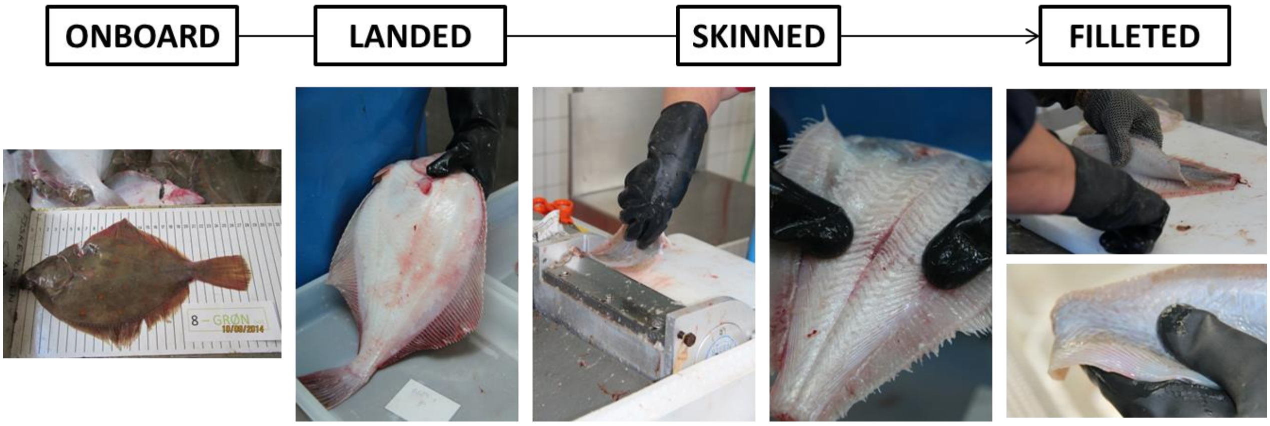
A. *Catch damage in the Danish bottom set nets fisheries*

1. Catch of bottom set nets is prone to damage due to its operation

Challenges in nets are that fish can die in the gear when the net is soaked, the netting can cause marks on the fish skin, and there is an increased risk of injuries due to predation or scavenging of fish in the gear (Auclair, 1984; Perez and Wahrlich, 2005; Petrakis *et al.*, 2010; Santos *et al.*, 2002; Suuronen *et al.*, 2012).

Damages in plaice captured with commercial gillnets were assessed using semi-quantitative indices of individual fish condition gathered in a Catch-damage-index (CDi) for onboard fish and a Processed fish-damage-index for whole, skinned and filleted plaice processed at a land-based factory (*Fig. 190*) (**Paper III**).

Figure 19. Assessment of whole, skinned and filleted plaice onboard the vessel and at land-based factory.



2. Major findings

Most of the assessed fish (99%) presented moderate or severe damage for at least one attribute. The CDi scores observed ranged from 0 to 9, i.e., none of the fish scored in the highest rating categories (10-12). The proportion of fish grading for score 2 at the attribute level were low except bruises, for which 40% were found in the body part. Bruises are a result of an accumulation of blood residue appearing as dark patches on the blind side of flatfish as a result of meshing, the fact that the fish struggled in the net, and handling (Botta *et al.*, 1987; Özyurt *et al.*, 2007).

Overall, gillnets delivered good quality fish (Susanne Kjærgaard Majid, Keka Fisk ApS, *pers. com.*). Damage in fish was significantly more likely for whole than filleted fish, but there was substantial heterogeneity among fish. Severe damage in whole fish may not matter in filleted fish, e.g., yarn marks and scale loss, whereas some damage may only be visible at the fillet level, e.g., severe gaping and jellied condition.

3. In the perspective of the EAF

Catch quality was observed as one of the main discarding drivers in the cod and plaice fisheries (Paper **II**).

Regarding socio-economic consequences, even if gillnets were able here to deliver good quality fish, prices for plaice in Denmark are in general low and show little variation, therefore calling for an additional change to better catch quality, e.g., new marketing opportunities such as direct sale.

4. Further development

Other more fragile species, e.g., round fish or dab, were observed to be more prone to damage than plaice, but catch numbers were too low for a detailed analysis. Further investigations could look into the differences between fish species, the factors responsible for the between-fish random variation, and the effect of different handling practices (vessel effect).

B. Effects of gear design and operational tactics

1. The controllable parameter soak time matters on raw material quality

Among the parameters that matter on the quality value of the raw material such as environmental variations or handling and storage methods, capture procedure, especially soak time, is a controllable parameter (Esaiassen *et al.*, 2013; Olsen *et al.*, 2014; Özogul and Özogul, 2004; Özyurt *et al.*, 2007). It might be an advantage to soak for long time periods to maximise catch per unit effort in some fisheries, but previous experiments have shown that the proportion of dead fish and degree of damage increase with soak time (Acosta, 1994; Hickford and Schiel, 1996; Hopper *et al.*, 2003; Petrakis *et al.*, 2010; Santos *et al.*, 2002; Suuronen *et al.*, 2012).

The effect of soak time on the degree of whole fish damage in plaice captured with commercial gillnets soaked for 12 and 24 hours was investigated (**Paper III**).

2. Major findings

Damage in fish was significantly more likely for longer soak times. Longer soak extended the probability for a caught-fish to be rubbed against the netting and show gear damage (93% for 24h and 85% for 12h) and skin abrasion (60% and 54%), with scale loss damages mainly located in the surroundings of yarn marks and associated with gear damages. Biting (43% and 34%), mostly located on fins and tail (96% of the damaged fish), was caused by scavengers and predators which had an increased chance to feed on the caught-fish at longer soak (Auclair, 1984; Perez and Wahrlich, 2005; Petrakis *et al.*, 2010; Santos *et al.*, 2002). Pressure damages (31% and 23%) were a result of the fish being squeezed close to the pelvic fin when the fisherman untangled it from the net (*Fig. 5*), which severity was expected to depend on mesh size and twine characteristics of the net, but could also be facilitated in damaged fish, i.e., those soaked for 24h. Overall effects were comparable to those of fish length and between-sets.

3. In the perspective of the EAF

Catch quality was one of the main reasons for discarding observed in the cod and plaice fisheries. With the landing obligation, discard of regulated species due to catch damage is not allowed anymore, therefore calling for solutions to improve catch quality in order to limit economic loss for the fisherman, quota deduction among others.

4. Further development

The effect of soak time on catch damage is expected to be higher for longer soak durations or more fragile species. Further investigations could look into the factors responsible for the between-fleets random variation.

- ✓ The selection properties of bottom set nets may be improved by changing the gear characteristics, but in many cases the fisher’s operational tactic plays a preponderant role.
- ✓ One can intend to minimize the catch that is unwanted, or to maximize the part of the catch that is wanted.
- ✓ By adjusting their soak tactic, i.e., 12h at day, fishers participating in the costal summer fishery for plaice can maximize their catch by catching more plaice at commercial size when they are more available to the gear, and limiting handling time by catching less dab and crabs when they are less available to the gear.
- ✓ High-grading and catch quality were the main reasons for discarding observed in the cod and plaice fisheries, and catch of undersized individuals due to the use of small mesh sizes was the main challenge identified in the sole fishery. In the North Sea cod fishery, there was an increased probability of cod discard with shallower waters.
- ✓ Damage in fish was significantly more likely for longer soak times in the plaice fishery. With the optimum soak time, gillnets could deliver good quality fish.

IV. SEABED EFFECT

A. In-situ quantification of bottom-set gillnets movements on the seabed

1. Gear components in contact with the seabed

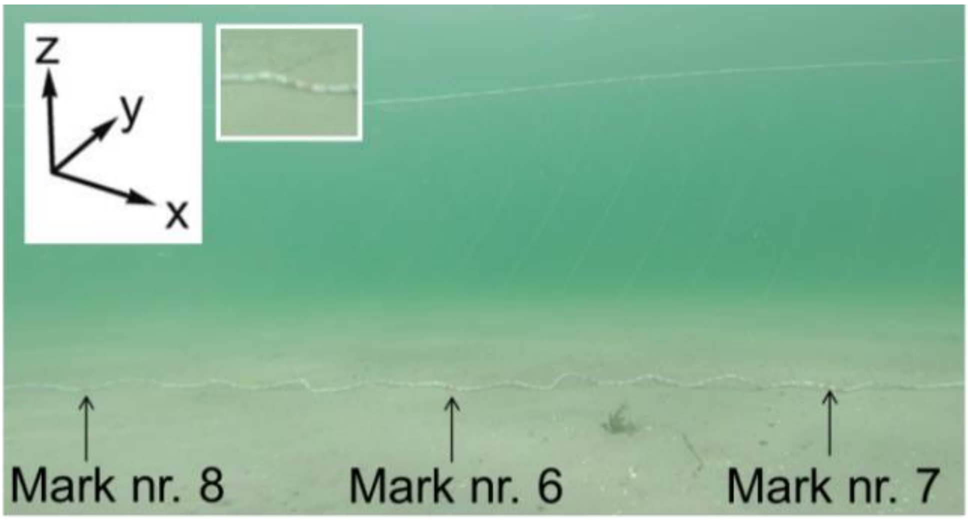
In bottom set nets, the gear components in contact with the seabed are the leadline, the anchors and the bridle lines (connecting the anchors to the gear). Nets may be dragged on the seabed and become tangled in bottom features as the gear moves with currents or turbulence, or may be snagged on benthic structures/organisms during retrieval of the gear (Shester and Micheli, 2011).

An in-situ gillnet experiment was carried out by adapting a stereo imaging method to the Danish coastal plaice fishery to assess the dynamic behavior of the leadline, i.e., the sweeping motion on the seabed and the penetration into the sediment (**Paper IV**).

2. Major findings

The leadline of bottom gillnets, fully deployed on the bottom, could sweep the seabed in sandy habitats up to about 2 m, ranging from 0.10 to 1.10m and 0.06 to 2.01m respectively in the X and Y dimensions (*Fig. 20*). Movements were the largest in the backward-forward dimension, which corresponded to the main direction of both the current and the waves in the experiment. The in-situ measurements of the leadline showed that movements were the smallest in the upward-downward dimension, ranging from 0.02 to 0.30m. The leadline was moving but not penetrating into the seabed, downward movements being most likely due to slight disparities in the seabed features.

Figure 20 Net fully deployed on the seabed – partly reproduced from *Savina, E., Krag, L.A., Madsen, N. Developing and testing a computer vision method to quantify 3D movements of bottom-set gillnets on the seabed. ICES Journal of Marine Research, 2017, fsx194, https://doi.org/10.1093/icesjms/fsx194*



The measured movements were representative only to a certain point of what really happens: as the nets were getting too far from or too close to the recording unit, it was not possible to take measurements anymore. Besides, current speeds during data collection were lower than the average range in coastal Danish waters. The present measurements of the movement of the leadline were therefore underestimated. However, the movement of the leadline was not unlimited as the fleets were anchored on the bottom.

3. In the perspective of the EAF

In terms of seabed disturbance, this means that the physical disruption of the seabed (penetration) of gillnets is minimal. The mechanism at stake is therefore partly different from that of active fishing gears, for which the habitat physical impact is partially due to seabed penetration (Eigaard *et al.*, 2016; Depestele *et al.*, 2016).

However, due to the sweeping movements, the leadline and netting could have potential direct damage to the benthos by snagging and entangling available entities. If we consider that a maximum of 30 km of nets are soaked in a typical bottom-set gillnets fishing operation (Montgomerie, 2015), we can roughly estimate the swept area to about 0.04 km^2 for light nets and 0.01 km^2 for heavy nets (based on a rectangle area calculation using the average measured range per mark in the Y dimension), which is much lower than any of the hourly swept area estimated for active fishing gears by Eigaard *et al.* (2016).

4. Further developments

The dynamic behavior of the leadline was analysed using a simple motion metrics in the three spatial dimensions, i.e., the maximum movement of the leadline in each dimension, but it would be interesting to further assess the nets behavior using our recordings of the spatio-temporal positions, e.g., with a spatio-temporal trajectory analysis.

Fishing gear disturbance is likely to have a more significant impact if it exceeds natural disturbance (Kaiser *et al.*, 2002). For example, shallow tide-swept and wave-impacted sandy habitats exhibit faunal communities that are well adapted to high rates of natural disturbance (Kaiser, 1998). Methods to further assess in-situ direct benthos damage by coupling mechanical to biological effects would give a more informative input in an EAF perspective.

It was difficult to draw a clear relationship between the nets and the current speed and direction. The complex effects of water flow, waves and wind, can change at a small scale, and influence the behavior of the gear (Shimizu *et al.*, 2004). These local differences in water flow could be a reason for the significant interacting effect of runs. Detailed measurement of the current direction and speed, e.g., using a current meter, in further experiments could provide with a better understanding of the environmental variables at stake.

Experiments were conducted in very shallow waters, which were needed to test how to operate the camera cages, also because water was turbid at the time of data collection. On the condition that an improved method allow to record in turbid waters, e.g., the previously mentioned adapted time-of-flight camera, further estimations should be run in deeper waters for which water flow conditions would be different as the turbulent boundary layer does not occupy the entire water column contrary to shallow waters (Soulsby, 1997; Otto *et al.*, 1990).

Observations only covered the soaking phase of a gillnetting operation, i.e., when the gear was fully deployed on the bottom, and not the retrieval of the gear, therefore not covering the total potential habitat effect of bottom gillnets. Shester and Micheli (2011) as well as Sørensen *et al.* (2016) observed the entanglement and removal of flora by set gillnets while being hauled. Effects of hauling are more likely to be destructive as more power is exerted through the nets (hauler) than when soaking, for which, e.g., a stone could eventually stop the net. It is however known from fishermen practices that the way the gear is handled when hauling can significantly reduce possible habitat damage, e.g., hauling in the current direction.

B. Effects of gear design and operational tactics

1. Gear characteristics and rigging play a key role in the net behavior

The gear characteristics and rigging specifications play a key role in the net behavior, and therefore its potential seabed effects. The internal force acting on the netting is not homogenous over its entire surface, with stronger force close to where the head- and leadlines are attached (Takagi *et al.*, 2007). Water flow pushes the netting to incline and bulge out of the vertical plane, lowering the headline height (Stewart, 1988; Takagi *et al.*, 2007). Shimizu *et al.* (2007) calculated that the leadline would slide across the sea bottom if the force acting on the leadline is larger than the coefficient of static friction, but sliding motions of bottom gill nets during fishing have not been directly observed in any study to our knowledge.

Two different types of commercial bottom gillnets, light and heavy, were used to give a gradient of commercial conditions. All nets were commercial plaice gillnets, and heavy and light nets differed only in the specifications of the head- and leadlines. The headline was different for the two gear types as it influences the inclination of the net and has commonly more buoyancy for heavier nets in commercial conditions (**Paper IV**).

2. Major findings

The gear configuration affected the sweeping of the nets, with light nets moving significantly more than heavy ones. Whereas the general perception is that heavy gears are more destructive to the habitat, such as in active gears (Kaiser *et al.*, 2002), it was demonstrated here that a heavier leadline would result in less movement, being the actual issue in terms of potential habitat damage of bottom-set gillnets. Therefore, gear configuration has a strong mitigation effect regarding the sweeping behavior of the leadline, and habitat damage could be reduced by using heavier nets.

3. In the perspective of the EAF

Bottom set nets frequently fish in areas where fishing with active gears is limited due to technical limitations in the use of the gear, e.g., in reef areas, which also happen to be the most commonly designated sites for conservation protection, e.g., under the Habitats Directive (Natura 2000 sites) (Sørensen *et al.*, 2016). The observed effects of each individual FO may be negligible, but the cumulated effects may be of importance at the scale of the fishery, especially if it is concentrated in particularly sensitive habitats.

Regarding the consequences for a potential change in net configuration, i.e., light versus heavy nets, on the fisher gains, light nets fish better as they have more slack, and potentially thinner twine diameter, but fall down and have reduced catch if the current is too high. In addition, lighter nets are more prone to damage and therefore need to be changed more often.

4. Further developments

In addition to the tested net configuration, i.e., light and heavy nets, other components of the fishing gear in gillnets could be looked at to mitigate their habitat effects. Bridles attached to either the head or bottom line will give the netting different types of curves which will affect the drag (Stewart and Ferro, 1985). The netting hanging ratio and length of fleets, as well as the way the nets are set out could also affect the leadline movement of bottom-set gillnets. In addition to the leadline, it was shown that the anchors could have an effect while hauling the gear (Sørensen *et al.*, 2016).

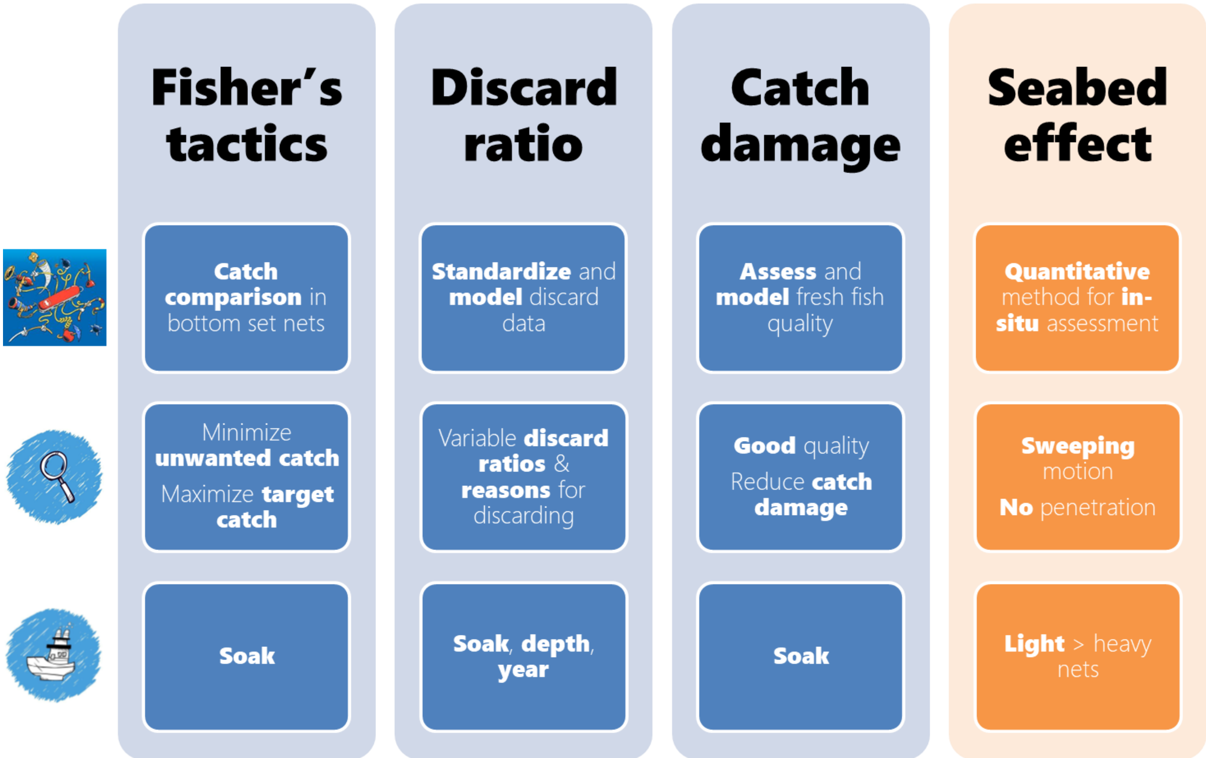
- ✓ The direct physical disruption of the seabed of gillnets was minimal as the leadline was moving but not penetrating into the seabed.
- ✓ The sweeping movements could be up to about 2m, but resulted in a total swept area per fishing operation lower than any of the hourly swept area estimated for active fishing gears.
- ✓ Whereas the general perception is that heavy gears are more destructive to the habitat, it was demonstrated here that light nets were moving significantly more than heavy ones.

VI. SUMMARY OF THE FINDINGS & FUTURE PERSPECTIVES

A. Summary of the findings and implications for the net fisheries

The Danish bottom set nets observed in the present work were able to select a limited number of species and a high fraction of marketable fish. In addition to the gear characteristics, fisher's tactics were shown to play a key role in the catch pattern, due to the fact that it is in the fisher's interest to adopt a tactic that maximize the catch value by balancing catch levels and handling time for the deployed nets (*Fig.* 21). Changes in operational tactics, e.g., soak time, is a powerful tool to limit unwanted catch, which can be use by the net fisheries to adjust to the landing obligation.

Figure 21. Summary of the findings



The direct physical disruption of the seabed was minimal as the leadline was not penetrating into the seabed. Whereas the general perception is that heavy gears are more destructive to the habitat, light nets were moving significantly more than heavy ones (*Fig.* 21). The expected changes in the rules governing access rights may create a major incentive for the industry to adopt gears that provide more fishing opportunities. In that respect, bottom set nets could play a key part, for example by being potentially compatible with restricted protected areas providing that gear design, e.g., heavy instead of light nets, is taken into consideration as mitigation measure. Bottom set nets are also likely to be compatible with other activities, e.g., offshore wind farms as the risk of hooking cables is negligible (no seabed penetration).

B. Future perspectives

Gear technologists have started to describe fishing pressure on community components, e.g., species composition, while comparing gears or fishing tactics. We can work with experimental data in a controlled sampling design, but key information also comes from commercial observations. However, because the observers at sea sampling plan was not designed for that purpose, the reduced number of observations and specific stratification allow to highlight some behaviour but not to extrapolate results, and impose to analyse some potentially confounding factors together, which might mask some effects and ultimately bias the analysis. In addition, assessing fishing pressure on community components require further information on the natural populations. Scientific trawl surveys, e.g., the International Bottom Trawl Survey (IBTS) in the North Sea, can be considered in some cases as a potential proxy for the community species composition. Scientific surveys give density estimates, which can be difficult to compare with passive gear fishing effort, but methods have recently been developed to standardize metrics for comparing fishing operations from different gears (Fauconnet *et al.*, 2015). However, sampling locations of the trawl survey are not always spatially and temporally concurrent with coastal bottom set nets fisheries, for technical reasons, e.g., not possible to trawl in rocky areas. As the EAF brings new demands to the scientific community, one might question the relevance of the content and stratification of the current European sampling data schemes.

Besides, for many of the potential fishing effects, the current scientific understanding does not allow to establish a clear relationship with fishing pressure, particularly regarding the effects on biogeochemical cycling or ecosystem resilience and functioning. It seems more and more relevant to support interdisciplinary research projects for coupling mechanical and biological effects of fishing on the ecosystem.

In addition to fishing pressure, fishing intensity has also to be accounted for. This is not always easy for fleets with relatively small vessels such as in the Danish gill- and trammel nets fisheries, because they do not all have high resolution spatial data. One alternative could be to work with stakeholders including fishers through interviews for a mapping of fishing hot spots and marine habitats.

Ultimately, management will influence the adoption of one gear towards another, thus discouraging or encouraging conservation goals, and will likely play a key role in the next few years on the development or on contrary the decrease of the Danish bottom set nets fisheries. The current allocation of specific quotas to coastal fisheries might beneficiate to the Danish gill- and trammel netters. Further development of netting practices could for example include the promotion of the opportunity of daily fresh fish supply by the coastal vessels, as selling whole fish directly to consumers has proven worthy for some Danish coastal gillnetters, e.g., the established and successful network http://havfriskfisk.dk/default.asp for the very small vessels. Then, improvement in whole fish quality could therefore make a difference.

Regarding the possibility to fish in restricted sensitive areas, further studies should be conducted on the effect of the sweeping behavior of the leadline (and anchors) on the benthic flora.

The reductions in fishing effort mean that natural mortality is becoming a major source of mortality in the North Sea, and the stock dynamics are increasingly influenced by natural processes and not by fisheries only (Ulrich *et al.*, 2016). Besides fishing effects on the ecosystem, it is necessary within an EAF to consider the effects of the environment on fisheries (Jennings and Revill, 2007). For example, the development of fisheries that are able to adapt to climate change and rising oil prices might be supported, among which bottom set nets are known to be fuel efficient (Jennings and Revill, 2007; Suuronen *et al.*, 2012). The increasing seal populations, however, and particularly the grey seal population in the Baltic, are forcing fishermen to stop use gillnets and switch to, e.g., trawling, or leave the fishery.

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Paper I

Effect of fisher's soak tactic on catch pattern in the Danish gillnet plaice fishery

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Abstract

Soak duration in the gillnet fisheries can vary from a few hours to several days. The industry reports a variation of soak tactics between target species, but also between seasons for the same species. These are determined by the robustness of the target species and the catch of unwanted species. Different soak tactics were compared to estimate the role that the choice of a soak tactic plays in the catch efficiency of both target and unwanted species. In the Danish summer gillnet fishery targeting plaice *(Pleuronectes platessa)*, nets are deployed approximately 12 hours (h) during day. Unwanted species are common dab (*Limanda limanda*) and edible crab (*Cancer pagurus*). The commercially used 12 h deployment during day was compared to 12 h deployment during night and 24 h deployment. On average, there were about 1.5 more catches of commercial size plaice (above 27cm), and 2 and 4 times less catches of the unwanted dab and edible crab, respectively, for 12 h at day compared to the other soak tactics (12 h at night or 24 h). Gillnetters participating in the coastal summer fishery for plaice follow the theoretical optimal soak tactic. The commercially used 12 h deployment during day maximises the catch of commercial sized plaice and limits handling time by catching less unwanted dab and crabs.

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ABSTRACT

Soak duration in the gillnet fisheries can vary from a few hours to several days. The industry reports a variation of soak tactics between target species, but also between seasons for the same species. These are determined by the robustness of the target species and the catch of unwanted species. Different soak tactics were compared to estimate the role that the choice of a soak tactic plays in the catch efficiency of both target and unwanted species. In the Danish summer gillnet fishery targeting plaice *(Pleuronectes platessa)*, nets are deployed approximately 12 h (h) during day. Unwanted species are common dab (*Limanda limanda*) and edible crab (*Cancer pagurus*). The commercially used 12 h deployment during day was compared to 12 h deployment during night and 24 h deployment. On average, there were about 1.5 more catches of commercial size plaice (above 27 cm), and 2 and 4 times less catches of the unwanted dab and edible crab, respectively, for 12 h at day compared to the other soak tactics (12 h at night or 24 h). Gillnetters participating in the coastal summer fishery for plaice follow the theoretical optimal soak tactic. The commercially used 12 h deployment during day maximises the catch of commercial sized plaice and limits handling time by catching less unwanted dab and crabs.

