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Ole Ritzau Eigaard (ed.)

DTU Aqua Report no. 409-2022

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Ole Ritzau Eigaard[1] (ed.), with contributions from Francois Bastardie[1], Katrina Bromhall[1], Mollie E. Brooks[1], Henrik Gislason[1], Ciaran McLaverty[1], Thomas Noack[1], Jeppe Olesen[1], Finbarr G O'Neill[2], Karin J. van der Reijden[1], Camille Saurel[1], Tim J.G. Wilms[1] and Grete E. Dinesen[1]

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Colophon

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Preface

This report presents the results from the project “Sandbanker og fiskeripåvirkning i relation til EU’s fiskeri- og miljøpolitik” (Grant Agreement No 33113-B-17-108), which was funded by the European Maritime and Fisheries Fund (EMFF) and the Ministry of Food, Agriculture and Fisheries of Denmark.

The main outcomes of the project are a number of scientific papers, manuscripts and reports that are presented as separate appendices of the report, while summaries from these appendices and syntheses of key results are presented as chapters in the report.

The project started in December 2018 and ended in June 2021.

Lyngby, September 2022

Ole Ritzau Eigaard
Senior Researcher

European Union
European Maritime and Fisheries Fund

HAV & FISK

Content

Executive summary

Objectives, effort, and deliverables

The primary project objectives and outcomes are organized within three overarching components, which have also formed the backbone of the work packages and associated tasks of the project.

Fishing footprint:
i) Development of a new methodology to estimate the exact spatial extent and gear footprint of Danish anchor seines.
ii) The development of a hierarchical method that combines different sources of fisheries monitoring data (VMS, AIS, and Black Box data) to produce high-precision fishing pressure maps (grid cell resolution of 100x100m) of Danish demersal fisheries.

Gear specific depletion rates:
i) Development of a new methodology that theoretically derives gear-specific depletion rates, based on gear design and component-specific penetration depths, for ten different commercial fishing gears.
ii) Quantification of the benthic impact (benthic fauna depletion) of the Danish Seine fishing gear based on in-project sea trials and experimental data.
iii) Quantification of the impact on the benthic fauna community from a standard and a modified sandeel otter trawl based on experimental data from sea trials previously conducted by DTU Aqua.
iv) Quantification of the impact on the benthic fauna community from a light-weight mussel dredge based on experimental data from sea trials previously conducted by DTU Aqua.

Fishery specific assessment of benthic impact:
i) Development of a new methodology to assess the amount of sediment mobilized by demersal fishing gears, based on the spatial distribution of both fishing activity and fine sediments, combined with gear-specific drag coefficients.
ii) Integration of project results and external science-based methods and results into a framework, tailored to assess the benthic impact from the different Danish fisheries with Mobile Bottom Contacting Gears (MBCGs) on sandbanks in the North Sea, and applied to the Danish North Sea sandbank fisheries for the period of 2018 – 2020.

Within these three overarching project components, a number of key deliverables have been produced – some in collaboration with other institutions and projects - during the project period:

- High resolution fishing pressure data and maps (100x100 meter grid cells) based on hierarchical integration of VMS, AIS, and BB data with logbook data
- Development of a predictive model of the geometry and dynamics of the Danish seine gear footprint.
- Development of a modelling tool to estimate the amount of sediment mobilization from fishing with different mobile bottom-contacting gears.
- Quantification of the depletion of benthic fauna associated with a gear passage of a Danish seine, a sandeel otter trawl (both conventional and modified), and a light mussel dredge.
- Integration of project deliverables (e.g., high resolution fishing pressure data, modelled data for natural physical disturbance, and gear specific depletion rates) into a gear-specific benthic impact assessment of the Danish fishery on North Sea sandbanks.

Key results and conclusions

From our application of ICES' (International Council for the Exploration of the Sea) standard assessment framework with improved input data (high-resolution fishing pressure data in 100x100 meter grid cells, an experimentally determined Danish seine depletion rate of 0.0069, and theoretically derived, gear-specific depletion rates for the other sandbank gears) it can be concluded that the sandbank habitats in the Greater North Sea are generally subject to a low impact from the Danish demersal fisheries that use them. The Relative Benthic State (RBS; ranging from 0 (highly impacted) to 1(not impacted)) of the sandbank habitats, considering only the pressure from Danish fishing effort, has an overall average grid cell value > 0.9. This low impact is a result of a combination of factors:

i. Most gears deployed on sandbank habitats by the Danish fleet, such as Danish seines and Sandeel otter trawls, are relatively light gears and have a low associated depletion rate.
ii. The natural disturbance of sandbank habitats is generally high and consequently, the local benthic community is adapted to physical disturbances similar to the physical disturbance from demersal fishing.
iii. The total fishing intensity (total fishery footprint and associated Swept Area Ratio (SAR) values) is generally low within sandbank habitats compared to e.g., the intensity of bottom trawl fishing on softer sediments in Skagerrak and Kattegat.

Fishing impacts are standardized with the landing values of individual fisheries to enable comparisons between fishing gears. The brown shrimp fishery with beam trawls has a relatively higher impact (reduction in RBS value per DKK of the landings) than the sandeel fishery with otter trawls, and the plaice fishery with Danish seines. In addition, Danish fishing impact in general (across all fisheries) is lower in the North Sea than in the Skagerrak and Kattegat.

The results presented here are very much in line with earlier findings, but in comparison to these other analyses we have (i) applied the methodology to fishing data at much higher spatial resolutions, (ii) used a novel, empirically derived depletion estimate for Danish seines, and (iii) focused specifically on sandbank habitats.

Whereas all the three steps above increase the estimation accuracy of sandbank impact and status assessment relating to fishing, they may cause false accuracy as well. Most other input data for the ICES RBS-assessment framework is not available at nearly the same high resolution as the fishing pressure data; more specifically, the North Sea wide estimates of local habitat type and benthic community composition, which serve as input in the determination of habitat sensitivity to fisheries, are based very much on extrapolations and have large uncertainties. This type of underwater data is very resource demanding to sample, but a better resolution in habitat maps is a prerequisite for fully utilizing the high-resolution fishing pressure data developed in this project and the methodological advances within benthic impact assessment in the wider scientific community.

Implementation and dissemination

With the above-described deliverables the key project objectives have been met, and all national stakeholders will profit from the project outputs, e.g., improved fishing pressure maps and impact assessments as a basis for future environmental and fisheries management and industry and NGO initiated conservation efforts.

Internationally, the outputs have been and will be disseminated mainly through the high number of scientific papers and manuscripts produced with contributions from this project (4 published scientific papers, 2 scientific manuscripts, 1 published scientific report). Furthermore, the project has involved leading European experts in several phases and deliverables of the project and the project coordinator has acted as co-chair of ICES-WGFBIT (ICES Working Group on Fisheries Benthic Impacts and Trade-offs) for the duration of the project, which has ensured knowledge transfer and synergy both ways.

Sammendrag på dansk

Projektformål, indsats og resultater

De primære projektmål og resultater er organiseret indenfor tre overordnede komponenter, som også har dannet rygraden i arbejdspakkerne og de tilhørende opgaver i projektet.

Fiskeriets fodaftryk på havbunden:
i) Udvikling af en ny metode til at estimere redskabsaftrykket og den nøjagtige rumlige udbredelse af fiskeriet med snurrevod.
ii) Integration af denne nye metode i big-data arbejdsgange baserede på fiskeriovervågningsdata (VMS, AIS og Black Box [BB] data) til at producere geografiske præcise kort (gitterceller/pixel opløsning på 100x100m) over Dansk fiskeris påvirkning af sandbanker i Nordsøen.

Bundfauna-dødelighed fra forskellige redskaber:
i) Udvikling af en ny teoretisk baseret metode, der kan estimere redskabsspecifikke dødeligheder ud fra redskabsdesign og -komponenter, for ti forskellige kommercielle fiskeredskaber i Nordsøen.
ii) Kvantificering af bundpåvirkningen (dødeligheden af bunddyr) for snurrevod baseret på feltforsøg og eksperimentelle data genereret indenfor projektet.
iii) Kvantificering af påvirkningen af bundfaunaen fra hhv. en traditionel og en modificeret tobis trawl baseret på eksperimentelle data indsamlet af DTU Aqua under tidligere feltforsøg.
iv) Kvantificering af påvirkningen af bundfaunaen fra en let muslingeskraber baseret på eksperimentelle data indsamlet af DTU Aqua under tidligere feltforsøg..

Redskabsspecifikke effekter på havbunden:
i) Udvikling af en ny metode til at estimere den mængde af bundpartikler (sediment) der frigives af bundslæbende redskaber, baseret på den rumlige fordeling af fiskeriaktivitet og sedimenter, samt den redskabsspecifikke vandmodstand.
ii) Integration af projektets delresultater og eksterne videnskabelige metoder og resultater i et effektvurderings-værktøj, der er skræddersyet til at vurdere bundpåvirkningen fra de forskellige danske fiskerier med bundslæbende redskaber på sandbanker i Nordsøen, samt anvendelse af det udviklede effektvurderings-værktøj på det danske fiskeri på sandbanker i Nordsøen for perioden 2018 - 2020.

Inden for disse tre overordnede komponenter er der i løbet af projektperioden blevet produceret en række centrale leverancer – nogle i samarbejde med andre institutter og projekter – i projektperioden:

- Geografisk præcise fisketrykdata og -kort (100x100 meter kvadrater/pixel størrelse) baseret på hierarkisk integration af AIS-, BB- og VMS -data med logbogsdata.
- Udvikling af en matematisk model til at beskrive og estimere geometrien og dynamikken i et snurrevodsredskab under fiskerioperationen.
- Udvikling af et modelleringsværktøj til estimering af den mængde af bundpartikler der bliver frigivet fra havbunden under fiskeri med de forskellige bundslæbende redskaber
- Kvantificering af dødeligheden af bunddyr forbundet med påvirkningen fra snurrevod, tobistrawl og en let muslingeskrabere
- Integration af delresultaterne (f.eks. data for fiskeritryk i høj rumlig opløsning, modellerede data for naturlig forstyrrelse, og redskabsspecifikke bundfauna-dødeligheder) i en redskabsspecifik konsekvensanalyse af de forskellige danske fiskerier på sandbanker i Nordsøen.

Hovedresultater og konklusioner

ICES' (det international havforskningsråd) standard metode til estimering af bundpåvirkning blev anvendt med forbedrede inputdata genereret i dette projekt (fin-skala VMS-AIS-BB baserede data for fisketryk i 100x100 meter kvadrater, eksperimentelt bestemt estimat for bunddyrsdødeligheden ved fiskeri med snurrevod [0,0069], og modellerede dødelighedsrater for de andre fiskeredskaber i Nordsøen), og ud fra resultaterne kan det konkluderes at påvirkningen af Nordsøens sandbanker fra det danske fiskeri generelt er lav. Indikatoren den 'relative bentiske tilstand' (RBS) spænder fra 0 (stærkt påvirket) til 1 (ikke påvirket) og den gennemsnitlige RBS-værdi for de fiskeripåvirkede sandbanker var > 0,9, når der kun indregnes påvirkningen fra dansk fiskeri. Denne relativt lave påvirkning skyldes en kombination af faktorer;

i. De fleste redskaber der anvendes på sandbanker, som f.eks. snurrevod og tobistrawl, er relativt lette og har en lav tilknyttet bunddyrsdødelighed.
ii. Den naturlige forstyrrelse af sandbanke habitater er generelt høj og derfor er det lokale bentiske samfund tilpasset fysiske forstyrrelser, der kan sammenlignes med de fysiske forstyrrelser fra fiskeriet med de relevante bundslæbende redskaber
iii. Intensiteten (den samlet udbredelse af fiskeriet og de tilhørende SAR -værdier) er generelt lav for det danske fiskeri på sandbanker sammenlignet med fiskeriintensiteten på andre naturtyper i Nordsøen, Skagerrak og Kattegat.

Når man standardiserer påvirkningen fra det enkelte fiskeri med fiskeriets landingsværdi, kan det ses, at hesterejefiskeriet med bomtrawl har en relativt større påvirkning (reduktion i RBS-værdi per krone i landingsværdi) end fiskeriet med trawl efter tobis og fiskeriet med snurrevod efter rødspætter. Det fremgår også, at der generelt (på tværs af alle fiskerier) er en lavere RBS-påvirkning per landingsværdi for fiskerierne i Nordsøen end i Skagerrak og Kattegat.

Resultaterne præsenteret her er i overensstemmelse med resultaterne fra tidligere undersøgelser, men til forskel fra disse andre analyser har vi beregnet ICES RBS-indikatoren ved brug af input data af forbedret kvalitet og en med mere fokuseret analyse i form af; (i) fiskeridata med meget højere rumlige opløsning, (ii) en ny eksperimentelt bestemt bunddyrsdødelighed for snurrevod, og (iii) en afgrænsning af analysen til sandbanke-habitater i Nordsøen, Skagerrak og Kattegat. Mens alle disse tre faktorer øger præcisionen af analysen, medfører de også en risiko for at overvurdere pålideligheden af resultaterne fordi de fleste andre inputdata til beregning af RBS-indikatoren ikke er tilgængelige i samme høje opløsning som data for fisketrykket. Dette gælder især de marine habitatkort og prøver af de marine bunddyrssamfund, som udgør fundamentet for at bestemme den habitatfølsomhed, som indgår i beregningen af RBS-indikatoren. Denne type af undervandsdata er meget ressourcekrævende at indsamle og derfor er kortlægningen af bundtyper og bunddyr i danske farvande meget mangelfuld, men en bedre opløsning og konfidens i de marine habitatkort er en forudsætning for fuldt ud at kunne udnytte de fin-skala data for fisketryk, der er udviklet i dette projekt, sammen med de seneste metodologiske fremskridt indenfor udviklingen af bentiske indikatorer.

Implementering og formidling

Med de ovenfor beskrevne leverancer er de centrale projektmål blevet opfyldt, og det forventes at alle nationale interessenter vil drage fordel af projektets output; f.eks. de meget mere geografisk præcise data og kort for fisketryk og bundpåvirkning som grundlag for fremtidens miljø- og fiskeriforvaltning og for indsatser med naturbeskyttelsen igangsat af fiskeindustri og NGO'er.

Internationalt har resultaterne primært været formidlet gennem de videnskabelige artikler og manuskripter, der er produceret i sammenhæng med projektet (3 publicerede videnskabelige artikler, 3 videnskabelige manuskripter). Desuden har projektet involveret førende europæiske eksperter i flere faser og leverancer af projektet, og projektkoordinatoren har fungeret som formand for ICES-WGFBIT (ICES Working Group on Fisheries Benthic Impacts and Trade-offs) i projektets varighed, hvilket har sikret viden overførsel og synergi begge veje.

1 Introduction and background

A key objective of this project has been to develop a management tool that enables assessing and comparing the effects of different fisheries to the seafloor, in particular in relation to the national Danish fisheries on sandbank habitat in the North Sea. In meeting this objective, the scientific work done in the EU-FP7 project BENTHIS ('BENTHIS/312088') and in the ICES (International Council for the Exploration of the Sea) working group on Fisheries Benthic Impacts and Trade-offs (WGFBIT) have been a corner stone. In both the WGFBIT expert group work (ICES, 2018) and in ICES advice on impact assessment in relation to descriptor 6 of EU's Marine Strategy Framework Directive (ICES, 2021), a central indicator of benthic impact is the Population Dynamic indicator (PD). This indicator estimates the amount of benthic biomass (relative to the local carrying capacity) that is able to persist if the current bottom trawling intensity continues for a long time. The method to calculate the PD indicator is based on the fisheries-induced depletion of the benthic community and its subsequent recovery. Gear-specific depletion estimates that represent the removal of benthos after a trawl passage are combined with fishing intensity data to determine the local benthos depletion. Subsequent recovery is estimated from the established relationship between recovery time and the estimated longevity distribution of the local, unimpacted benthic community.

