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National Institute of Aquatic Resources

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Ciarán McLaverty, Grete E. Dinesen, Ole Ritzau Eigaard, Jeppe Olesen, Mollie E. Brooks, Esther Beukhof, Katrina Bromhall, Josefine Egekvist, P. Daniel van Denderen, Alexandros Kokkalis, Karin J. van der Reijden, Jonathan Stounberg, and Jens Kjerulf Petersen

DTU Aqua Report no. 440-2023

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Colophon

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DTU Aqua Report no.:	440-2023
Year:	Scientific work finalised April 2023. Report published December 2023
Reference:	McLaverty, C., Dinesen, G.E., Eigaard, O.R., Olesen, J., Brooks, M.E., Beukhof, E., Bromhall, K., Egekvist, J., van Denderen, P.D., Kokkalis, A., van der Reijden, K.J., Stounberg, J. & Petersen, J.K. (2023). Effects of coastal fisheries on benthic fauna. DTU Aqua Report no. 440-2023. National Institute of Aquatic Resources, Technical University of Denmark, 73 pp.
Cover photo:	View of fishing vessels on the beach at Thorupstand. Photo: Ciaran McLaverty
Published by:	National Institute of Aquatic Resources, Henrik Dams Allé, 2800 Kgs. Lyngby, Denmark
Download:	www.aqua.dtu.dk/publikationer
ISSN:	1395-8216
ISBN:	978-87-7481-373-6

DTU Aqua Reports contain results from research projects, reviews of specific topics, expositions for authorities etc. Unless stated in the colophon, the reports are not peer reviewed, which means that the content has not been reviewed by researchers outside the project group.

Preface

This report presents the results from the project 'KYSTEFFEKT – det kystnære fiskeris effekter på bundfauna' (COASTEFFECT – Effects of coastal fisheries on benthic fauna), rant Agreement No 33113-B-20-178, which was funded by the European Maritime and Fisheries Fund (EMFF) and the Danish Fisheries Agency. The project period was 2020-2023.

The main outcomes of the project are scientific papers, manuscripts, and reports that are presented as chapters and appendices in the report.

Lyngby, April 2023
Ciaran McLaverty
Postdoctoral Researcher

European Union
European Maritime and Fisheries Fund

HAV & FISK

Content

Summary

Rationale: Fishing with bottom-towed gears (otter trawls, beam trawls, seines, and dredges), hereafter 'bottom trawling', accounts for the majority of commercial fishing effort (kWh) in Danish waters. Despite its widespread use here and throughout the globe, the scientific understanding of how bottom trawling impacts coastal and nearshore seabed ecosystems is comparatively deficient. One of the reasons for this is that smaller coastal vessels are poorly represented in commercial fisheries monitoring data, and methods used to estimate the distribution and intensity of fisheries are less suited to the fishing behaviour of coastal vessels. In addition, manmade and natural pressures are widespread in coastal areas, and their effects on the seabed often obscure the detectable impacts of bottom trawling. Key marine environmental policy directives such as the European Water Framework Directive (WFD) (2000/60/EC) have also placed a greater emphasis on the assessment and quantification of ecological status in coastal areas. However, much of the focus of the WFD has centred on improving our understanding and monitoring of diffuse pressures, such as nutrient enrichment and chemical pollution. Comparatively little attention has been given to understanding physical pressures such as bottom trawling, despite its widespread use in coastal areas. We aim to address several knowledge gaps facing the management of bottom trawling in coastal areas in this report, and by extension, provide evidence-based management recommendations for the sustainable management of coastal bottom trawling in Denmark.

Improving methods to estimate coastal bottom trawling footprints: A key first step of this project was to improve the existing methods used to estimate the fishing behaviour and intensity of coastal fishing vessels, and refine the methodology for data processing of non-standard fishing gear types (i.e., Danish seines). We did this by combining three different sources of spatial fishing data (VMS, AIS, and black box (BBS)), with information on vessels position, speed, and heading, and daily logbook information to reconstruct bottom trawling tracks using interpolations methods. Moreover, a hierarchical merging method was developed that prioritizes the most detailed data source (BBS, then AIS, then VMS) for a given spatial location. The approach resulted in an improved fishing intensity estimation method that is also well-suited to fishing gears with non-standard fishing patterns, such as Danish seines, thereby significantly improving the accuracy of gear footprint estimation in coastal areas. The main output included estimates and maps of total bottom trawling effort (all bottom-towed gears) in Danish coastal areas for the period 2005 to 2017 presented using 100x100 meters grid cells.