1. Introduction

Approximately 40% of the European fishing vessels deploy set gillnets as main fishing gear (E.C., 2017). In Denmark, gillnetters represents approximately 90% of the fishing fleet. Many of the European gillnetters participate in small-scale fisheries and play a vital role in the coastal areas (Veiga et al., 2016). Gillnets are, in general, considered to be highly size selective, with larger mesh sizes catching larger fish (Stergiou and Erzini, 2002; He and Pol, 2010). All species are not, however, equally vulnerable to the gear (Fonseca et al., 2002; Valdemarsen and Suuronen, 2003; He and Pol, 2010; Breen et al., 2016). Limiting unwanted species is in the fisher's interest as it reduces handling time, which can be intensive in gillnet fisheries. Handling time affects the fishing power, i.e., the number and length of gillnets that can be handled during a fishing trip (Morandeau et al., 2014; Fauconnet and Rochet, 2016). The selection properties of gillnets may be improved by altering mesh size, netting material, or twine size. But due to the nature of the gear, one would most likely also impair the catch efficiency of the net. More complex gears proved to successfully reduce bycatch, e.g., gillnets that float above the seabed (norsel-mounted nets) to reduce bycatch of red king crab (*Paralithodes camtschaticus*) in the cod (*Gadus morhua*) fishery (Godøy et al., 2003), but are usually limited in passive fisheries (Kennelly and Broadhurst, 2002; Andersen et al., 2012; Eliasen et al., 2014; Fauconnet et al., 2015; Breen et al., 2016; Fauconnet and Rochet, 2016). In many cases, the fisher's operational tactic plays a dominant role. It also has the advantage of no additional capital cost (SigurÐardóttir et al., 2015).

Soak duration in the gillnet fisheries varies considerably. In Denmark, it can be from a few hours in the wreck fishery for cod to several days in the turbot (*Scophthalmus maximus*) or monkfish (*Lophius piscatorius*) fisheries. It can even vary between seasons for the same species. Time of day and soak duration are easily adjustable factors which appear to play a key role in the gillnet fisheries. Previous studies suggested a relationship between soak time and catch size for short soak times (up to 6 h) but none for longer soak times (Acosta, 1994; Gonçalves et al., 2008; Hickford and Schiel, 1996; Losanes et al., 1992; Minns and Hurley, 1988; Rotherham et al., 2006; Schmalz and Staples, 2014). The soak tactic should ensure an acceptable catch rate of commercial species to optimize landings with regard to fishing effort, fuel consumption and labour cost (Hickford and Schiel, 1996; Hopper et al., 2003). The theoretical optimal soak tactic in a given gillnet fishery is the one that best maximizes catches of target species while minimizing unwanted catch. However, not all fishing tactics are associated with catch maximization. Some fishers are satisfied with recovering the

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operating costs only, or minimizing physical and economic risks (Salas and Gaertner, 2004). This can especially be relevant in small-scale fisheries, which represent a majority of the gillnetters (Salas and Gaertner, 2004).

To investigate the effect of soak tactic on catch pattern in the gillnet fisheries, the following questions were addressed:

- What role does the choice of soak tactic play in the catch pattern, i.e., how big is the difference in catches of target and unwanted species between different soak tactics employing differences in time of the day and duration?
- If the catch efficiency is different, is this difference size dependent?
- Are the fishers able to adjust to use the theoretical optimal soak tactic?

We used the Danish summer plaice (*Pleuronectes platessa*) gillnet fishery in the Skagerrak (ICES area IIIa) as a case study. The plaice fishery in the Skagerrak is one of the most important commercial gillnet fisheries in Denmark (Ulrich and Andersen, 2004). It takes place in coastal sandy and shallow fishing grounds. It is characterized by shorter soaks in the summer compared to the winter to reduce the excessive bycatch of edible crabs (*Cancer pagurus*). Pincers of the larger edible crabs can be sold, but crabs are mostly seen as a nuisance by gillnetters as they can severely increase handling time. It is common practice to crush the larger crabs in order to facilitate their disentanglement from the netting. Most of the other non-target species, such as dab (*Limanda limanda*), usually represent low selling value at the fish auction. We carried out a gillnet experiment following commercial practices with three different soak tactics, i.e., the commercially used 12 h (h) during day, as well as 12 h at night and 24 h to document differences in species composition, catch efficiency and specifically examine whether the fishermen have adopted the best theoretical soak tactic.

2. Materials and methods

2.1. Experimental design and sea trials

Trials were conducted on the Danish commercial gillnetter Skovsmose HG5 (11.99m, 171 kW) for eight consecutive days in September 2014. A total of 27 identical plaice gillnets (http://daconet.dk/) with all specifications corresponding to commercial practice were used (Table 1). A total of nine fleets each consisting of three gillnets tied together were constructed. Every day, three fleets were soaked for 24 h. Simultaneously, three fleets were soaked for 12 h during the day and three others during the night (Figs. 1 and 2). The soak durations of 12 and 24 h covered the usual range of commercial practices in Danish coastal waters. Gillnets were set at a known sandy bottom habitat at the same depth. Soak tactics were alternated at each position. Fleets were positioned with the current, parallel to the coast, and anchored at both ends using 6 m bridle lines and 4 kg anchors following commercial practices. Fleets were hauled according to commercial practices using a hydraulically-powered net hauler with top roller (http://www.net-op.dk/). Two fishers disentangled the catch from the netting on a sorting table during hauling.

Table 1
Specifications of an individual net panel used in the experimental set-up. Height is given as stretched height.

Gear specifications		
Net	Type	Gillnet
	Target species	Plaice
Twine	Diameter	0.30 mm
	Type	Monofil
	Material	Nylon
	Color	Snow-white
	Knot	Double
Mesh size	Nominal (bar length)	68 mm
Dimensions	Height (mesh depth)	2 m (14.5)
	Length (No. of knots)	82 m (4800 kn)
	Hanging ratio	25%
Floatline	Buoyancy per 100 m	900 g
Leadline	Weight per 100 m	5 kg

2.2. Data collection

All fish and invertebrate mega-fauna were sorted to species level and counted. Fish total length was measured to the nearest cm below on a measuring board (E.U., 2016). Invertebrates were measured with a caliper to the nearest mm below as carapace width for edible (*Cancer pagurus*), common (*Carcinus maenas*) and swimming (*Liocarcinus depurator*) crabs (ICES, 2015). Carapace height was measured for hermit crabs (*Pagurus bernhardus*). Diameter was measured for common (*Asterias rubens*), Northern (*Leptasterias muelleri*) and spiny (*Marthasterias glacialis*) starfish and edible sea urchin (*Echinus esculentus*). Data were collected at the fleet level to account for the between-fleet variation (Millar and Anderson, 2004). It was not always possible to process invertebrates as soon as they were hauled aboard and some were therefore kept in the vessel cooling room or frozen for later analysis.

2.3. Species composition

Relative abundance was calculated per fleet as the ratio between the number of individuals of a given species and the total number of individuals. Species occurrence was calculated as the ratio between the number of fleets where a given species was present and the total number of fleets (per soak tactic).

2.4. Catch comparison analysis

The method developed by Herrmann et al. (2017) for investigating the effect of design changes on catch efficiency in passive gears was used. The catch comparison analysis aimed to determine whether; (1) there was a significant difference in the catch efficiency between the different soak tactics tested, and (2) a potential difference between the different soaks could be related to the size of the individuals. Catch data of each soak tactic were summed over the different fleets to account for the variability in numbers and sizes of the individuals available at the specific time and position of each fleet's deployment. The experimental summed catch comparison rate cc_l is given by:

$$cc_l = \frac{\sum_{j=1}^{bq} nb_{lj}}{\sum_{i=1}^{aq} na_{li} + \sum_{j=1}^{bq} nb_{lj}} \tag{1}$$

where na_{li} and nb_{lj} are the numbers of individuals measured in each length class l for soak tactic a in fleet i and for soak tactic b in fleet j, respectively. aq and bq are the number of fleets deployed with soak tactics a and b, respectively. aq and bq were identical in our experiment (3 fleets × 7 cruise days for each soak tactic).

The experimental cc_l is often modelled by the function $cc(l, \boldsymbol{v})$, or catch comparison curve, which expresses the probability of finding a fish of length l in one of the fleets of soak tactic b given that it was found in one of the fleets of soak tactic a or b. $\boldsymbol{v}$ represents the parameters describing the catch comparison curve. The function $cc(l, \boldsymbol{v})$ has the following form:

$$cc(l, \boldsymbol{v}) = \frac{exp(f(l, v_0, ..., v_k))}{1 + exp(f(l, v_0, ..., v_k))} \tag{2}$$

where f is a polynomial of order k with coefficients v_0 to v_k. The values of the parameters $\boldsymbol{v}$ describing $cc(l, \boldsymbol{v})$ are estimated by minimizing the following equation:

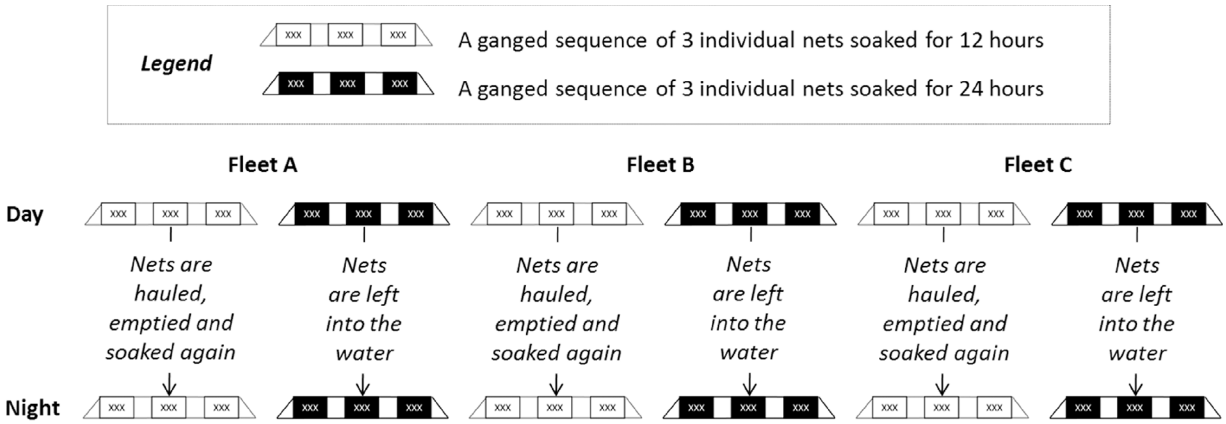

Fig. 1. Sampling design.

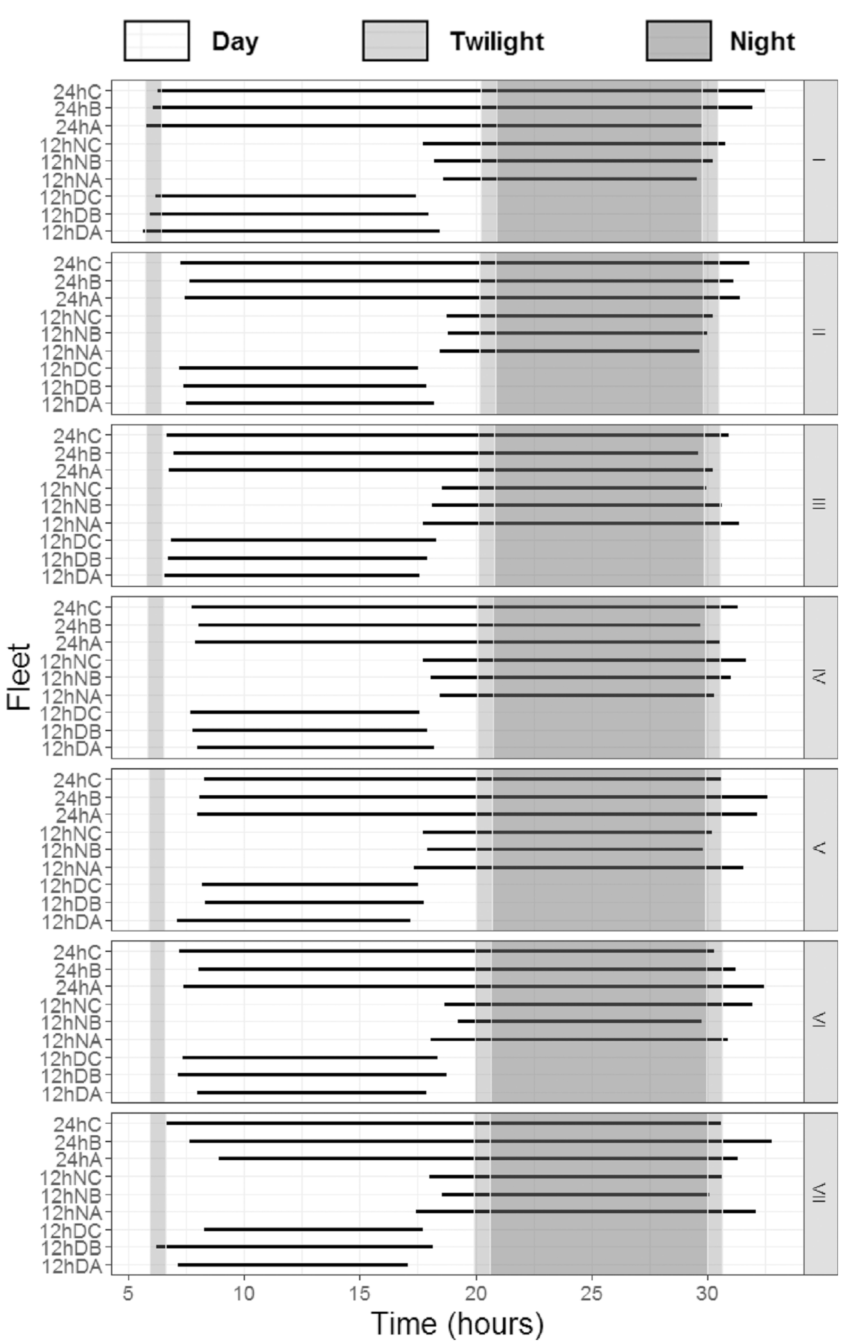

Fig. 2. Time in the day when fleets were soaked by sampling day (from I to VII). Civil twilight was used to define dawn and dusk. Fleets were labelled as a combination of soak tactic (12hD for 12 h at day, 12hN for 12 h at night and 24 h for 24 h) and fleet identification (A, B or C).

$$-\sum_{l}\left\{\sum_{i=1}^{aq} na_{li}\times\ln(1.0-cc(l,\boldsymbol{v}))+\sum_{j=1}^{bq} nb_{lj}\times\ln(cc(l,\boldsymbol{v}))\right\} \tag{3}$$

where the inner summations represent the summations of the data from the fleets and the outer summation is the summation over the length classes l.

The method developed by Herrmann et al. (2017) accounts for multiple competing models to describe the data using multi-model inference and therefore accounts for the uncertainty in model selection (Burnham and Anderson, 2002). f was considered up to an order of 4 with parameters v_0 to v_4. Leaving out one or more of the parameters $v_0 \ldots v_4$ led to 31 additional models that were considered as potential models for the catch comparison $cc(l, \boldsymbol{v})$ between a and b. The models were ranked and weighed according to their AICc values. AICc are AIC values corrected for finite sample sizes in the data (Akaike, 1974; Burnham and Anderson, 2002). The combined model for the estimation of $cc(l,\boldsymbol{v})$ resulting from the multi-model averaging was calculated by:

$$\mathrm{cc}(l,\boldsymbol{v})=\sum_{i} w_i\times \mathrm{cc}(l,\boldsymbol{v}) \quad \text{with} \quad w_i=\frac{exp(0.5\times(AICc_i-AICc_{min}))}{\sum_j exp(0.5\times(AICc_j-AICc_{min}))} \tag{4}$$

where the summations are over the models with a AICc value within +10 of the model with the lowest AICc value ($\mathrm{AICc_{min}}$) (Katsanevakis, 2006; Herrmann et al., 2014).

Contrary to the catch comparison rate $cc(l, \boldsymbol{v})$, the catch ratio $cr(l,\boldsymbol{v})$ gives a direct relative value of the catch efficiency between the soak tactics a and b, e.g., if the catch efficiency of both soak tactics is equal, $cr(l,\boldsymbol{v})$ should be 1.0. The catch ratio $cr(l,\boldsymbol{v})$ is related to the summed catch comparison, and was calculated in its functional form in addition to the catch comparison rate as follow (for further details, see Herrmann et al., 2017):

$$cr(l,\boldsymbol{v})=\frac{aq\times cc(l,\boldsymbol{v})}{bq\times(1-cc(l,\boldsymbol{v}))} \tag{5}$$

The Efron 95% confidence limits for both the catch comparison rate and the catch ratio were estimated using 1000 bootstrap repetitions (Efron, 1982). Applying double bootstrapping method accounts for:

(1) between-fleet variation in the availability of fish and catch efficiency, by randomly selecting aq and bq fleets from the pool of fleets of soak tactics a and b, respectively (initial resampling), and
(2) within-fleet uncertainty in the size structure of the catch data, by randomly selecting fish from each fleet, with a total number of fish similar to that sampled in the fleet (bootstrapping of the initial resampling).

As the combined model method was applied to each bootstrap repetition, the effect of uncertainty in model selection was also accounted for in the confidence limits.

The ability of the combined model to describe the experimental data was evaluated based on the p-value. It quantifies the probability of obtaining by chance a difference at least as large as the one observed between the experimental data and the model, assuming that the model is correct. The p-value should therefore not be < 0.05 for the combined model to describe the experimental data sufficiently well. To identify sizes with significant difference in catch efficiency, length classes in which the confidence limits for the combined catch comparison curve did not contain $bq/(aq + bq)$, i.e., 0.5 in our case, were checked for.

One may logically assume a linear relationship between soak duration and the amount of catches, i.e., two times more catches for 24 h than for 12 h. Therefore, when comparing 24 h to 12 h, the expected catch ratio was calculated if, for 24 h, the catch rate was twice as high than for 12 h at day (2 × 12 h D) or 12 h at night (2 × 12 h N). Another logical approach is to consider that the resulting catches after 24 h are the sum of the catches for 12 h at day and 12 h at night. Therefore, when comparing 24 h to 12 h, the expected catch ratio was calculated if, for 24 h there were to be the summed amount of catches caught for 12 h at day and 12 h at night (12 h D + 12 h N). For the calculation of the expected catch ratio, the $cr(l,\boldsymbol{v})$ given when comparing 12 h at night to 12 h at day for the length class representative of the main bulk of catches was used.

A length-integrated average value for the catch ratio was also estimated by:

$$cr_{average}=\frac{\frac{1}{bq}\sum_{l}\sum_{j=1}^{bq} nb_{lj}}{\frac{1}{aq}\sum_{l}\sum_{i=1}^{aq} na_{li}} \tag{6}$$

where the outer summation covers the length classes in the catch during the experimental sea trials. The Efron 95% confidence limits for $cr_{average}$ was assessed by incorporating it into each of the bootstrap iterations. $cr_{average}$ is specific for the population structure encountered during the experimental sea trials. For the target species plaice, $cr_{average}$ was estimated for fish below and above Minimum Conservation Reference Size (MCRS), also previous Minimum Landing Size (MLS), i.e., 27 cm.

Only the three most abundant and commonly occurring species, i.e., plaice, dab and edible crab were looked at in the catch comparison analysis. The lower and upper length classes were set as the nearest multiple of 5 of the minimal and maximal observed values for all soak tactics respectively, for each of the three species, i.e., 20–55 cm for plaice, 15–40 cm for dab and 55–200 mm for crabs. The number of individuals caught per length class for the three different soak tactics were compared as follows; 12 h at night compared to 12 h at day, 24 h compared to 12 h at day, and 24 h compared to 12 h at night. For the calculation of the expected catch ratios, the $cr(l,\boldsymbol{v})$ given when comparing 12 h at night to 12 h at day for the length class representative of the main bulk of catches was used, i.e. 35 cm for plaice, 25 cm for dab and 115 mm for crab.

2.5. Software

Catch comparison analysis were performed by SELNET (Herrmann et al., 2012). Graphs were produced by the open-source software R 3.2.3 (R Core Team, 2016) using the packages ‘dplyr’ (Wickham and François, 2015) and ‘ggplot2’ (Wickham, 2009).

3. Results

3.1. Description of the data and species composition

Fleets were set at an average depth of 5.4 m ± 0.6 m representative of shallow summer fishing grounds in the Danish coastal gillnet fishery. The average soak duration was 23.8 ± 1.2 h for the 24 h fleets, 10.7 h ± 0.9 h for the 12 h at day fleets, and 12.4 h ± 1.1 h for the 12 h at night fleets (Fig. 2).

There was a total of 2431 fish and 1512 invertebrates caught and assessed onboard the fishing vessel from 63 different fleets (3 soak patterns × 3 fleets × 7 sampling days). There were 19 and 8 different species caught for fish and invertebrates respectively, all fleets included (Table 2). The number of individuals per fleet was highly variable (Table 2).

Overall, species composition between soak tactics was similar (Table 2). Plaice, common dab and edible crab were the most abundant species for all soak tactics. Plaice, dab and edible crab were also the most commonly occurring species for all soak tactics.

3.2. Catch comparison analysis

The catch comparison curves properly reflected the trend in the experimental points (Fig. 4). The experimental rates were subject to increasing binomial noise outside the length classes representing the main bulk of the catches (Fig. 3). The ability of the catch comparison

Table 2
Mean and range (min-max) number, length of individuals caught per fleet (3 individual nets for a total length of 246m) relative abundance (min-max) and occurrence per soak tactic (12hD for 12 h at day, 12hN for 12 h at night and 24 h for 24 h) for invertebrates and fish species. Length is pooled over fleets, and given in mm for invertebrates and in cm for fish.

Species	Soak	Number	Length	Relative abundance (%)	Occurrence (%)
INVERTEBRATES					
Edible crab *(Cancer pagurus)*	12hD	9 (1–29)	114 (66–194)	13.5 (4.2–39.7)	71
	12hN	26 (10–80)	117 (58–197)	46.4 (23.8–77.3)	100
	24h	30 (7–74)	118 (57–193)	35.5 (14.9–58.7)	100
Common shore crab *(Carcinus maenas)*	12hD	2 (1–4)	56 (38–69)	5.9 (0.4–15.4)	57
	12hN	2 (1–4)	60 (50–68)	5.6 (1.1–13.3)	43
	24h	3 (1–11)	58 (36–70)	3.7 (0.8–16.9)	90
Common starfish *(Asterias rubens)*	12hD	4 (1–10)	104 (31–167)	7.6 (2.0–14.3)	29
	12hN	5 (1–16)	108 (54–186)	6.2 (2.0–13.1)	24
	24h	1 (1–2)	102 (39–164)	2.2 (1.2–5.1)	38
Edible sea urchin *(Echinus esculentus)*	12hD	–	–	–	–
	12hN	–	–	–	–
	24h	1	105	1.5	5
Hermit crab *(Pagurus bernhardus)*	12hD	–	–	–	–
	12hN	–	–	–	–
	24h	2 (1–3)	NA	2.5 (0.8–5.4)	14
Northern starfish *(Leptasterias muelleri)*	12hD	1 (1–1)	118 (118–119)	3.1 (3.0–3.2)	10
	12hN	2 (1–4)	103 (67–152)	3.8 (1.5–6.5)	24
	24h	1	158	1.0	5
Spiny starfish *(Marthasterias glacialis)*	12hD	1 (1–1)	112 (100–125)	3.3 (1.4–5.3)	10
	12hN	1	140	1.0	5
	24h	–	–	–	–
Swimming crab *(Liocarcinus depurator)*	12hD	3 (1–4)	41 (19–49)	7.2 (0.6–16.7)	57
	12hN	1 (1–2)	43 (37–50)	3.0 (0.8–6.9)	38
	24h	1 (1–2)	46 (40–58)	1.5 (0.7–2.4)	52
FISH					
Atlantic cod *(Gadus morhua)*	12hD	4 (1–10)	35 (22–53)	6.5 (0.8–13.7)	33
	12hN	3 (1–9)	36 (27–46)	4.2 (0.8–13.0)	29
	24h	2 (1–4)	30 (19–40)	2.3 (1.1–6.2)	43
Atlantic herring *(Clupea harengus)*	12hD	1	22	0.4	5
	12hN	–	–	–	–
	24h	2 (1–3)	36 (24–44)	2.2 (1.5–3.6)	19
Atlantic mackerel *(Scomber scombrus)*	12hD	1 (1–1)	33 (29–37)	2.6 (2.6–2.7)	10
	12hN	1 (1–1)	32 (30–34)	1.2 (0.8–1.5)	14
	24h	1	30	1.2	5
Brill *(Scophthalmus rhombus)*	12hD	–	–	–	–
	12hN	1	28	1.1	5
	24h	–	–	–	–
Common dab *(Limanda limanda)*	12hD	6 (1–14)	25 (19–31)	16.4 (3.1–33.3)	100
	12hN	7 (1–24)	26 (19–37)	12.2 (1.4–19.7)	100
	24h	13 (2–31)	25 (18–32)	15.7 (3.1–33.3)	100
Common sole *(Solea solea)*	12hD	–	–	–	–
	12hN	2 (1–4)	34 (23–39)	2.6 (0.8–5.8)	43
	24h	1 (1–2)	35 (30–39)	1.6 (0.8–2.0)	33
European flounder *(Platichthys flesus)*	12hD	2 (1–3)	32 (29–35)	2.5 (0.8–4.8)	19
	12hN	1 (1–1)	32 (26–37)	2.1 (0.8–4.3)	14
	24h	2 (1–3)	30 (21–37)	2.0 (0.8–6.4)	38
European plaice *(Pleuronectes platessa)*	12hD	31 (6–206)	31 (21–47)	53.2 (28.6–89.5)	100
	12hN	20 (4–58)	31 (21–53)	30.9 (13.3–48.8)	95
	24h	26 (8–73)	31 (20–46)	34.8 (12.3–58.0)	100
Garfish *(Belone belone)*	12hD	1	65	4.3	5
	12hN	–	–	–	–
	24h	–	–	–	–
Greater weever *(Trachinus draco)*	12hD	2 (1–3)	34 (29–38)	6.0 (0.4–13.6)	38
	12hN	1	35	1.8	5
	24h	2 (1–4)	32 (26–39)	2.6 (1.2–7.3)	48
Lemon sole *(Microstomus kitt)*	12hD	1	29	3.0	5
	12hN	–	–	–	–
	24h	2	28 (26–29)	3.1	5
Pollack *(Pollachius pollachius)*	12hD	2	35 (30–40)	5.1	5
	12hN	–	–	–	–
	24h	–	–	–	–
Saithe *(Pollachius virens)*	12hD	1	28	1.4	5
	12hN	1	29	1.3	5
	24h	1	35	1.5	5
Sculpin *(Myoxocephalus spp.)*	12hD	–	–	–	–
	12hN	–	–	–	–
	24h	1	24	1.2	5
Tadpole fish *(Raniceps raninus)*	12hD	–	–	–	–
	12hN	–	–	–	–
	24h	1	25	1.5	5
Turbot *(Psetta maxima)*	12hD	2 (1–4)	25 (19–36)	2.7 (1.2–5.1)	48

(continued on next page)

Table 2 *(continued)*

Species	Soak	Number	Length	Relative abundance (%)	Occurrence (%)
	12hN	2 (1–4)	24 (19–35)	4.0 (2.3–6.7)	57
	24h	3 (1–9)	23 (18–34)	3.9 (1.2–12.2)	76
Twaite shad *(Alosa fallax)*	12hD	1 (1–2)	34 (22–41)	1.4 (0.4–2.7)	29
	12hN	–	–	–	–
	24h	2 (1–2)	27 (23–34)	1.6 (1.0–2.2)	10
Whiting *(Merlangius merlangus)*	12hD	2 (1–2)	18 (12–24)	5.5 (0.4–11.8)	19
	12hN	1	15 (14–16)	1.3 (1.0–1.8)	14
	24h	2 (1–2)	13 (11–17)	2.3 (1.8–2.7)	14
Red gurnard *(Chelidonichthys lucernus)*	12hD	1 (1–2)	25 (19–29)	5.3 (2.7–11.8)	38
	12hN	1 (1–1)	30 (22–39)	2.1 (0.8–4.5)	29
	24h	2 (1–3)	26 (20–31)	2.1 (0.7–3.6)	33

curves to describe the experimental data was also verified by the fit statistics with all but one p-value > 0.05 (Table 3). The p-value slightly below 0.05 (12 h at night compared to 12 h at day for plaice with a p-value of 0.0399) was not considered a serious issue. As there was no systematic pattern in the deviation between the experimental and estimated rates, such a p-value was assumed a result of over dispersion in the data. All results described below were when looking at the main bulk of the catches within reasonably narrow confidence limits.