The PD method is recommended by ICES and selected as the basis for the analyses in this project because it has several advantages. A key feature is the sensitivity over a broader range of trawling intensities compared to many other methods (ICES, 2018) and another is that the method can differentiate between fishing gears that differ in depletion rate in relation to the sediment penetration depth of the gear. The gear-specific depletion estimates required for the PD method are derived from meta-analyses of all available trawl impact studies worldwide on infauna and epifauna (Hiddink et al., 2017; Sciberras et al., 2018), which makes them globally applicable. However, regional assessments are still dependent on local data of the fishing intensity and the longevity composition of the benthic community. For the Greater North Sea area, the PD-method is currently applied using benthic community information (longevity) that is estimated at a very coarse scale. This is potentially a significant caveat in the biological input parameters, which needs to be addressed/validated with data from a broader range of benthic biota and areas (ICES, 2018).

BENTHIS and ICES also highlight a number of caveats and improvement potentials with respect to the fisheries data used in the developed PD standard assessment framework. Among other things it is pointed out that i) for several fisheries (metiers) a gear-specific depletion rate has not yet been established and that ii) the scale (spatial resolution) of the fishing intensity data feeding into the assessment framework can be improved from the current standard (C-square size of approx. 15 km^2 in the North Sea). This resolution is a compromise resulting from EU-GDPR (General Data Protection Regulation) rules associated with the use of VMS (Vessel Monitoring System) data.

This project seeks to overcome these two barriers to a more realistic fishery-specific benthic impact assessment of the Danish sandbank fisheries in the North Sea. Hence, the project aims to establish gear-specific depletion rates for all the Danish sandbank fisheries/metiers in the North Sea and to improve the spatial resolution of the fishing pressure data for the standard assessment through the combined use of AIS (Automatic Identification System), VMS (Vessel Monitoring System), and BB (Black Box) data.

2 Improved estimates of the exact fishing footprint

2.1 The seafloor footprint geometry of Danish Seines

(O'Neill and Noack 2021, appendix A1)

Introduction

In order to quantitatively describe the performance and environmental impact of Danish anchor seines, it is necessary to understand the geometry and dynamics of the seine gear, and in particular of the ropes. The ropes are the components of the of demersal seine gear that are most in contact with the seabed. They can be many kilometres long (typically 6 to 8 km in the Northeast Atlantic), yet little is known about how they behave when fishing. Madsen et al (2016) developed a mechanical cable-element model of Scottish seine rope dynamics, which simulates the physical behaviour of ropes of a Scottish seine during the fishing process, and which has been used to compare the efficiency of different types of initial deployment patterns (Madsen et al 2017).

Here, we developed a kinematic description of the Danish seine rope dynamics and show how a relatively simple analytical curve (a piriform) can be parameterised to characterise the geometry and dynamics of seine ropes, using basic positional and operational data for a given haul. We then demonstrate how we can estimate the area fished, and the speed, direction, and angle of attack of any part of the seine net rope, at any time during the fishing process. This sort of information is fundamental to a better understanding of the capture process of Danish anchor seines, their whole gear selectivity, and their environmental impact (Breen et al, 2004; O'Neill and Ivanović, 2016; O'Neill et al, 2018).

Materials and methods

Piriform curve

Piriform means pear-shaped and is a particular example of tear dropped-shaped curves. It is a quartic curve and in cartesian coordinates can be expressed as

$$a^4y^2 = b^2x^3(2a - x)$$

where *a* is half the distance from the tip to the base of the tear drop and *b* is the perpendicular distance to the curve from this mid-point (Figure 2.1.1) (Weisstein, 2020). The maximum perpendicular distance from the mid-line is $\frac{3\sqrt{3}}{4}b$, which occurs at three quarters of the way along the mid-line. The total surface area of a piriform is πab.

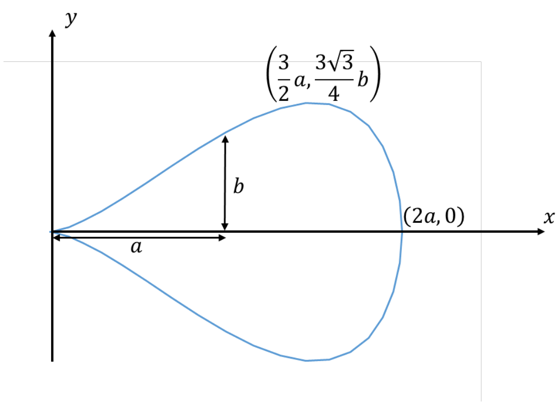

Figure 2.1.1. General description of a piriform curve (see text for details).

Here, we use the data of Noack et al (2019) to show that the piriform can be used to describe the geometry of the Danish seine following deployment and during towing and hauling. Noack et al. (2019)

defined a deployment (or setting) phase, a herding phase, and a catching phase. We defined three slightly different phases to describe the fishing operation of Danish seines: the deployment phase; the towing phase; and the hauling phase. Their focus was on fish behaviour and capture, and while our deployment phases are the same, their herding phase encompasses all our towing phase and the first part of our hauling phase, and their catching phase is the latter part of our hauling phase. Nevertheless, we used the positional data of Noack et al. (2019) to parameterise the piriforms during each of the phases.

Fitting the piriform curves

Deployment phase

During the deployment phase, the ropes and net are set out from an anchored buoy in a rough teardrop shape. The deployment usually finishes at a point along the return leg when the entire seine rope is laid out, after which the towing phase begins. We assume that during the deployment phase the vessel follows the path of a partial piriform. From the ships track data, we estimated for each haul (i) the distance from the anchor to the point where the rope crosses the axis of symmetry of deployment and (ii) the distance from the end point of deployment back to the anchor. We then used this information to parameterise the piriform.

Towing phase

During the towing phase, we assume that the seine ropes move from the deployment piriform configuration to a slenderer piriform shape, when the vessel returns to the anchor. At this point we can estimate (i) the distance between the net and the vessel and (ii) the path along which the net is subsequently hauled. We subsequently used this information to parameterise the piriform.
In order to model the path of the seine rope during the towing phase we use information on the towing speed of the rope and on the net position during this phase.

Hauling phase

During the hauling phase, we describe the rope geometry by piriforms of decreasing length and width, which are symmetric around the line with which the net is hauled. The ropes are hauled with increasing speed and when we scale the time with the corresponding hauling duration, the distance measurements between the net and the vessel are very consistent and well described by a quadratic curve.

Results

To demonstrate the ability of the piriform model to characterise the geometry and dynamics of the seine ropes, we use the average parameter values and times of the six Noack et al (2019) hauls. Figure 2.1.2 shows the modelled position of the seine ropes at equal time intervals from the deployment configuration through the towing phase, while Figure 2.1.3 shows the position of the ropes during the hauling phase.

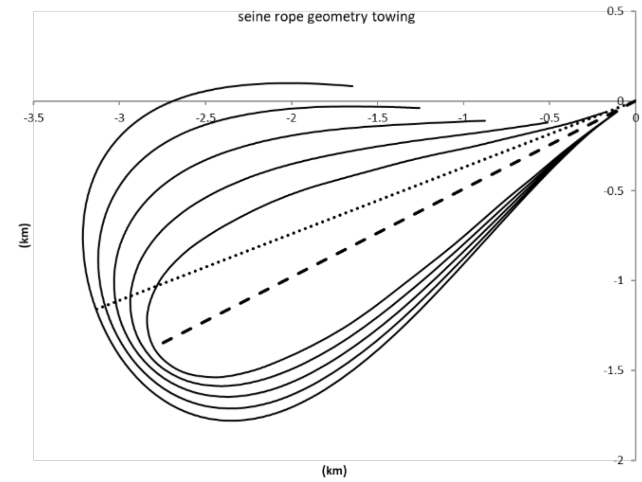

Figure 2.1.2. The geometry of the seine ropes at equally spaced time intervals during the towing phase. The dotted line is the line of symmetry around which the seine gear was deployed (and identifies *λ*(t_d)) and the dashed line is the line of symmetry the ropes have after the towing phase (and identifies *λ*(t_t)).

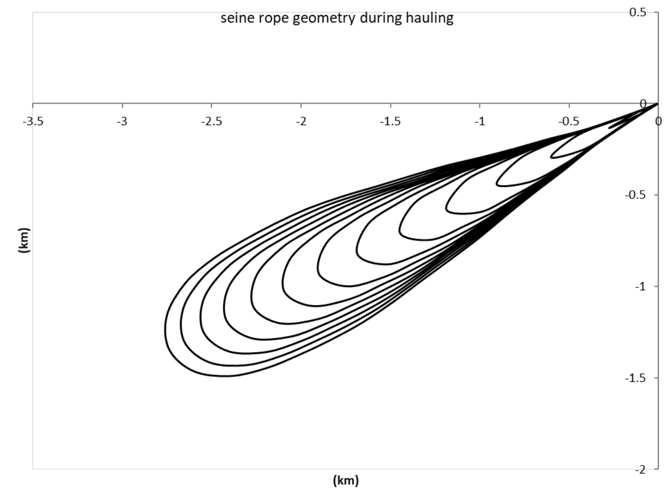

Figure 2.1.3. The geometry of the seine ropes at equally spaced time intervals during the hauling phase.

We can calculate the velocity and angle of attack of a given position of the rope (where the angle of attack is the angle between the direction of seine rope and how it is aligned on the seabed). This information can be used to provide a much more detailed, quantitative understanding of the interaction of the seine ropes and the seabed. Figure 2.1.4a shows the speed of the seine ropes at each point of the swept area, from which it is clear (i) that the first rope deployed does not move much during the towing phase, in comparison to the considerable movement of the second rope; and (ii) that during the hauling phase, the ropes move slowly at first but are then hauled progressively faster so that the central part of the gear reaches speeds similar to that experienced by the second rope during the towing phase. The average rope speed is 0.57 ms^{-1} with a more or less equal distribution between 0.1 and 1.0 ms^{-1} (Figure 2.1.4b). Similarly, we can determine other parameters, such as the component of the speed that is perpendicular to the seine rope and the hydrodynamic drag of the seine ropes.

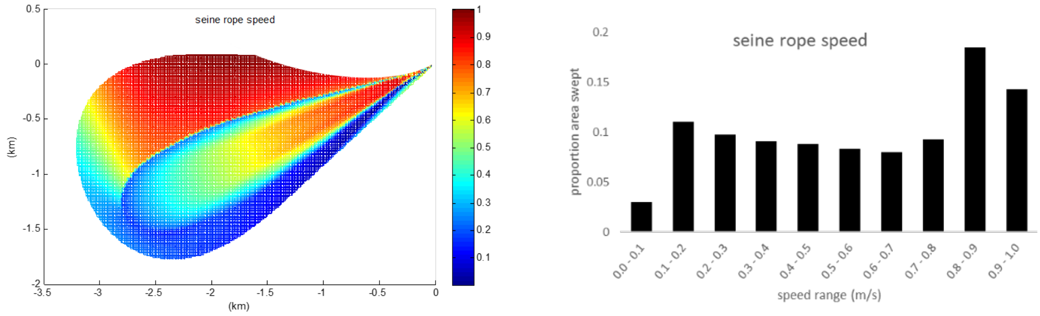

Figure 2.1.4. (a) The seine rope speed at each point of the area swept during towing and hauling and (b) these data summarised identifying the percentage area swept in 0.1 ms^{-1} intervals.

Discussion

This study has demonstrated how the geometry of seine net ropes on the seabed, during deployment, towing and hauling, can be described by piriform curves. This allows us to characterize the geometry of seine gears and to describe the speed, direction, and angle of attack for any part of the seine net rope, at any time during the fishing process.

This type of information will be very useful in assessing and quantifying the operational performance and environmental impact of seine gears. For example, it will provide insights into issues such as fish herding and seine gear efficiency. The maximum sustainable swimming speed of fish can play a key role in the fish capture process (Breen et al, 2004). Hence, the component of the speed that is perpendicular to the seine rope is likely to be important in relation to fish herding. This is the speed at which the seine rope will approach a stationary fish and the speed at which a fish will have to swim if it is to remain ahead of the rope. In addition, in relation with physical impact studies, this study will allow for detailed estimations of i) the swept area, ii) the amount of sediment mobilised by the fishing gear and iii) the extent to which the fishing gear penetrates the seabed. When it comes to habitat alteration and benthic mortality, the momentum of the ropes might be an important factor, which is determined by the absolute speed over the ground. For processes such as sediment mobilisation, the hydrodynamic drag of the seine ropes is important and is dependent on both their speed and angle of attack (O'Neill and Summerbell, 2016).

2.2 Estimation of DK fishing pressure in high spatial resolution

Introduction

This project aimed to improve the spatial resolution of fishing data that could feed into the PD impact assessment framework. The standard resolution currently used is at the level of C-squares, which are 0.05 x 0.05 longitude and latitude degrees. The exact surface of these squares varies with latitude and is approximately 15 km^2 in the North Sea. This resolution is a compromise resulting from EU-GDPR (General Data Protection Regulation) rules associated with the use of VMS (Vessel Monitoring System) data.

Here, we describe and demonstrate how we have substantially improved the spatial resolution of Danish fishing pressure data through the combined use of Vessel Monitoring System (VMS), Automatic Identification System (AIS), and Black Box (BB), data and logbook data. The new resolution of 100 x 100 meter provides more accurate estimates of the annual swept area and paves the way for a substantially improved pressure and impact assessment of the Danish sandbank fisheries using the PD impact assessment framework.

Materials and methods

Fisheries data

We obtained both AIS and VMS data from all Danish demersal fishing vessels for the period 2012 to 2020. In addition, we obtained BB data from the vessels that had this data available (i.e., vessels fishing for mussels and oysters). Both the AIS and the VMS provide satellite-based recordings ('pings') of the vessels position, speed, and course, which can be merged to the daily logbooks in which fishermen mandatorily report the used fishing gear and retained catches (Hintzen et al., 2012). Although similar information is recorded, VMS and AIS have some differences. The VMS is a controlling system, created to track and monitor commercial fishing activities. It is obligatory for fishing vessels >12 m since 2012 and has a ping interval of around an hour in Denmark. Spatial coverage is almost 100%. The AIS, on the other hand, is primarily designed to prevent collisions. Its ping interval is around five seconds, but spatial coverage is limited, especially further offshore (Vespe et al., 2016; Shepperson et al., 2018). The BB devices are on-board devices that monitor the fishing effort of bivalve dredgers by logging vessel position, speed, and winch activity every ten seconds.

Fishing tracks

In line with the methodology used in (Hintzen et al., 2012), we have recreated fishing tracks based on the satellite recordings. When available, we used BB data, second priority was AIS data, but otherwise VMS data was used. We interpolated the recordings to every second (Hintzen et al., 2010), and gear-specific speed profiles were used to determine if a vessel was fishing (Jennings and Lee, 2011). Then, the swept area was subsequently calculated by combining the positions identified as 'fishing' with the width of the gear deployed.