Relative impacts of bottom trawling, eutrophication, and natural pressures in coastal areas: We examined the relative effects of key human and natural pressures on seabed communities across four coastal areas of Denmark. Organic enrichment (measured as total organic content) was found to be the strongest driver of seabed communities across the areas examined. Its effects were wide reaching, with both positive (e.g. increases in benthic biomass in the Wadden Sea) and strongly negative effects (afaunal and severely depleted communities in South Fyn) observed. Variables such as bottom current velocity also had strong effects, with impacts to benthic functional and taxonomic composition observed in several areas. Although the effects of bottom trawling were evident in several areas, the severity of impacts on seabed fauna were highly dependent on the degree of background natural and human pressures at a given location, and the dynamics of the particular gear type. For example, shrimp beam trawling

in the Wadden Sea resulted in clear negative effects on the seabed, irrespective of the strong currents present in the area, while Danish seines in exposed areas of Jammer Bay had lower effects on community and trait composition. Under moderate levels of organic enrichment, the effects of bottom trawling became more difficult to detect. This was evidenced by the mixed impacts of shellfish dredging on fauna in Limfjorden. However, we found that the ecological impacts of bottom trawling were undetectable in areas experiencing intense eutrophication and seasonal hypoxia, such as observed in South Fyn, despite intensive bottom trawling taking place with relatively deep-penetrating gears.

Experimental effects of a Danish seine on benthic fauna: We further examined the effects of Danish seines, a relatively shallow-penetrating gear, on the seabed via experimental trials in Jammer Bay. The experiment was carried out by sampling a relatively undisturbed area of seabed directly before and after a Danish seine haul. Overall, the effects of the gear on benthic fauna were low, with no observed impacts at the community level. However, we did observe some changes to the abundance and biomass of specific species, particularly in the case of the horseshoe worm *Phoronis* sp. This observation supports corroborates the findings from other Danish seine studies and suggests that species with a prominent position at the sediment surface and/or fragile tubes may be sensitive to impacts from the Danish seine. Based on this, we conclude that Danish seines are likely to result in lesser impacts to seabed fauna and benthic ecosystems than from otter and/or beam trawl gears (i.e. gear used in similar areas/habitats), and therefore have the potential to reduce the ecological impacts of bottom trawl fisheries if used to replace more deep-penetrating gears.

An assessment of benthic indicators used to detect and monitor coastal bottom trawling impacts: Using monitoring data collected under the Danish NOVANA monitoring program and high-resolution fishing effort data, we examined how bottom trawling and environmental pressures affect coastal benthic fauna across all Danish coastal areas. We further investigated the ability of 8 widely used benthic monitoring metrics (indicators and indices) to detect impacts on benthic biological quality. The results of this study found that bottom trawling resulted in negative effects on benthic abundance and species richness, and a clear response to bottom trawling was also observed for the WFD-specific Benthic Quality Index (BQI). In contrast, indices designed specifically for use under the WFD, such as AZTIs Marine Biotic Index (AMBI), multivariate AMBI (M-AMBI), and the Danish Quality Index (DKI), were unresponsive to bottom trawling. This is likely a result of these indices being originally designed to monitor eutrophication and chemical pollution, which are common pressures in coastal areas. Given the clear effects of bottom trawling on abundance and species richness, coupled with the lack of response of widely used indices such as AMBI and DKI, we highlight a considerable risk that coastal monitoring programmes may fail to identify impacts on benthic macrofauna caused by bottom trawling.

Bottom trawling impacts on benthic state in WFD water bodies: The International Council for Exploration of the Sea (ICES) recently developed the assessment approach, Fisheries Benthic Impact Tools (FBIT) with several functional indicators to estimate impacts of bottom trawling on Benthic Broad Habitat Types (BBHTs) over large spatial scales. The approach uses information on benthic longevity biomass-distributions, based on gear specific mortality and benthic habitat specific recovery rates, as well as bottom trawling intensity and environmental variables to estimate the state i.e. Relative Benthic State (RBS) and the Impact (1-RBS) on benthic habitats. Using this approach, the median longevity of benthic faunal biomass appeared to be greatest in the southern Kattegat and deeper areas of the Belt Seas, thereby indicating higher sensitivity in these areas. In contrast, lower sensitivity scores were associated with areas along the west coast of Jutland. We also observed that bottom trawling led to a number of benthic habitat types falling below thresholds for Good Ecological Status (GES) in coastal areas as measured by the RBS, indicating poor ecological quality. These areas included shallow subtidal sands and coarse sediments in the Wadden Sea, shallow muds on the east coast of Jutland, and heavily dredged areas of Limfjorden and Isefjorden. In contrast, RBS scores over >0.8 were observed in most areas and years where fishing does not take place, indicating Good Ecological Status, according to RBS indicator. However, it should be noted that while the FBIT approach provides an alternative state indicator for assessments of benthic health and is linked directly to several pressure variables, the RBS values are designed to be reflective of bottom trawling impacts, and thus do not directly inform of the effects of other pressures on the seabed. Boundary issues were also observed for the oxygen and salinity models, which affected RBS and impact estimates in some near-shore areas. These aspects may have resulted in overestimates in the impacts of bottom trawling, and underestimates in the effects of naturally decreasing salinity levels and human-induced nutrient enrichment and oxygen depletion in the inner Danish waters. Accordingly, improvements in availability of coastal environmental model data for these parameters would greatly benefit assessments based on the FBIT RBS and Impact indicators for Danish coastal waters.