The results for plaice indicated lower catches for 12 h at night compared to 12 h at day, as the catch ratio was below 1.0. However, these results were not statistically significant due to wide confidence limits (Table 3, Fig. 3). An indication of lower catches for 24 h compared to 12 h at day was also found for smaller individuals. But again, these results were not significant due to wide confidence limits (Table 3, Fig. 3). The results indicated higher catches for 24 h compared to 12 h at night, with no length dependency, but without any significant difference (wide confidence limits) (Table 3, Fig. 3). When comparing 24 h to 12 h at day, for the main bulk of the catches, the estimated catch ratio for 24 h was significantly lower than the expected catch ratio 2 × 12 h D (catch rate twice as high), but not significantly different from 12 h D + 12 h N (summed amount of catches) (Fig. 4). When comparing 24 h to 12 h at night, for the main bulk of the catches, the estimated catch ratio for 24 h was significantly lower than the expected catch ratio 12 h D + 12 h N (summed amount of catches), but not significantly different from 2 × 12 h N (catch rate twice as high) (Fig. 3). This meant that catches for 12 h at night were indeed

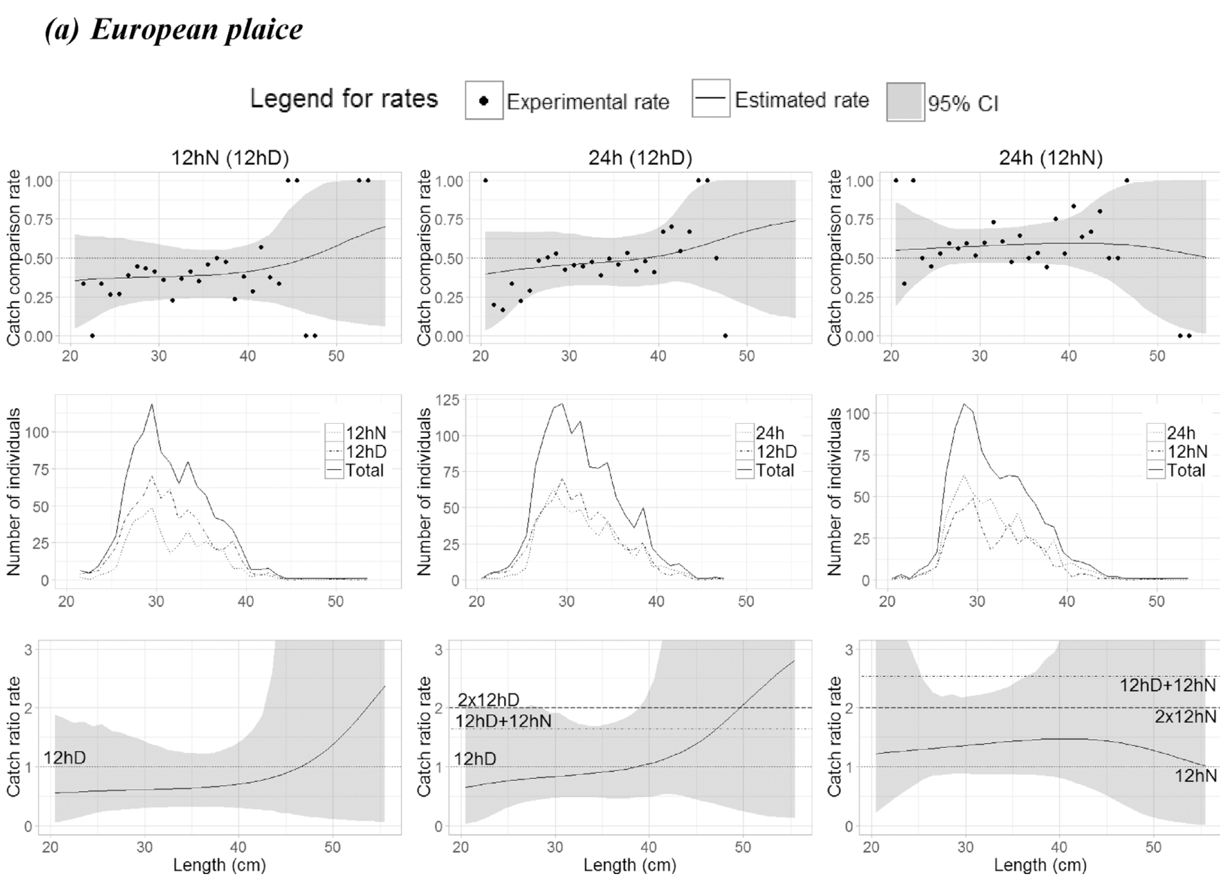

Fig. 3. Catch comparison rate (upper row), population curve (middle) and catch ratio (lower row) for the three catch comparison analysis of different soak tactics, i.e., 12 h at night (12hN) compared to 12 h at day (12hD) (left column), 24 h (24 h) compared to 12hD (middle column) and 24 h compared to 12hN (right column), estimated for (a) European plaice, (b) common dab and (c) edible crab. The catch comparison rates ('Estimated rate', black curve) are given with the Efron 95% confidence interval ('95% CI', shaded area), the experimental rates ('Experimental rate', points) and the expected rate in case of no effect of the soak tactics change investigated (horizontal stippled line). The population curves are given for the summed population per soak tactic and the summed total population. The catch ratios ('Estimated rate', black curve) are given with the Efron 95% confidence interval ('95% CI', shaded area) and the expected ratio in case of no effect of the soak tactic change investigated (12hD = 24 h or 12hN = 24 h), 2 times more catch in 24 h than in the (2 × 12hD, 2 × 12hN), or 24 h catch as the summed of the estimated 12hD and 12hN catch based on the results of the comparison 12hN compared to 12hD (12hD + 12hN) (horizontal stippled lines).

(b) Common dab

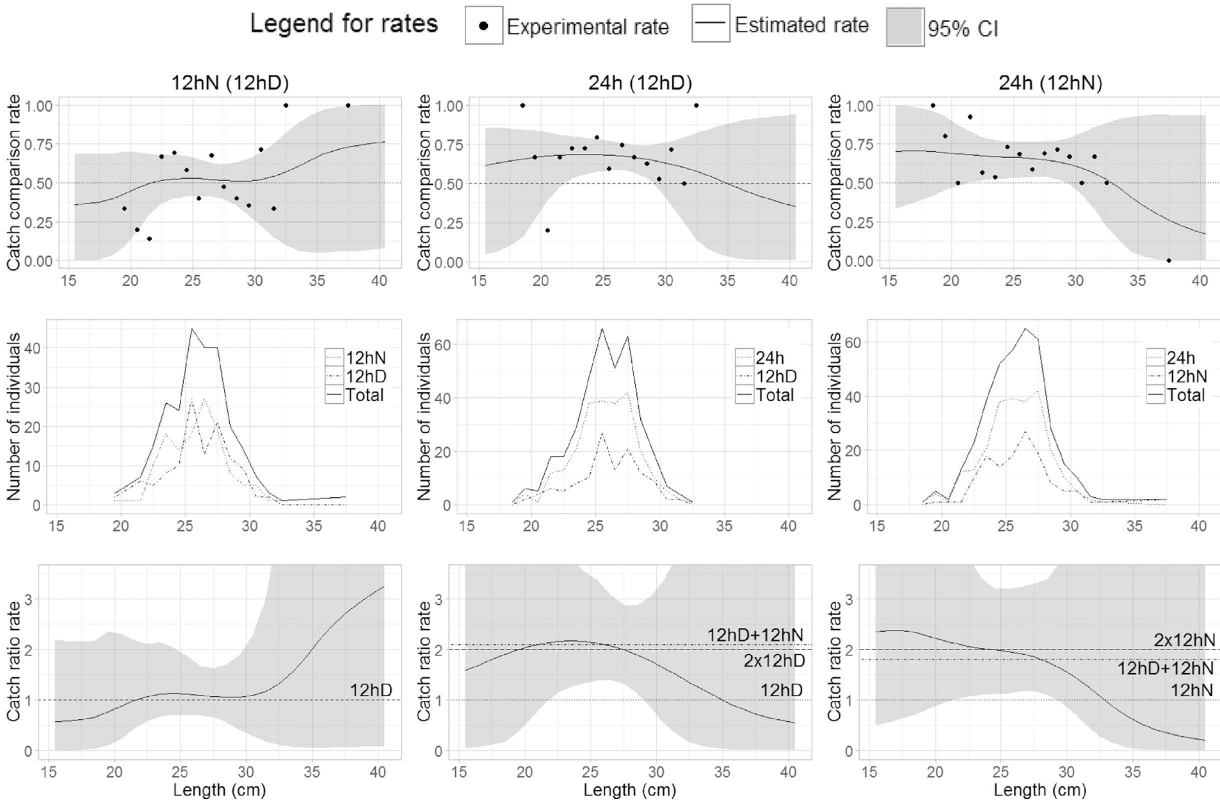

Fig. 3. (*continued*)

(c) Edible crab

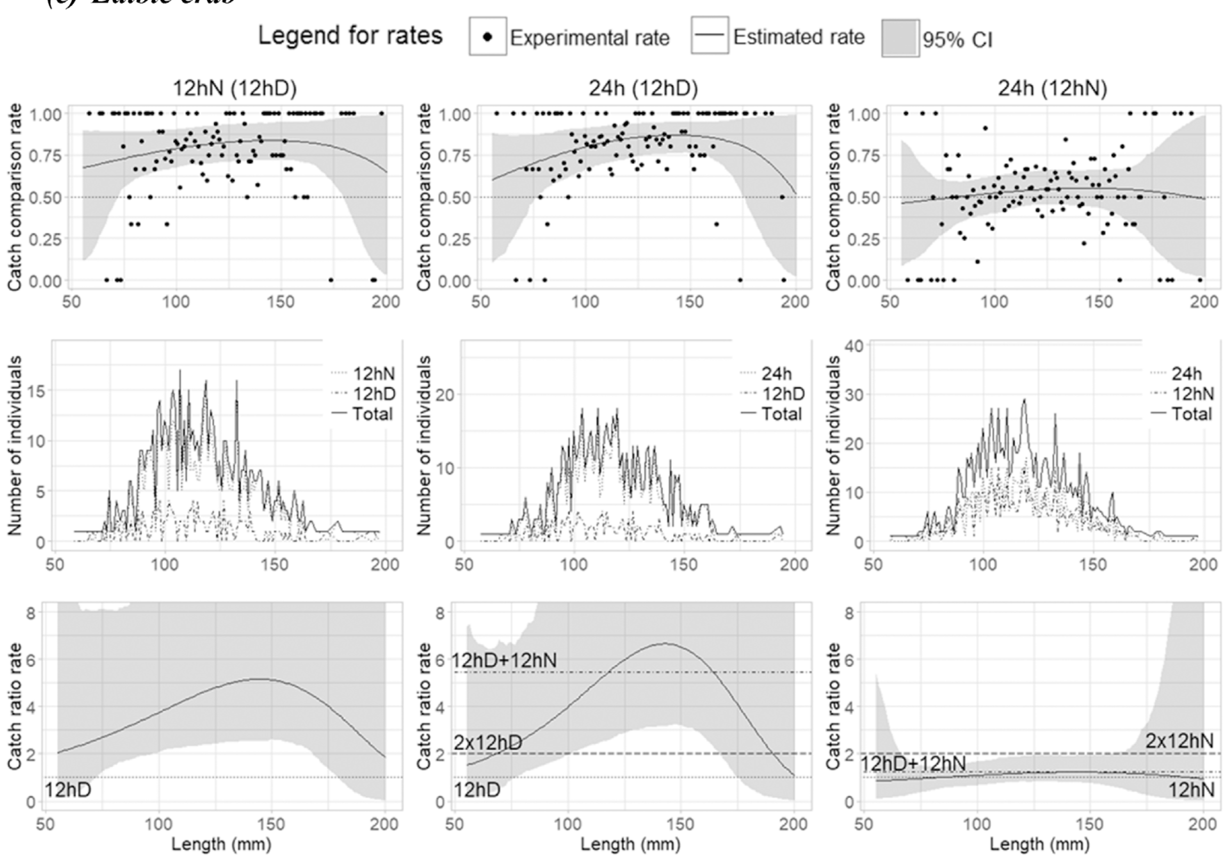

Fig. 3. (*continued*)

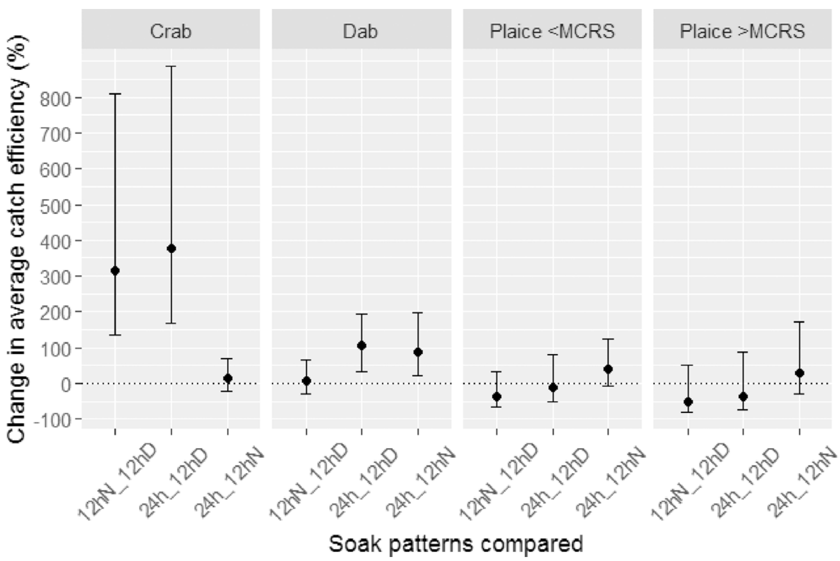

Fig. 4. Average changes in catch ratio for the different soak tactics compared: 12 h at night compared to 12 h at day (12hN_12hD), 24 h compared to 12 h at day (24h_12hD), 24 h compared to 12 h at night (24h_12hN) for edible crab (1st column), common dab (2nd column), and European plaice below (3rd column) and above (4th column) MCRS (27 cm). The vertical bars represent the Efron 95% confidence intervals.

significantly different from those for 12 h at day. This also confirmed the previous observation of lower catches for 12 h at night compared to 12 h at day. On average, there were 52% and 35% less catches of individuals below and above MCRS respectively, for 12 h at night compared to 12 h at day (Table 3, Fig. 4).

The results for dab showed no difference between 12 h at night and 12 h at day (Table 3, Fig. 3). There were significantly higher catches for 24 h compared to both 12 h at day and 12 h at night (Table 3, Fig. 3). On average, there were twice as many catches for 24 h compared to 12 h at day and night (Table 3, Fig. 4). There was no strong indication of a length dependency in the data (Fig. 3).

The results for edible crab showed significantly higher catches for both 12 h at night and 24 h compared to 12 h at day (Table 3, Fig. 3). On average, there were four and five times more catches for 12 h at night and 24 h respectively, than 12 h at day (Table 3, Fig. 4). The results showed no difference between 12 h at night and 24 h (Table 3, Fig. 3). There was no strong indication of a length dependency in the data (Fig. 3).

4. Discussion

27 different species were caught in the gillnets, but in very limited numbers compared to the target plaice and the unwanted species crab and dab. Plaice, crab and dab were therefore driving the fishing tactic.

A significant variation in catch efficiency was found between the tested soak tactics. On average, there were about 1.5 times more catches of the target species plaice above 27 cm for 12 h at day compared to the other soak tactics. Plaice usually show nocturnal behaviours (Froese and Pauly, 2015) but the current results do not support this. Contrary to plaice, there was no difference in the availability of dab to the gear between day and night. There was a simple relationship between catches and soak duration with twice as many catches for 24 h compared to 12 h (both day and night). On average, there were about 4 times less catches of the unwanted edible crab for 12 h at day compared to the other soak tactics. The differences in the availability of edible crabs to the gear were probably a result of the night effect and not the soak duration. Indeed, observations in the Skagerrak have shown that edible crabs prefer to forage in shallow water at night (Karlsson and Christiansen, 1996). With such a difference in catch efficiency on a limited time scale, soak tactics are a powerful tool for fishers to adjust to different fishing conditions.

Regarding length dependency, there was an indication of a higher probability for smaller individuals to be caught at day than at night. Indeed, it was observed in a laboratory study that the behavior of juvenile plaice in the light was dominated by swimming on the sand surface, with little activity on the bottom during darkness (Burrows, 1994). The indication of lower catches for 24 h compared to 12 h at day was surprising as it would be reasonable to expect at least the same amount of catches as for half of the soak duration. This could be explained by the availability of small plaice concentrated on few sampling days at day time. There was no strong indication of a size dependency in the data for dab or for crab.

The theoretical optimal soak tactic in a given gillnet fishery is the one that best maximize catches of target species while minimizing unwanted catch. Together with avoiding unwanted catch of crab and dab, gillnetters targeting plaice in the observed coastal summer fishery managed to maximize their catch of the target species using shorter soaks in daylight (12 h at day). Fishers also have an economic interest in reducing the soak duration to prevent quality degradation of the entangled catch by scavengers and predators common in passive fishing gears (Borges et al., 2001; Morandeau et al., 2014; Savina et al., 2016).

The experiment intended to evaluate commercial practices in the summer plaice gillnet fishery in the shallow Skagerrak fishing grounds. However, the use of soak tactics as an efficient tool for fishers to adjust to different fishing conditions are expected in other fisheries, seasons or areas, e.g., to avoid hagfish (*Myxinidae* spp.) or amphipods (*Amphipoda* spp.) in deeper waters.

Individual fishing experience was reported to be an important factor in relation to catch efficiency (Salas and Gaertner, 2004). Fishers use their experience to optimize their income under changing conditions. By using the substantial differences in catch efficiency provided by an alteration to their soak tactics, gillnetters have the ability to adjust to diverse fishing conditions much more easily and efficiently than by changing the characteristics of their gear. The understanding and documentation of such fishing strategies are essential to be able to evaluate and explore potential effects of relevant management measures by assessing the ability of fishers to adjust to new circumstances. For example, with the new landing obligation, fishers in Denmark using mesh sizes between 80 and 120 mm full mesh in the sole (*Solea solea*) fishery are facing larger bycatch of regulated round fish. They have started to change their soak tactics, which could be described as a “real time monitoring” of discards. Several fleets are soaked in the same time, one being lifted at regular intervals to check for the amount of unwanted catch (Chairman of Hirtshals fishermen organization, *Pers. Com.*).

Acknowledgments

The authors wish to thank the skipper Kim Skovsmose and the local

Table 3
Catch ratio results and fit statistics obtained in the catch comparison analysis for European plaice, common dab and edible crab. p-value, deviance and degrees of freedom (DOF) are given as bias corrected mean. *cr*(20, $\boldsymbol{v}$) is the catch ratio at species size 20 cm. Values in () represent 95% confidence limits.

	12hN (baseline: 12hD)	24 h (baseline: 12hD)	24 h (baseline: 12hN)
EUROPEAN PLAICE			
cr(20, v)	0.55 (0.05–1.89)	0.66 (0.03–2.03)	1.22 (0.23–6.10)
cr(25, v)	0.60 (0.24–1.72)	0.77 (0.34–2.00)	1.29 (0.78–2.48)
cr(30, v)	0.61 (0.30–1.40)	0.84 (0.47–1.91)	1.37 (0.88–2.20)
cr(35, v)	0.64 (0.31–1.22)	0.92 (0.47–1.72)	1.44 (0.88–2.45)
cr(40, v)	0.72 (0.29–1.47)	1.07 (0.50–2.48)	1.47 (0.80–3.34)
cr(45, v)	0.92 (0.21–6.09)	1.44 (0.43–62.28)	1.43 (0.47–20.03)
cr(50, v)	1.45 (0.10–135.25)	2.13 (0.23–1.19*10^5)	1.25 (0.12–205.08)
cr(55, v)	2.36 (0.06–2.52*10^3)	2.81 (0.13–4.96*10^9)	1.02 (0.01–677.48)
$cr_{average\ <\ MCRS}$ (%)	47.83 (18.72–150.00)	61.96 (26.60–188.57)	129.55 (68.63–272.73)
Δ $cr_{average\ <\ MCRS}$ (%)	−52.17 (−81.28 to 50.00)	−38.04 (−73.4 to 88.57)	29.55 (−31.37 to 172.73)
$cr_{average\ >\ MCRS}$ (%)	64.73 (31.92–133.12)	90.18 (49.89–180.45)	139.33 (93.64–223.23)
Δ $cr_{average\ >\ MCRS}$ (%)	−35.27 (−68.08 to 33.12)	−9.82 (−50.11 to 80.45)	39.33 (−6.36 to 123.23)
p-value	0.0399	0.2177	0.0815
Deviance	37.39	27.95	34.18
DOF	24	23	24
COMMON DAB			
cr(15, v)	0.57 (0.00–2.20)	1.59 (0.05–5.76)	2.35 (0.50–315.93)
cr(20, v)	0.87 (0.23–2.31)	2.07 (0.65–4.72)	2.19 (0.92–6.70)
cr(25, v)	1.11 (0.70–1.87)	2.13 (1.38–3.37)	1.96 (1.13–3.20)
cr(30, v)	1.09 (0.29–2.28)	1.64 (0.56–3.34)	1.47 (0.74–4.57)
cr(35, v)	2.17 (0.05–30.53)	0.93 (0.02–7.97)	0.54 (0.03–13.76)
cr(40, v)	3.26 (0.09–34 625.83)	0.55 (0.01–15.84)	0.20 (0.00–13.59)
$cr_{average}$ (%)	108.26 (68.71–164.08)	204.13 (132.43–293.41)	188.55 (120.57–299.11)
Δ $cr_{average}$ (%)	8.26 (−31.29 to 64.08)	104.13 (32.43–193.41)	88.55 (20.57–199.11)
p-value	0.0087	0.1333	0.1613
Deviance	23.63	14.97	15.49
DOF	10	10	11
EDIBLE CRAB			
cr(55, v)	2.06 (0.13–8.43)	1.53 (0.12–7.39)	0.86 (0.09–5.39)
cr(65, v)	2.37 (0.46–8.16)	1.89 (0.34–6.43)	0.91 (0.19–2.17)
cr(75, v)	2.72 (1.27–8.12)	2.36 (0.94–6.67)	0.96 (0.38–1.50)
cr(85, v)	3.11 (1.71–8.23)	2.94 (1.40–7.98)	1.02 (0.56–1.45)
cr(95, v)	3.55 (1.96–8.93)	3.65 (1.76–9.79)	1.07 (0.64–1.59)
cr(105, v)	4.00 (2.22–10.37)	4.45 (2.20–11.32)	1.12 (0.71–1.73)
cr(115, v)	4.44 (2.32–12.00)	5.28 (2.52–13.23)	1.17 (0.80–1.85)
cr(125, v)	4.81 (2.44–14.01)	6.02 (2.90–15.64)	1.20 (0.82–1.94)
cr(135, v)	5.08 (2.52–15.43)	6.53 (3.11–17.07)	1.22 (0.82–1.95)
cr(145, v)	5.16 (2.55–16.26)	6.64 (3.19–18.63)	1.23 (0.78–1.96)
cr(155, v)	5.02 (2.55–18.22)	6.24 (3.05–18.05)	1.22 (0.69–1.96)
cr(165, v)	4.62 (2.24–20.31)	5.31 (2.17–19.68)	1.19 (0.50–2.14)
cr(175, v)	3.96 (1.31–29.56)	4.01 (0.98–29.86)	1.14 (0.25–3.38)
cr(185, v)	3.12 (0.47–50.20)	2.63 (0.29–53.61)	1.07 (0.09–7.99)
cr(195, v)	12.23 (0.09–80.84)	1.48 (0.06–76.06)	0.99 (0.03–31.59)
cr(200, v)	1.82 (0.03–95.90)	1.06 (0.02–86.91)	0.94 (0.02–78.93)
$cr_{average}$ (%)	415.50 (234.05–910.53)	475.97 (268.07–986.57)	114.55 (78.12–168.59)
Δ $cr_{average}$ (%)	315.50 (134.05–810.53)	375.97 (168.07–886.57)	14.55 (−21.88 to 68.59)
p-value	0.0851	0.4408	0.3536
Deviance	126.50	104.48	114.98
DOF	106	103	110

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Paper II

Discard of regulated species under the landing obligation in the Danish bottom set nets fisheries for cod, sole and plaice in the North Sea

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Manuscript

Abstract

This study aimed at (1) describing discards of regulated fish species under the landing obligation, i.e., cod, haddock, sole and whiting (2) investigating the effects of soak duration, depth, latitude and longitude on discards and (3) establishing the relative contribution of different discarding drivers for the regulated species in the Danish bottom set nets fisheries for cod, plaice and sole in the North Sea using the discard data from observers at sea. We used discard ratio to standardize bottom set nets data, and a beta distribution to model cod discard ratio in the cod fisheries. Discard ratios ranged from 1.10% for cod in the cod fishery to 100% for whiting in the sole fishery, with high variability between fishing operations, species and fisheries. The relative contribution of different discarding drivers was established for each regulated species in all three fisheries using a hierarchical decision tree. High-grading and catch quality were the main reasons for discarding in the cod and plaice fisheries, and catch of undersized individuals due to the use of small mesh sizes was the main challenge identified in the sole fishery. We showed that the use of a beta distribution provided with an easy approach to further explore the effects of potential explanatory variables on discard ratios. We found that in the North Sea cod fishery, there was a decreased probability of cod discard with depth, with greater effect in the more recent years.