Demersal seines, however, operate in a different way that does not allow for a similar calculation (Eigaard et al., 2016). From an anchor point, the vessel sails a circle while setting the gear consisting of a net with two long ropes attached to either side. When the vessel reaches the anchor point again, it starts hauling both ropes, which herd the fish into the net, while the net tightens and eventually closes (Figure 2.2.1A). The process of determining the footprint of demersal seines followed a two-step procedure; whenever AIS data were available and characteristic teardrop shapes were observed in the fishing tracks, these teardrop-shaped areas were classified as fished (Figure 2.2.1B). Whenever AIS data were insufficient, VMS-based fishing tracks were used to determine anchor points, and a circle with a fixed diameter was allocated to each anchor point as the swept area (Figure 2.2.1C), resulting in a cruder positioning of the actual gear footprint.

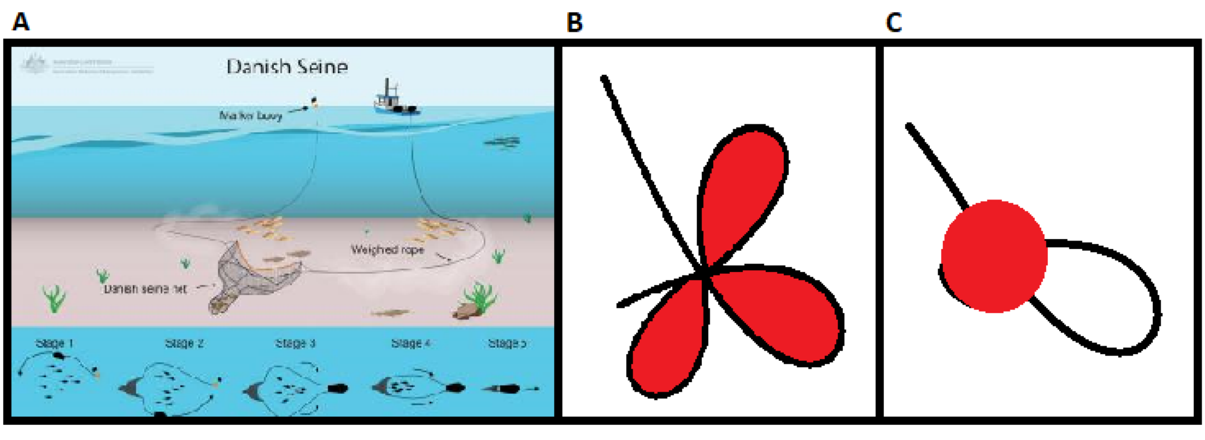

Figure 2.2.1. Danish anchor seine fishery operation (A), AIS-based process of determining the footprint of Danish seines (B), and VMS-based approach for determining the footprint of Danish seines (C).

Results

The addition of the more detailed AIS and BB monitoring data on top of the regular VMS data, and the inclusion of the new methodology for calculating the gear-footprint of Danish seines allowed for a more exact determination of the fisheries footprint. These are then processed using the standardized estimation method for fishing pressure maps and indicators, which resulted in the production of Swept Area Ratio (SAR) maps with a grid cell resolution of 100 x 100 meters for the total Danish fishery with mobile bottom-contacting gears in the Danish EEZ (Figure 2.2.2). This methodology is based on a gridded representation of the fishing intensity, for which the ratio between Swept Area and surface area (here: $0.01km^2$) is determined for each grid cell. A ratio over 1 means that the entire surface of the grid cell is generally fished more than once a year.

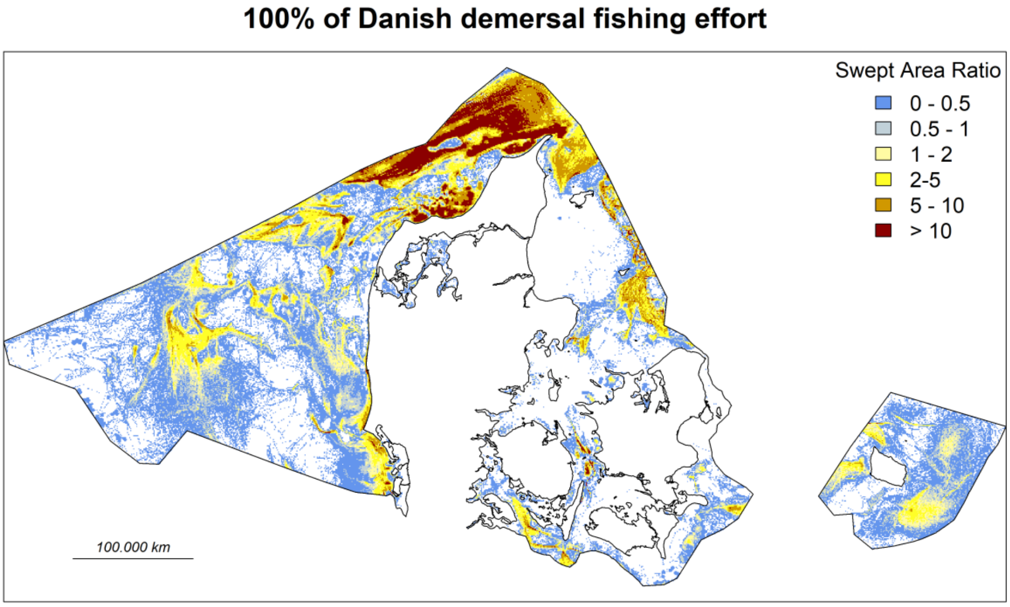

Figure 2.2.2. Map of fishing pressure of the total Danish fishery in the Danish EEZ with mobile bottom-contacting gears in the six-year period from 2015 to 2020. Fishing pressure is calculated and displayed as average annual swept area ratios (SARs) in grid cells of a 100x100 meters resolution.

Discussion

This methodological advancement has substantial implications for a better monitoring and management of the benthic pressure and impact from fisheries, as scale has an enormous importance for the correct estimation of fishing pressure and impact indicators. As an example, Amoroso et al. (2018) demonstrated that different geographical grid cell resolutions resulted in a substantial difference of overall fishing impact estimates. At a resolution of 0.5 ° x 0.5 ° longitude x latitude degrees, it is estimated that 48% of the seabed is affected by bottom trawling. At a resolution of 0.01 ° x 0.01 °, this estimate is only 9%. With the availability of the high-resolution fishing pressure maps developed in this project, the basis for a better management of the Danish fishing effort has improved significantly.

3 Gear specific depletion rates

3.1 Modelling of gear specific depletion rates

(Rijnsdorp et al. 2020, appendix A2)

Introduction

State of the art impact-assessment tools (ICES, 2020) require, among others, input data of gear depletion rates, and empirically based estimates are currently only available for four major gear groups (otter trawls, beam trawls, towed dredges, and hydraulic dredges) from a meta-analysis conducted by Hiddink et al. (2017). This resolution of depletion rates is too crude to allow specific assessments of the different fishing gears (metiers) within each of these overarching gear type groups. For instance, it precludes the comparison of the benthic impact from sandeel trawls and Danish seines, which are gears typically deployed on sandbanks in the Danish fishery. These two gears differ substantially in design and dimensions (Eigaard et al. 2016) and it is therefore logic to assume that they are quite different in their impacts on the benthic fauna during fishing operations. To enable a better resolution in the impact assessment of the different gear types embedded within the four overarching groups, theoretical depletion rates were estimated for a number of trawl gears at international workshops and with international experts contracted with this project (Professor. Adriaan D. Rijnsdorp, Wageningen University, Senior researcher Finbarr G. O'Neill, Marine Scotland, Senior researcher Jochen Depestele, ILVO, and Professor Ana Ivanovic, University of Aberdeen)

Materials and methods

Empirical estimates of the benthic biomass depletion rate associated with a single gear passage are available from a meta-analysis by Hiddink et al. (2017). Depletion rates were quantified for four overarching types of mobile bottom contacting gears: otter trawls (median: 0.06; 5–95% range: 0.02–0.16), beam trawls (median: 0.14; 5–95% range: 0.07–0.25), towed dredges (median: 0.20; 5–95% range: 0.13–0.30), and hydraulic dredges (median: 0.41; 5–95% range: 0.35–0.48). This meta-analysis did not consider the different otter trawl metiers, the demersal seines, and the brown shrimp beam trawl.

Because the depletion rate scales with the penetration depth of the gear (Hiddink et al., 2017), theoretical depletion rates of the different otter trawl metiers and seines were estimated using the width of gear elements that penetrate ≥ 2cm into the seafloor relative to the total gear width (termed subsurface ratio [SSR] *sensu* Eigaard et al., 2016). The subsurface ratio of the standard otter trawl was set equal to the mean subsurface ratio of all otter trawl metiers weighted by their swept area (subsurface ratio = 0.18) (Table 3.1). The depletion rate for each individual otter trawl metier *m* was then estimated by 0.06 x SSRm/0.18. The depletion rate of the SDN was set at the lowest depletion rate estimated of the otter trawls (OT_SPF: 0.009). Although the TBB_CRU is a beam trawl, the depletion rate was assumed to be similar to the reference otter trawl because it only has a light bobbin ground rope and no tickler chains.

Results

Theoretical depletion rates were estimated for ten different métiers representing the major mobile bottom-contacting gears (MBCGs) active in the North Sea and European waters (Table 3.1): one fishery using a dredge to target molluscs, mainly scallops (DRB_MOL); five métiers using an otter trawl to target crustaceans *Nephrops or Pandalus* (OT_CRU), demersal fish species (OT_DMF), *Nephrops* and benthic fish (OT_MIX_1), bentho-pelagic fish species (OT_MIX_2) and small pelagic fish species

(OT_SPF); two seine fisheries, Danish seiners (SDN) and fly shooters (SSC); and two beam trawl fisheries targeting brown shrimp (TBB_CRU) and flatfish (TBB_DMF).

Table 3.1. Metiers, Main gear type, main target species, subsurface ratio, and the depletion rates (d), feeding into the PD-based impact assessment framework. The subsurface ratio is calculated as the proportion of the gear footprint where gear components penetrate the seafloor by 2 cm [adapted from Eigaard et al. (2016, 2017)]. The displayed table is from Rijnsdorp et al. 2020 (Appendix 2).

Métier	Main gear type	Target species	Subsurface ratio	Depletion rate
DRB_MOL	Dredge	Scallops	1.000	0.200
OT_CRU[a]	Otter trawl	Nephrops, Pandalus, mixed fish	0.304	0.100
OT_DMF[b]	Otter trawl	Cod or plaice	0.078	0.026
OT_MIX_1	Otter trawl	Mixed fish	0.229	0.075
OT_MIX_2	Otter trawl	Mixed bentho-pelagic fish	0.220	0.073
OT_SPF	Otter trawl	Sprat or sandeel	0.028	0.009
SDN	Seine (Danish, anchor)	Plaice, cod	0.000	0.009[c]
SSC	Seine (Scottish, flyshoot)	Cod, haddock, flatfish	0.050	0.016
TBB_CRU	Beam trawl	Brown shrimp	0.522	0.060
TBB_DMF	Beam trawl	Flatfish	1.000	0.140

[a]Including OT_MIX_CRU and OT_MIX_CRU_DMF.
[b]Including OT_MIX_DMF_BEN.
[c]Set equal to lowest depletion rate of any otter trawl metiers.

Discussion

The objective of deriving theoretical depletion rates for the subgroups of the mobile bottom-contacting gears was to allow for a fishery-specific parameterization in the Population Dynamic (PD) model, which is central in the methodology advised by ICES for assessing the seafloor impact from bottom trawling (ICES, 2020). With this differentiation of depletion rates, moving from just four empirically established estimates for the overarching gear types (otter trawls, beam trawls, towed dredges and hydraulic dredges) (Hiddink et al. 2017) to the 10 depletion rates covering e.g. different otter trawl fisheries (Table 3.1) this objective has been met. Ideally, experimental work would be conducted to confirm or adjust the theoretically established depletion rates above, but this is a very resource demanding exercise, and not feasible for all metiers within the near future.

3.2 Quantifying the impact of a Danish Seine Gear

(Bromhall et al. 2021, Appendix A3)

Introduction

The Danish seine is a trawl gear that is thought to have a low physical seabed impact due to its relatively light weight and gear design (Buhl-Mortensen, 2013). While a number of studies have estimated the physical footprint of the Danish seine (Eigaard et al., 2016), and aspects such as gear performance (Noack et al., 2019), and sustainability (Dinesen et al., 2018), relatively little is known of the direct ecological effects of the Danish seine on seabed macrofauna.

The aim of this study was to quantify the impact of the Danish seine to benthic macrofauna in sandy habitats, where most of their effort is directed to. Previous studies have shown that the removal of fauna from a single pass of a fishing gear can be relatively minor, but the cumulative effect can be substantial (Collie et al., 1997, Burridge et al., 2003). Therefore, we also tested whether cumulative impacts of the Danish seine increased the depletion of benthic macrofauna by comparing the results of single and multiple hauls. This was done using a BACI experimental design (Before-After-Control-Impact) at two sandy locations in the North of Jutland, Denmark, using a commercial Danish seiner (Fig 3.2.1).

Material and methods

Data collection

The Danish seine footprint is heterogeneous whereby 99% is impacted by the lighter seine ropes, and 1 % by the relatively heavier ground gear and net (Noack et al. 2019). Therefore, to improve the accuracy of our depletion estimates, we applied targeted sampling within the areas impacted by two different gear components. We measured the impact of the Danish seine on three whole community indicators: density, species richness and biomass. These indicators were divided into the large component (>4 mm) and the pooled community (>1 mm) using two sieves, as the large component (>4 mm) has previously been shown to be a more sensitive indicator of trawling impact (McLaverty et al., 2020). In addition, we compared the depletion of these benthic indicators after a single and multiple hauls.

Data analysis

Bayesian models were used to assess the effect of the Danish seine on benthic infaunal indicators. We computed BACI ratios following the protocol described in Conner et al. (2016). To support whether significant BACI interactions were likely to have been caused by fishing, we additionally calculated CI contribution and CI divergence (Chevalier et al., 2019).

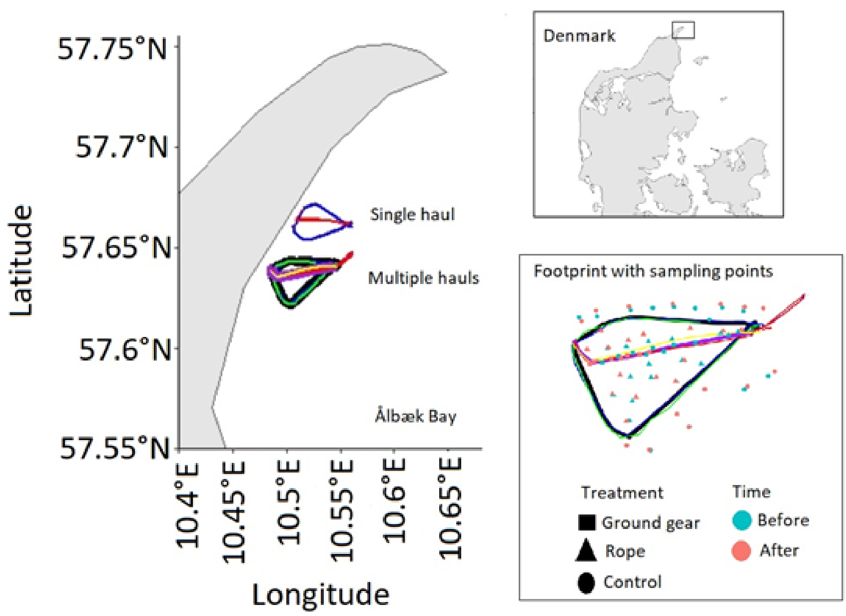

Figure 3.2.1. Map of the study sites in Ålbæk Bay showing the gear footprints at each site. The inset shows an example of the sampling points with respect to the fisheries footprint.