Conclusions: The project provides several key findings regarding the ecological impacts of bottom trawling in coastal areas. These include new evidence regarding the effects of bottom trawling relative to other coastal pressures, concerns regarding the ecological metrics used to monitor coastal bottom trawling, significant impacts of bottom trawling on benthic fauna across coastal areas, as well as applied and field-based trials of theoretical impact indices and alternative fishing gears. These findings are expected to contribute directly to the evidence base of human impacts in coastal areas and may aid in the development and improvement of ecosystem-based fisheries management for coastal areas. Based on the findings, we suggest a number of management recommendations for consideration, including:

- Low impact gears such as Danish seines have the potential to reduce trawling impacts to benthic fauna, and therefore improve the ecological integrity of coastal habitats.
- Applying black box devices to all coastal vessels would greatly improve the understanding of bottom trawling impacts in coastal areas and provide documentation of the exact magnitude and location of impacts, thereby improving fisheries and environmental management, as well as being useful for the fishers themselves.
- Widely used benthic indices such as the DKI and AMBI are poorly suited to tracking and monitoring bottom trawling. Other indices (e.g. abundance or BQI) should therefore be applied in conjunction with standard indicators to ensure bottom trawling induced changes to benthic communities caused are also identified in monitoring programmes. Based on our findings, a more thorough review of potential coastal bottom trawling indicators could be undertaken, which may include indicator development.
- Given the strong effects of diffuse and persistent pressures such as eutrophication in some areas, management strategies aiming to improve the health of coastal marine environments (e.g. via Marine Protected Areas) should be prioritised outside of these areas, and in locations where the exclusion of pressures such as bottom trawling can more directly benefit the ecological quality of the seabed.

Sammendrag på dansk

Fiskeri med bundpåvirkende redskaber (trawl, bomtrawl, vod og skraber), herefter kaldet 'bundtrawl', tegner sig for størstedelen af erhvervsfiskeriet (kWh) i de danske farvande. På trods af den udbredte anvendelse af bundtrawl her og over hele kloden er den videnskabelige forståelse af, hvordan bundtrawling påvirker kystnære bentiske økosystemer forholdsvis mangelfuld. En af grundene er, at mindre kystfartøjer er dårligt repræsenteret i kommercielle fiskeriovervågningsdata og metoder, der anvendes til at estimere fiskeriets fordeling og intensitet, og er dermed mindre egnede til kystfartøjers fiskerimønstre. Derudover er menneskeskabte og naturlige presfaktorer vist udbredt i kystzonen, og deres effekter på havbunden skjuler ofte de ellers påviselige effekter af bundtrawl. Vigtige havmiljøpolitiske direktiver såsom det europæiske vandrammedirektiv (2000/60/EF) har også lagt vægt på vurdering og kvantificering af økologisk tilstand i kystområder. Imidlertid har meget af fokus i vandrammedirektivet været centreret om at forbedre vores forståelse og overvågning af diffuse presfaktorer såsom tilførsel af næringsstoffer og kemisk forurening. Forholdsvis lidt opmærksomhed har været rettet mod at forstå effekter af fysiske belastninger såsom bundtrawl, på trods af dets udbredte anvendelse i kystområder. I denne rapport vil videnshuller, som forvaltningen af bundtrawl i kystområder står over for, blive adresseret og i forlængelse heraf kommer vi med evidensbaserede anbefalinger til en bæredygtig forvaltning af fiskeri med bundtrawl i danske kystvande.