Discard of regulated fish species under the landing obligation in the Danish bottom set nets fisheries for cod, sole and plaice in the North Sea

Esther Savina, Ludvig A. Krag

ABSTRACT

This study aimed at (1) describing discards of regulated fish species under the landing obligation, i.e., cod, haddock, sole and whiting (2) investigating the effects of soak duration, depth, latitude and longitude on discards and (3) establishing the relative contribution of different discarding drivers for the regulated species in the Danish bottom set nets fisheries for cod, plaice and sole in the North Sea using the discard data from observers at sea. We used discard ratio to standardize bottom set nets data, and a beta distribution to model cod discard ratio in the cod fisheries. Discard ratios ranged from 1.10% for cod in the cod fishery to 100% for whiting in the sole fishery, with high variability between fishing operations, species and fisheries. The relative contribution of different discarding drivers was established for each regulated species in all three fisheries using a hierarchical decision tree. High-grading and catch quality were the main reasons for discarding in the cod and plaice fisheries, and catch of undersized individuals due to the use of small mesh sizes was the main challenge identified in the sole fishery. We showed that the use of a beta distribution provided with an easy approach to further explore the effects of potential explanatory variables on discard ratios. We found that in the North Sea cod fishery, there was a decreased probability of cod discard with depth, with greater effect in the more recent years.

KEYWORDS

Beta distribution; Discard ratio; Gillnet; Trammel net; Landing obligation

1. Introduction

The new Common Fisheries Policy has introduced an obligation to land species which are subject to catch limits (E.U., 2013). The landing obligation entered into force for demersal fisheries in the North Sea (ICES area IV) in January 2017 (E.U., 2016). All catches of cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), sole (*Solea Solea*), whiting (*Merlangius merlangus*), Northern prawn (*Pandalus borealis*) and Norway lobster (*Nephrops norvegicus*) caught by gillnets and trammel nets are therefore to be landed.

About 80% of active Danish vessels are bottom set nets (by number, with 1838 active vessels under 12m with gillnet as main gear as of December 2016) (E.C., 2016). Bottom set nets, and especially gillnets, are, in general, considered as being size selective, with larger mesh sizes catching larger fish (Stergiou and Erzini, 2002; He and Pol, 2010). However, all species are not equally vulnerable to the gear, and nets can catch various species. Thus, most of the cost in conducting bottom set nets fisheries lies in the bycatch of unwanted species. In the new landing obligation system, all catch of regulated species are to occupy space in the vessel's hold and be deduced from the vessel's quotas. We wondered if the landing obligation would have an economic impact on fishers, and used the discard ratio (DR) of regulated species, i.e., the ratio of regulated species discarded biomass and total caught biomass, as a proxy for the non-profitable fraction of the landed catch.

Danish bottom set netters in the North Sea target successively plaice, sole and cod throughout the year, depending on the season. If small mesh sizes, i.e., less than 120mm, are used in the sole fishery, identical gear and mesh sizes can be used in the cod and plaice fisheries, yet resulting in the preferred catch of the target species. The high variability found in discard ratios of several passive fisheries, even using the same gear and in adjacent areas, reflect the versatility of nets and indicate the need to evaluate discards for each fishery (Gonçalves *et al.*, 2007; Batista *et al.*, 2009; Morandeau *et al.*, 2014).

Over-quota and undersized discards were shown to be minor in other bottom set nets fisheries, but not all species or quality conditions have commercial value and can therefore also be discarded (Borges *et al.*, 2001; Santos *et al.*, 2002; Kelleher, 2005; Gonçalves *et al.*, 2007; Batista *et al.*, 2009; Morandeau *et al.*, 2014). As different discarding behavior may call for different mitigation measures, we explored the discarding drivers in the Danish North Sea bottom set nets.

The selection properties of nets may be improved to limit bycatch (mesh size, netting material, twine thickness), but due to the nature of the gear, one would most likely also impair the catch rate of the target species. New selective technologies involving more complex gear are limited in passive fisheries, and therefore, in many cases, the fisher's operational tactic plays a preponderant role (Kennelly and Broadhurst, 2002; Andersen *et al.*, 2012; Eliasen *et al.*, 2014; Fauconnet *et al.*, 2015; Breen *et al.*, 2016; Fauconnet and Rochet, 2016). It has the advantage of no additional economic cost, workload or risk (Sigurðardóttir *et al.*, 2015). Discards are highly variable in time and space, as local species diversity, season, depth or weather conditions are known to affect catch composition (Gray *et al.*, 2005; Stergiou *et al.*, 2006; Gonçalves *et al.*, 2007; Cambiè *et al.*, 2010). It was also suggested to reduce nets soak time in order to minimize the amount of damaged fishes (Acosta, 1994; Borges *et al.*, 2001; Gray *et al.*, 2005; Gonçalves *et al.*, 2007; Batista *et al.*, 2009; Cambiè *et al.*, 2010; Savina *et al.*, 2016). We explored the effect of different explanatory variables on the discards in the Danish North Sea bottom set nets fisheries.

Measuring gillnet fishing effort is challenging due to the combination of a complex mix of netting characteristics, net length, and soak time (Depestele *et al.*, 2012). We can standardize discard per target species (Depestele *et al.*, 2012), per net length and soak time (Gonçalves *et al.*, 2007), per net number (Perez *et al.*, 2005), or use the discard ratio (Rochet and Trenkel, 2005). The discard ratio is the ratio between discard and total catches, and may be computed for individual species or combined groups of species (Kelleher, 2005). Discard ratios, by including the landed portion of the FO, are inherently standardized to a wide range of effort variables, e.g., gear type, mesh size, net length or soak duration (Paradinas *et al.*, 2016). Discard ratios are measures of proportions taking any continuous value ranging between 0 and 1, which can appropriately be described by a beta distribution – assuming that a transformation is applied for the two extremes, i.e., 0 and 1 (Ospina and Ferrari, 2012; Warton and Hui, 2011). Proportions are commonly used in descriptive studies, but the lack of available software to handle such data had restricted until recently the uptake of the beta distribution for statistical regression. Discard ratios have recently been modelled using beta distribution in a Bayesian hierarchical model by Paradinas *et al.* (2016). Instead, we used beta distribution in a likelihood based approach with the use of the newly developed open-source software R package glmmTMB (Magnusson *et al.*, 2017).

The Danish bottom set nets fisheries for cod, plaice and sole in the North Sea were taken as a case study using the discard data from observers at sea. As catch of Norway lobsters or Northern prawns are very rare in the Danish bottom set nets (cf. mesh size), focus was given on regulated fish species, i.e., cod, haddock, sole and whiting. This study aimed at (1) describing discards of regulated fish species under the landing obligation, (2) investigating the effects of soak duration, depth, latitude and longitude on discards and (3) establishing the relative contribution of different discarding drivers for the regulated species. We used discard ratio to standardize bottom set nets data, and a beta distribution to model cod discard ratio in the cod fisheries. The relative contribution of different discarding drivers was established for each regulated species in all three fisheries using a hierarchical decision tree.

2. Material and methods

2.1. On-board observer data

Data was collected on-board commercial fishing vessels by scientific observers during regular fishing operations as part of the national sea sampling programme carried out under a national program before 2002 and later under the European Union Data Collection Framework (E.C., 2008). A limited part of the bottom set net fleet is conducting self-sampling, i.e., fishermen are asked to land their discards on randomly chosen days, which are then handled by the observer as a normal discard trip (Storr-Paulsen *et al.*, 2012).

We extracted fishing operations (FO) by bottom set gill- and trammel nets targeting cod, plaice and sole in the North Sea from 1998 to 2016. The Minimum Conservation Reference Size (MCRS) below which the sale of catches is restricted to non-human consumption products was established based on the previous Minimum Landing Size (MLS), which did not change for the four species of interest, i.e., cod, haddock, sole and whiting, in the North Sea in the years of interest.

To find out how well the bottom set nets fisheries were covered by the observer sampling program, we also collected information on the Danish landings by species and landing harbour. Representativeness of the discard data was approximated by calculating the ratio between the total landed catch in weight of the target species of all the FO sampled by fishery in the discard data and the total Danish landings in weight in the North Sea for each target species. We used data for both data sets from 1998 to 2015 only (no landing data for 2016).

2.2. Calculation of species abundance, occurrence and discard ratio

We calculated the relative abundance in each FO and the occurrence in all FO of each regulated fish species in each fishery. Relative abundance was calculated per FO as the ratio between the number of individuals of a given species and the total number of individuals. Relative abundance was divided into 5 classes: abundant (0.9-1.0), common (0.5-0.9), frequent (0.2-0.5), occasional (0.05-0.2) and rare (<0.05) species. Species occurrence was calculated as the ratio between the number of FO where a given species was present and the total number of FO per fishery. Species occurrence was divided into 4 classes: very common (≥0.75), common (0.50-0.75), uncommon (0.25-0.50) and rare (<0.25) species.

We calculated the discard ratio (DR) by FO in weight for each of the four regulated fish species under the new landing obligation, i.e., cod, sole, haddock and whiting, as the ratio between weight of regulated species discard and weight of total catch.

2.3. Inferences on the causes of discarding

The specific reasons for discarding individual fish were not recorded as part of the Danish sampling programme. We modified the approach developed by Catchpole *et al.* (2014) to establish the relative contribution of discarding drivers using a hierarchical decision tree to assign the discards in number to one of the following categories. The first category included fish discarded below the MLS ('Under MLS'). The second category included fish discarded above MLS but below the Minimum Marketable Size (MMS), i.e., the minimum length at which fish were landed for each species, fishery and year combination ('Under MMS'). The third category included fish discarded above the MLS but with no MMS ('No market'). The last category included fish discarded above MLS and MMS, either for poor quality or quota restriction ('Other').

2.4. Data subsetting and modelling discard ratios

A balanced analysis design is a key step for obtaining causal inferences on observational studies, which can be done by ensuring that the data are sufficiently balanced across the combinations of the potentially confounding factors and the factor of interest (Rubin, 2008; Nikolic *et al.*, 2015). We applied the modelling approach to a subset of the discard data with more than 50 observations, i.e., discard ratio of cod in the North Sea cod fishery in quarter 4 for years 1998, 2000 and 2001.

We modelled discard ratios by applying a Beta Generalized Linear Mixed Model (GLMM). As the two extremes, i.e., 0 and 1, were included in the discard ratios calculated for the FO of bottom set nets, we applied the following transformation (1) so that the beta distribution can be used, with DRt the transformed response variable, DR the response variable, i.e., the discard ratio, and N the sample size (Smithson and Verkuilen, 2006; Zuur *et al.*, 2013).

$$DRt = \frac{(DR \times (N-1) + 0.5)}{N} \tag{1}$$

Soak duration, depth, latitude and longitude were considered as potential explanatory variables (Table 3). As longitude and latitude were both correlated with depth, with deeper waters to the North and the West, depth was not included in the same models that included longitude and latitude. The explanatory variables were standardized so that they each had a mean of zero and standard deviation of one, in order to help improve convergence and put the estimated coefficients on the same scale allowing effect sizes to be more easily compared (Zuur *et al.*, 2009). We included vessel as random effect.

The discard ratio for each FO i in vessel j can be modelled using a beta distribution with probability π_{ij}, parameterized using mean π_{ij} and precision parameter φ. The mean is linked to the response through a logistic link function and a linear predictor, i.e., the combination of coefficients and explanatory variables X_{ij} x β. φ is inversely related to the dispersion. The term z_j is the random intercept for vessel, imposing a correlation on all FO from the same vessel.

$$\text{Discard ratio}_{ijk} \sim \text{Beta}(a_{ij}, b_{ij}) \text{ with } a_{ij} = \varphi \times \pi_{ijk} \text{ and } b_{ij} = \varphi \times (1- \pi_{ij}) \quad (2)$$

$$E(\text{Discard ratio}_{ij}) = \pi_{ij} \quad (3)$$

$$\text{var}(\text{Discard ratio}_{ij}) = \pi_j(1- \pi_j) / (\varphi + 1) \quad (4)$$

$$\text{Logit}(\pi_{ij}) = X_{ij} \times \beta + z_j \text{ with } z_j \sim N(0, \sigma^2_{\text{vessel}}) \quad (5)$$

Candidate models were all possible variations of the two following full models:

DRt ~ Soaking_std * Depth_std * Year + (1|Vessel) (6)

DRt ~ Soaking_std * Lat_std * Lon_std * Year + (1|Vessel) (7)

We used an information-theoretic approach to select the best model(s) using Akaike Information Criterion (AIC) (Akaike, 1974; Burnham and Anderson, 2002; Zuur *et al.*, 2009). The relative difference in AIC values between models (dAIC) was used to rank the models, and only models with less than 10 dAIC were presented. Ratios of Akaike weights (evidence ratios) of the selected models were used to calculate the relative importance of the covariates (and random effects) by summing the Akaike weights of all the models including the variable of interest (Burnham and Anderson, 2002; Zuur *et al.*, 2009). Output of the highest ranked model was given to compare effect sizes of the covariates.

Analyses were performed using glmmTMB (Magnusson *et al.*, 2017) with the open-source software R (R Core Team, 2016).

3. Results

3.1. Data collected

A total of 611 FO was collected, with a majority of observations for the cod fisheries (Table 1). The approximated representativeness of the discard data by fishery was low, ranging from 0.04 in the sole fisheries to 0.12% in the plaice fishery (Table 1).

All sampled FO targeting cod in the North Sea used gillnets with full mesh size ranging from 130 to 180mm. The highest coverage for the cod fisheries was between 1998 and 2001 in the last quarter of the year (Fig. 1). All sampled FO were west of Denmark, from the shallow coastal waters up to 157m depth (Fig. 2, Table 1).

Sampled FO targeting plaice in the North Sea used either gillnets (44 FO) or trammel nets (58 FO) with full mesh size ranging, as in the cod fishery, from 130 to 180mm (Table 1). The highest coverage for the plaice fishery was in 1998 and 1999, with the highest number of FO in the first quarter (Fig. 1). All sampled FO were west of Denmark, from the very shallow coastal waters to about 50m depth (Fig. 2).

Sampled FO targeting sole in the North Sea used gillnets only with full mesh size less than 114mm (Table 1). The highest coverage for the sole fishery was in 1998 and 1999 in the second quarter (Fig. 1). FO were sampled along the coasts of Belgium, Netherlands and Denmark, from the very shallow coastal waters to about 40m depth (Fig. 2).

In all three fisheries, the number of nets used was very variable from one FO to the other, with more nets used in the sole fisheries (Table 1). Individual net lengths were relatively comparable, ranging from 47 to 92m (Table 1).

3.2. Species abundance and occurrence

In the cod fishery, the target species cod was a common species with on average 86.7% relative abundance (Table 2). Other regulated fish species were occasional or rare species with respectively 5.20, 1.40 and 0.92% relative abundance for haddock, sole and whiting (Table 2). Regarding occurrence, cod was a very common species with on average 99.4% occurrence. Other species were uncommon with 29% occurrence for haddock and rare with respectively 3.39 and 11.4% occurrence for sole and whiting (Table 2).

In the plaice fishery, the catch was dominated by the unregulated target species plaice, cod being an occasional species with 6.94% relative abundance and the other three species being rare with respectively 0.53, 1.86 and 0.28% relative abundance for haddock, sole and whiting (Table 2). Regarding occurrence, cod was very common (88.2% occurrence), sole and whiting common (71.6 and 70.6% occurrence) and haddock uncommon (39.2%) (Table 2).

In the sole fishery, cod and sole were equally frequent with respectively 27.6 and 28.5% relative abundance for cod and sole (Table 2). Whiting was rare with 2.27% relative abundance and no haddock was caught (Table 2). Regarding occurrence, sole and whiting were very common with respectively 100 and 84.2% occurrence, and cod was common with 71% occurrence (Table 2).

3.3. Discard ratios

Discard Ratios (DR) are presented in Table 2.

DR for cod was low in the cod and sole fisheries, but relatively high (43.2%) in the plaice fishery. The variability between FO was relatively high in all three fisheries.

DR was low for haddock in the cod fisheries, but relatively high (64.2%) in the plaice fisheries. The variability in DR between FO was high in the plaice fisheries.

DR for sole was low in all three fisheries, respectively 12.5, 2.60 and 4.69% for the cod, plaice and sole fisheries. The variability in DR between FO was high in the plaice fisheries.

DR for whiting was high in all three fisheries, respectively 90.7, 98 and 100% in the cod, plaice and sole fisheries. The variability in DR between FO was high in the cod and plaice fisheries.

On average, weights of discards per kg of target species were low for the four regulated species in all three fisheries, even though it could go up to 1.37kg for whiting in the sole fisheries (Table 2). Discard weight, dependent on fishing effort, was more than 10kg on average for cod in the plaice fisheries (Table 2). There was a high variability from one FO to the other, with discard weight up to more than 50kg for cod in the cod fisheries, sole and whiting in the sole fisheries and cod in the plaice fisheries (Table 2).

3.4. Causes of discarding

In all three fisheries, most discards of whiting had no market, except in the sole fishery in 1999 with a higher proportion of discards under MLS (Fig. 3).

Most discards of the three other species in the cod fisheries were due to high-grading (‘Under MMS’) and poor quality or quota restrictions (‘Other’) (Fig. 3).

In the plaice fishery, most discards of cod and haddock were due to poor quality or quota restrictions (‘Other’) and no market, whereas most of the sole discards were under MLS (Fig. 3).

In the sole fishery, most of the discards were under MLS, except for cod in 1998 (‘Other’, Fig. 3).

3.5. Effects of soak duration, depth, latitude and longitude on the discard ratios in the North Sea cod fisheries

We modelled the effects of soak time, depth, latitude, longitude, year and vessel in the Danish North Sea cod fisheries. Out of the three models with less than 10 dAIC presented, the first two were in the 95% confidence set of models (Table 4). Based on the output of the highest ranked model, the probability of cod discard decreased with depth, with greater effect in the more recent years (Table 5). Standard deviation of the random effect of vessel was 0.33, at a relatively lower order of magnitude than the fixed effects (Table 5). The chosen best model was only 1.2 times more likely to be the best model than the next best model (Table 4), and the relative importance of each variable confirmed that depth, year and soak time were more important in determining discard ratio for cod in the cod fishery than latitude and longitude (Table 6).

Discussion

3.6. Representativeness of the sampled data

The cod fishery typically takes place between November and March in the North Sea, i.e., during the cold months of the year providing with good fish quality and prices. The cod fishery can also take place in the summer on wrecks, either with short soak time or in deeper waters not to impair fish quality due to warmer waters. The fishery for cod uses with relatively large mesh sizes, i.e., between 120 and 200mm full mesh, and relatively short soak durations not to compromise the target fish quality. Both gill- and trammel nets can be used, the latter being ‘all-round nets’ used for both plaice and cod by smaller vessels.

As cod prices decrease after New Year, the cod fishery is replaced by the plaice fishery which typically takes place in the first quarter of the year. The fishery uses either gill- or trammel nets with the same mesh sizes as the cod nets, i.e., between 120 and 220mm full mesh, but soak durations are longer.

The sole fishery typically takes place from the second quarter of the year and follows the migration of the fish from the Channel to the North Sea, starting in March in Belgium and the Netherlands until May in coastal Danish waters. The fishery uses gillnets with small mesh sizes below 120mm full mesh.

Collection of discard data onboard commercial vessels may be biased by a change in the fisher attitude due to the presence of an observer, but a study comparing data collected with an observer onboard and by the fishermen did not show any significant difference (Lart, 2002; Benoît and Allard, 2009).

Even though the estimated representativeness of the observers at sea data for the three fisheries was low, all characteristics of the fisheries, i.e., seasonality, fishing grounds, type of gear, mesh size, soak duration, were comparable to current commercial practices. However, the aim of the study was to highlight some discarding behaviour in the Danish bottom set nets, but no inference could be drawn from the extrapolation of results due to the low representativeness of the data.

3.7. Catch pattern and discard ratio

In the cod fishery, catch of flat fish was limited as those prefer sandy habitats, whereas the cod fishery usually takes place on rough bottoms or wrecks. Regarding the other round fish haddock and whiting, both species would require smaller mesh sizes for an optimal catch than those used in the cod fishery. Besides, haddock shows a schooling behavior which made its catch less likely.

The plaice fishery takes place in sandy bottoms which could explain the limited catch of cod, preferring rougher bottoms. As in the cod fishery, the use of relatively large mesh sizes reduced the chance to catch haddock and whiting. Even though sole also prefers sandy habitats, the plaice fishery is not concomitant in space – less coastal, and in time – mostly in the first quarter, to the preferred presence of sole. Both fish are flat but both size and body geometry are different, making the catch of soles less likely than plaice. Besides, sole weight less which impacted the relative abundance given here in weight.

Even though the small mesh sizes used in the sole fishery should capture most of other species, the fishery takes place in coastal sandy areas, whereas cod is found in rougher bottoms or wrecks, and haddock in deeper waters, therefore limiting the catch of other round fish species. Whiting was very common but not so abundant, which could be explained by the relative low weight of the small individuals caught compared to the total catch.

3.8. Reasons for discarding

Whiting has no commercial value in the demersal fisheries, and it was therefore not surprising that most if the discard were due to the absence of market. A higher proportion of discards under MLS in the sole fishery for whiting was possible as small mesh sizes were used.

Most discards of the three other species in the cod fisheries were above MLS, which made sense considering the relatively large mesh sizes used in the fishery, i.e., 120-220mm full mesh. The importance of high-grading (proportion of discards under MMS) for cod was representative of a common practice in this fishery where catch of small individuals of size category 5 for example was not considered worth spending on quota.

In the plaice fishery, most discards of cod and haddock were due to poor quality or quota restrictions (‘Other’) and no market. Low catch rates of cod and haddock in the plaice fishery could explain the importance of the driver ‘No market’, i.e., no sufficient quantities to warrant sale. Soak durations in the plaice fishery were longer than in the other fisheries, and could explain the significance of the driver ‘Other’ due to poor condition of the round fish cod and haddock which were more prone to damage than the target species plaice. In the case of cod, quota restrictions, known to drive the fisher tactics and make them change fishery, could also play a key role in the importance of the driver ‘Other’. Even though relatively large mesh sizes are used in the plaice fishery, i.e., 120 to 220mm full mesh, most of the sole discards were under MLS, and could have been captured by other means than gilling, e.g., with the mesh in the mouth.

In the sole fishery, most of the discards were under MLS, and can be explained by the use of relatively small mesh sizes, i.e., below 120mm full mesh. Soak durations were on average longer than in the cod fishery (Table 1), and could explain the high proportion of cod discarded under the driver ‘Other’, i.e., poor condition in that case.

Thus, high-grading and catch quality were the main reasons for discarding observed in the cod and plaice fisheries, whereas catch of undersized individuals due to the use of small mesh sizes was the main challenge identified in the sole fishery.

As the MLS has remained the same through the years of interest, making assumptions on the proportions of discards under MLS was rather safe. But regarding quota restriction included in the driver ‘Other’, fisher tactics have most likely changed with the implementation of individual transferable vessel quotas (ITQ). Before 2007, the allocation of quota for most demersal stocks was seasonal through a catch-ration system. In

2007, ITQ were implemented in the Danish demersal fishery, with a yearly quota attribution, giving more chance to fishers to optimize their catch on price rather than on quota as before.

3.9. Effects of soak duration, depth, latitude and longitude on the discard ratios in the North Sea cod fisheries

Depth, year, soak time and vessel were more important in determining discard ratio for cod in the cod fishery than latitude and longitude, with an increased probability of cod discard with shallower waters. Smaller cods are usually found in the coastal waters, which could explain the higher discards with shallower depths. Longer soak durations are known to impair individual fish condition, especially in fragile fish such as cod, but the fact that the dataset was restricted to FO in the last quarter of the year, i.e., coldest months, was likely to have limited the effect of soak duration compared to the effect of depth. Regarding vessel effect, no significant relationships were found between discard and characteristics of the fishing vessels (length, tonnage, power) (Borges *et al.*, 2001), but potential sources of variation were expected from differences in the fisher tactic or unobserved gear characteristics.

We showed that the use of a beta distribution provided with an easy approach to further explore the effects of potential explanatory variables in discard ratios. We used the cod discards in the cod fishery, for which enough sampled FO were available for a modelling approach, as a case study, but discards in that case were in general very limited, i.e., 1.1% on average. Considering a higher sampling effort for species and/or fisheries with higher concern, e.g., the sole fishery, one could use such an approach to test for mitigation measures by testing for the effects of, e.g., fishing grounds or time of the day, on discards. Indeed, as sole is given high value on the markets, one strategy may be to find tactics limiting bycatch of the other species, even if the later would result in lower catch of the target species.

3.10. Management implications

Three métiers are currently sampled in the North Sea, based on mesh size, i.e., <120mm, 120-220mm and >220mm, but with no distinction between gear, i.e., gill- or trammel nets, and target species (Storr-Paulsen *et al.*, 2012). The use of high cod gillnets of height about 3.5m is mainly kept to the bigger vessels, both because of the space used onboard and the cost of having several net types throughout the year. Smaller vessels would usually prefer the use of trammel nets for both the cod and plaice fisheries with limited height, i.e., about 1.80m. One could expect differences between gill- and trammel nets, as the higher variety of capture mechanisms, i.e., gilling, wedging, entangling and pocketing, associated with trammel nets accounts for a greater diversity of species and wider size ranges, thus potentially higher discards, compared to gill nets (Borges *et al.*, 2001; Erzini *et al.*, 2006; Gonçalves *et al.*, 2007; Batista *et al.*, 2009). One could consider a modified stratification sampling scheme for the observers programme adapted not only to the mesh size of the FO, but also representative of the other characteristics defining the fisheries, i.e., gear and target species.

In general under the new landing obligation, the industry has not faced yet any major issue in fisheries using full mesh sizes between 130 and 200mm, e.g., the cod and plaice fisheries, as there are typically little discard (Chairman of Hirtshals fishermen organization, *Pers. Com.*). As disentangling catch from the netting can be time consuming, and as netters usually operate on vessels less than 12m with limited crew, handling time is a major limiting factor for additional fishing power, and it was shown that fishers can adjust their strategy to limit the amount of unwanted catch (Ref to paper in Fisheries Research when DOI). However for fisheries using smaller mesh sizes between 80 and 120mm full mesh, e.g., the sole fishery, fishermen are facing larger bycatch of the round fish cod, haddock, saithe and whiting, and have started to change their tactics with the new landing obligation which could be described as a “real time monitoring” of discards: several fleets are soaked in the same time, one being lifted at regular intervals to check for the amount of unwanted catch (Chairman of Hirtshals fishermen organization, *Pers. Com.*).

The difficulty of reducing discards due to limited size selectivity in the small mesh sizes fisheries without impairing the catch of the target species has been acknowledged in the discard plan by granting to bottom set netters catching sole a minimis exemption up to a maximum of 3% of their total annual catches of sole. The change in the fishermen activity to target a range of fish species throughout the year (Ulrich and Andersen, 2004), partly to adjust to regulations, e.g., quota restriction on cod, could also help here to minimize the relative annual discards proportion for sole.