Results

Rope single haul

After a single haul of the Danish seine rope there was a mean loss in the pooled species richness (-3 %) and a mean loss in the density (-11 %), biomass (-8 %) and species richness (-9 %) of the large fauna (4 mm)(Table 3.2, Figure 3.2.2). However, for all indicators zero was included in the 95% credible interval (CI), indicative of no 'significant' effect.

Rope multiple hauls
After multiple hauls of the Danish seine rope, there was a mean loss in all of the whole community indicators, except the large taxa species richness (Table 3.2; Figure 3.2.2). The depletion ranged between –4% and -13% but included zero in the 95% credible interval.

Ground gear single haul
The pooled density and large taxa species richness and biomass increased after trawling. The increase was estimated to be 24 %, 10 % and 11 % respectively (Table 3.2; Figure 3.2.2) but included zero in the 95% credible interval.

Ground gear multiple hauls
After multiple hauls of the ground gear, the density and species richness (both the large and pooled components) and the biomass of the large taxa increased relative to the control (Table 3.2; Figure 3.2.2). These mean increases ranged from a 4 % increase in species richness (pooled) to a 132 % increase in biomass. There was a 97.6 % probability that the pooled density increased and a 92 % probability that biomass increased.

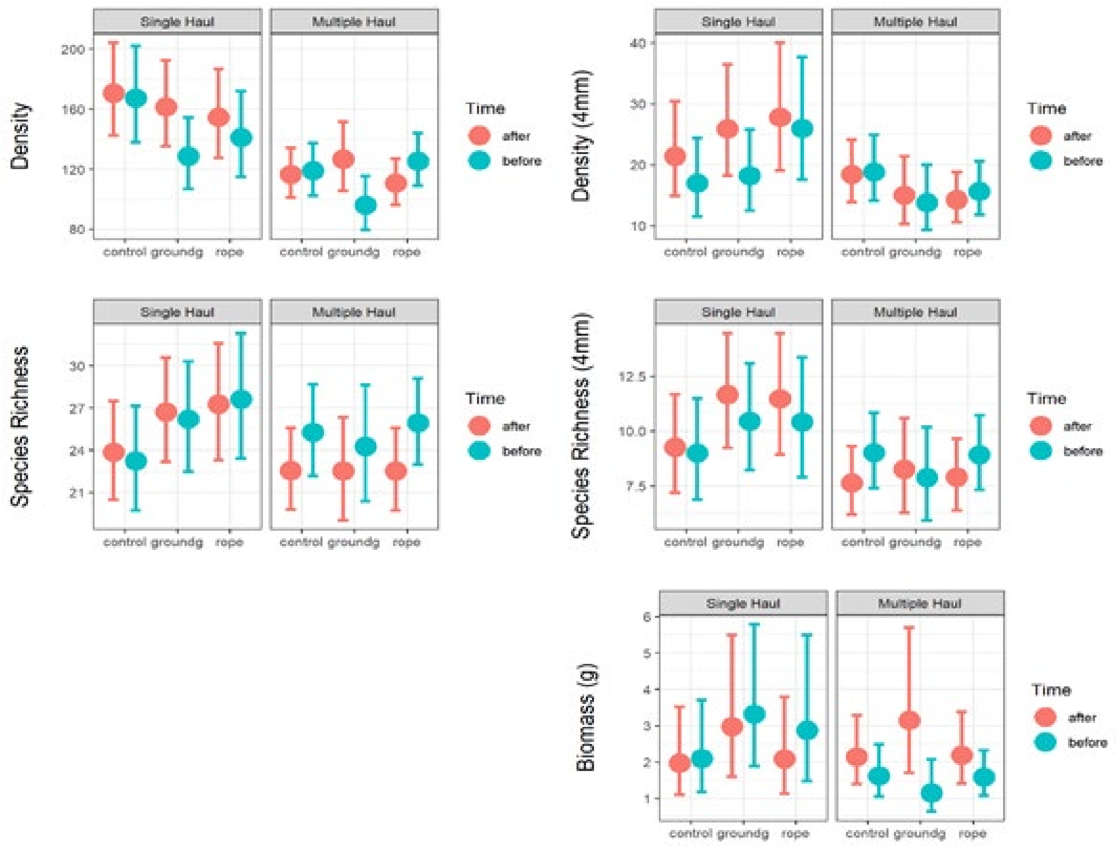

Figure 3.2.2: The mean response 'Before' and 'After' experimental fishing (+/-95% credible interval) separated by the control, ground gear, and rope sites subjected to single and multiple hauls for the density (top), the species richness (middle), and biomass (bottom) for the pooled community (left) and the large fauna component (right).

Whole gear depletion rate
We combined the four depletion rates (single rope, single ground gear, multiple-rope, and multiple ground gear) into a single, overall depletion rate for the entire gear, based on the pooled density values. For this, we first averaged the depletion rates of the single and multiple hauls, for rope and ground gear separately. We then determined the overall depletion rate by summing the rope and ground gear depletion rates, considering their general ratio in the footprint (Noack et al., 2019). This resulted in a gear-specific depletion rate of 0.0069 for the Danish seine.

Table 3.2. Summary of the mean response size with the 95% Bayesian Credible Interval (CI), the probability of a negative effect of fishing (i.e., the probability of negative effect of fishing relative to the control effect), the probability of a positive CI contribution (i.e. Absolute change in impact sites was larger than control), and the probability of CI divergence (i.e. sites became more dissimilar after the fishing treatment).

	Variable	No. Hauls	Mean response (95 % CI)		Prob. of negative fishing effects	Prob. of a positive CI contribution	Prob. of CI divergence
Rope	Density (P)	Single	+8%	(-32% to 52%)	35%	54%	39%
		Multiple	-10%	(-43% to 15%)	80%	72%	49%
	Density (4 mm)	Single	-11%	(-32% to 52%)	69%	51%	38%
		Multiple	-4%	(-43% to 15%)	61%	47%	58%
	Species Richness (P)	Single	-3%	(-27% to 25%)	62%	57%	39%
		Multiple	-3%	(-22% to 20%)	60%	60%	48%
	Species Richness (4 mm)	Single	-9%	(-31% to 65%)	38%	62%	62%
		Multiple	+6%	(-26% to 48%)	40%	41%	51%
	Biomass (4 mm)	Single	-8%	(-76% to 150%)	67%	65%	38%
		Multiple	-13%	(-55% to 140%)	46%	52%	61%
Ground gear	Density (P)	Single	+24%	(-14% to 72%)	11%	79%	16%
		Multiple	+36%	(3% to 81%)	3%	93%	25%
	Density (4 mm)	Single	-8%	(-112% to -66%)	65%	68%	66%
		Multiple	+16%	(-61% to 99%)	36%	53%	38%
	Species Richness (P)	Single	-1%	(-24% to 28%)	52%	54%	48%
		Multiple	+4%	-21% to 36%	38%	43%	44%
	Species Richness (4 mm)	Single	+10%	-29% to 63%	36%	62%	66%
		Multiple	+20%	-20% to 89%	16%	39%	41%
	Biomass (4 mm)	Single	+11%	-69% to 185%	54%	65%	45%
		Multiple	+132%	-24% to 460%	8%	90%	69%

Discussion
The Danish seine has been considered to be an 'environmentally friendly' fishing method due to its lightweight gear, lack of penetrating gear components (doors/shoes/weights/clumps/tickler chains), and low fuel consumption (Suuronen et al., 2012; Eigaard et al., 2016; Noack et al., 2017; Dinesen et al., 2018). In terms of its ecological impact, we found that its depletion rate of the benthic macrofaunal community was generally low. We were able to establish that there were differential effects between the two gear components, and unexpectedly, that the greatest fauna reduction occurred within the area disturbed by the seine ropes.

The penetration of the Danish seine ropes is expected to inflict a surface impact similar to the sweeps and bridles from an otter trawl (sediment penetration depth 0-2 cm) (Eigaard et al, 2016). It was therefore unexpected that the ropes inflicted the largest impact on the benthic community indicators. No consistent effects of the benthic indicators were detected, both after a single haul and after multiple hauls. There was either relatively low certainty about whether they were depleted (low probability of negative fishing effects), or they were not supported to be related to fishing (CI contribution and CI distribution probabilities close to 50%). These results indicate that the impact of the ropes was very small, which makes it difficult to detect the effect. This is in line with observations of the Danish seine ropes on sandy sediments, in which the impact is described as having a 'smoothing effect with no pronounced changes to the seafloor' (Noack et al, 2019).

Counter intuitively, most benthic community indicators showed a positive effect of the Danish seine ground gear. Previous studies have shown that density increases after trawling disturbance are often due to increases in scavenging taxa (Kaiser and Spencer, 1994; Ramsay et al, 1997; Groenewold and Fond 2000). However, the experimental set-up allowed potential scavengers to disperse, by delaying sampling with 72 hours after fishing (Groenewold and Fond, 2000). Furthermore, the attracted scavengers generally are not a part of the macro-infaunal component that we studied here (Bremner et al., 2003). The observed positive effects of the ground gear could, based on CI contribution and CI divergence, not be related to the fishing treatment. We therefore conclude that we did not find significant impact from the ground gear.

3.3 Quantifying the impact of a Sandeel otter trawl

(Bromhall et al. 2021, Appendix A4)

Introduction

The Dogger Bank is a 17,600 km^2 sandbank located in the southern central North Sea (Stride, 1959). It has always been an important feature for commercial fisheries, including for cod, haddock, plaice, sole, dab and sandeel. For Denmark, the Dogger Bank supports the countries' largest fishery, the sandeel fishery, with a value of half a billion Danish kroner. The Dogger Bank is located within the Exclusive Economic Zones (EEZ) of the UK, Germany, the Netherlands and Denmark, whereby the UK, the Netherlands, and Germany designated the Dogger Bank under the Habitats Directive as a part of the Natura 2000 network of protected areas. In the designation process, the Netherlands and Germany identified fishing with bottom contacting gears as one of the greatest threats to the Dogger Bank habitat. At the moment, fishing with bottom contacting gear is still allowed at the Dogger Bank, with its environmental status is monitored on an annual basis.

Gear modifications may offer an alternative strategy to spatial closures, whereby fisheries managers may allow fishing to continue with gears that have a reduced physical seabed impact (McConnaughey et al., 2020). The aim of this study was to assess whether gear modification could reduce the benthic depletion from the sandeel fishery. Here, experimental trawling was conducted with a conventional sandeel trawl and a modified (Dyneema) sandeel trawl to directly compare the benthic depletion rates.

Materials and methods

A modified sandeel otter trawl was designed to reduce the physical impact to the seabed. The heavy otter doors were replaced with lighter pelagic doors and the sweeps and part of the net were replaced with lightweight Dyneema material (Figure 3.3.1).

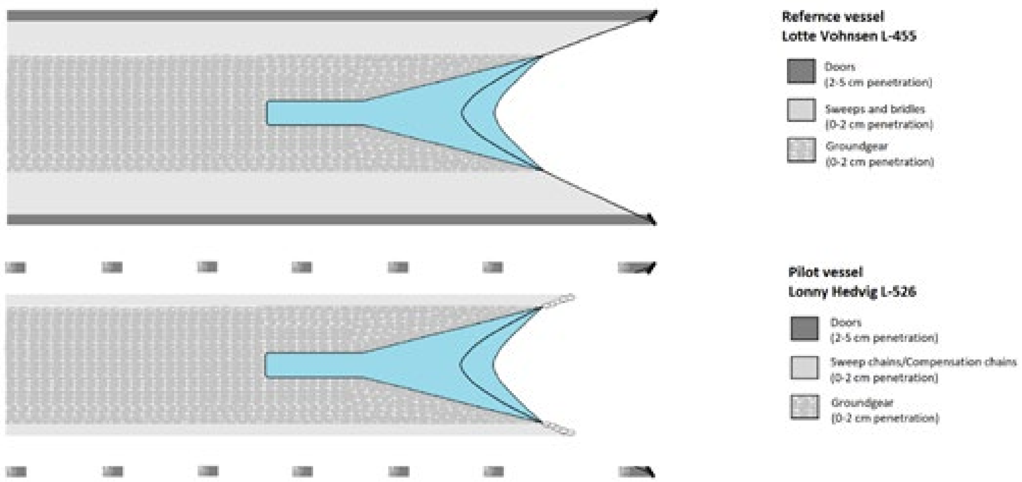

Figure 3.3.1: A conceptual footprint of the conventional sandeel trawl (top) and the modified Dyneema sandeel trawl (bottom).

To assess the impact from the modified sandeel trawl, relative to the conventional sandeel trawl, we determined benthic macrofaunal indicators (community biomass and species richness) after experimental trawling. The study took place on Dogger Bank in the Central North Sea (Figure 3.3.2, left) and the study site was a 3.6 nm^2 area located inside the Dutch EEZ. The experimentally fished sites were subsequently compared to un-impacted nearby control locations to determine differences in depletion rates (Figure 3.3.2, right).

Benthic infaunal samples were taken in June 2013 and 2014 after experimental trawling using a Van Veen grab (0.1m^2). The treatments consisted of a transect, within which there were four stations where five replicates were taken per station (N = 20 per treatment). This was repeated in 2013 and 2014 (N = 60 per year). Benthic faunal depletion was measured by comparing benthic faunal metrics from the trawled treatments with the non-impacted control treatment.

Side scan sonar (SSS) transects were taken using a Edgetech 4125 SAR, 600kHz combined with an AirMar PB150 Weather Station for geographical positioning. Scanning used a low frequency (600kHz) with a viewing width of 120 m either side and 10m above the seabed. SSS transects were taken before and after trawling in 2013 and 2014 at each of the three treatment locations.