Forbedring af metoder til at estimere områder påvirket af bundtrawl: Et vigtigt første skridt i dette projekt var at forbedre de eksisterende metoder til estimering af fiskeri og dets intensitet og forfine metoder til databehandling af ikke-standardiserede fiskeredskabstyper (dvs. snurrevod). Vi gjorde dette ved at kombinere tre forskellige kilder til geografisk lokalisering af fiskeri (VMS, AIS og Black Box (BBS)) med information om fartøjets position, hastighed og kurs og daglig logbogsinformation til at rekonstruere bundtrawlspor ved hjælp af interpolationsmetoder. Desuden blev der udviklet en hierarkisk metode, der prioriterer den mest detaljerede datakilde (BBS, derefter AIS, så VMS) for en given geografisk placering. Fremgangsmåden resulterede i en forbedret metode til estimering af fiskeriintensitet, der også er velegnet til fiskeredskaber med ikke-standardiserede fiskemønstre, såsom snurrevod, og vil derved forbedre nøjagtigheden af estimeringen af redskabernes fodaftryk i kystområder markant. Hovedresultatet omfattede estimater og kort over den samlede bundtrawlindsats (alle bundpåvirkende redskabstyper) i danske kystområder for perioden 2005 til 2017 præsenteret ved brug af 100x100 meter grid.

Relative påvirkninger af bundtrawl, eutrofiering og naturlige presfaktorer i kystområder: Vi undersøgte de relative effekter af forskellige menneskeskabte og naturlige presfaktorer på bundfauna på tværs af fire kystområder i Danmark. Organisk berigelse (målt som samlet organisk indhold) viste sig at være den stærkeste styrende faktor for sammensætningen af bundfauna på tværs af de undersøgte områder. Effekterne var vidtrækkende med observationer af både positive (f.eks. stigninger i bentisk biomasse i Vadehavet) og stærkt negative effekter (alvorligt forstyrret bundfauna ud for det sydlige Fyn). Variable som bundstrømhastighed havde også stærke effekter på bundfaunaen og der blev observeret effekter på funktionel og taksonomisk sammensætning af bundfaunaen i flere områder. Selvom effekterne af bundtrawl var tydelige i flere områder, var omfanget af effekterne på bundfaunaen variabel og afhængig af graden af naturlige og menneskelige påvirkninger i et givet område og redskabstype. For eksempel medførte bomtrawl efter rejer i Vadehavet klare negative effekter på bundfaunaen, uanset de

høje strømhastigheder i området, mens snurrevod i eksponerede områder i Jammerbugten havde mindre effekt på bundfaunaens sammensætning. Ved moderate niveauer af organisk berigelse blev virkningerne af bundtrawl vanskeligere at opdage. Dette blev bevist af de blandede effekter af muslingefiskeri på bundfaunaen i Limfjorden. Vi fandt også, at effekter af bundtrawl var umulige af påvise i områder med høj grad af eutrofiering og sæsonbetinget iltsvind, som blev observeret i ud for det sydlige Fyn på trods af, at området havde været udsat for intensivt bundtrawl med redskaber med relativt dyb nedtrængning i havbunden.

Effekter af snurrevod på bundfaunaen: Vi undersøgte yderligere virkningerne af snurrevod - et relativt lavt bundpåvirkende redskab - på havbunden via forsøg i Jammerbugten. Forsøget blev udført ved at udtage prøver af et relativt uforstyrret havbundsområde direkte før og efter et snurrevodstræk. Samlet set var virkningerne af redskaberne på bundfaunaen lave, uden observerede påvirkninger på samfundsniveau. Vi har dog observeret nogle ændringer i mængden og biomassen af specifikke arter, især *Phoronis* sp. Denne observation understøtter resultaterne fra andre snurrevodsundersøgelser og antyder, at arter i sedimentoverfladen og/eller med skrøbelige rør kan være følsomme over for påvirkninger fra snurrevoddet. Baseret på dette konkluderer vi, at snurrevod sandsynligvis vil resultere i mindre påvirkninger af havbundens fauna og bentiske økosystemer end fra andre bundtrawlredskaber (dvs. redskaber brugt i lignende områder/habitater), og derfor har potentialet til at reducere økologiske virkninger af bundtrawlfiskeri, hvis det bruges til at erstatte redskaber med en påvirkning, der går dybere i bunden.