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Table 1. Number of fishing operations and different vessels in brackets (FO) sampled by the Danish observers at sea sampling program between 1998 and 2016 for bottom set nets, i.e., gillnets (G) or trammel nets (T) (Gear) in the cod, plaice and sole fisheries (Target) in the North Sea, together with the mean and range (min-max) of the soak duration in h (Soak) and catch of target species in kg (Target landed), and the range (min-max) of the full mesh size in mm (Mesh), the total net number (Net nr), the length of an individual net in m (Net l) and the depth of the fishing operation in m (Depth). The representativeness of the sampled observations (Rep.) was estimated as the proportion of the target species landings compared to all landings for that species in Denmark in the period (1998-2015) in weight.

Target	Gear	FO	Soak (h)	Mesh (mm)	Net nr	Net l (m)	Depth (m)	Target landed (kg)	Rep. (%)
Cod	G	471 (19)	14 (1-44)	130-180	2-240	55-75	25-157	155 (1.5-4068)	0.10
Plaice	G, T	102* (16)	53 (2-123)	130-180	5-200	50-92	0-56	837 (19.5-3640)	0.12
Sole	G	38 (5)	29 (9-50)	92-114	90-448	47-72	5-42	98.6 (20.0-360)	0.04

* 44 FO by gillnet (G) and 58 by trammel net (T)

Table 2. Fish species under the landing obligation for gill- and trammel nets in the North Sea as given by the discard plan (E.U., 2016) applicable in 2017 and 2018 with their Minimum Landing size (MLS) or currently Minimum Conservation Reference Size (MCRS) as fish total length in cm, together with their abundance in % (Abundance) and occurrence in % (Occ.) in sampled fishing operations by observers from 1998 to 2016, their discarding weight in kg for one kg of the target species (Discard per kg target), their mean and range (min-max) of discard weight in kg per fishing operation and discard ratio in %.

Species	MLS (cm)	Abundance (%)	Occ. (%)	Discard per kg target (kg)	Discard (kg)	DR (%)
North Sea cod fisheries						
Cod	35	86.7 (3.24-100)	99.2	0.03 (0.00-0.20)	3.91 (0.10-45.4)	1.10 (0.00-16.7)
Haddock	30	5.20 (0.05-39.7)	29.0	0.02 (0.00-0.12)	1.30 (0.20-6.50)	14.8 (0.00-100)
Sole	24	1.40 (0.14-3.80)	3.39	0.03 (0.00-0.06)	0.35 (0.30-0.40)	12.5 (0.00-100)
Whiting	27	0.92 (0.01-11.8)	11.4	0.01 (0.00-0.10)	0.67 (0.02-6.50)	90.7 (0.00-100)
North Sea plaice fisheries						
Plaice	-	*78.2 (0.93-98.0)*	*100*	*0.02 (0.00-0.17)*	*5.00 (0.15-26.5)*	*2.44 (0.00-100)*
Cod	35	6.94 (0.03-81.8)	88.2	0.02 (0.00-0.22)	10.7 (0.15-104)	43.2 (0.00-100)
Haddock	30	0.53 (0.02-4.79)	39.2	0.01 (0.00-0.08)	1.37 (0.18-4.50)	64.2 (0.00-100)
Sole	24	1.86 (0.05-16.8)	71.6	0.03 (0.00-0.41)	0.88 (0.05-8.00)	2.60 (0.00-100)
Whiting	27	0.28 (0.01-3.44)	70.6	0.00 (0.00-0.04)	1.90 (0.03-11.7)	98.0 (32.6-100)
North Sea sole fisheries						
Cod	35	27.6 (0.05-77.8)	71.0	0.18 (0.00-0.73)	9.11 (0.15-44.0)	11.2 (0.00-100)
Haddock	30	-	-	-	-	-
Sole	24	28.5 (12.2-56.3)	100.0	0.06 (0.00-0.37)	7.04 (0.10-54.3)	4.69 (0.00-27.1)
Whiting	27	2.27 (0.01-24.2)	84.2	0.11 (0.00-1.37)	10.1 (0.03-69.5)	100 (100)

Table 3. Characteristics of each fishing operation tested as explanatory variables and random effect in the modelling approach of discard ratios for cod in the North Sea cod fishery

Code	Definition	Type	Unit	Calculation
Soak_std	Soak duration	Continuous	min	Time difference between end and start, standardized
Lat_std	Latitude	Continuous	Decimaldegree	Mean point of the nets at deployment, standardized
Lon_std	Longitude	Continuous	Decimaldegree	Mean point of the nets at deployment, standardized
Depth_std	Depth	Continuous	m	Standardized
Vessel	Vessel	Categorical	7 levels	-
Year	Year	Categorical	3 levels	-

Table 4. Relative difference in AIC values between models (dAIC), degree of freedom (df) and AIC weights (weight) for the models with a relative difference in AIC less than 10 – also 95% confidence set of models, ranked by AIC weight. N=325

Rank	Model	dAIC	df	weight (%)
1	DRt ~ Depth_std * Year + (1|Vessel)	0.0	8	53.01
2	DRt ~ Soaking_std + Depth_std * Year + (1|Vessel)	0.3	9	45.77
3	DRt ~ Soaking_std * Depth_std * Year + (1|Vessel)	9.7	14	0.41

Table 5. Output of the selected model.

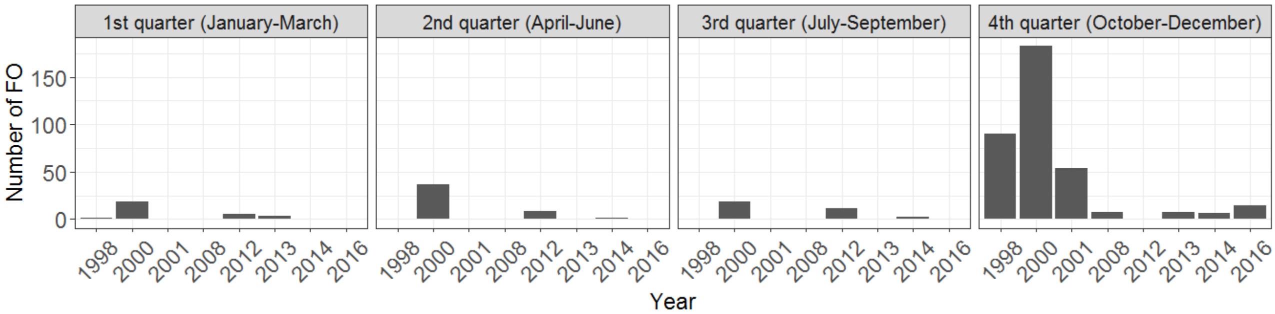
Variable	Estimate (sd)
Depth_std	0.42 (0.15)
Year2000	0.04 (0.24)
Year2001	-0.69 (0.28)
Depth_std:Year2000	-0.78 (0.17)
Depth_std:Year2001	-1.39 (0.43)
Intercept	-4.55 (0.19)
Standard deviation of the random effect (1|Vessel): 0.33	

Table 6. The relative importance of each explanatory variable. A value close to 1 indicates that the explanatory variable is present only among the best models according to AIC.

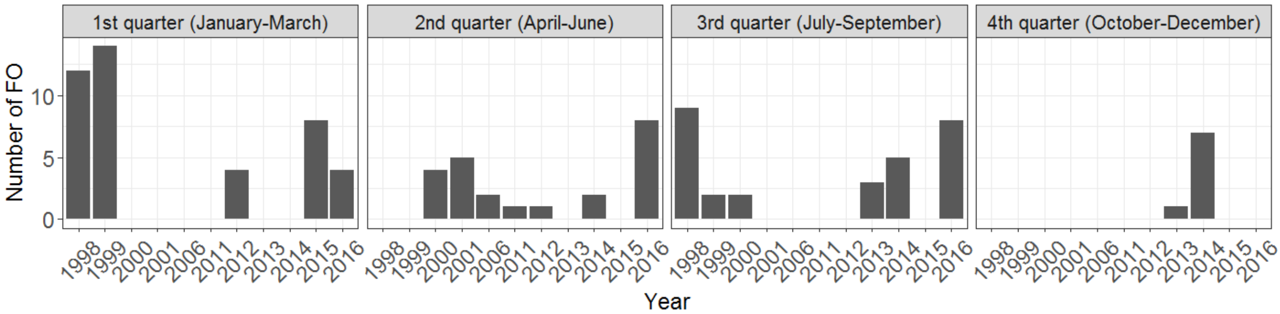
Variable	Evidence ratio (%)
Soaking_std	45
Depth_std	99
Year	99
Latitude	0
Longitude	0

Figure 1. Number of fishing operations (FO) sampled by year and quarter for the North Sea (a) cod, (b) plaice and (c) sole fisheries.

(a) North Sea cod fishery



(b) North Sea plaice fishery



(c) North Sea sole fishery

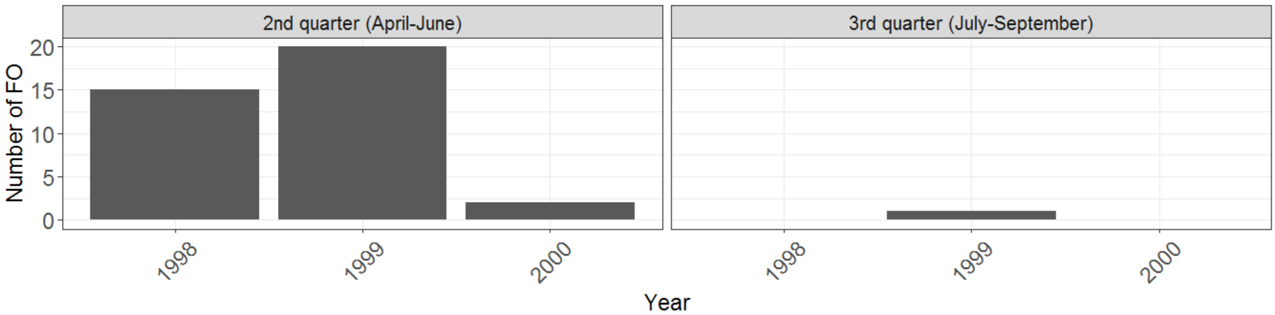
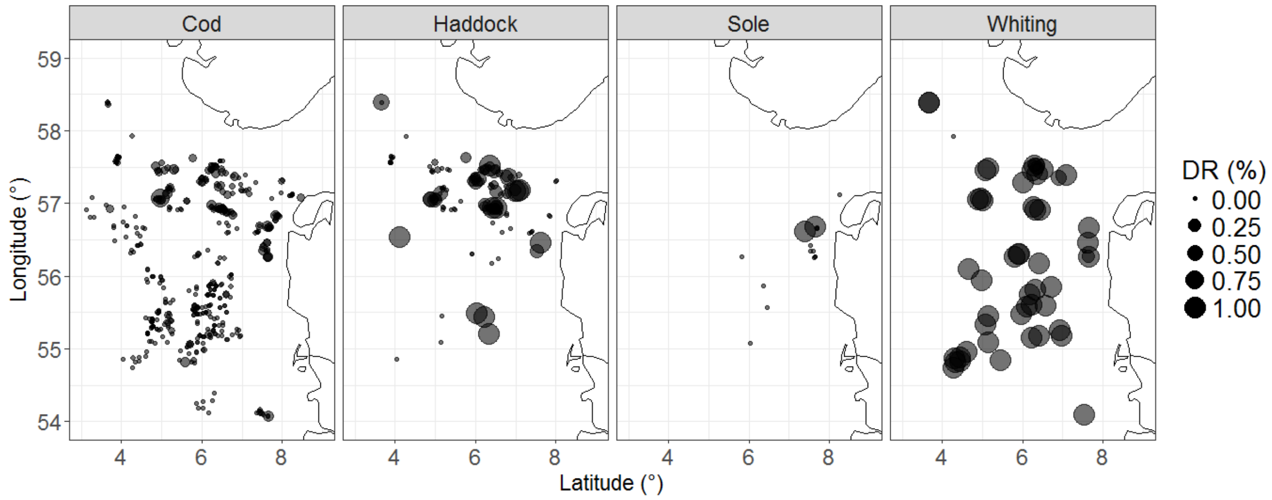
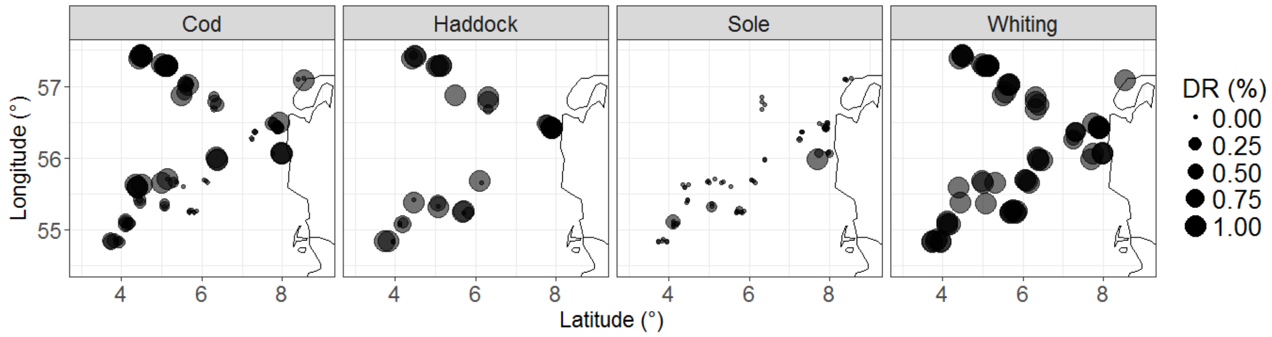


Figure 2. Locations of the gill- and trammel netters fishing operations sampled in the observers at sea programme from 1998 to 2016 and their discard ratios for the four regulated fish species in the (a) cod, (b) plaice and (c) sole fisheries

(a) North Sea cod fisheries



(b) North Sea plaice fisheries



(c) North Sea sole fisheries

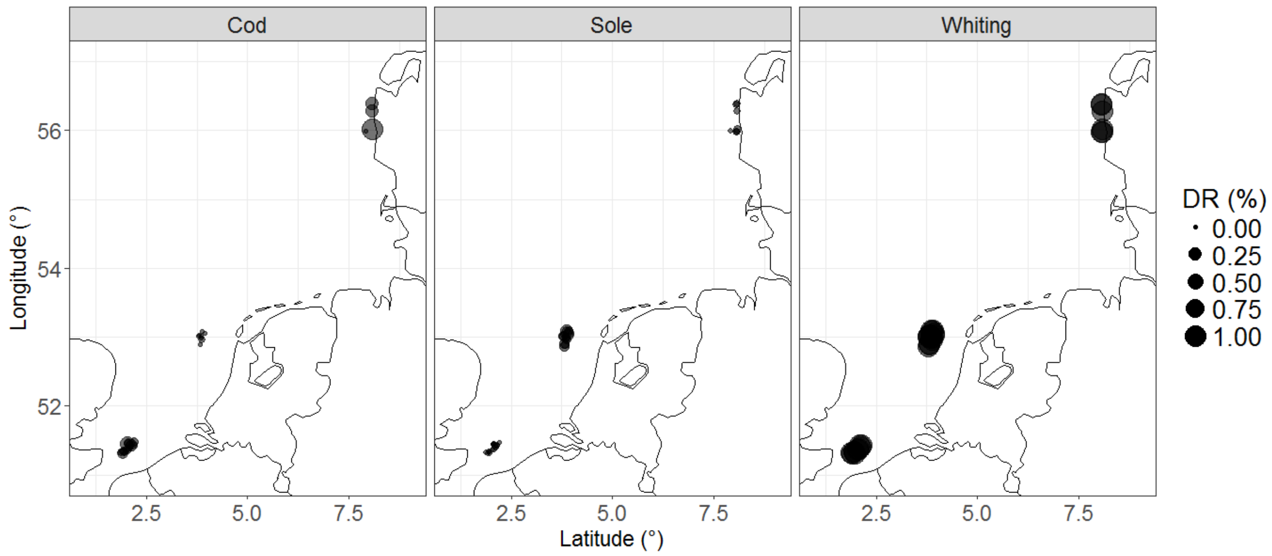
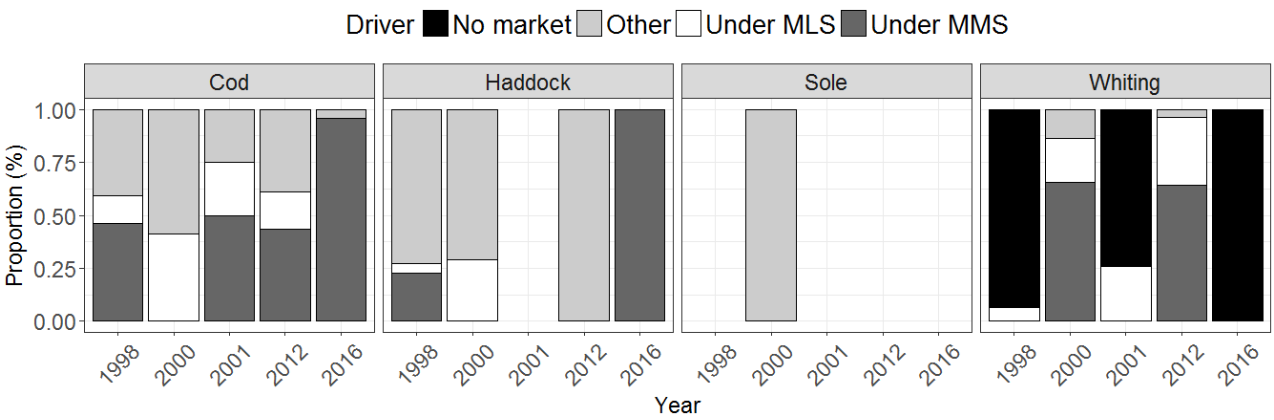
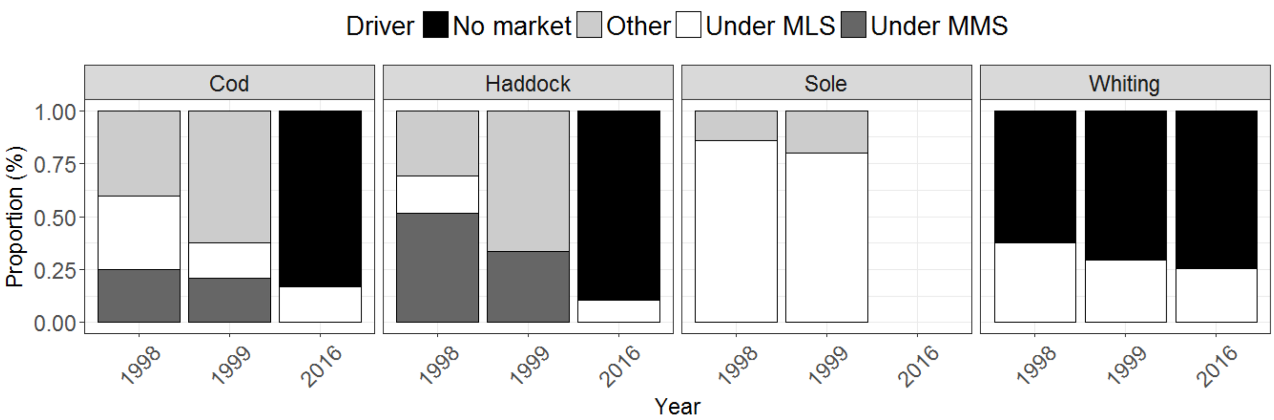


Figure 3. Annual proportional contributions of the inferred drivers to the discard quantity generated by Danish gill- and trammel netters in the North Sea for each of the four regulated fish species in the (a) cod, (b) plaice and (c) sole fisheries. Only years with more than 15 fishing operations were included.

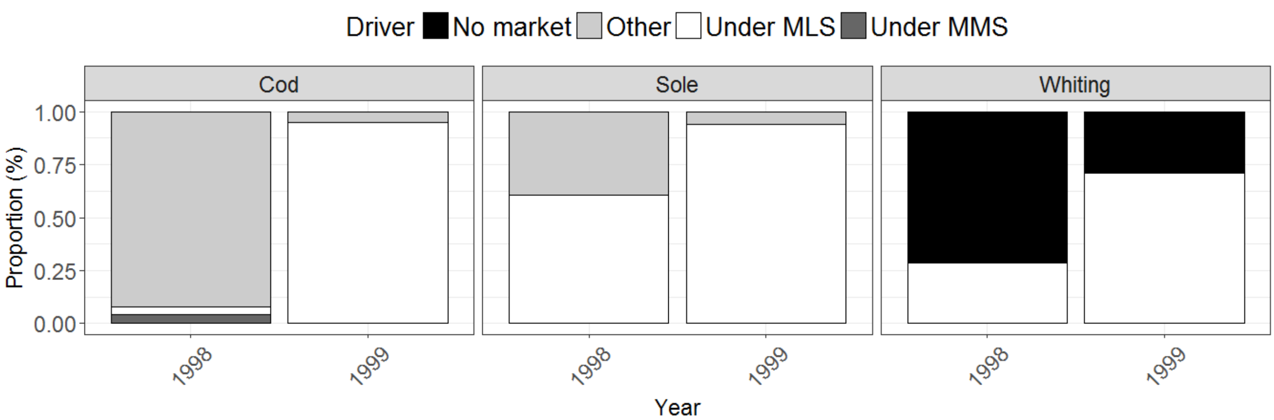
(a) North Sea cod fisheries



(b) North Sea plaice fisheries



(c) North Sea sole fisheries



Paper III

Testing the effect of soak time on catch damage in a coastal gillnetter and the consequences on processed fish quality

Savina, E., Karlsen, J.D., Frandsen, R.P., Krag, L.A., Kristensen, K., Madsen, N.

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Abstract

This study aims at testing how to improve catch quality aboard a coastal gillnetter by looking at an easily controllable parameter known to have an effect on the degree of fish damage, soak time, and investigating if the registered damages on whole fish have an effect on processed products such as fillets. Plaice (*Pleuronectes platessa*) was captured with commercial gillnets soaked for 12 and 24 hours. Damages were assessed using semi-quantitative indices of individual fish condition gathered in a Catch-damage-index for onboard fish and a Processed fish-damage-index for whole, skinned and filleted plaice processed at a land-based factory. Cumulative link mixed modelling allowed the estimation of the size of effects. Damage in fish was significantly more likely for longer soak times but effects were comparable to those of fish length and between-sets, making a change in soak time not so substantial for improving plaice quality in coastal gillnetting. Damage in fish was significantly more likely for whole than filleted fish, but there was substantial heterogeneity among fish. Severe damage in whole fish may not matter in filleted fish whereas some damage may only be visible at the fillet level.

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Testing the effect of soak time on catch damage in a coastal gillnetter and the consequences on processed fish quality

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ABSTRACT

This study aims at testing how to improve catch quality aboard a coastal gillnetter by looking at an easily controllable parameter known to have an effect on the degree of fish damage, soak time, and investigating if the registered damages on whole fish have an effect on processed products such as fillets. Plaice (*Pleuronectes platessa*) was captured with commercial gillnets soaked for 12 and 24 hours. Damages were assessed using semi-quantitative indices of individual fish condition gathered in a Catch-damage-index for onboard fish and a Processed fish-damage-index for whole, skinned and filleted plaice processed at a land-based factory. Cumulative link mixed modelling allowed the estimation of the size of effects. Damage in fish was significantly more likely for longer soak times but effects were comparable to those of fish length and between-sets, making a change in soak time not so substantial for improving plaice quality in coastal gillnetting. Damage in fish was significantly more likely for whole than filleted fish, but there was substantial heterogeneity among fish. Severe damage in whole fish may not matter in filleted fish whereas some damage may only be visible at the fillet level.

1. Introduction

The gillnet fleet is of importance in Denmark and is gaining interest as an alternative practice towards improved environmental sustainability with regard to energy use and ecosystem effects (Andersen, Ulrich, Eigaard, & Christensen, 2012; Suuronen et al., 2012). The coastal vessels provide the opportunity of daily fresh fish supply, but maintaining profitable is challenging, and calls for solutions to help improve catch production. Raw material is increasingly identified as a key factor in fish quality, and catch damages may result in reduced price or discarding (Esaiassen, Akse, & Joensen, 2013; Lawler, 2003; Margeirsson, Jonsson, Arason, & Thorkelsson, 2007; Santos, Gaspar, Monteiro, & Vasconcelos, 2002). In the gillnet fisheries, more fish are discarded due to poor quality than being below the legal minimum landing size (Batista, Teixeira, & Cabral, 2009; Borges et al., 2001; Gonçalves et al., 2008; Morandeau et al., 2014). Challenges in gillnets are that fish can die in the gear when the net is soaked, the netting can cause marks on the fish skin, and there is an increased risk of injuries due to predation or scavenging of fish in the gear (Auclair, 1984; Perez & Wahrlich, 2005; Petrakis, Cheilari, & Cambiè, 2010; Santos et al., 2002; Suuronen et al., 2012). Improvement in catch quality is important for the coastal gillnet fisheries as it may limit wastage of raw materials, maximize production for the industry and benefit to consumers.

Among the parameters that matter on the quality value of the raw material such as environmental variations or handling and storage methods, capture procedure, especially soak time, is a controllable parameter (Esaiassen et al., 2013; Olsen et al., 2014; Özogul & Özogul, 2004; Özyurt et al., 2007). It might be an advantage for the fishermen to soak for long time periods to maximize catch per unit effort, but previous experiments have shown that the proportion of dead fish and degree of damage increase with the soak time (Acosta, 1994; Hickford & Schiel, 1996; Hopper et al., 2003; Petrakis et al., 2010; Santos et al., 2002; Suuronen et al., 2012). Natural variations such as fish length are also known to influence quality (Esaiassen et al., 2013). As there might be no effect of the registered damage on whole fish in processed products such as fillets, severity of catch damage in whole fish has to be analysed against the quality of processed products

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(Esaiassen et al., 2013).

In the coastal fishery, fish is usually landed less than one day after capture and freshness, i.e., age of the raw material, which is usually perceived as the most important attribute of the quality of fish, is not appropriate (Denton, 2003; Esaiassen et al., 2013; Martinsdóttir, Luten, Schelvis-Smit, & Hyldig, 2003). Instead, previous studies have used semi-quantitative indices of individual fish condition grouped in an index to evaluate whole or processed fish damage in fishing gears (Depestele, Desender, Benoît, & Polet, 2014; Digre, Hansen, & Erikson, 2010; Digre, Tveit, Solvang-Garten, Eilertsen, & Aursand, 2016; Karlsen, Krag, Albertsen, & Frandsen, 2015; Olsen, Tobiassen, Akse, Evensen, & Midling, 2013; Rotabakk, Skipnes, Akse, & Birkeland, 2011). Most studies used hypothesis testing which does not allow for the estimation of the size of effects, unlike model-based methods such as cumulative link mixed modelling which is appropriate for ordinal multi-category responses. It also tolerates random effects which are relevant here to account for within-haul (or set) correlations as well as to tackle scoring subjectivity, i.e., there may be differences in the assessment when all fish in a set are in similar condition or when they show a broader range of damage severities (Benoît, Hurlbut, & Chassé, 2010).