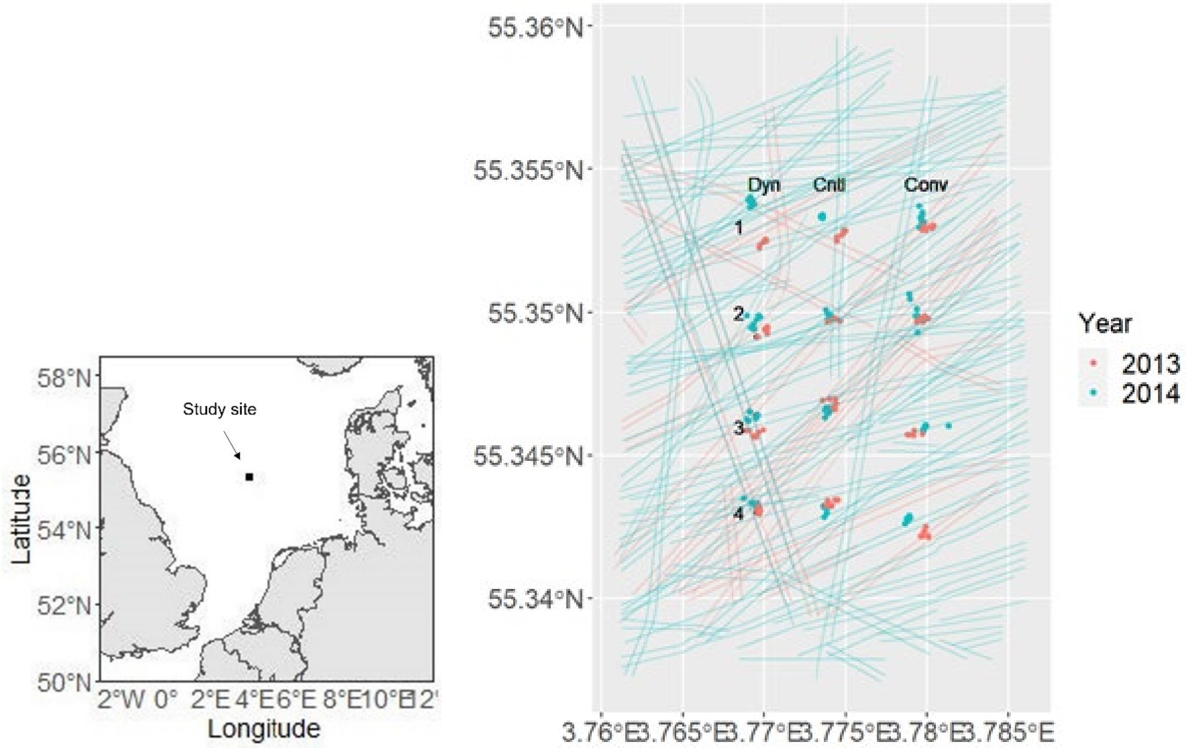

Figure 3.3.2: Left: location of study site in the North Sea. Right: Side Scan Sonar images identified trawl tracks (lines) at the study site each year (pink lines for 2013 and blue for 2014). The dots show the sample points each year ('Dyn' = area/transect with samples impacted from modified trawl, 'Cntl' = area/transect with control samples, and 'Conv' = transect/area with samples impacted from conventional trawl).

Results

Side scan sonar images showed there were a number of trawling tracks visible at the study site prior to our experimental trawling (Figure 3.3.2). Nonetheless, the conventional trawl site had a significant lower macrofaunal biomass than the control site (Figure 3.3.3A), which was not observed for the modified trawl site. Species richness did not show any difference between sites (Figure 3.3.3B).

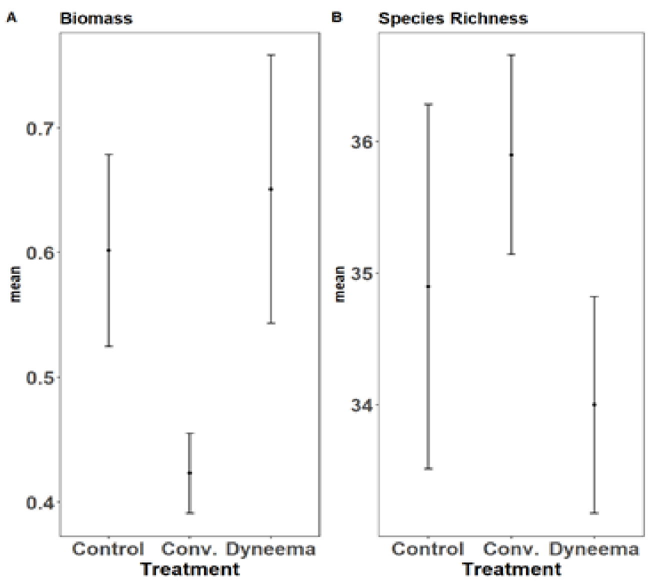

Figure 3.3.3: Mean benthic faunal (A) biomass and (B) species richness for the control, conventional trawl ('Conv.') and modified sandeel trawl (Dyneema) sites.

Discussion

Our analyses showed that there was a significant decline in benthic faunal biomass after impact from the conventional sandeel trawl, whereas no depletion of faunal biomass was found from the modified trawl. These results suggest that switching to a modified sandeel trawl could reduce the benthic impact from the sandeel fishery. However, the depletion rates observed in our study are likely affected by the background trawling at the sampling sites. Generally, depletion of benthic fauna is larger in habitats where fishing has been absent or negligible for ten years prior to impact (Sciberras et al., 2018), indicating that our estimates are likely conservative.

Here, the benthic depletion for the conventional sandeel trawl was estimated as -30 %. This is relatively high, being comparable to the depletion rates of towed (-20 %) and hydraulic dredges (-41 %; Hiddink et al., 2017). However, most gears have a wide range of depletion rates reported in different studies (Sciberras et al. 2018). In addition, depletion rates for trawl gears are estimated based on the entire footprint (e.g. Eigaard et al., 2016; Hiddink et al., 2017), whereas our estimates come from within the area impacted by the deeper penetrating ground gear and net, which constitutes only ~37% of the gear footprint. Taking this into account, the depletion rate would be ~-11 % (i.e., 0.37 * -0.3 = -0.11). This is more similar to the depletion rate estimate for the overarching otter trawl gear (-6%) reported in (Hiddink et al. 2017). The inclusion of the remaining gear components (sweeps, trawl doors) is likely to result in a lower depletion rate, as the high-impact doors only comprise approx. 3% of the overall footprint, while the low-impact sweeps constitute approx. 60% of the footprint (Valdemarsen et al., 2007).

3.4 Quantifying the benthic impact of a light mussel dredge

(Bromhall et al. 2021, Appendix A5)

Introduction

Dredges are relatively small, compact, and heavy gears, which are dragged along the seabed to harvest bivalves (Eigaard et al., 2016). They have a relatively high impact on the benthic community and seabed. A modified, lighter dredge gear has been developed and put to use since 2012, which has been shown to cause significantly less physical impact to the seabed (Frandsen et al., 2015). The direct impact to the benthic macrofauna, however, is less well understood and found to be highly dependent on local environmental conditions (McLaverty et al., 2020).

A large proportion of the Danish fishery for the blue mussel, *Mytilus edulis* (Linnaeus, 1758), takes place in the Limfjord, in the North of Jutland, Denmark. This area is highly affected by eutrophication, which has had a positive effect on the blue mussel population, by supporting high biomasses and rapid growth (Dolmer et al., 2001). Eutrophication effects on the benthic community are well understood and generally result in an increase of opportunistic species (Pearson and Rosenberg, 1978). However, there is a paucity of research regarding the effects of trawling in organically enriched areas.

The aim of this study was to investigate the direct (dredge track) and indirect (adjacent to the dredge track) effects of the light dredge on *M. edulis* associated macrofauna in a highly eutrophic system. The study represents the first experimental dredging study on benthic macrofauna using this type of fishing gear.

Material and methods

Data collection

We assessed the impact of the light dredge on the macrofauna associated with *M. edulis* beds, using a Before-After Control-Impact (BACI) experimental design. For this, we conducted experimental dredging with a commercial light dredge in an area that was unfished for four years prior (fished site). We compared the macrofaunal density, species richness and biomass from the fished site with an area where no dredging occurred (control site). We specifically looked at the effect of dredging within the dredge track (direct) and an area immediately adjacent to the dredge track (within 5 m; indirect), as well as the short-term recovery of the site after four months.

Results

The effect of dredging on the macrofauna associated with blue mussels beds was most pronounced in the dredge track (Figure 3.4.1). Macrofaunal density and species richness were significantly reduced after dredging in the dredge track, but not adjacent to the track. Nevertheless, the area adjacent to the track also showed a significant BACI interaction. This interaction is likely to be caused by the strong increase of all three macrofaunal indicators at the control site, and should therefore be interpreted with caution.

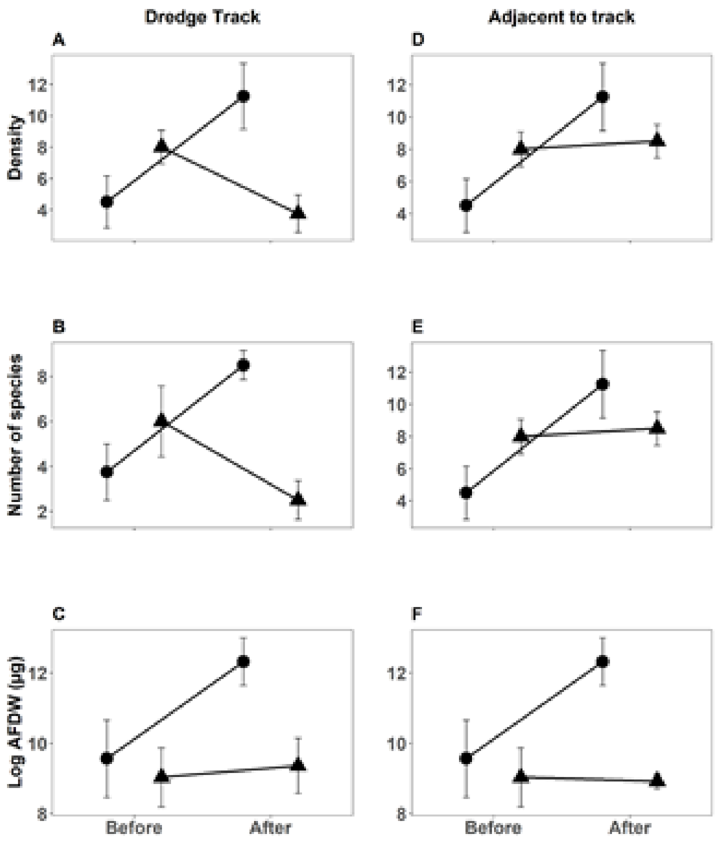

Figure 3.4.1: The mean (±SE) macrofaunal density (A, D), species richness (B, E), and biomass (C, F) before and after dredging in the control site (circles) and fished site (triangles), for the samples within the dredge track (left) and those adjacent to the dredge track (right).

Short-term effect

Four months after dredging, the macrofauna density appeared to have recovered, as the control and the fished sites showed equal densities (Figure 3.3.2). The observed increase in density was largely due to one opportunistic polychaete worm, *Capitella capitata* (Fabricius, 1780), which made up 81%

and 60% of the macrofaunal density in the fished and control site respectively. Species richness, on the other hand, remained significantly lower at the fished site compared to the control site four months after dredging (Figure 3.4.2).

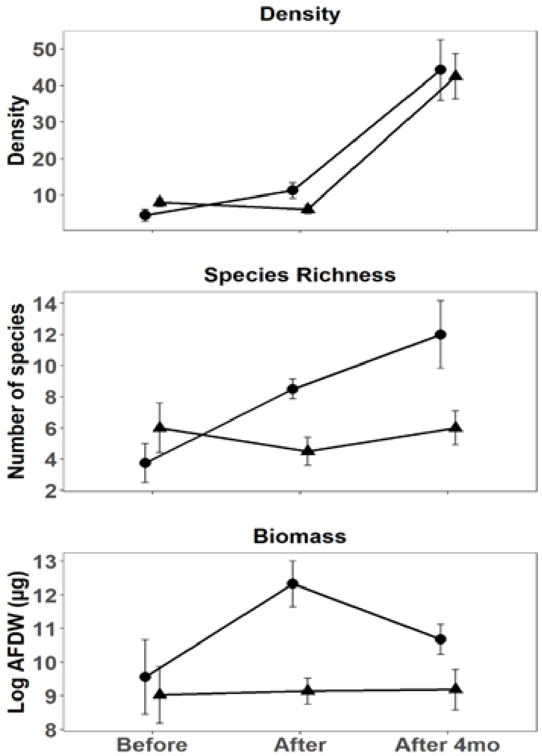

Figure 3.4.2: The difference in macrofaunal density, species richness, biomass (±SE) before dredging, after dredging, and four months after dredging in the control site (circles) and fished site (triangles).

Discussion

These results provide a first estimate of the depletion of benthic macrofauna and its subsequent recovery after fishing with the modified dredging gear used in the Danish mussel fishery.

Direct and indirect effects of the light dredge

Our observations of declined density and species richness after trawling are congruent with many other experimental studies (Hall et al., 1990; Thrush et al., 1995; Dolmer et al., 2001; Carvalho et al., 2011). This decline is thought to be caused by the direct physical contact with the gear, with the largest impact expected from the metal frame (Rumohr and Krost, 1991; Eigaard et al., 2016). We observed almost no difference in density and species richness before and after the experimental trawling in the area adjacent to the trawling. Nevertheless, this area showed a significant BACI interaction, indicating a potential effect of the experimental fishing. This interaction is probably due to the steep increase of density and species richness at the control site. However, the fact that the area adjacent to the trawl path did not show a similar increase could indicate adverse effects of the experimental fishing. Potentially, the fishing can cause for sediments to mobilize, which could lead to higher sediment accumulation near the fished path with adverse effects for the benthic community present (Miller et al., 2002; Pastor et al, 2020). Alternatively, the patchiness of mussel beds could have affected our estimates of macrofaunal density and species richness, as smaller beds usually have lower density and richness (Norling and Kautsky, 2007; McLaverty et al., 2020), despite our efforts to control for mussel bed size in the sampling.

Short-term effects of the light dredge

Four months after trawling, both the fished and the control site showed an equal density of macrofauna, suggesting a full recovery of the fished site. The observed macrofaunal densities had increased tremendously since the experimental fishing, probably as the result of the seasonal recruitment that occurs at the onset of spring (Peterson and Jensen, 1911). However, this new community was dominated by the opportunistic polychaete *Capitella capitata*, which thrives in eutrophic conditions as it can tolerate hypoxic sediments (Macleod et al., 2008), expresses opportunistic reproduction (Quian and Chai, 1994), and rapidly colonises defaunated patches (Bolam and Fernandes, 2002). Species richness of the fished site, on the other hand, remained low after four months. Yet, species richness was slowly increasing at the fished site, which suggest that recovery was in progress. These observations may indicate that macrofaunal density is a poor indicator of the short-term effects of dredging, especially in eutrophic systems.

4 Fishery impacts

4.1 Modelling sediment mobilization by bottom trawls

(Rijnsdorp et al. 2021, Appendix A6)

Introduction

The seafloor is inhabited by a large diversity of organisms and plays an important role in the decomposition of organic material and the recycling of nutrients to the overlying water. Bottom trawling impacts seafloor habitats and communities and disturbs bio-geochemical processes by mixing and mobilizing the fine sediment. To support sustainable fisheries management, methods have been developed to quantify the trawling impacts on the community biomass and composition. However, a method to quantify the mobilization of sediments by different bottom trawls is lacking. The work presented here attempts to fill this gap by adding an urgently needed tool to the box of trawling impact assessment methodologies.

Materials and methods

The method developed enables scientists to estimate the amount of sediment mobilized by bottom trawls based on the dimensions of the bottom trawl components and the silt content of the fishing grounds. It builds on the knowledge that the amount of sediment mobilized is a function of the hydrodynamic drag of the trawl and the percentage of fine particles of the sediment (O'Neill and Ivanovic, 2016; O'Neill and Summerbell, 2018). For this, the bottom trawls are separated into its main components, and the hydrodynamic drag of each component is estimated from its shape, frontal surface area and speed. Combined with the percentage of fine particles of the sediment, this allows for an estimation of the compound-specific quantity of mobilized sediment. These are then summed up to estimate the quantity of mobilized sediment by the whole gear.