En vurdering af bentiske indikatorer, der bruges til at detektere og overvåge virkningerne af kystbundtrawl: Ved hjælp af overvågningsdata indsamlet under det danske NOVANA program og højopløselige fiskeriindsatsdata undersøgte vi, hvordan bundtrawl og miljøbelastninger påvirker bundfauna på tværs af alle danske kystområder. Vi undersøgte yderligere 8 udbredte bentiske indikatorer og indeks anvendelig til at påvise effekter af bundtrawl på bundfauna. Resultaterne af denne undersøgelse viste, at bundtrawl resulterede i negative effekter på bundfauna tæthed og artsrigdom, og en klar reaktion på bundtrawl blev også observeret for det WFD-specifikke bentiske kvalitetsindeks (BQI). Derimod reagerede indekser designet specifikt til brug under vandrammedirektivet, såsom AZTIs Marine Biotic Index (AMBI), multivariate AMBI (M-AMBI) og Dansk Kvalitets Indeks (DKI), ikke på bundtrawl. Dette er sandsynligvis et resultat af, at disse indeks oprindeligt er designet til at overvåge eutrofiering og kemisk forurening, som er de mest udbredte antropogene påvirkninger i de kystnære områder. I lyset af de klare effekter af bundtrawl på tæthed og artsrigdom, kombineret med den manglende respons fra udbredte indeks som AMBI og DKI, er der en betydelig risiko for, at kystovervågningsprogrammer ikke kan identificere påvirkninger på bundfauna forårsaget af bundtrawl.

Bundtrawls påvirkninger af bentisk tilstand i vandområder i vandrammedirektivet: Det Internationale Havundersøgelsesråd (ICES) udviklede for nylig vurderingsmetoden Fisheries Benthic Impact Tools (FBIT) med flere funktionelle indikatorer til at estimere effekterne af bundtrawl på bentiske brede habitattyper (BBHT'er) over store rumlige skalaer. Fremgangsmåden bruger information om biomassefordelinger af bundfauna-biomassens levetid baseret på redskabsspecifik dødelighed og bentiske habitatspecifikke genetaberingshastigheder samt bundtrawlsintensitet og miljøvariable til at estimere tilstanden, dvs. relativ bentisk tilstand (RBS) og effekten (1) - RBS) på bentiske levesteder. Ved at bruge denne tilgang synes middellevetiden for bundfauna-biomasse at være størst i det sydlige Kattegat og dybere områder af Bælthavet, hvilket indikerer højere følsomhed i disse områder. I modsætning hertil var der lavere følsomhedsscore forbundet med områder langs den jyske vestkyst. Vi observerede også, at bundtrawl førte til, at en række bentiske habitattyper faldt under tærsklerne for god økologisk status (GES) i kystområder som bestemt af RBS, hvilket indikerer dårlig økologisk kvalitet. Disse områder omfattede lavvandede sandbunde og grove sedimenter i Vadehavet, lavvandede mudderbunde på den jyske østkyst og meget fiskede områder af Limfjorden og Isefjorden. I modsætning hertil blev RBS-score over >0,8 observeret i de fleste områder og år, hvor der ikke fiskes, hvilket indikerer god økologisk tilstand ifølge RBS-indikatoren. Det skal dog bemærkes, at mens FBIT-tilgangen giver en alternativ tilstandsindikator til vurdering af havbundens tilstand og er knyttet direkte til flere forskellige presfaktorer, er RBS-værdierne designet til at afspejle bundtrawl-påvirkninger og vil dermed ikke direkte informere om effekten af andet antropogent pres på havbunden. Problemer modellering af ilt- og saltholdighedsforhold påvirkede RBS og effektvurdering i nogle kystnære områder. Disse aspekter kan have resulteret i overvurderinger af virkningerne af bundtrawl, og undervurderinger af virkningerne af naturligt faldende saltholdighedsniveauer og menneskeskabt næringsstofberigelse og iltsvind i de indre danske farvande. Følgelig vil forbedringer i tilgængeligheden af data for disse parametre i høj grad gavne vurderinger baseret på FBIT.

Konklusioner: Vigtige nøgleresultater af projektet omfatter ny viden om effekterne af bundtrawl i forhold til andre kystnære presfaktorer, om anvendeligheden af diverse indeks til detektion ef effekter af bundtrawl, dokumentation for effekter af bundtrawl i kystzonen betydelige på tværs af kystområder. Resultaterne kan bidrage direkte til vidensgrundlaget vedrørende effekter af menneskelige påvirkninger i kystområder og kan hjælpe med udvikling og forbedring af en økosystembaseret fiskeriforvaltning for kystområder. Baseret på resultaterne foreslår vi en række anbefalinger til overvejelse af de relevante myndigheder, herunder:

- Redskaber med lille påvirkning af havbunden - som snurrevod - har potentiale til at reducere trawl-effekter på bundfaunaen og dermed forbedre den økologiske integritet af kysthabitater.
- Anvendelse af Black Box anordninger på alle fiskefartøjer i kystvandene vil i høj grad forbedre forståelsen af effekter af bundtrawl i kystområder og give dokumentation for det faktiske omfang og præcise geografiske placering af effekterne, og dermed forbedre forvaltningsmulighederne, samt være nyttig for fiskerne selv.
- Meget anvendte bundfaunaindeks som DKI og AMBI er ikke velegnede til at detektere effekter af bundtrawl. Andre indeks (f.eks. bunddyr tæthed eller BQI) bør derfor anvendes sammen med standardindikatorer for at sikre, at ændringer i bunddyr-samfund forårsaget af bundtrawl også kan identificeres i overvågningsprogrammer. Baseret på vores resultater kan der med fordel gennemføres en mere grundig gennemgang af potentielle indikatorer og indeks, som også kan omfatte udvikling af nye eller justering af eksisterende indikatorer.
- I betragtning af de kraftige effekter på bundfauna af diffuse presfaktorer, såsom eutrofiering, bør forvaltningsstrategier, der sigter mod at forbedre tilstanden af havmiljøet (f.eks. via beskyttede marine områder) prioriteres uden for eutrofierede områder og på steder, hvor udelukkelse af belastninger såsom bundtrawl mere direkte kan gavne havbundens økologiske kvalitet.

1. Introduction

1.1 Coastal fisheries in Denmark

Despite its relatively small land area, Denmark's coastline and numerous islands constitute one of the longest coasts in Europe (~8,750 km). Fishing is a key part of Danish culture and tradition, with coastal fisheries dating back to 7000 BC (Enghoff et al 2007). Today, Denmark is one of the largest fish producing nations in Europe, with several important commercial fisheries operating in coastal areas (Gislason et al., 2021). Bottom trawling, a fishing method where bottom-contacting fishing gears (otter trawls, beam trawls, seines, and dredges) are towed over the seabed to capture fish and invertebrate species, accounts for the greatest effort (kWh) in Danish waters (Skov et al., 2019), and is widespread in coastal areas (Figure 1.1)

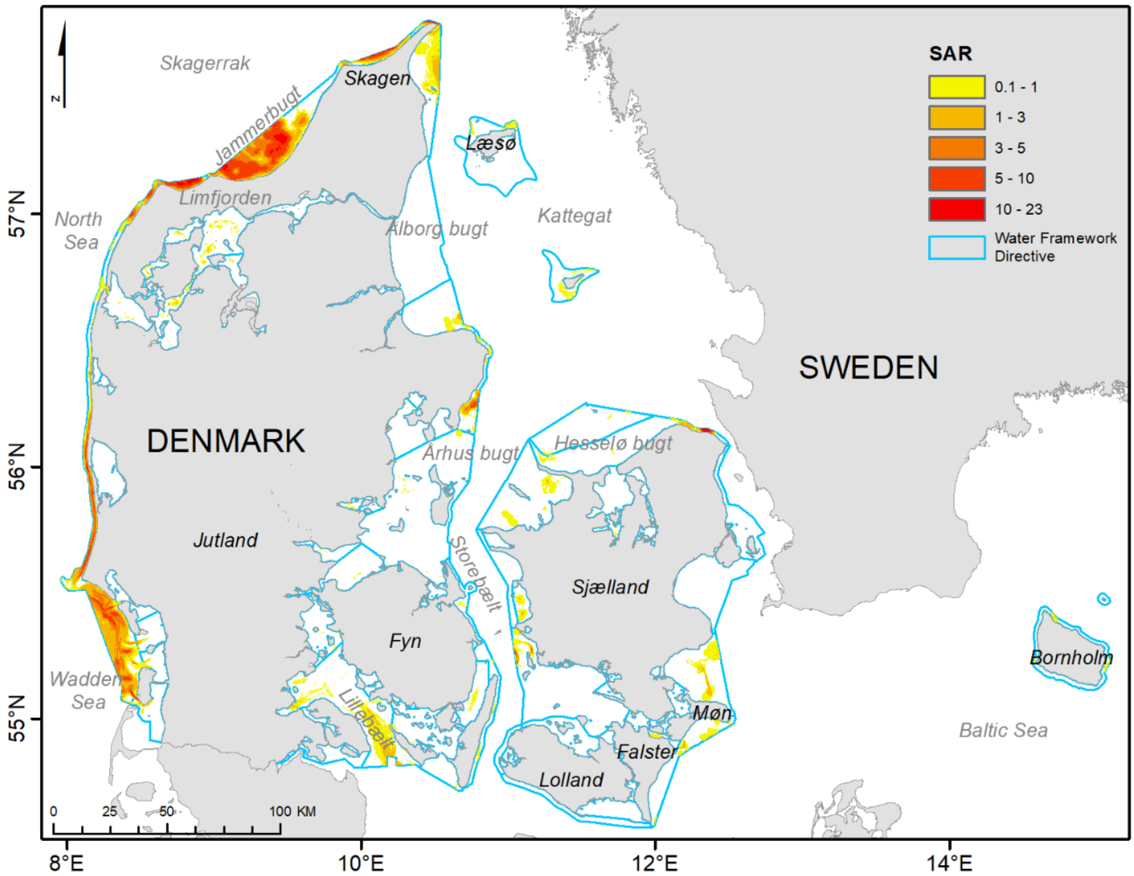
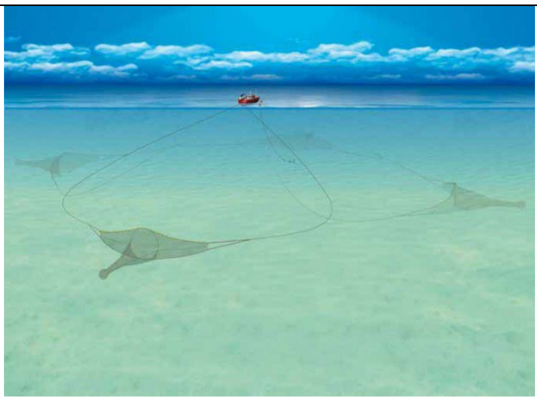