This study aimed at assessing (1) the effect of soak time in comparison with an uncontrollable natural variation, fish length, and set effect on catch damage onboard a commercial gillnetter and (2) the change in quality between whole fish, and skinned and filleted products at a land-based processing factory. Plaice (*Pleuronectes platessa*), one of the main target species in the Danish coastal gillnet fisheries, was taken as a case study.

2. Materials and methods

2.1. Experimental design and sea trials

Trials were conducted on the commercial gillnetter HG5 Skovsmose (11.99 m, 171 kW) in the Skagerrak coastal waters for eight consecutive days in September 2014. Commercial plaice gillnets with 136 mm nominal stretched mesh size and 0.30 mm twine were used in all sets. Each net was 2 m (stretched) high, 82 m long and slackly hung with a hanging ratio of 25%. Three individual nets were attached together by connecting the sink and float lines at the start and end of each net (2 m apart of one another) to form a fleet, i.e., a ganged sequence. In total, nine fleets were constituted. The soak times 12 and 24 hours (h) covered the usual range of commercial practices in Danish coastal waters. Every day, three fleets were soaked for 24 h. Simultaneously, three fleets were soaked for 12 h during the day and three others during the night to account for a possible day-night effect. The nets were located over a single known habitat type, sandy bottom, at the same depth. Fleets were randomly positioned to avoid any spatial effect, and spaced by a minimum distance of 111 m in latitude and 60 m in longitude to prevent competition between them. Fleets were set with the current, parallel to the coast, and anchored at both ends using 6 m bridle lines and 4 kg anchors following commercial practices. Fleets were hauled aboard the vessel using a hydraulically-powered net hauler with top roller.

2.2. Handling of the catch

Two professional fishermen disentangled the catch from the netting on a sorting table during hauling, and put it in open mesh baskets making sure not to overfill them. The same scientist sorted all captured fish from the baskets, measured and assessed whole plaice for catch damage on deck immediately after hauling in a dedicated work station protected from wind to prevent dehydration of fish. Plaice below the legal minimum landing size of 27 cm (E.U, 2013), dead fish or those below the freshness category B according to the European Union scheme (E.U, 1996) and considered unfit for consumption were not landed according to commercial practices. Retained fish were handled following standard commercial practices. Fish were washed to remove debris in the open mesh baskets with an adequate supply of clean seawater from a hose. The two professional fishermen gutted the fish, i.e., the intestinal tract and internal organs were removed, by hand with a knife. Gutted fish were cleaned in a washing tank for a minimum of five minutes with seawater to remove blood and viscera from the belly cavity. The scientist checked for the quality of bleeding by gutting. Fish were discharged down a chute to the cooling room below deck, where the individuals from the three soak times were stored separately in standard plastic boxes in shallow layers surrounded by fine melting ice following standard commercial practices for later assessment at a fish processing factory.

2.3. Quality assessment

All captured plaice were assessed for catch damage onboard the vessel (Fig. 1) using a Catch-damage-index (CDi) initially elaborated for gadoids by Esaiassen et al. (2013) and adapted for flatfish with the following minor adaptations. The CDi scheme lists damages caused by fishing gear and handling onboard together with scores relative to the severity of the damage and its influence on the quality of the raw material (Table 1). Damages were scored according to their position on the fish and were considered moderate when in fin or tail part and severe when in body part. A fish was considered dead if it did not show gill movement and was unresponsive to touch immediately after hauling the catch onboard. As all the individuals were faultlessly bled by gutting and there was no use of gaffs, the two attributes 'poorly bled' and 'gaffing damage' were not included in the assessment scheme. The scores for each attribute in the CDi scheme ranged from 0 for flawless to 2 for most severe (Table 1, see Fig. 2 for examples of ratings). The CDi was then calculated for each individual by summing the scores for all attributes. The CDi scale ranged from 0 for flawless to 12 for most severe.

To limit the variation in factors that could have an influence on the assessment of landed fish at the processing factory, only sets for which similar storage conditions could be guaranteed were included in the analysis. The assessment was exclusively run for the 12 h soaks at night and 24 h soaks, and only for five of the seven days of data collection. Onboard storage of the fish assessed at the factory lasted no more than 4 h. After landing, eight fish from each of the two soak time categories (12 h at night and 24 h) were randomly picked and labelled (Fig. 1). These fish were kept until the next day in a cooling room at 2 °C in two standard commercial plastic boxes. The boxes were kept one on top of the other with an empty plastic box on top to prevent differential drying of the fish. On the day following hauling of the net, fish were brought to the fish factory, and assessed for quality by the same quality representative from the factory using a Processed fish-damage-index developed for the purpose of this experiment. This scheme lists the attributes looked at by exporting companies when fish is evaluated at the fish auction: skin or surface appearance, bruises or discolouration, and texture (Karlsen et al., 2015, Table 2). Such a scheme provides a finer degree of discrimination than the EU quality grading scheme currently in use (E.U, 1996). The scores for each attribute in the Processed fish-damage-index scheme ranged from 0 for flawless to 2 for most severe (Table 2, see Fig. 2 for examples of ratings). Gaping is when the individual flakes of muscle come apart giving the fish flesh a broken appearance. A fish in pre-rigor or rigor stage is considered to be of good freshness by the

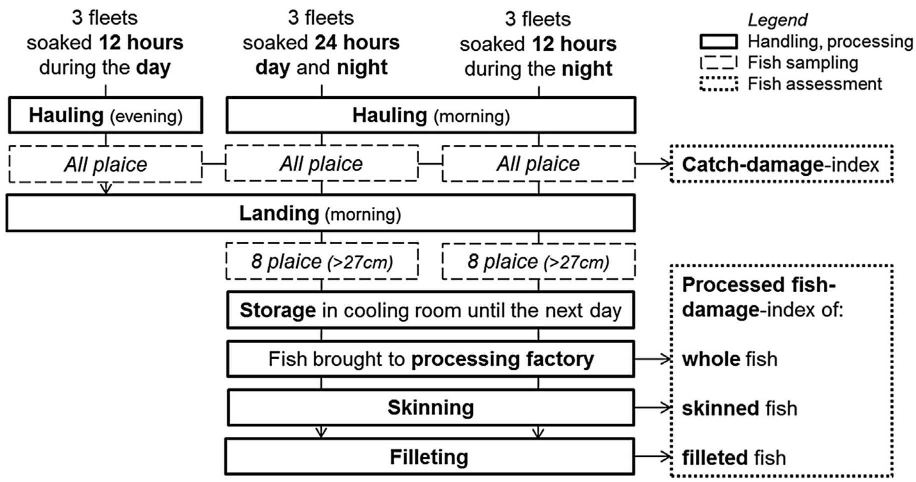

Fig. 1. Experimental design and data collection.

Table 1
Assessment scheme showing the attributes and rating scores used to calculate the Catch-damage-index for fish assessed onboard the fishing vessel.

Damage	Description	Score
Dead in gear	Live	0
	Dead	2
Gear damage	No marks	0
	Stripes, fin damage	1
	Deep marks, crushing	2
Bruises	No	0
	In fin/tail part	1
	In body part	2
Skin abrasion	No	0
	Minor	1
	Severe, perforated skin	2
Pressure injuries	No	0
	Squeezed in fin/tail part	1
	In body part	2
Biting injuries[a]	No	0
	Damaged fins/tail	1
	Deep wounds/bite marks	2

[a] Some of the recorded injuries could be due to fraying and not biting.

buyer and was ranked as flawless for the attribute ‘texture’. Assessments included three processing steps, whole fish, after skinning, and after filleting (Fig. 1). Skinning and filleting were done with a skinner (Steen ST 111) and by hand, respectively, by a person specialized in hand-filleting of plaice working at the factory. Visual and tactile assessments of fish were conducted by the same quality representative under the guidance of a scientist who did not attend the assessment at sea. Both were unaware of how each specific fish had been caught. The Processed fish-damage-index was then calculated for each individual by summing scores for all attributes. The Processed fish-damage-index scale ranged from 0 for flawless to 6 for most severe.

In order to look at the relationship between CDi and Processed fish-damage-index, we assessed fish using both schemes on the same individuals for the four last days of the sea trial, i.e., 64 fish (4 days $\times$ 2 soaks x 8 fish). However, for simplifying tracking of fish, assessment of fish using CDi was run a second time for this purpose after landing and not directly on deck. It was therefore not possible to assess the attribute ‘Dead in gear’ in that case.

More objectives quality assessments methods such as computer vision evaluation of loin colour (Erikson & Misimi, 2008) or texture analyzer (Einen & Thomassen, 1998) have been developed, but visual assessment was chosen for CDi as it can easily be implemented on a vessel at sea, and for the Processed fish-damage-index as this is how the exporters and processing companies currently evaluate fish.

2.4. Statistical analysis

Cumulative link mixed modelling was used to model CDi as a function of soak time and fish length. It is a generalization of logistic regression which models ordinal responses, allows for random effects, and tends to work well for sensometric data (Christensen & Brockhoff, 2013). To model CDi, i.e., the response variable Y_i with a value from 0 to 12 representing the degree of fish damage summed for all attributes, as a function of soak time and fish length, the full cumulative link mixed model fitted to the data was:

$$\mathrm{logit}(P(Y_i \le j)) = \theta_j - \beta_1(soak_i) - \beta_2(length_i) - u(set_i), \tag{1a}$$

with i=1,…,n, j=1, …, J−1 and $u(set_i) \sim N(\sigma_u^2)$.

This is a model for the cumulative probability of the i^{th} rating falling in the j^{th} category or below, where i index all n observations (fish) and j index the response categories (J=13). The parameters $\beta_1(soak_i)$ and $\beta_2(length_i)$ describe the effect of the explanatory variables, respectively soak time and fish length, on the log odds of response in category j or below, and are assumed to have the same effect for each of the $J-1$ cumulative logits. The random effect of sets $u(set_i)$ is added to the model to avoid pseudo-replication by accounting for mechanisms that could generate positive association among clustered observations (Fryer, 1991; Millar & Anderson, 2004). The random effect is assumed to be the same for each cumulative probability, independent and normal identically distributed. At each setting of the explanatory variables, the multicategory model assumes that the counts in the categories of the outcome have a multinomial distribution and $\{\theta_j\}$ are the threshold parameters. Maximum likelihood estimates of the parameters, i.e., the values of the parameters of a chosen model which make the observed data most likely, were provided using the adaptive Gauss-Hermite quadrature method with 10 quadrature nodes (Christensen, 2015). A condition number of the Hessian not larger than 10^6 was an indication of having a successful model (Christensen, 2015). Four models were considered for selection of a final one, the full model (1a) and three simpler nested versions (1b, 1c, 1d):

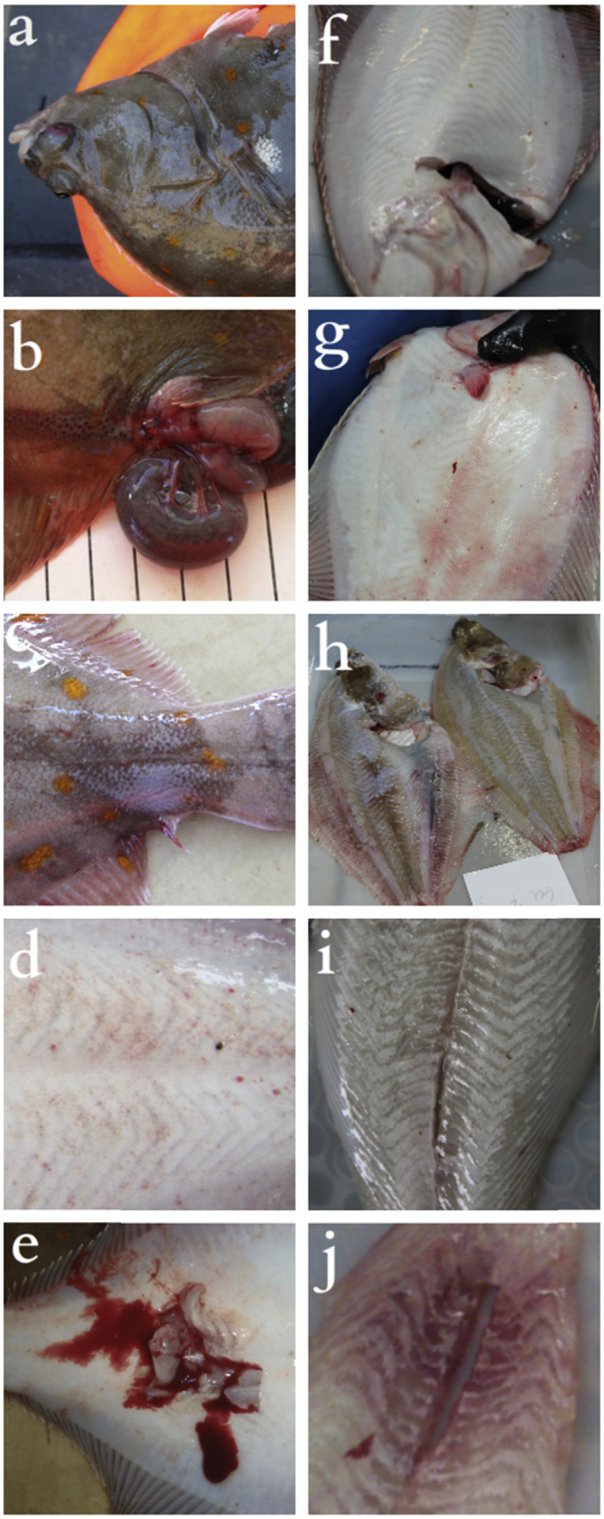

Fig. 2. Examples of ratings of fish onboard the vessel: (a) flawless fish, (b) stripes from gear damage and pressure injuries, (c) stripes from gear damage and descaling, (d) bruises in body part and (e) severe wound, and at the factory: (f) whole fish with no bruises, (g) whole fish with bruises on body part, (h) skinned fish with various degree of bruises, (i) filleted fish with moderate gaping and (j) filleted fish with severe gaping due to injury.

Table 2
Assessment scheme showing the attributes and rating scores used to calculate the Processed fish-damage-index for fish at three different processing steps.

Step	Attribute	Description	Score
Whole	Surface	Glossy, no scale loss	0
		Bright, few scale loss	1
		Dull, many scale loss	2
	Bruises	No	0
		Few	1
		Many	2
	Texture	Pre-rigor or rigor	0
		Firm	1
		Soft	2
Skinned	Surface	Smooth	0
		Few gapings	1
		Many gapings	2
	Bruises	No	0
		Few	1
		Many	2
	Texture	Pre-rigor or rigor	0
		Firm	1
		Soft	2
Filleted	Surface	Smooth	0
		Few gapings	1
		Many gapings	2
	Bruises	No	0
		Few	1
		Many	2
	Texture	Normal	0
		Jelly	2

$$\mathrm{logit}(P(Y_i \le j)) = \theta_j - \beta_2(length_i) - u(set_i) \tag{1b}$$

$$\mathrm{logit}(P(Y_i \le j)) = \theta_j - \beta_1(soak_i) - u(set_i) \tag{1c}$$

$$\mathrm{logit}(P(Y_i \le j)) = \theta_j - \beta_1(soak_i) - \beta_2(length_i) \tag{1d}$$

Significance of the parameters of the full model (1a) was tested using the likelihood ratio statistic with the Anova method, which measures the evidence in the data for extra complexity in the full model relative to a simpler model. It is not relevant to test whether the thresholds are equal to zero, so no p-values were provided for this test (Christensen, 2015). Concordance with the log-likelihood and the Akaike Information Criterion were used for selecting the final model (Akaike, 1974). The predicted probabilities of the final model were computed at different experimental conditions for illustrative purpose.

In the same manner, the full cumulative link mixed model fitted to the data to model Processed fish-damage-index as a function of processing step was:

$$\mathrm{logit}(P(Y_i \le j)) = \theta_j - \beta(step_i) - u(fish_i), \tag{2a}$$

with i=1, …, n, j=1, …, J−1 and $u(fish_i) \sim N(\sigma_u^2)$.$i$ index all n observations (fish), j indexes the response categories (J=7) and $\beta(step_i)$ describes the effect of the processing step on the log odds of response in category j or below, with filleting as baseline. The random effect of fish $u(fish_i)$ was added to account for the fact that assessments throughout processing steps were observed on the same fish. Three models were considered for selection of a final one, the full model (2a) and two simpler nested versions (2b, 2c):

$$\mathrm{logit}(P(Y_i \le j)) = \theta_j - u(fish_i) \tag{2b}$$

$$\mathrm{logit}(P(Y_i \le j)) = \theta_j - \beta(step_i) \tag{2c}$$

One can consider that CDi and Processed fish-damage-index represent an underlying variable, unobserved and unmeasurable, integrating the many ways in which each attribute interact to determine the overall quality condition of a fish. Hence, interest here was in CDi and Processed fish-damage-index, and not in the rating of single attributes, which were therefore not modelled. Detailed results are given as supplementary material. All calculations and graphs were conducted in R (R Core Team, 2015) using the packages 'ordinal' (Christensen, 2015) and 'ggplot2' (Wickham, 2009).

3. Results and discussion

3.1. Catch-damage-index

3.1.1. Level of catch damage of newly caught fish

Fleets were set at an average depth of 5.4 m (standard deviation: ±0.6 m) representative of shallow summer fishing grounds in the Danish costal gillnet fishery. Of a total of 1601 caught plaice, 1338 individuals from 62 different sets (3 soak times × 3 fleets × 7 days) were assessed onboard the fishing vessel. One set was without fish. Fish for which assessment was uncertain or data were missing, were not used in the analysis (263 individuals). Most of the assessed fish (99%) presented moderate or severe damage for at least one attribute. The CDi scores observed ranged from 0 to 9, i.e., none of the fish scored in the highest rating categories (10–12). The proportion of fish grading for score 2 at the attribute level were low except bruises, for which 40% were found in the body part. Bruises are a result of an accumulation of blood residue appearing as dark patches on the blind side of flatfish as a result of meshing, the fact that the fish struggled in the net, and handling (Botta, Bonnell, & Squires, 1987; Özyurt et al., 2007).

3.1.2. Effect of soak time on catch-damage-index

The average soak time was 23.8 h (standard deviation: ±1.2 h) for the 24 h fleets, 10.7 h (±0.9 h) for the 12 h day fleets, and 12.4 h (±1.1 h) for the 12 h night fleets. The coefficient for soak was significant and positive indicating that higher CDi scores were more likely for 24 h than for 12 h soaks, i.e., fish soaked for 24 h were assessed to have a lower quality than those soaked for 12 h (Table 3, Fig. 3). This is in line with observations in other gill- and trammel nets studies (Acosta, 1994; Auclair, 1984; Borges et al., 2001; Hickford & Schiel, 1996).

Higher CDi scores for 24 h soaks were not due to a greater damage severity at the attribute level, i.e., in both soaks the same proportion of assessed fish (46%) scored 2 for at least one attribute, but to the accumulation of damages in several attributes. There were proportionally more fish grading in higher scores when caught in the 24 h than 12 h sets regarding the three following attributes. Longer soak extended the probability for a caught-fish to be rubbed against the netting and show gear damage (93% for 24 h and 85% for 12 h) and skin abrasion (60% and 54%), with scale loss damages mainly located in the surroundings of yarn marks and associated with gear damages. Biting (43% and 34%), mostly located on fins and tail (96% of the damaged fish), was caused by scavengers and predators which had an increased chance to feed on the caught-fish at longer soak (Auclair, 1984; Perez & Wahrlich, 2005; Petrakis et al., 2010; Santos et al., 2002). Pressure damages (31% and 23%) were a result of the fish being squeezed close to the pelvic fin when the fisherman untangled it from the net, which severity was expected to depend on mesh size and twine characteristics of the net, but which could also be facilitated in damaged fish, i.e., soaked for 24 h.

There were no differences in mortality whereas this has been observed in other gill- and trammel net studies (Bettoli & Scholten, 2006; Buchanan et al., 2002; Chopin, Arimoto, & Inoue, 1996; Losanes, Matuda, & Fujimori, 1992). Our mortality rate of 8.4% was lower than that reported in other studies using similar gears at comparable water temperature conditions (Batista et al., 2009; Bettoli & Scholten, 2006; Chopin et al., 1996; Murphy, Heagey, Neugebauer, Gordon, & Hintz, 1995; Schmalz & Staples, 2014), most likely because plaice is a robust species, giving here mortalities in range with those observed in trawl-caught plaice (Revill, Broadhurst, & Millar, 2013).

3.1.3. Effect of soak time compared to that of fish length

The coefficient for fish length was significant and negative indicating that higher CDi scores were less likely for larger fish, i.e., larger fish were assessed to have a higher quality than smaller fish (Table 3, Fig. 3). There were proportionally more small fish rating in higher scores for skin abrasion (75% for 20–29 cm and 31% for 40–53 cm, respectively) and biting (41% and 26%). Smaller fish were more likely caught with the netting behind the gill and around the largest part of the body engendering scale loss, contrary to larger fish which can be caught by the head region (snagging). The relatively lower mass of smaller plaice compared to larger ones could render them more susceptible to injuries such as biting as suggested by Revill et al. (2013).

3.1.4. Effect of soak time compared to between-sets variation

The estimated standard deviation of the random effects suggested substantial heterogeneity among sets in their response probabilities, i.e., fish of the same size and soaked for the same duration had lower or higher CDi depending on the set they were caught in (Table 3, Fig. 3). Information on day and fleet were pooled in the set random effect. Fish length did not vary between sets (mean per set ±standard deviation: 31.4 ±1.36 cm). A daily systematic effect was not likely in our study, which was conducted over a relatively short time scale. Even though all variables not of interest were kept as constant as possible, for example bottom type or depth, local bottom disparities, varying small-scale meteorological conditions such as wind or current, or varying net geometry from one fleet to the other may account for the large variation among sets. Besides, the time interval from the fleet is soaked until

Table 3
Maximum likelihood estimates and standard errors (S.E.) of the parameters in the final model for the CDi, i.e., soak time $\widehat{\beta}_1(\mathrm{soak_i})$, fish length $\widehat{\beta}_2(\mathrm{length_i})$, set $\widehat{\sigma}^2_{u(\mathrm{set_i})}$ and thresholds $\{\hat{\theta}_j\}$, and the Processed fish-damage-index, i.e., processing step $\widehat{\beta}(\mathrm{step_i})$, fish $\widehat{\sigma}^2_{u(\mathrm{fish_i})}$ and thresholds $\{\hat{\theta}_j\}$), and their significance levels (p-value) based on the likelihood ratio test. No p-values are provided for the thresholds.

Parameter	Estimate	S.E.	p-value
CDi			
Soak	0.54	0.26	<0.05
Fish size	−0.070	0.012	<0.001
Set	0.85	NA	<0.001
Thresholds	−6.65	0.48	
	−4.64	0.42	
	−3.26	0.41	
	−1.84	0.40	
	−0.52	0.40	
	0.99	0.41	
	2.24	0.43	
	3.79	0.52	
	5.31	0.81	
Processed fish-damage-index			
Step: whole	2.00	0.37	<0.001
Step: skinned	−1.24	0.39	<0.001
Fish	1.68	NA	<0.001
Thresholds	0.059	0.32	
	2.37	0.39	
	5.37	0.61	
	7.52	1.12	

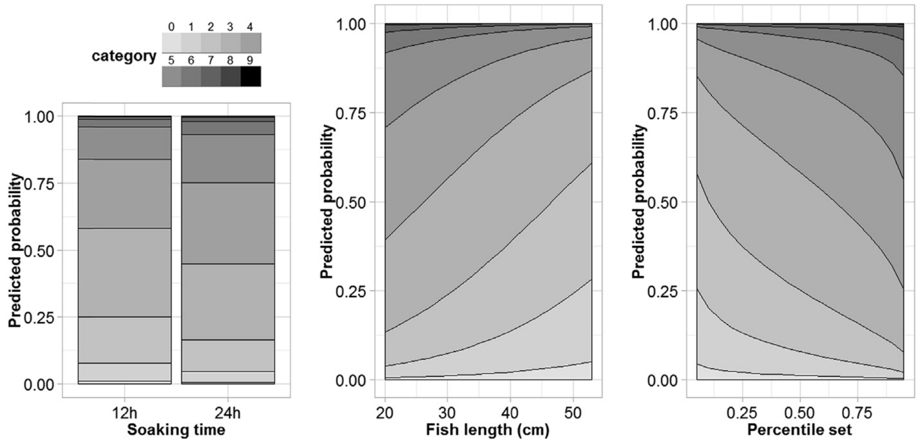

Fig. 3. Rating probabilities in the different CDi categories depending on the effect of soak time, for an average-length fish (31 cm) and average set-effect (50% percentile set) [left]; the effect of fish length, at 12 h soak for an average set-effect [middle]; and the set random effect, at 12 h soak for an average-length fish (31 cm) [right]. CDi categories range from 0 in light grey for flawless to 9 in black for most severe.

the fish is caught in the net may vary largely from one set to the other and have profound consequences for the damage level.

3.2. Processed fish-damage-index

3.2.1. Level of damage of landed fish

A total of 80 landed fish were assessed (8 fish × 2 soak times × 5 days) as whole, skinned and filleted fish. The Processed fish-damage-index scores observed ranged from 0 to 4 for all attributes, i.e., none of the fish scored in the highest rating categories (5–6). All fish assessed were in a pre-rigor or rigor stage, and few fish (a maximum of 2.5% per attribute of all fish assessed) scored in the highest rates regarding bruises or surface at the three processing steps. In the opinion of the local expert at the fish factory, the overall quality of the landed fish in this study was very good. There may be several reasons for this. Fish in very bad conditions and the smallest ones, more prone to damage, were not landed. The weather conditions during the sea trials were good. Appropriate handling and storage are important to keep the quality of fish at a high level after capture (Hopper et al., 2003). Fish were correctly bled, which reduces the blood remains in the flesh and improves the fillet whiteness (Ashie, Smith, Simpson, & Haard, 1996; Roth, Torrissen, & Slinde, 2005; Olsen et al., 2014).

3.2.2. Relationship between CDi and processed fish-damage-index

All fish randomly sampled for further analysis at the fish factory showed low score in the CDi scheme, ranging from 1 to 6 (on a scale of 0–10 without considering the attribute 'Dead in gear'), as well as in the Processed fish-damage-index scheme for whole fish, ranging from 0 to 3 (on a scale of 0–6). Results of the comparison showed a positive relationship between CDi and Processed fish-damage-index for whole fish. Whole fish with low CDi scores, from 1 to 2, showed a median Processed fish-damage-index score of 1 and those with higher CDi scores, from 3 to 6, a median score of 2.

3.2.3. Processed fish-damage-index throughout processing

Comparison of Processed fish-damage-index throughout the three observed steps, i.e., whole, skinned and filleted fish, was done with filleting as baseline, therefore comparing whole and skinned fish, respectively, with filleted fish.