Results

The method is applied to the Dutch beam trawl fishery for flatfish, using multiple types of traditional tickler chain beam trawls and electric pulse trawls (Figure 4.1.1.). It shows that small vessels (< 221 kW) typically mobilize between 4.2 to 4.6 kg per m^2 of swept area, independent of the gear type used (Pulse versus tickler chain gears). For the larger vessels (> 221 kW), the gear type is relevant, and the vessels with tickler chains mobilize on average more sediment per swept area than the pulse gears (Tickler chains: 7-9.4 kg/m^2; Pulse: 4.6 – 5.6 kg/m^2; Figure 4.1.2). This difference could easily be explained by the differences in penetration depth of the gears. However, it should be noted that the spatial distribution of the different fishing gears, and with that the percentage of fine particles in the fished sediment, could also contribute to the observed differences. A comparison with in situ measurements from the literature showed that our approach provides reasonable estimates of the quantity of mobilized sediment by different gears.

Figure 4.1.1. A conventional Sumwing beam trawl with tickler chains (left) and a Pulse wing with electrodes (right) used in the Dutch beam trawl fishery for sole in the North Sea.

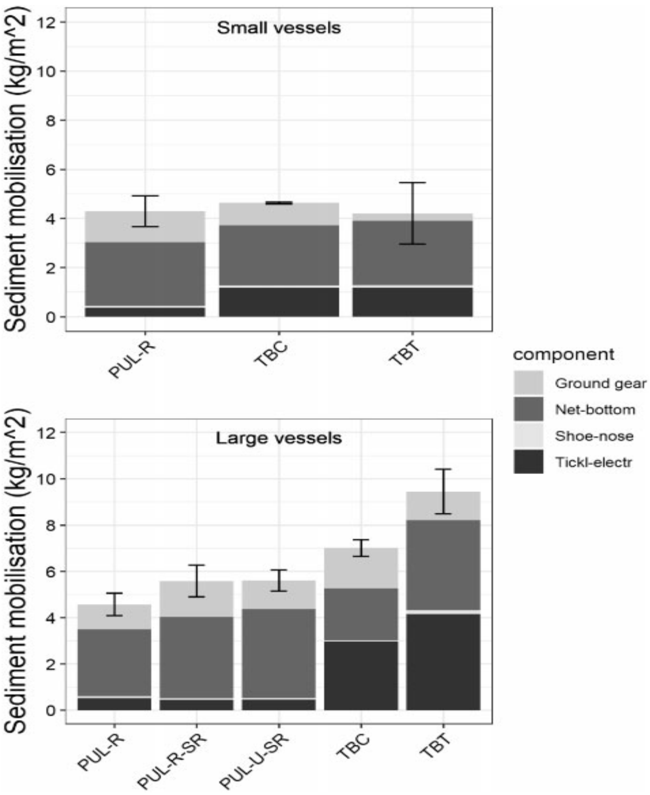

Figure 4.1.2. Sediment mobilization (kg/m^2) of the gear components of three different pulse trawls (PUL-R, PUL-R-SR, PUL-U-SR), a conventional chain mat beam trawl (TBC), and tickler chain beam trawl (TBT) of small vessels (221 kW; top panel) and large vessels (>221 kW; bottom panel). The bars show the standard deviation of the sediment mobilization of the whole gear.

Discussion

With the development and validation of this compound-based method for quantifying drag and sediment mobilization, we have provided policy-makers and fisheries managers with a quantitative means to assess the physical impacts of different fishing gears and fishing methods across sediment types. The method allows ranking of different gears in terms of their impact, but could also be used to directly compare fisheries impact with the physical impact of natural events (such as storms and tides) and of other uses of the seabed (such as mineral extraction and mining). Accordingly, it will permit a rationale and objective approach to fulfil the requirements of the Common Fisheries Policy and the Marine Strategy Framework Directive. The method presented by the authors could additionally be used to provide estimates of trawling-induced sediment mobilization for mechanistic models of the biogeochemical cycle and hence, improve understanding of trawling impacts on these processes. Furthermore, the compound-based estimation of the hydrodynamic drag will provide a better understanding of the forces required to tow a trawl gear across the seabed and contribute to the development of more fuel-efficient gears that will reduce CO_2 and NO_x emissions from the fishing industry.

4.2 Fishery-specific impacts on the benthic communities on sandbanks

Introduction

An accurate assessment of bottom trawling impact on the seafloor requires a good spatial knowledge of both the fisheries and the seafloor communities (Eigaard *et al.*, 2016, 2017; van der Reijden *et al.*, 2018). The PD (Population Dynamic) assessment framework, developed by ICES WGFBIT, accounts for the differences in gear types and community sensitivity (ICES, 2018; Rijnsdorp *et al.*, 2020). The model determines the Relative Benthic State (RBS) based on the depletion of the community by combining gear-specific depletion rates (Hiddink *et al.*, 2017; Sciberras *et al.*, 2018) with fishing intensity distributions, and recovery estimates from a logistic growth model based on the longevity composition of the local community (Rijnsdorp *et al.*, 2018; Hiddink *et al.*, 2019).

With the assessment framework in place[1], the PD model can be used to evaluate fishing impact for specific regions, or specific types of habitats. However, this does require to include input data at a spatial resolution and at a level of detail that allow the framework to provide information at the relevant scale and accuracy. Here, we have applied this model to estimate the benthic impacts of the Danish demersal fisheries in sandbank habitats. To provide the most accurate estimates, we have drastically increased the spatial resolution from the fishing intensity distributions, included a new, empirical depletion rate for the sandbank-directed Danish seine fishing gear, and accounted for multiple redefined delineations of the sandbank habitat type.

Materials and methods

Sandbank habitat

Sandbanks are included in the Habitats Directive Annex 1 as "*sandbanks which are slightly covered by sea water all the time*". The definition of this habitat type, however, is rather vague: *"Sublittoral sandbanks, permanently submerged. Water depth is seldom more than 20 m below Chart Datum. Non-vegetated sandbanks or sandbanks with vegetation belonging to the Zosteretum marinae and Cymodoceion nodosae."* (Commission, 1992). We therefore defined three different levels of sandbank habitats, each with a little more detail, based on bathymetry (Figure 4.2.1A) and MSFD-Broad Habitat Type (MSFD-BHT; Figure 4.2.1B) in the Greater North Sea region. The first level (SB1) covers all areas with a sandy sediment type under the MSFD-BHT definition, and that are shallower than 50m (Figure 4.2.1C).

The second (SB2) and third (SB3) sandbank habitat definitions also include the 'bank' aspect of the sandbank habitats, a local elevation of the seafloor. This elevation is determined by the application of Bathymetric Position Indices (BPI), which represent the relative depth of a location in relation to their surroundings at different scales (Verfaillie *et al.*, 2007). We have taken the BPIs on the 5, 10 and 50 km surroundings from (van der Reijden *et al.*, 2021). For the SB2 definition, we have included all locations qualified in the SB1 habitat, which were elevated in either the 5, 10, or 50km BPI (Figure

[1] https://github.com/ices-eg/FBIT

4.2.1D). For the SB3 habitat, we included all locations qualified in the SB1 habitat, which were elevated in either the 5 or 10 km BPI (Figure 4.2.1E).

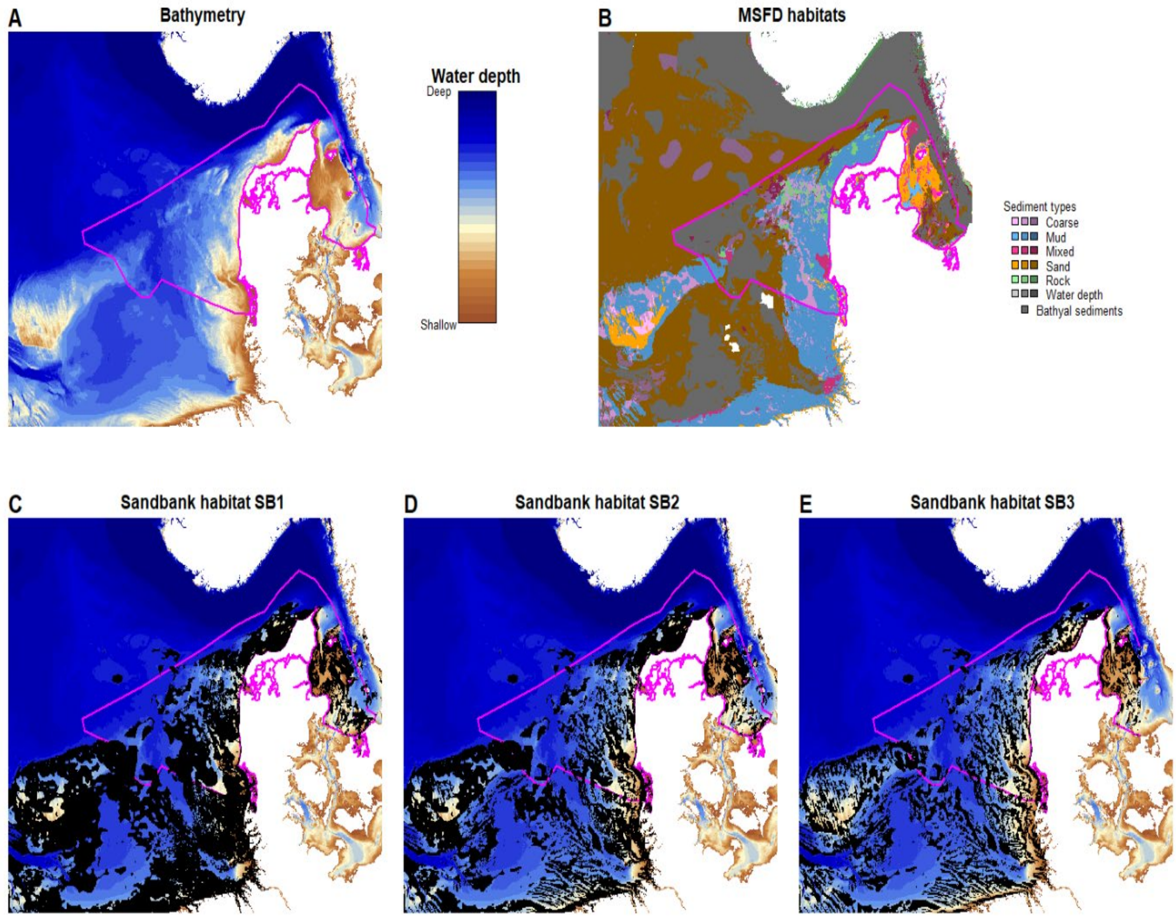

Figure 4.2.1. Sandbank habitat definitions and their input data. Bathymetry (A) and MSFD habitat Broad Habitat Types (B) represent the input for all three sandbank habitats (C-E), which are depicted in black. The Danish EEZ is shown in pink.

Fisheries data

We included the high-resolution fishing effort data that resulted from section 2.2; i.e. the annual Swept Area Ratio (SAR) at a resolution of 100 x 100 meter for the years 2018-2020. However, for the Danish seines (SDN_DMF) and the semi-pelagic otter trawlers (OT_SPF), we additionally looked at the catch composition as well, to enable identification of sandeel-directed fisheries (OT_SPF_TBS), remaining semi-pelagic trawling (OT_SPF_REM), and plaice-directed seines (SDN_DMF_RSP; Table 4.2.1). In this, OT_SPF_TBS has over 40% of their catch (in kg) comprised of sandeel (species of the family Ammodytidae), whereas SDN_DEM_RSP has more than 40% of plaice, *Pleuronectus platessa* Linnaeus, 1758, in their catch. For this analysis, we focus on those gear types that target the sandy habitats: TBB_CRU, OT_SPF_REM, OT_SPF_TBS, TBB_DMF, and SDN_DMF_RSP (Table 4.2.1, Figure 4.2.2).

Relative Benthic Status assessment

Depletion rates

Total depletion rates are the product of the gear-specific total Swept Area Ratio (SAR) with the gear-specific depletion estimate. Here, we used the depletion estimates (Table 4.1.2) from the theoretical modelling study described in section 3.1 (Rijnsdorp *et al.*, 2020), in combination with the new, empirical estimate for the Danish seine estimate as described in section 3.2.

Table 4.2.1. Fishing métiers and their fraction of fishing effort on the three sandbank habitats. Fractions over 25% are given in bold.

Sandbank habitat	Year	OT_CRU	TBB_CRU	OT_SPF_REM	OT_SPF_TBS	OT_DMF	OT_MIX	TBB_DMF	SDN_DMF_REM	SDN_DMF_RSP	SSC_DMF	DRB_MOL
SB1	2018	0,03	**0,78**	**0,41**	**0,47**	0,13	**0,26**	**0,38**	0,03	**0,56**	0	0,03
	2019	0,03	**0,76**	**0,47**	**0,68**	0,1	0,15	**0,29**	0,03	**0,56**	0	0,02
	2020	0,03	**0,81**	**0,46**	**0,75**	0,09	0,19	**0,28**	0,02	**0,47**	0,02	0,01
	Average	0,03	**0,78**	**0,45**	**0,63**	0,11	0,2	**0,32**	0,03	**0,53**	0,01	0,02
SB2	2018	0,02	**0,68**	0,25	**0,46**	0,11	0,15	**0,37**	0,03	**0,56**	0	0,03
	2019	0,02	**0,65**	**0,34**	**0,66**	0,09	0,07	**0,28**	0,03	**0,54**	0	0,02
	2020	0,02	**0,7**	**0,3**	**0,73**	0,07	0,09	**0,28**	0,02	**0,43**	0,01	0,01
	Average	0,02	**0,68**	**0,3**	**0,62**	0,09	0,1	**0,31**	0,03	**0,51**	0	0,02
SB3	2018	0,02	**0,51**	0,23	**0,42**	0,08	0,11	**0,31**	0,03	**0,42**	0	0,02
	2019	0,02	**0,54**	0,25	**0,6**	0,07	0,06	**0,26**	0,02	**0,39**	0	0,01
	2020	0,02	**0,53**	**0,27**	**0,67**	0,06	0,08	0,24	0,02	**0,29**	0,01	0
	Average	0,02	**0,53**	0,25	**0,56**	0,07	0,08	**0,27**	0,02	**0,37**	0	0,01

OT = Otter trawling, TBB = Beam trawling, SDN = Danish seine, SSC = Scottish seine, DRB = Dredges.
CRU = Crustaceans, SPF = semi-pelagic fisheries, REM= remaining, TBS = sandeel, MIX = mixture of demersal fish species and Norway lobster, DMF = Demersal fish species, RSP = Plaice, MOL = molluscs.