Figure 1.1:Average bottom trawling effort in coastal areas during the study period examined in this report (2005 – 2017). Effort is presented in grid cells of 100 × 100 m for all bottom trawling gears pooled. For the purposes of this report, Water Framework Directive water bodies (blue) provide a proxy for coastal areas. Place names are provided in black and sea areas in grey text. SAR: swept area ratios. Note - the speed-filtering method used in Chapter 2 can result in grid cells falsely mapped as fished in some circumstances where vessels slow down for other reasons than trawling. This is especially the case close to some harbours (e.g., south of Anholt and south of Skagen).

There are four main types of bottom trawling gear used in Danish coastal areas (Figure 1.2). Beam trawls are used to catch brown shrimp *Crangon crangon* along the west coast of Jutland

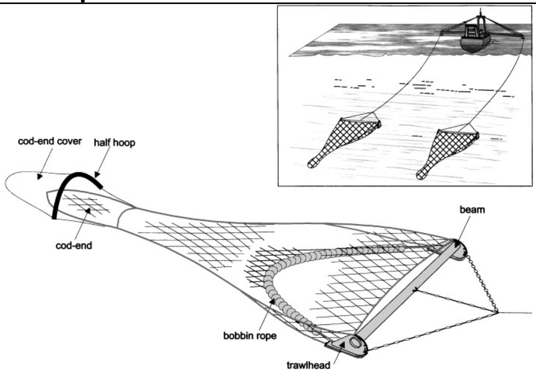
and in the Wadden Sea. In the southern Skagerrak and Jammer Bay, Danish seines target European plaice *Pleuronectes platessa*, but also Atlantic cod *Gadus morhua*, common dab *Limanda limanda*, and other flatfish (Hoffman, 2016). On the east coast of Jutland and between the islands, otter trawls are widely used to capture flatfish and gadoids. Bivalve dredging for blue mussel *Mytilus edulis* also takes place along the east coast, although the majority of effort is concentrated in the inland fjords of Limfjorden (Nielsen et al., 2021).

Danish seine



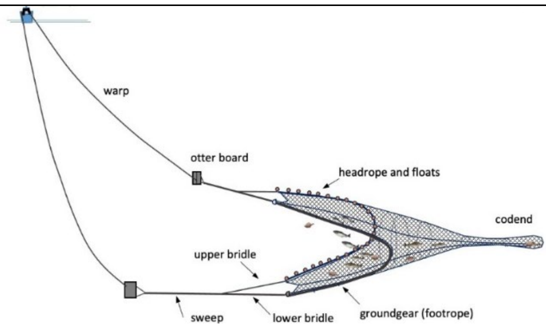
(www.seafish.org)

Shrimp beam trawl



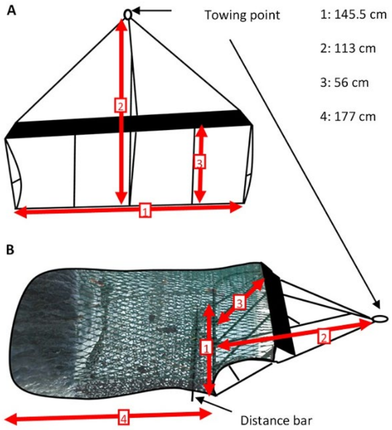
(Reproduced from Polet 2000)

Otter trawl



(FAO 2001)

Mussel dredge: (A) front (B) side



(Reproduced from Frandsen et al. 2015)

Figure 1.2: Illustrations of the four main bottom towed gears used in Danish coastal areas.