The coefficient for whole fish was significant and positive indicating that higher damage index scores were more likely for whole than for filleted fish, i.e., filleted fish had a higher quality than whole fish (Table 3, Fig. 4). Yarn marks and scale loss in whole fish may not be severe enough to impair the filleted fish. Damage may also be located in an area which is normally trimmed at processing (fins, tail) such as with bruises, which was supported by our results (55% and 39% of bruised whole and filleted fish, respectively).

The coefficient for skinned fish was significant and negative indicating that higher Processed fish-damage-index scores were less likely for skinned than for filleted fish, i.e., skinned fish had a higher quality than filleted fish (Table 3, Fig. 4).

Severe gaping and jellied condition, i.e., waterish meat which is not related to the catching method (Templeman & Andrews, 1956), were only visible at the fillet level. Gaping could be caused by rigor, injuries or rough handling, for instance during machine skinning of fish in rigor (Stroud, 1981). Some bruises were also not found before the fish was filleted. Our bruising rate in filleted fish (39%) was in line with observations on fillets from gillnet-caught cod (34% with bruises exceeding 2 cm) and on trawl-caught round and flatfish (27–33% with bruises or blood spots) (Botta et al., 1987; Digre et al., 2010; Karlsen et al., 2015).

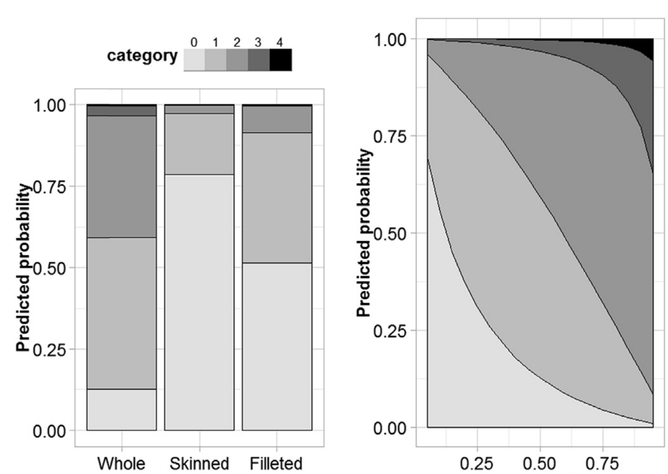

Fig. 4. Rating probabilities in the different Processed fish-damage-index categories depending on the effect of the processing step, for an average fish-effect (50% percentile fish) [left]; and the fish random effect, for whole fish [right]. Processed fish-damage-index categories range from 0 in light grey for flawless to 4 in black for most severe.

3.2.4. Effect of processing step compared to that of between-fish variation

The effect of processing step was on the same order of magnitude as the random variation. The estimated standard deviation of the random effects suggested substantial heterogeneity among fish (Table 3, Fig. 4). Such intraspecific variation is in agreement with a higher variability of a catch-damage-index for plaice compared to other species in Depestele et al. (2014). There can be several reasons for this. Analysis of the CDi showed an effect of fish length on the quality of whole fish, which was also observed in processed fish by Love (1975) who found more severe surface drying in smaller fish and more gaping, whereas larger fish are more prone to show jellied condition (Templeman & Andrews, 1956). Some fish are also inherently softer than others, e.g. starving or spawning individuals, and therefore more prone to gaping when skinned or filleted (Esaiassen et al., 2013; Love, 1975).

3.3. Implications for the coastal gillnetting fishery

3.3.1. Effect of soak time on catch damage and catch rate

The effect of soak time was calculated to be equal to the effect of a fish-length difference of 8 cm (0.54/0.07), and was on the same order of magnitude as the between-sets random variation, making a change in soak time not so substantial for improving plaice quality in coastal gillnetting. The effect of soak time on catch damage is expected to be higher in other species or longer soak durations.

Soak time should also guarantee an acceptable catch rate of commercial fish to optimize landings with regard to fishing effort, fuel consumption and labour cost (Hickford & Schiel, 1996; Hopper et al., 2003). There were no difference between soaks in the number of target species caught (plaice above the minimum landing size) (*unpublished results*), which is in line with previous studies suggesting a relationship between soak time and catch size for short soak times (up to 6 h) but none for longer soak times (Acosta, 1994; Gonçalves et al., 2008; Hickford & Schiel, 1996; Losanes et al., 1992; Minns & Hurley, 1988; Rotherham et al., 2006; Schmalz & Staples, 2014).

3.3.2. From fish quality to commerciality

The CDi scheme was in agreement with the quality rankings used at the fish auction regarding commerciality of plaice, where fish must be free of pressure marks and injuries in category Extra, free of blemishes and bad discolouration in category A, and a small proportion of fish with more serious pressure marks and superficial injuries in category B (E.U, 1996). An evaluation of the physical damages in relation to commerciality is also found in the scale of damaged fish developed by Petrakis et al. (2010) that can be related to our assessment. Fish with no or moderate damages, e.g. eyes and gills eaten or small bites, i.e., corresponding to the low and medium CDi ratings, are usually fit for commercial purpose, but not those with severe damage, e.g. the abdominal area eaten or with only skin and skeleton remain, i.e., corresponding to the highest CDi ratings.

The fish will either be sold as whole fish or as raw material for further processing. Most of the processed plaice produced in Denmark is sold as frozen fillets (FAO, 2014). Bruises do not impair the taste of fillets, but they are not attractive to consumers, and the fish processing factory would usually remove the part of the flesh with these marks, which reduce fillet weight and final profit (Kenney, Rahman, Manuel, & Winge, 2015; Roth et al., 2007). Marks on the fins and tail may not impair the yield in fillet as it is standard procedure to remove these parts during filleting. Minor marks on the thicker part of the fillet can be accepted and used for products of lower value compared with flawless fillets, but fillets with major marks on the thicker part or severe gaping are minced and sold as low quality product or destructed (Margeirsson, Nielsen, Jónsson, & Arason, 2006).

Other factors than quality may account for most of variation in prices, such as fish size, with lower prices per kg for small plaice, or market demand, but prices for plaice in Denmark are in general low and show little variation (Hopper et al., 2003; Lawler, 2003; Tsikliras & Polymeros, 2014).

3.3.3. Conclusion

Cumulative link mixed modelling worked well with our semi-quantitative indices, but it was difficult to directly estimate processed product quality from catch damage as some damage on whole fish had no effect on the fillet produced whereas others may only be visible at the fillet level.

Damage in fish was significantly more likely for whole than filleted fish. Selling whole fish directly to consumers has however proven worthy for some Danish coastal gillnetters, for which improvement in whole fish quality could make a difference. Damage in fish was significantly more likely for longer soak times but effects were comparable to those of fish length and between-sets, making a change in soak time not so substantial for improving plaice quality in coastal gillnetting. Further investigations could look into the factors responsible for the between-sets random variation.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.foodcont.2016.05.044.

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Paper IV

Developing and testing a computer vision method to quantify 3D movements of bottom-set gillnets on the seabed

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Abstract

Gillnets are one of the most widely used fishing gears, but there is limited knowledge about their habitat effects, partly due to the lack of methodology to quantify such effects. A stereo imaging method was identified and adapted to quantify the dynamic behavior of gillnets in-situ. Two cameras took synchronized images of the gear from slightly different perspectives, allowing to estimate the distance from the observation unit to the gear such as in the human 3D vision. The sweeping motion on the seabed and the penetration into the sediment of the leadline of light and heavy commercial bottom gillnets deployed in sandy habitats in the Danish coastal plaice fishery were assessed. The direct physical disruption of the seabed was minimal as the leadline was not penetrating into the seabed. Direct damage to the benthos could however originate from the sweeping movements of the nets, which were found to be higher than usually estimated by experts, up to about 2 m. The sweeping movements were for the most part in the order of magnitude of 10 cm, and resulted in a total swept area per fishing operation lower than any of the hourly swept area estimated for active fishing gears. Whereas the general perception is that heavy gears are more destructive to the habitat, light nets were moving significantly more than heavy ones. The established methodology could be further applied to assess gear dynamic behavior in-situ of other static gears.

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Developing and testing a computer vision method to quantify 3D movements of bottom-set gillnets on the seabed

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Gillnets are one of the most widely used fishing gears, but there is limited knowledge about their habitat effects, partly due to the lack of methodology to quantify such effects. A stereo imaging method was identified and adapted to quantify the dynamic behaviour of gillnets in-situ. Two cameras took synchronized images of the gear from slightly different perspectives, allowing to estimate the distance from the observation unit to the gear such as in the human 3D vision. The sweeping motion on the seabed and the penetration into the sediment of the leadline of light and heavy commercial bottom gillnets deployed in sandy habitats in the Danish coastal plaice fishery were assessed. The direct physical disruption of the seabed was minimal as the leadline was not penetrating into the seabed. Direct damage to the benthos could however originate from the sweeping movements of the nets, which were found to be higher than usually estimated by experts, up to about 2 m. The sweeping movements were for the most part in the order of magnitude of 10 cm, and resulted in a total swept area per fishing operation lower than any of the hourly swept area estimated for active fishing gears. Whereas the general perception is that heavy gears are more destructive to the habitat, light nets were moving significantly more than heavy ones. The established methodology could be further applied to assess gear dynamic behaviour *in situ* of other static gears.

Keywords: coastal waters, environmental impact, fishing gear, gillnet, habitat, stereo vision.

Introduction

Ecosystem effects of fisheries and in particular habitat damage is of high interest in an Ecosystem Approach to Fisheries as some fishing gears can remove or damage habitat forming structures, potentially reducing the complexity, diversity and productivity of benthic environments (Jennings and Kaiser, 1998; Kaiser *et al.*, 2000, 2002; Hermsen *et al.*, 2003; Grabowski *et al.*, 2014). The Marine Strategy Framework Directive defines seabed integrity as one of the descriptors required by the European Union member states to ensure Good Ecological Status (E.C., 2008). Methods are being developed for assessing the responsiveness of different seabed habitats to fishing activities, resulting in habitat sensitivity maps, which can be used in marine spatial planning (Eno *et al.*, 2013). Eco-labelling initiatives have started to take gear impacts on habitats into account in their assessments (Olson *et al.*, 2014). In this context, providing documentation for the habitat effect of fishing gears is of prime importance, especially for small-scale fisheries where maintaining profitability may be challenging and where there are benefits to keeping fishing in traditional fishing grounds, including sensitive areas, or where higher prices could be obtained from eco-labelling.

Gillnets stand as the fourth most important general gear type (out of eight) contributing to the global marine catches (in weight, based on data from 1950 to 2001, Watson *et al.*, 2006). About 40% of the European fishing vessels belong to the small-scale bottom-set gillnets fleet (by number, as of December 2016), with 33 644 active vessels under 12 m with set gillnets (GNS) as main gear, and up to 80% in Denmark for example (by number, with 1838 active vessels under 12 m with GNS as main gear as of December 2016) (E.C., 2016). It is generally assumed that habitat impacts of fixed gears are lower than those of mobile gears (Suuronen *et al.*, 2012; Grabowski *et al.*, 2014). However, these conclusions are based on few experimental studies. For example, there were only five studies regarding fixed gears, i.e. longlines, traps and gillnets, out of 97 used for the latest assessment in New England, United States (Grabowski *et al.*, 2014). Taking a closer look at bottom gillnets, the lack of studies regarding habitat impact might be attributed to the general assumption of negligible effects (Uhlmann and Broadhurst, 2013). However, after *in situ* observation at two rocky reefs, Shester and Micheli (2011) identified set gillnets as a priority conservation concern due to their potential to damage habitat-forming species. In the Welsh part of the Irish Sea, Eno *et al.* (2013) assessed nets sensitivity as high to medium for high to low fishing intensities in 8 habitats out of 31, mostly rock with associated branching species such as kelp, seaweeds or maerl beds. There is no direct evidence of potential effect for many of the current habitat-gear combinations, and the degree to which fixed gears drift on the bottom has to be quantified for the different bottom types (Eno *et al.*, 2013; Grabowski *et al.*, 2014).

There is limited knowledge about the habitat effects of bottom gillnets partly due to historical focus on active gears, but also because data collection and analysis calls for the development of appropriate innovative assessment methodologies. Several optical or acoustic techniques have been developed as complementary tools to assess the impact of mobile gears on the seabed (Smith *et al.*, 2003; Humborstad *et al.*, 2004; O'Neill *et al.*, 2009; Lucchetti and Sala, 2012; Depestele *et al.*, 2016). However, not all techniques provide a spatial resolution fine enough to assess bottom gillnets. Others are restrictive in sampling duration. Eventually, not all techniques can easily and safely be operated around bottom gillnets, prone to entanglement. Video offers more precision and less bias than direct visual observation, as it is possible to view each recording repeatedly or at lower speed (Neuswanger *et al.*, 2016). Nevertheless, the value of a video recording as informative data also depends on the ability to extract relevant measurements (Struthers *et al.*, 2015; Neuswanger *et al.*, 2016). Waterproof action cameras are now commonly available tools to deliver cost efficient high-definition underwater video recordings (Struthers *et al.*, 2015) using simple deployment platforms.

In bottom-set gillnets, the gear components in contact with the seabed are the leadline, the anchors and the bridle lines (connecting the anchors to the netting). Gillnets may be dragged on the seabed and become tangled in bottom features as the gear moves with the water flow while fully deployed on the seabed. Gillnets may also be snagged on benthic structures or organisms during retrieval of the gear (Shester and Micheli, 2011). The gear characteristics and rigging specifications play a key role in the net behaviour, and therefore its potential seabed effects. The net is spread vertically by the buoyancy of floats on the headline and weight in the leadline (Takagi *et al.*, 2007; He and Pol, 2010). The gear is usually moored at both ends with weights or anchors, which can cause vertical and horizontal deformation of the netting (Shimizu *et al.*, 2007; He and Pol, 2010). Water flow pushes the netting to incline and bulge out of the vertical plane (Stewart, 1988; Takagi *et al.*, 2007). Shimizu *et al.* (2007) calculated that the leadline would slide across the sea bottom if the force acting on the leadline is larger than the coefficient of static friction, but sliding motions of bottom gill nets during fishing have not been directly observed in any study to our knowledge.

The aim of the study was to identify, adapt, test and use a suitable methodology for assessing the dynamic behaviour of the leadline of bottom gillnets, i.e. the sweeping motion on the seabed and the penetration into the sediment. An *in situ* pilot experiment using stereo imaging was carried out in the Danish gillnet coastal plaice fishery.

Material and methods

Stereo imaging: general principle and quantitative measurements with VidSync

Stereo imaging consists of two cameras taking synchronized images of a scene from slightly different perspectives, or vantage points, which then allow to estimate the distance to an object such as in the human 3D vision. If an object is uniquely identified in both images and if the translation and rotation of one camera relative to the second is known, it is then possible to estimate the location of the object in 3D space (Schmidt and Rzhanov, 2012).

The free open-source Mac application VidSync (www.vidsync.org) was developed based on the OpenCV library computer vision algorithms by Neuswanger *et al.* (2016) to process stereo video recordings. The mathematical calculations of 3D measurements and their application in VidSync are detailed by Neuswanger *et al.* (2016).

Before the proper calculation of the 3D coordinates of a point, one has to correct for lens distortion and establish the perspective of each camera. Lens distortion is induced by the fisheye lens of the camera, meant to widen its angle of view, but particularly pronounced when the camera records underwater through housing and prone to bias calculations. Correction factors, or distortion parameters, can be found by locating nodes on a chessboard pattern or calibration frame and arranging them into straight lines. The same chessboard pattern can be used to calculate the projection matrices for each camera by matching the known physical 2D node coordinates on each face of the calibration frame with screen coordinates, which are recorded in VidSync by clicking on the centre of each node on the video recordings.

The 3D coordinates of a point are calculated in VidSync by iterative triangulation, aiming at establishing two lines-of-sight that approximately intersect at the point of interest, which is undertaken by clicking on the different points of the leadline, on each video recording. The calibration frame is the only source of information on the scaling of distances from which VidSync reconstructs a 3D space from the 2D video recordings.

Pilot experiment: location of the sea trials, net type and gear specifications

The pilot experiment took place in ICES area IIIa (Kattegat) off the coast of Northern Denmark aboard a small research vessel (5 m) on 10 September 2015. Because of its importance regarding Danish traditional commercial fishing grounds, and as the probability that the leadline would slide across the sea bottom is higher for smooth surfaces than for rough surfaces (Shimizu *et al.*, 2007), the experiment took place on sandy bottom. Nets were deployed in shallow waters, i.e. 1.5–3 m depth, to operate the observation units as best as possible in relation to the deployed gillnets in the relatively turbid waters. Our experimental conditions were at the lower depth range of commercial practices, but many coastal vessels participating in the gillnet plaice fishery, usually fish between 2 and 8 m in the summer and autumn. All

Table 1. Specifications of individual net panels used in the experimental set-up for light and heavy gear types.

Gear specifications		Light	Heavy
Net	Type	Gillnet	
	Target species	Plaice	
Twine	Diameter	0.30 mm	
	Type	Monofil	
	Material	Nylon	
	Knot	Double	
Mesh size	Nominal (bar length)	68 mm	
Dimensions	Height (mesh depth)	1.1 m (8.5)	
	Length (knot length)	82 m (4800)	
	Hanging ratio	25%	
Headline	Type (Hau Line mono)	**1.5**	**2.5**
	Buoyancy per 100 m	**600 g**	**1200 g**
Leadline	Type (Hau sinkline lead-free)	**1.5**	**3**
	Weight per 100 m	**3.9 kg**	**11 kg**

Height is given as stretched height. Headline and leadline types are given as specified by the net maker Daconet (firm's internal specification without unit). Specifications differing between the two gear types, light and heavy, are emphasized in bold.

observations were made away from the surf zone in calm weather to limit the influence of waves.

Two different types of commercial bottom gillnets, light and heavy, were used to give a gradient of commercial conditions. All nets were commercial plaice gillnets, and heavy and light nets differed only in the specifications of the head- and leadlines (Table 1). The headline was different for the two gear types as it influences the inclination of the net and has commonly more buoyancy for heavier nets in commercial conditions. It is commercial practice to work with such a net height when targeting plaice (1.1 m). Mesh size was selected according to the fish target at the chosen trial location, i.e. plaice on sandy habitat. Both net types were made by Daconet (www.daconet.dk) with the same manufacturing process.

Pilot experiment: stereo recording units and their calibration

Each observation unit was composed of a simple metallic frame made of 1 cm diameter steel sticks (Figure 1). Each metallic frame was ballasted with concrete poured in 7.5 cm diameter and 12.5 cm long polyvinyl chloride (PVC) tubes at each foot. The use of a light frame ensured a surface as small as possible for limiting drag, whereas the heavy feet guaranteed that the frame would remain in position when lowered on the seabed. Two cameras in their waterproof housing were mounted on the frame at a distance of 65 cm from each other and protected by netting (Figure 1). The use of netting aimed at preventing entanglement of the netting of the gillnet into the frame when in contact. Cameras were GoPro Hero 3 and 3+ cameras, each pair of a recording unit having identical settings (type of camera and video mode). For all fleets, the video resolution was set to 1080p SuperView, i.e. the sides of the video were stretched out for greater viewing, the frame per second was set to 30, and the field of view was set to Ultra Wide. Initial testing of the set-up with resolution set to 4 K and frame per second set to 12 resulted in measurement errors exceeding 25%.

A 3D calibration frame of 80 × 51 × 31 cm with a 9-by-15 node pattern in the front face and an 8-by-5 node pattern in the

Figure 1. The observation unit.

back face was used (Figure 2). The front face was made of perspex acrylic glass (PMMA) (http://vink.dk/), which can refract light when looking at the back frame and slightly change the apparent position of the nodes (Neuswanger *et al.*, 2016). A correction was applied to compensate for light refraction by the front frame based on the thickness of the material (35 mm), the refractive index of the material (PMMA, 1.491), and the refractive index of the medium (salt water, 1.342) (Neuswanger *et al.*, 2016).

Each observation unit, consisting of two cameras mounted on a metallic frame was submerged in water and calibrated at the Nordsøen Oceanarium (http://nordsoenoceanarium.dk/).

Pilot experiment: experimental set-up and measurement of water flow speed

Three individual net panels were attached at the floatlines to form a fleet, similar to commercial practice (Figure 3a). All fleets were set in a straight line parallel to the coast and the predominant current direction. Fleets were anchored at both ends with four kg anchors using six metres bridle lines following commercial practices. As the motion at a specific section of the net depends on its relative position (Shimizu *et al.*, 2004), each stereo recording unit was positioned on the seabed facing the middle length of the fleet, i.e. the part of the net the most likely to slide assuming that the nets are set in a straight line, at about 1–2 m from the net (Figure 3b). Three fleets were soaked at the same time for two to three hours during the day. Fleets soaked together formed a run. Data were collected while the gear was fully deployed on the seabed.

Nets were marked with different red tape patterns on the leadline to ensure that these marks would easily be uniquely identified on the video recordings (Figures 3 and 4). A high resolution clock (B. Lundgren, pers. comm.) was recorded at the beginning of every recording, providing a distinctive feature to synchronize the video recordings from the left and right cameras to the nearest video frame.

The water speed was recorded using two sets of a GPS device (GP-102, www.canmore.com.tw) attached to a buoy and left drifting during data collection (Figure 5). A holed PVC tube with attached lead hanging from the buoy was used to make sure that the measurement gave the current speed in the water column and not at the surface (wind drift). Use of the flow speed average from the bottom up to the net height could lead to more precise calculation by incorporating vertical difference in flow speed caused by the bottom boundary layer, but it is commonly accepted to use the current speed measured at the median net height in the mid-point location between the nets (Matuda and Sannomiya, 1977a, b; 1978; Matuda, 1988; Shimizu *et al.*, 2007).

Hourly instantaneous horizontal seawater velocities (2D) at 1 m depth were also extracted from the Forecasting Ocean Assimilation Model 7 km Atlantic Margin model (FOAM AMM7) (EU Copernicus, 2017). The 7 km resolution of the model restricts its utility in the coastal zone where strong sub-grid scale variability in shallow water bathymetry affects the wave field, and modelled data was therefore used as an overall indication of water flow speed in the area, but not for instantaneous measurement at each net position.

Pilot experiment: data analysis

The position of the calibration frame defined the 3D coordinate system, i.e. the origin (0, 0, 0) was the bottom left point on the front face of the calibration frame, the front and back faces were found in the $x-z$ plane, with the front face in the plane $y = 0$ and the back face in the plane y = distance between both faces (Figure 2). Thus, the net movements in the X dimension were positive when the net moved rightward or negative leftward (Figure 4). The movements in the Y dimension were positive when the net moved backward or negative forward. As the observation units were facing the coast during deployment, the movements in the Y dimension were positive when the net moved towards the coast and negative towards the open sea. The movements in the X and Y dimensions represent the sweeping motion of the net. The movements in the Z dimension were positive when the net moved upward, i.e. lifting off the seabed, or negative downward, i.e. dropping on the seabed. The movements in the Z dimension represent the seabed penetration.

We checked for data entry mistakes or calibration problems by examining diagnostic error measures provided for each 3D point by Vidsync (Neuswanger *et al.*, 2016). To quantify actual errors in 3D measurements, the calculated (VidSync) and measured (measuring tape) distances between two nodes as well as between the two faces of the calibration frame were compared in a first control test, and the calculated and measured distances between two coloured threads on the leadline of both light and heavy gillnets were compared in a second control test. The first point calculated was set as a reference starting point with a given position of zero in the three dimensions, and the position value of this reference point was subtracted from the position values of the following points. The dynamic behaviour of the leadline was analysed using a simple motion metrics in the three spatial dimensions, i.e. the maximum distance covered by the leadline in each dimension, calculated as the difference between the maximum and the minimum position values of each mark.

Significant differences between light and heavy net configurations were tested for as follows. Data exploration was applied following Zuur *et al.* (2010). The effect of net configuration (light or heavy), Run (I or II) and dimension (X–Z) on the maximum movement of the leadline was initially modelled as a linear regression model containing sensible interactions based on experimental knowledge and data exploration as in model (1). A log-transformation was applied on the response variable as a solution to heterogeneity of variance. As the video recording duration varied between marks (Table 2), duration was used as an offset. The linear regression model is given by

$$\log(\mathrm{Y}_i) = \beta\,(\mathrm{Dimension}_i, \mathrm{Net}_i, \mathrm{Run}_i) + 1 * \log(\mathrm{Duration}_i) + \varepsilon_i \text{ with } \varepsilon_i \sim N(0, \sigma_i^2), \qquad (1)$$

where Y_i is the maximum movement of the ith mark, β is the population slope and ϵ_i is the residual normally distributed with expectation 0 and variance σ_i^2.

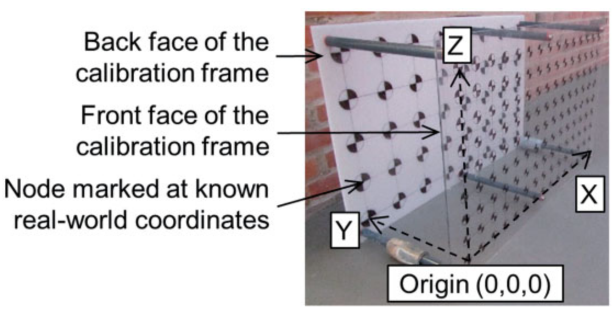

Figure 2. The calibration frame.

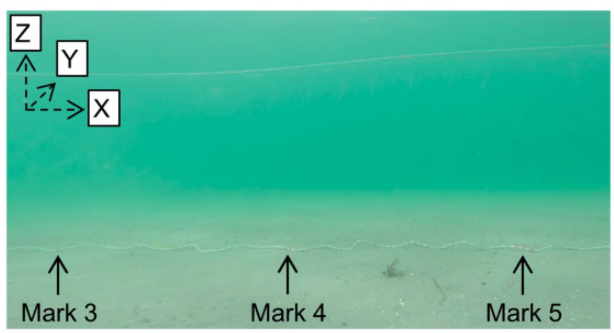

Figure 4. An *in situ* example (fleet Ic) of the positions of three different marks (identified from 3 to 5) on the leadline of the same net recorded in the three dimensions (X–Z).

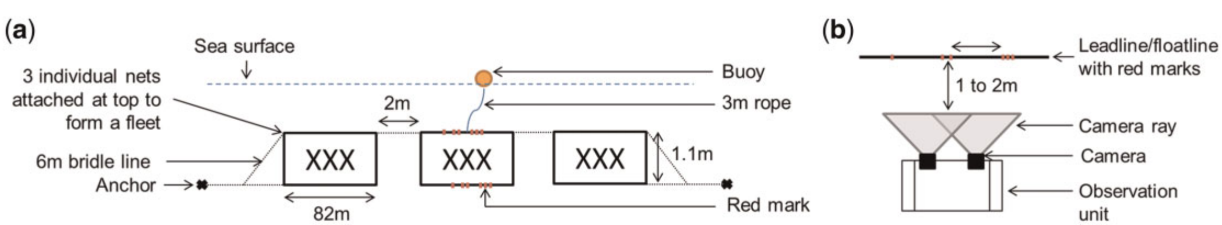

Figure 3. Experimental set-up for stereo imaging with (a) side view of a fleet, i.e. a ganged sequence of 3 individual gillnets, set on the bottom, (b) top view of the observation unit positioned in front of a net.