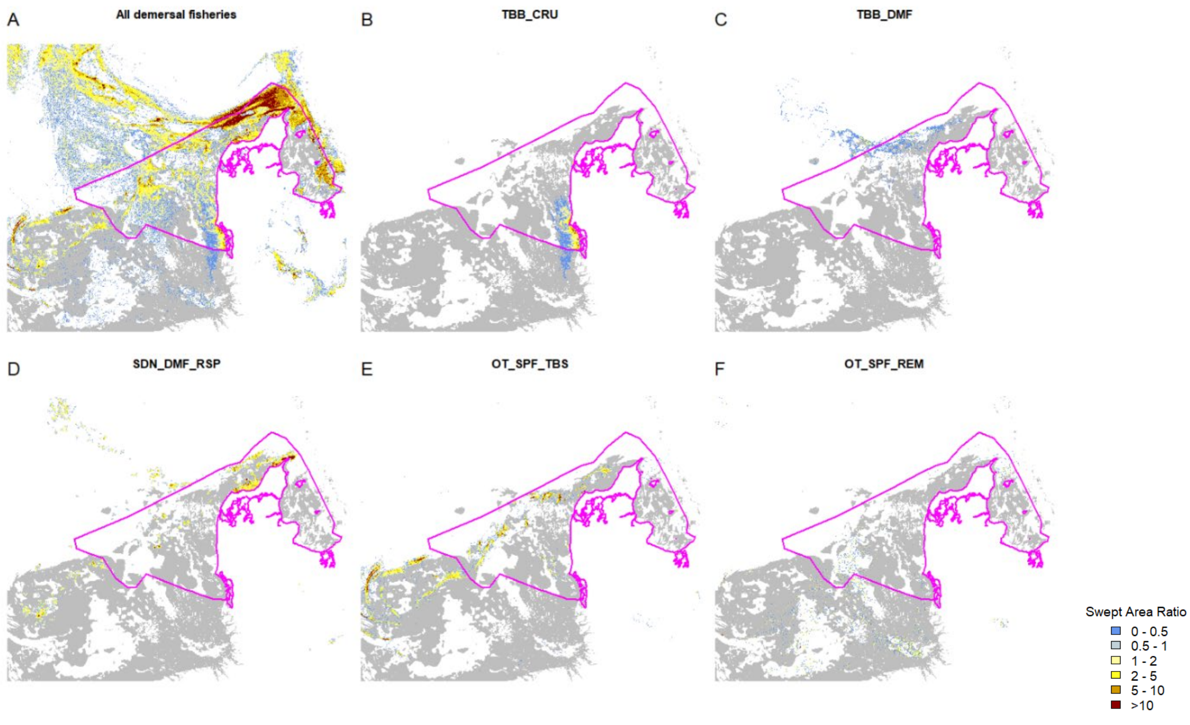

Figure 4.2.2. Fishing activity of all demersal fisheries (A) and sandbank-directed fisheries separately (B-F). Sandbank habitat SB1 is depicted in grey for comparison. Shown SAR represent the average annual SAR for 2018-2020. The Danish EEZ is shown in pink.

Community recovery

Longevity composition of the benthic community was modelled for the entire North Sea (Rijnsdorp *et al.*, 2018) and Kattegat (van Denderen *et al.*, 2020) based on endobenthos samples and environmental conditions (Figure 4.2.3A)[2]. These environmental conditions included among others the natural disturbances created by tidal currents (Figure 4.2.3B), and water depth as an estimate for wind-driven wave disturbance.

Table 4.2.2. Depletion rates used in this study.

Gear	Depletion rate
TBB_CRU	0,060
TBB_DMF	0,140
SDN_DMF_RSP	0,0069
OT_SPF_TBS	0,009
OT_SPF_REM	0,009
DRB_MOL	0,200
OT_DMF	0,026
OT_CRU	0,100
OT_MIX	0,075
SSC_DMF	0,016

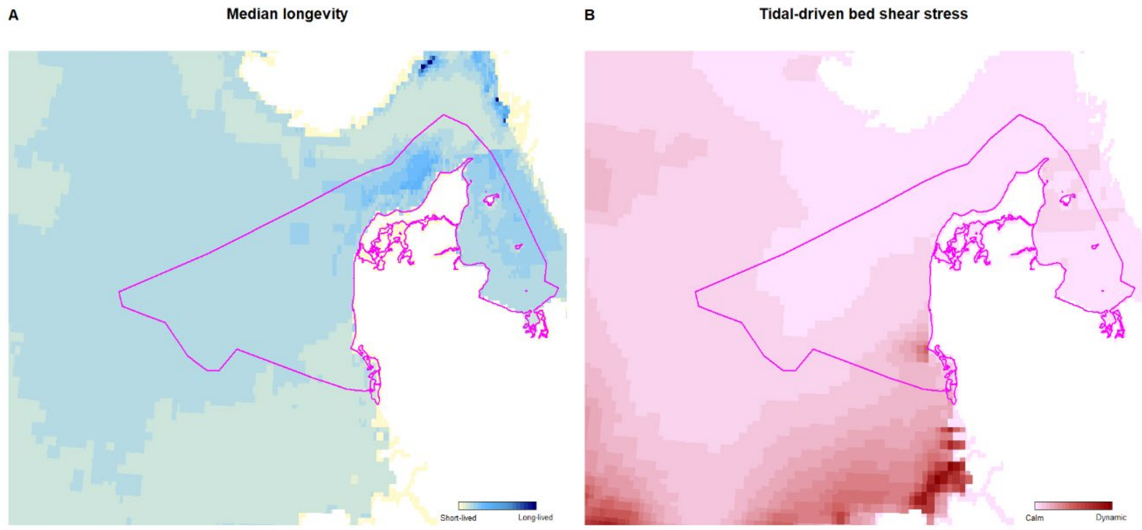

Figure 4.2.3. Input data for the community recovery estimates used in the model. (A) shows the modelled median longevity and (B) the tidal-driven bed shear stress used to model this longevity. The Danish EEZ is shown in pink.

RBS estimation

The RBS was estimated for the average demersal fishing effort over 2018-2020, and for all demersal gears combined, for all sandbank-directive gears combined, and for each sandbank-directed gear separately.

Results

Over the years 2018-2020, an average of 354 fishing vessels were active for the Danish demersal fleet, landing 157.8 $x10^6$ kg of catch with a worth of 900.7 $x10^6$ DKK (Table 4.1.3). From the sandbank-directed fishing gears, the sandeel fisheries (OT_SPF_TBS) yielded the majority of the catches (78.2 $x10^6$ kg) and was responsible for the largest revenue (143.6 $x10^6$ DKK). However, fisheries for Brown shrimp, *Crangon crangon* (Linnaeus, 1758) (TBB_CRU) achieved the highest relative revenue

[2] The data used is freely available at the WKFBIT github page: https://github.com/ices-eg/FBIT

22.6 x10^6 DKK for 0.7 x10^6 kg). This fishery also has the lowest aggregation of fishing effort. Compared to 100% fishing effort, more than halve of the fished grid cells remain unfished with 90% of the fishing effort. For other fisheries, this percentage is higher, indicating that they concentrate their fishing activity to very specific fishing grounds. The total fraction of impacted grid cells is relatively low, which is easily explained by the large part of the study area that is usually not targeted by Danish fishermen. However, for the brown shrimp fisheries (TBB_CRU), the Danish seines (SDN_DMF_RSP), and the sandeel fisheries (OT_SPF_TBS), the fraction fished grid cells increases over the three sandbank habitat types. This is in line with the preference for sandbank habitats for their fishing activity. The still low percentages can be explained by the large study area.

Benthic status of the habitat

The RBS of the different sandbank habitats is quite positive, with an overall RBS > 0.9 (Table 4.2.3). In the North Sea, the RBS is dominantly affected by the brown shrimp fisheries (TBB_CRU), with little impact of any other sandbank-directed fishery (Figure 4.2.4)

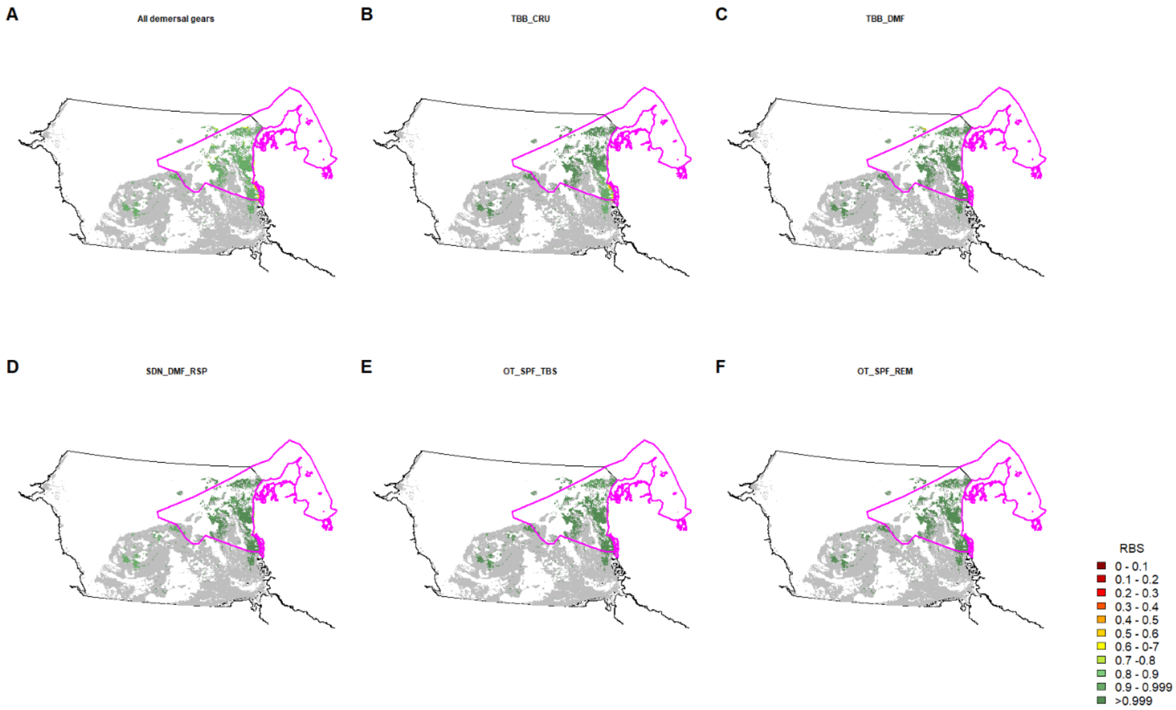

Figure 4.2.4. Relative Benthic State of the sandbank habitat in the North Sea. Unfished SB1 habitat is shown in grey, and the Danish EEZ is depicted in pink.

In the Skagerrak area, the overall RBS is lower, with the most impacted areas at the border of the sandbank area (Figure 4.2.5). This indicates that, although all sandbank directed fisheries are responsible for some of this reduced status; it dominantly is a result of other fisheries (Figure 4.2.5).

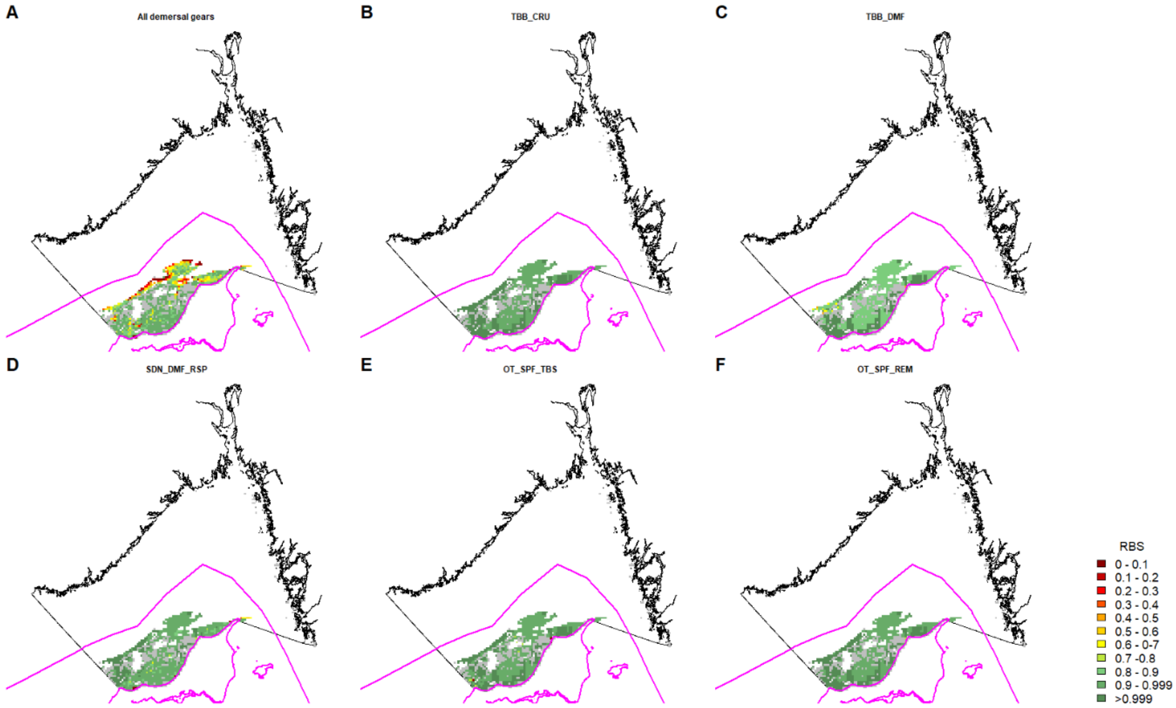

Figure 4.2.5. Relative Benthic State of sandbank habitat in the Skagerrak. Unfished SB1 habitat is shown in grey, and the Danish EEZ is depicted in pink.

There are only a few sandbank areas in the Kattegat (Figure 4.2.6). In the central area south of the small island Anholt; there are some spots with lower RBS values. Nevertheless, these are generally not caused by any sandbank-directed fishery.

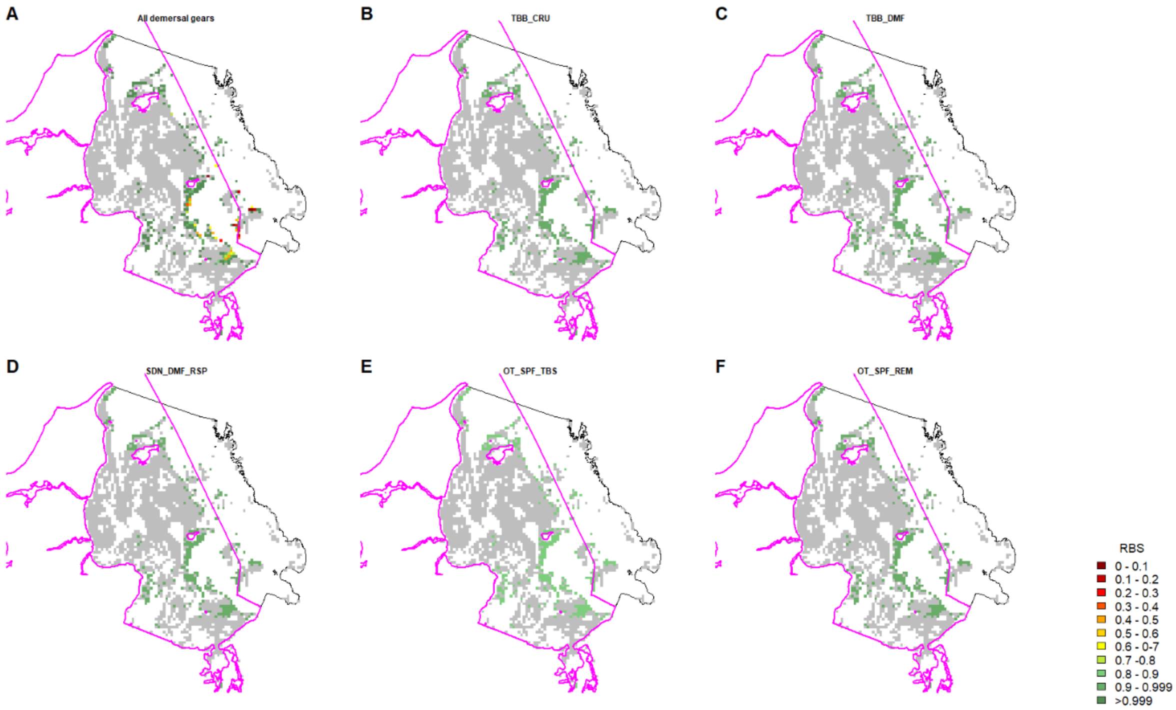

Figure 4.2.6. Relative Benthic State of sandbank habitat in the Kattegat. Unfished SB1 habitat is shown in grey, and the Danish EEZ is depicted in pink

Standardized impact

To allow for a fair evaluation of fishing impact and to enable comparisons between fishing gears, the local revenue of the fishing activity should be taken into account (Rijnsdorp *et al.*, 2020). We therefore standardized the benthic impact with the local revenue (Figure 4.2.7). The impact per landings ratio has been determined by dividing the reduction of the benthic state with the yielded revenue (defined as the total landings in both kg and DKK).

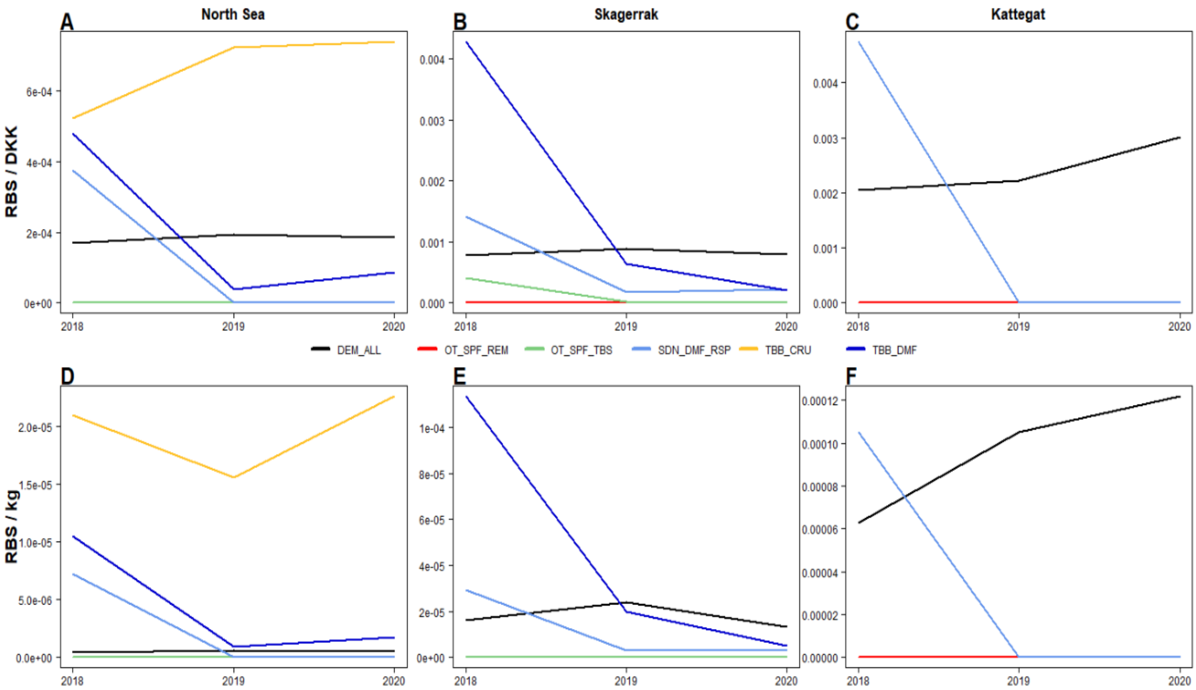

Figure 4.2.7. The trade-off between benthic impact and revenue, for both the total profit (in DKK; A-C) and the total amount (in kg; D-F), for the sandbank habitat type 1 in the North Sea (A,D), the Skagerrak (B,E), and the Kattegat (C,E) separately.

The largest standardized impact is made in 2018 by the beam trawl and Danish seine, in the Skagerrak and Kattegat respectively (Figure 4.2.7). The impact of both semi-pelagic otter trawls (OT_SPF) is very low, as is the general impact of all demersal gears combined in the sandbank habitats. The fishery for brown shrimp, on the other hand, has on average a larger standardized impact than the other gears.

Table 4.2.3. Average annual metrics of the different sandbank-directed demersal fisheries and for all demersal fisheries combined (DEM_ALL). For each gear, we show the average number of vessels active, the landings (in x106 kg and x106 DKK). We further show superficial (SAR) and subsurface Swept Area Ratio (SUB), and the fraction of grid cells of a habitat type impacted (%), for all habitats combined and the three sandbank habitat types. In addition, aggregation (90%) represents the percentage of remaining grid cells impacted when only 90% of the fishing effort takes place. The Greater North Sea region is taken as study area.

Gear	All habitats							SB1				SB2				SB3			
	Nr. of vessels	Landings kg	Landings DKK	SAR	SUB	Grid cells impacted	Aggregation (90%)	SAR	SUB	Grid cells impacted	RBS	SAR	SUB	Grid cells impacted	RBS	SAR	SUB	Grid cells impacted	RBS
TBB_CRU	26	0,7	22,6	1,21	0,63	0,64	49,38	1,18	2,15	2,39	0,976	1,45	0,62	2,15	0,973	1,44	0,62	2,1	0,971
TBB_DMF	4	0,2	4,8	0,28	0,28	0,56	65,59	0,28	1,09	0,88	0,987	0,28	0,28	1,09	0,983	0,29	0,28	1,13	0,981
OT_SPF_TBS	52	78,2	143,6	2,07	0,06	1,98	57,72	2,14	6,82	5,51	0,988	2,2	0,06	6,82	0,985	2,37	0,06	6,99	0,983
OT_SPF_REM	27	11,1	20,7	0,55	0,02	1,03	61,47	0,54	1,86	2,19	0,990	0,54	0,02	1,86	0,987	0,54	0,02	1,99	0,985
SDN_DMF_RSP	13	0,7	12,2	2,26	0	1,5	72,83	2,49	3,83	3,12	0,984	2,52	0	3,83	0,980	2,61	0	3,26	0,979
DEM_ALL	354	157,8	900,7	2,1	0,25	21,47	58,12	1,79	20,06	19,05	0,920	1,98	0,17	20,06	0,913	1,98	0,17	20,14	0,910

Discussion

It can be concluded that the sandbank habitats in the Greater North Sea are generally subjected to a low impact from Danish demersal fisheries. Their relative benthic state, which ranges between 0 (completely impacted) and 1 (no impact) has an overall value > 0.9 when determined for only the Danish fishing impact. The five demersal gears that are dominantly active in sandbank habitats cause for relatively little impact. This is due to a combination of factors. Except from the traditional beam trawlers for demersal fishes like plaice (TBB_DMF), most gears directed to sandbank habitats are relatively light and have a low impact resulting in low benthos depletion rates (Table 4.2.2). Secondly, the natural disturbance of sandbank habitats is generally high, especially when compared to the deeper areas with muddy sediments (Bricheno *et al.*, 2015). Because of the shallowness of the sandbank areas, waves frequently disturb the sandy sediments (Aldridge *et al.*, 2015). Consequently, the local benthic community is adapted to physical disturbances similar to the physical disturbance caused by demersal fishing (van Denderen *et al.*, 2015). This is in line with the life history of the main target species of sandbank directed fisheries: sandeels (OT_SPF_TBS), brown shrimp (TBB_CRU), plaice (TBB_DMF, SDN_DMF_RSP), and sprat, *Sprattus sprattus* (Linnaeus, 1758) (OT_SPF_REM). These species are characterized by traits that allow them to sustain in dynamic habitats, such as short lifespans with high reproduction rates, opportunistic diets, high mobility, and small body sizes (Bolam *et al.*, 2014; van Denderen *et al.*, 2015; Kenny *et al.*, 2018).

It can be observed that especially the brown shrimp fisheries have a relatively large impact on the seafloor. Their dominant fishing ground around the town of Esbjerg is one of the few sandbank habitats with reduced RBS values. Moreover, the standardized impact (benthic impact relative to fishing revenue) is also relatively high. This could be a consequence of the small meshes required to catch brown shrimp, or the heavy components of the beam trawl gear (Eigaard *et al.*, 2016).

The conclusions presented here are very much in line with earlier findings (Rijnsdorp *et al.*, 2020; Mazor *et al.*, 2021), which is to be expected since the methodology used is very similar. However, we have applied the methodology to (i) fishing data at much higher resolutions, (ii) using a novel, empirically derived depletion estimate for Danish seines, and (iii) focus specifically on sandbank habitats. Whereas all three steps increase the estimation accuracy of Danish sandbank habitat status, they may also cause for some false accuracy as well. Most input data is not available at the high resolution of the fisheries data. More specifically, the North Sea wide estimates of local habitat type and benthic community that serve as input in the determination of its sensitivity to fisheries have some large uncertainties (Galparsoro *et al.*, 2012; van der Reijden *et al.*, 2021). The benthic community distributions are based on endobenthos samples from dominantly the southern North Sea (Rijnsdorp *et al.*, 2018), and a few samples from the Kattegat (van Denderen *et al.*, 2020). The epifauna community that is more prone to experience physical contact with demersal fishing gears (Collie *et al.*, 2000; Hiddink *et al.*, 2017; Sciberras *et al.*, 2018; Tiano *et al.*, 2020) is not or limited included. In addition, the benthic composition of grab-derived samples is extrapolated/modelled based on modelled environmental parameters (Rijnsdorp *et al.*, 2018), each with their own inaccuracies (Stephens and Diesing, 2015). Assuming that the trade-off between spatial resolution and data accuracy is respected for the input data by their authors, our interpolation of the input data to the high resolution used by the fisheries data could have increased uncertainties of this input data. To enable the detailed analyses as presented here with high accuracy, international efforts are required to improve our knowledge on the fine-scale spatial distribution of both habitats and benthic communities in the Greater North Sea.

5 Conclusions and perspectives

With the above described and appended deliverables, in terms of scientific papers and reports and other dissemination products, the key project objectives of the application have been met, and all national stakeholders in terms of Policy, management, industry and NGOs will profit significantly from the project outputs;

- The development of a predictive model on the geometry and dynamics of the Danish seine gear footprint (Section 2.1) will improve the accuracy of fishing pressure data and maps and enlarges our understanding of the gear operations.
- The hierarchical integration of Black Box (BB), Automated Identification System (AIS), and Vessel Monitoring System (VMS) data with logbook data to produce high-resolution fishing pressure maps at the scale of 100x100 meters grid cells (Section 2.4) is a giant leap forwards and improves the accuracy of our knowledge base for national management of the environment and fisheries, as well as industry and NGO-initiated conservation efforts.
- The development of a theoretical model to determine metier-specific depletion rates (Section 3.1), and the experimentally based quantification of benthos depletion rates for Danish seines (Section 3.2), sandeel otter trawls (Section 3.3) and mussel dredges (Section 3.4), are concrete and important contributions that fill existing knowledge gaps and that quickly will become integrated in international science-based management and advisory tools.
- So far, the research focus in the field of fisheries benthic impacts has been very much on the direct physical effects in the actual gear footprint, but more recently awareness has increased that the sediment mobilization and subsequent distribution outside the trawl tracks can have adverse effects as well. The development of a modelling framework that estimates the total amount of mobilized sediment from fishing with different mobile bottom-contacting gears, represents an important tool and a first step in quantifying the pressure and impact from this process (Section 4.1)
- The above-described results have been integrated in the high-resolution impact assessment on sandbank habitats presented in this report (Section 4.2), which could form the basis for habitat-specific evaluations in the context of national and international framework directives.

Nationally and internationally, the above outputs mainly have been and will be disseminated through scientific papers and manuscripts produced with contributions from the project (4 published scientific papers, 2 scientific manuscripts produced, 1 published scientific report). Furthermore the project has involved leading European experts in several phases and deliverables of the project and the project coordinator has acted as co-chair of ICES-WGFBIT for the duration of the project, which has ensured knowledge transfer and synergy both ways.

In addition to the outcomes being picked up in the international scientific literature, the project's research focus and the implementation of methods and results will continue after the project within the advisory work in several ICES expert groups (e.g. ICES WGFBIT and ICES-WGSFD [Working Group on Spatial Fisheries Data]), as well as within the national advisory work that DTU Aqua provides to the Ministry and dissemination to the industry and the NGOs. A number of new projects (e.g. the EMFF project "KYSTEFFEKT - det kystnære fiskeris effekter på bundfauna") also include work packages that are built around further development and implementation of the results from this project.

6 Project Dissemination (Appendices)

The main outcomes of the project are a number of scientific papers and manuscripts that are listed below as separate appendices of this report. While summaries from these appendices and syntheses of key results are presented as chapters in the report, due to copyright limitations and publishing considerations these appendices are not enclosed with the report. *Not all of the listed appendices are published but more information can be provided upon request (ore@aqua.dtu.dk)*.

Appendix 1: The seafloor footprint geometry of Danish Seines
O'Neill FG, Noack T. *The geometry and dynamics of Danish anchor seine ropes on the seabed.* ICES journal of Marine Science. 2021;78(1):125-133. DOI: 10.1093/icesjms/fsaa198.

Appendix 2: Modelling of gear specific depletion rates
Rijnsdorp AD, Hiddink JG, van Denderen PD, Hintzen NT, Eigaard OR, Valanko S et al. *Different bottom trawl fisheries have a differential impact on the status of the North Sea seafloor habitats.* ICES Journal of Marine Science. 2020;77(5):1772-1786. DOI: 10.1093/icesjms/fsaa05.

Appendix 3: Quantifying the impact of the Danish Seine - a 'low environmental impact' fishing gear - on seabed macrofauna
Bromhall K, Eigaard OR, Wilms TJG, Noack T, McLaverty C, O'Neill FG, Dinesen GE. *Quantifying the impact of the Danish Seine - a 'low environmental impact' fishing gear - on seabed macrofauna*. Manuscript.

Appendix 4: Quantifying the impact of a standard and a modified sandeel otter trawl on seabed macrofauna
Bromhall K, Dinesen GE, Eigaard OR, O'Neill FG, Hiddink JG. *Quantifying the impact of a standard and a modified sandeel otter trawl on seabed macrofauna.* Manuscript.

Appendix 5: Experimental effects of a lightweight mussel dredge on benthic fauna in a eutrophic MPA
Bromhall, K., Dinesen, G. E., McLaverty, C., Eigaard, O. R., Petersen, J. K., & Saurel, C. (2022). *Experimental Effects of a Lightweight Mussel Dredge on Benthic Fauna in a Eutrophic MPA*. Journal of Shellfish Research, 40(3), 519-531. https://doi.org/10.2983/035.040.0309

Appendix 6: Modelling sediment mobilization by bottom trawls
Rijnsdorp AD, Depestele J, Molenaar P, Eigaard OR, Ivanović A, O'Neill FG. *Sediment mobilization by bottom trawls: a model approach applied to the Dutch North Sea beam trawl fishery.* ICES Journal of Marine Science. 2021;78(5):1574-1586. DOI: 10.1093/icesjms/fsab029.

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