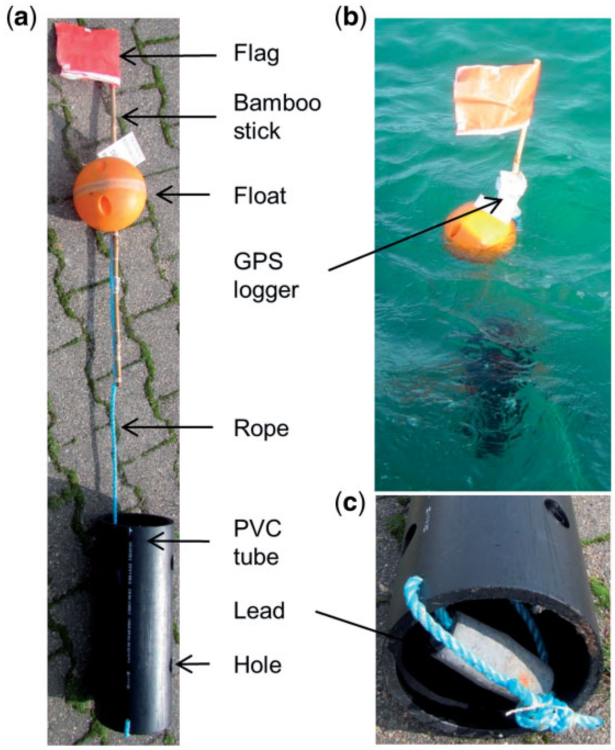

Figure 5. Drifting device to measure current speed and direction with (a) full view of the device, (b) view of the device at sea, and (c) close-up view of the lower end of the PVC tube which allows to measure at the median net height in the water column. Two similar devices were left drifting between the nets during data collection.

Table 2. Run, fleet and net type for each of the eight marks on the leadline of gillnets observed in the pilot sea trial.

Mark	Run	Fleet	Net type	Clip (min)	Max. distance (m)			Max. swept area (m^2)
					X	Y	Z	
1	I	Ia	Heavy	125	0.32	0.19	0.05	0.06
2	I	Ib	Light	13	0.82	2.01	0.26	1.65
3	I	Ic	Heavy	128	0.30	0.44	0.07	0.13
4	I	Ic	Heavy	133	0.59	0.73	0.12	0.43
5	I	Ic	Heavy	101	0.21	0.56	0.06	0.12
6	II	IIa	Light	132	1.10	1.06	0.02	1.17
7	II	IIb	Heavy	29	0.14	0.29	0.04	0.04
8	II	IIb	Heavy	138	0.29	0.06	0.03	0.02

Clip gives the total duration in min of the recorded images for each observed mark. The maximum distance (Max. distance) gives the maximum distance in m covered by the movements of each observed mark in the X–Z dimensions. The maximum swept area (Max. swept area) gives the maximum swept area in m^2 covered by the movements of each observed mark in the X–Z dimensions.

Model selection was applied to model (0) by dropping individual explanatory variables one by one based on hypothesis testing (F-statistic), and resulted in the preferred model (2):

$$\log(Y_i) = \beta\ (\text{Dimension}_i) + \gamma\ (\text{Net}_i, \text{Run}_i) + 1 * \log(\text{Duration}_i) + \varepsilon_i \text{ with } \varepsilon_i \sim N\left(0, \sigma_i^2\right). \qquad (2)$$

All parameters were tested significant at p-value < 0.001. The four assumptions that allow the sample data to be used to estimate the population data are: normality, homogeneity, independence and fixed explanatory variable (i.e. measurement error in the explanatory variable is small compared with the noise in the response variable). The chosen model (2) was validated by visual inspection of the residuals.

The video recordings were processed with VidSync version 1.66 (www.vidsync.org). All other analyses were performed by the open-source software R 3.2.3 (R Core Team, 2016).

Results

Data collected and error measures

Video recordings from five fleets were clear and long enough for analysis, i.e. three fleets for Run I and two fleets for Run II (Table 2). Nets were deployed at 3 and 1.5–2 m depth, respectively, for Runs I and II. All video recordings were collected in good weather and sea conditions. Modelled hourly water velocities were (average $\pm$ *SD*) 0.049 $\pm$0.003 and 0.031 $\pm$ 0.027 m.s^{-1}, respectively, for Runs I and II, which was in agreement with measured water velocities of 0.028 $\pm$ 0.025 m.s^{-1} for Run II. A total of eight marks could be uniquely identified on the leadline, i.e. one mark for Fleet Ia, Ib, IIa, two marks for Fleet Ic and three marks for Fleet IIb (Table 2). Total video recordings duration per mark ranged from 13 to 138 min, with an average of (mean $\pm$ *SD*) 73 $\pm$ 84 min for light nets and 109 $\pm$41 min for heavy nets (Table 2). An extract of one of the recordings is given as an example (Supplementary Material).

Diagnostic error measures provided for each 3D point by Vidsync did not show any data entry mistake or calibration problem.

Distortion corrections reduced the distortion error, i.e. the distance between the input screen points and the reprojected screen points, by (mean $\pm$ *SD*) 54 $\pm$ 12% for all cameras in all recording units. The remaining distortion per point was 0.94 $\pm$ 0.21 pixels on average for all cameras in all recording units. There was a slight increase in absolute error for calculations near the edge or centre of the screen for some of the video recordings.

In the first control test, the calculated (Vidsync) and measured (measuring tape) distances between two nodes as well as between the two faces of the calibration frame were compared. The Vidsync calculated distances were quite close to the measurements of the real distances, with on average all measurement errors smaller than 10% (Figure 6a).

In a second control test, the calculated (Vidsync) and measured (measuring tape) distances between two coloured threads on the leadline of three light and four heavy gillnets were compared. The Vidsync calculated distances were quite close to the measurements of the real distances, with on average all measurement errors smaller than 25% (Figure 6b). However, overall, measurement errors for heavy nets in Run I were up to around 150%, underestimating the calculated distances compared with the measured ones.

Based on *in situ* stereo vision measurements, the presented methodology can quantify the dynamic behaviour of the leadline of commercial bottom gillnets gillnet.

Dynamic behaviour of the leadline and maximum distance covered by the leadline

Marks were either stationary, e.g. Mark 1 in the Y dimension, moved regularly continuous, e.g. Mark 1 in the X dimension, or moved with a sudden step, e.g. Mark 6 in the X and Y dimension

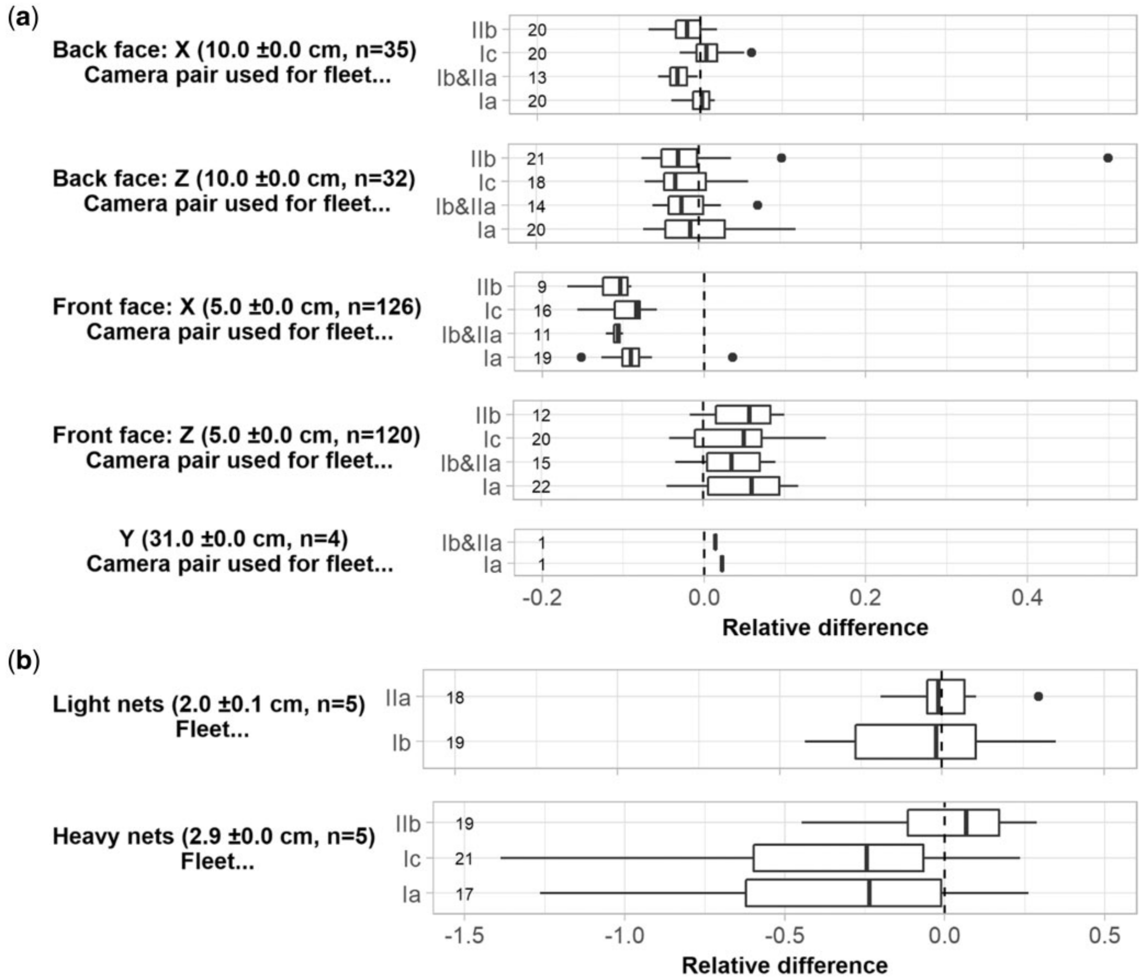

Figure 6. (a) Relative difference of the calculated distances (with Vidsync) compared with the measured distances (with a measuring tape) between two nodes of the calibration frame on the back and front faces in the X (horizontal) and Z (vertical) dimensions, and between the back and front faces of the calibration frame (Y). (b) Relative difference of the calculated distances (with Vidsync) compared with the measured distances (with a measuring tape) between two coloured threads on the leadline of light and heavy bottom gillnets. On both (a) and (b), the horizontal dashed line stands for reference as no difference between measured and calculated. The distances measured are given as an average ± *SD* with n the number of observations on the left of each plot. The number of the calculated distances used for the comparison is given on the right of each corresponding boxplot.

(Figure 7). Overall, marks on the same net moved similarly, e.g. Marks 3 to 5 on Fleet Ic, even though local disparities were found, e.g. Marks 7 and 8 on Fleet IIb (Figure 7). When moving, all marks moved in a single direction in all dimensions, e.g. to the right only for Mark 1 or to the left only for Mark 6 (Figure 7). However, not all fleets moved in the same direction, e.g. not all moved leftwards or towards the coast (Figure 7).

The leadline was moving but not penetrating into the seabed as seen from the recorded images; downward movements as calculated values in the Z dimension being most likely due to slight disparities in the seabed features. The leadline was apparent in most of the footages, except in rare occasions in which about 5 cm in length were not visible. The sea bottom was slightly bumpy and it was not possible to see if the leadline was covered by sand or only behind a bump in these few occasions.

The maximum distance covered by each mark on the leadline ranged from 0.14 to 1.10 m, 0.06 to 2.01 m, and 0.02 to 0.26 m in the X, Y and Z dimensions, respectively, with an average of (mean ± *SD*) 0.96 (±0.20) for light and 0.31 (±0.15) m for heavy nets, 1.5 (±0.67) for light and 0.38 (±0.25) m for heavy nets, and 0.14 (±0.17) for light and 0.06 (±0.03) m for heavy nets, in the X, Y and Z dimensions, respectively (Table 2). The maximum swept area covered by the movements of each observed mark (X and Y dimensions) ranged from 0.02 to 1.65 m^2, with an average of 1.41 (±0.34) and 0.13 (±0.15) m^2 for light and heavy nets, respectively (Table 2). The leadline movements in the three dimensions were found to be significantly different, with larger maximum movements in the Y dimension (Table 3). Whatever the net type, the leadline moved 1.14 (0.49–2.65) times more in the Y dimension (backward–forward) than in the X dimension (rightward–leftward), and 7.30 (3.15–16.89) times more in the Y than in the Z dimension (upward–downward) (Figure 8).

Differences between net types and runs

The leadline movements were significantly different for the two tested net configurations: for both runs, light nets were moving more than heavy nets (Table 3). Whatever the dimension, light

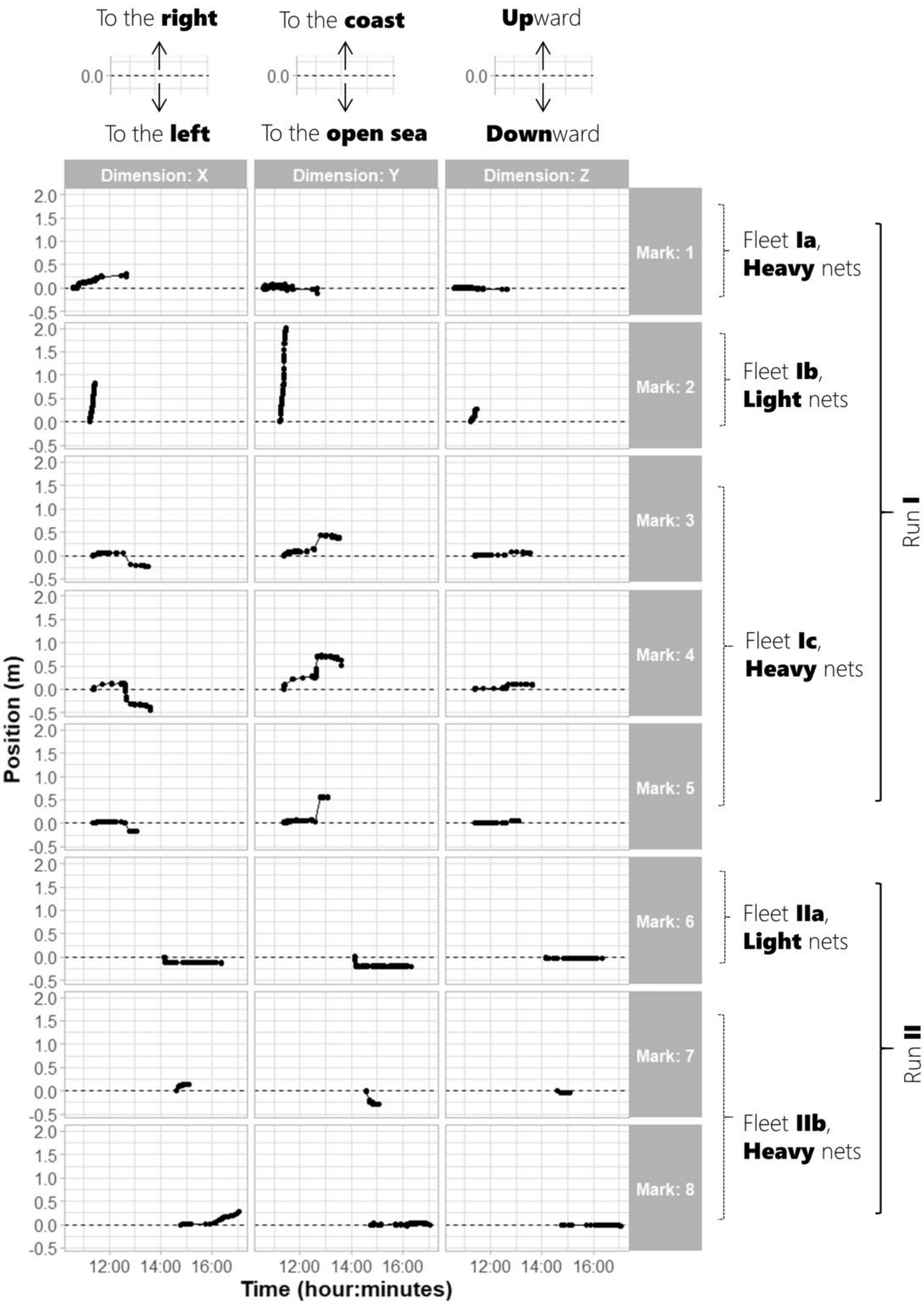

Figure 7. Time plot of the relative position of the eight marks on the leadline of light and heavy gillnets observed in the pilot sea trial, in the X–Z dimensions. The relative position is given in m as the distance from the initial position (horizontal dashed line). Time is given as the real time of the day in hour:minutes.

Table 3. Estimates and standard errors (s.e.) of the parameters in the chosen model for the log expected maximum movement of the leadline. All parameters were tested significant at *p*-value <0.001.

Parameters	Estimate (s.e.)
β (*Dimension$_i$*)	
Dimension X	−5.56 (0.54)
Dimension Y	−5.43 (0.54)
Dimension Z	−7.42 (0.54)
γ (*Net$_i$, Run$_i$*)	
Light net, Run I	3.29 (0.69)
Light net, Run II	0.00 (0)
Heavy net, Run I	−0.19 (0.54)
Heavy net, Run II	−0.34 (0.59)

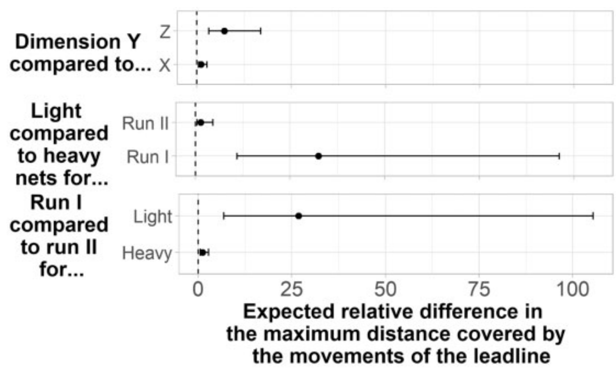

Figure 8. Expected relative difference (95% confidence limits) in the maximum distance covered by the movements of the leadline for the different experimental configurations.

nets moved 32.53 (95% confidence limits: 11.01–96.09) times more than heavy nets in Run I, and 1.41 (0.43-4.61) in Run II (Figure 8). A significant interacting effect of runs (Table 3) was found, with both light and heavy nets moving more in Run I than Run II. Light nets moved 26.79 (6.81–105.47) times more in Run I than in Run II, and heavy nets moved 1.16 (0.50-2.68) times more in Run I than in Run II. This is in line with higher water velocities in Run I compared with Run II.

Discussion

Stereo-imaging for quantifying gear dynamic behaviour *in situ*

The dynamic behaviour of the leadline of commercial bottom gillnets could be quantified in details using the presented methodology based on measurements of in-situ stereo vision recordings. The methodology quantifies both the seabed penetration and sweeping motion of the leadline. This methodology can be further applied to assess habitat effect of other gear types, especially other static gears such as creels and pots, or more generally further assess gear dynamic behaviour *in situ*. Indeed, as net geometry affects the gear selectivity, an improved understanding of the gear dynamic behaviour would provide a better insight into the capture process (Shimizu *et al.*, 2004; Herrmann *et al.*, 2009).

The stereo-imaging experimental set-up, i.e. the choice of camera separation and the dimensions and position of the calibration frame, was configured to measure relatively small objects close to the cameras. Accuracy and precision decreased as distance from the cameras increased. The nets were not expected to move in such an order of magnitude, but a larger chessboard, i.e. large enough to fill the screen, could have helped limit our measurement errors. The fish eye effect could be reduced by limiting the field of view (instead of choosing ultra wide setting).

A variety of challenges were faced when deploying the observation units near the nets at sea, among which water turbidity, also noticed as a limitation for optical methods by Lucchetti *et al.* (2012) and Struthers *et al.* (2015). The video recordings could also appear blurry due to the scattering effects of particles in the water column, and images could be exposed differently from the two cameras due to irregular lightning and displacement between the cameras (Schmidt and Rzhanov, 2012). These optical limitations reduced the number of recorded images that could be processed. A camera that only captures light reflected from objects further away than a certain distance could be used to remove the effects of scattered light and therefore solve the issue of water turbidity (under development, L.A. Krag, pers. comm.).

Calibration and distortion corrections obtained in a tank were used for processing the *in situ* video recordings. The same camera specifications, i.e. camera settings and relative orientation, for each recording unit, were used but any optical adjustment such as removing a camera from its underwater housing to change a battery or a change of the angle between the cameras during transportation/aboard the vessel may have affected the parameters and therefore the results. The control tests did not show major issues, and one can therefore rely on the order of magnitude of the results. But, the cameras should remain fixed throughout the experiment in a later use of the stereo-imaging method.

Pilot estimation of gillnets 3D dynamic behaviour and their seabed effects

The leadline of bottom gillnets, fully deployed on the bottom, could sweep the seabed in sandy habitats up to about 2 m, for the most part in the order of magnitude of 10 cm. Movements were either continuous or in a sudden step, which was different from the periodical displacement observed by Shimizu *et al.* (2004). This could be due to a different initial net shape and spread of the leadline for each fleet when reaching the sea bottom (Shimizu *et al.*, 2007), or local water flow disparities. The in-situ measurements of the leadline showed that movements were the smallest in the Z dimension, less than a few centimetres. The leadline was moving but not penetrating into the seabed as seen from the recorded images, downward movements as calculated values in the Z dimension being most likely due to slight disparities in the seabed features.

In terms of seabed disturbance, this means that the physical disruption of the seabed (penetration) of gillnets is minimal compared with the sweeping of the gear, whereas seabed penetration was observed as partly responsible for habitat physical impact in active fishing gears (Depestele *et al.*, 2016; Eigaard *et al.*, 2016). The potential direct damage to the benthos would therefore originate from the sweeping movements of the gillnets; as the leadline and netting can snag and entangle available entities. The sweeping movements of plaice gillnets in the Danish fishery were found to be higher than usually estimated by experts, but cannot be compared with other *in situ* measurements as these are the first quantitative measurements to our knowledge. A maximum of 30 km of nets are soaked in a typical bottom-set gillnets fishing operation (Montgomerie, 2015). The swept area can roughly be estimated to about $0.04\,km^2$ for light nets and $0.01\,km^2$ for heavy nets (based on a rectangle area calculation using the average measured range per mark in the Y dimension as presented above, i.e. 1.5 for light and 0.38 m for heavy nets). This is lower than any of the hourly swept area estimated for active fishing gears by Eigaard *et al.* (2016), ranging from $0.05\,km^2$ for beam trawl to $1.5\,km^2$ for Scottish seining surface impact. However, the swept area of an active gear is swept once by the gear, whereas passive gear is likely to sweep the same area multiple times. The measured movements were representative only to a certain point of what really happens: as the nets were getting too far from or too close to the recording unit, it was not possible to take measurements anymore. The present measurements of the movement of the leadline are therefore underestimated. However, the movement of the leadline was not unlimited as the fleets were anchored on the bottom. For the same reason, a major difference between longer soak durations on the estimated swept area was not expected.

The dynamic behaviour of the leadline was analysed using a simple motion metrics in the three spatial dimensions, i.e. the maximum distance covered by the leadline in each dimension. However, how fast the leadline moves is also expected to play a key role in the assessment of the potential effects of the leadline movement on the seabed. Indeed, the fastest movements of the leadline are the ones most likely to cause damage. As observed previously, marks moved either regularly continuous, or with a sudden step, and speed was therefore not a good indicator. Further assessment should include a spatio-temporal trajectory analysis, with focus on acceleration, i.e. change in velocity with time.

The observations of the pilot project only covered the soaking phase of a gillnetting operation, i.e. when the gear was fully deployed on the bottom, and not the retrieval of the gear, therefore not covering the total potential habitat effect of bottom gillnets. Shester and Micheli (2011) observed the entanglement and removal of kelp plants and gorgonian corals by set gillnets while being hauled. Effects of hauling are more likely to be destructive as more power is exerted through the nets (hauler) than when soaking, for which, e.g. a stone could eventually stop the net. It is however known from fishermen practices that the way the gear is handled when hauling can significantly reduce possible habitat damage, e.g. hauling in the current direction.

Gear configuration as mitigation measure

As demonstrated in this experiment, the gear configuration affects the sweeping of the nets, with light nets moving significantly more than heavy ones. Whereas the general perception is that heavy gears are more destructive to the habitat, such as in active gears (Kaiser *et al.*, 2002), it was demonstrated here that a heavier leadline would result in less movement, being the actual issue in terms of potential habitat damage of bottom-set gillnets. Therefore, gear configuration has a strong mitigation effect regarding the sweeping behaviour of the leadline, and habitat damage could be reduced by using nets mounted with heavier leadlines.

In addition to the tested net configuration, i.e. light and heavy nets, other components of the fishing gear in gillnets could be looked at to mitigate their habitat effects. Bridles attached to the head or bottom line will give the netting different types of curves which will affect the drag (Stewart and Ferro, 1985). Twine diameter, mesh size, netting hanging ratio and length of fleets, as well as the way the nets are set out could also affect the drag and therefore the leadline movement of bottom-set gillnets.

General applicability of the results

Due to the limited number of observations and choice of model, movement values presented here were not meant to be predicted outside of the experimental conditions. Water flow speeds during data collection were lower than the average range in coastal Danish waters ($0.26–0.77\ m.s^{-1}$) (National Geospatial-Intelligence Agency of the United States Government, 2013). Therefore, such experimental conditions of mild sea conditions gave conservative estimates. The flow from waves, induced by wind, and current, induced by both tides and wind, represents the most common flow condition on the seabed for shallow water depths at our scales of interest (spatial and temporal) (Jensen and Jónsson, 1987; Otto *et al.*, 1990; Myrhaug, 1995; Soulsby, 1997). The complex effects of water flow, waves and wind, can change at a small scale, and influence the behaviour of the gear (Shimizu *et al.*, 2004). These local differences in water flow could be a reason for the significant interacting effect of runs. When moving, all marks moved in a single direction in all dimensions, which indicated that movements were not caused by the local action of waves, i.e. flow and surge which would have resulted in, e.g. repeated forward-backward movements. When moving, not all fleets moved in the same direction, which indicated that movements were not caused by the overall action of waves, i.e. towards the coast. Detailed measurement of the current direction and speed in further experiments could provide with a better understanding of the environmental variables at stake. Very shallow waters were needed to test how to operate the camera cages, and also because water was turbid at the time of data collection. Further estimations should be run in deeper waters for which water flow conditions would be different, as the turbulent boundary layer does not occupy the entire water column contrary to shallow waters (Otto *et al.*, 1990; Soulsby, 1997). This is conditioned on an improved method that allows to place an observation unit quite close to the net at such depths, e.g. using a sonar, and external lightning to compensate for the reduced light conditions.

Because the pilot project was located in very shallow waters, a small net height was chosen. It is commercial practice to work with such a net height, but higher nets may have an influence on the overall gear equilibrium and drag. So may caught fish, but it is generally assumed that fish would not have a great effect (Shimizu *et al.*, 2007).

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

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