1.2 Challenges to assessments of fishery impacts in coastal areas

Despite bottom trawling being widespread in coastal areas, scientific understanding of the effects of these fisheries on the seabed are impeded by several factors. To date, most research regarding the fleet level effects of commercial fisheries on the seabed has been focussed in offshore areas. This is a result of better data coverage for the larger offshore vessels, and more established methods available for estimating fishing intensity in these areas (Hintzen et al., 2010, Eigaard et al. 2017). In contrast, smaller coastal vessels are poorly represented in commercial fisheries data, and methods are less suited for their fishing behaviour. In addition, a range of anthropogenic and natural pressures occurs along the coast. It can therefore be difficult to detect and quantify fisheries impacts to the seabed in these dynamic environments, and under high natural disturbance (Szostek et al., 2016). Of particular relevance to Denmark is the widespread occurrence of nutrient enrichment and oxygen depletion in coastal areas, presenting a range of obstacles to fishery impact assessments (McLaverty et al., 2020a), as well as well as large gradients in salinity, currents, and tides (McLaverty et al. 2023).

The introduction of key marine environmental policy directives, such as the European Water Framework Directive (WFD) (2000/60/EC), placed a greater emphasis on the assessment and quantification of ecological status in coastal areas. The WFD defines coastal waters as the nearshore area extending to 1 nautical mile (nm) from shore, or up to 12 nm where chemical status is assessed. Under the WFD, member states are required to monitor and assess the state of a range of biological quality elements, such as benthic macrofauna, in these areas. This is typically carried out using ecological indicators, designed to measure and track progress towards Good Ecological Status (GES), as defined by reference or desired conditions (Rice et al., 2012; Van Hoey et al., 2010). However, many of the indicators used to monitor benthic communities in coastal areas under the WFD were originally developed for other purposes than assessing bottom trawling impacts, namely to assess the effects of nutrient enrichment and eutrophication. Accordingly, many WFD indices have been shown to be appropriate for monitoring the diffuse effects of nutrient enrichment and chemical pollution in coastal areas (Borja et al., 2015). Comparatively little attention has been given to the response of these indicators to more direct physical pressures, such as bottom trawling. This presents a problem to sustainable coastal fisheries management, given the scale of coastal bottom trawling in Europe (Eigaard et al., 2017) and Danish waters (Figure 1), and as evidence from offshore areas suggests that WFD indices may be poor indicators of bottom trawling disturbance (Gislason et al., 2017).

The monitoring of fisheries impacts on the seabed in Danish coastal waters is also potentially hampered by the location of the national benthic monitoring sites. In response to a series of hypoxic events in the Kattegat, Belt Seas, and the Øresund in the 1980s, the harmonised national aquatic monitoring programme (known today as the NOVANA programme) was established (Conley et al., 2000). The aim of the programme then was to monitor nutrient enrichment in marine and freshwater areas (Svendsen et al., 2005). However, in more recent times these data have also been applied to a wider range of assessments, and the location of monitoring stations do not necessarily correspond well with the range and distribution of bottom trawling effort in Danish waters (Figure 5.1). This may explain why fisheries impact assessments using NOVANA data have produced mixed results (Gislason et al., 2017; Pommer et al., 2016). If this were the case, this spatial mismatch has the potential to hinder assessments of the ecosystem effects of trawl fisheries in Danish waters, and the fulfilment of monitoring commitments in coastal regions under the WFD, MSFD, and the EU Habitats and Birds Directives (for Natura 2000 sites).

1.3 Report outline

This report aims to address a range of knowledge gaps associated with bottom trawling impacts in the coastal zone. The outputs of this report are therefore expected to enable improved evidence-based management advice for the sustainable management of bottom trawling in Denmark. In the following chapters, the report describes and assesses the impacts of bottom trawling on seabed ecosystems across Danish coastal areas using a combination of monitoring data and dedicated data collection.

The report is comprised of the following key components:

- The development and improvement of methods to estimate fishing intensity for coastal bottom trawlers (Chapter 2)
- An examination of the relative effects of human and natural pressures on benthic fauna in key coastal fishing grounds (Chapter 3)
- Results of a controlled bottom trawling experiment undertaken to assess the benthic impacts of a ‘low impact’ demersal gear (Danish seine) (Chapter 4)
- An assessment of coastal bottom trawling impacts on benthic fauna using monitoring data, and an evaluation of benthic indicators used to monitor bottom trawling impacts in coastal areas (Chapter 5)
- The application of the ICES Fisheries Benthic Impact Tools (FBIT) and the Relative Benthic State (RBS) and Impact (1-RBS) indicators to estimate bottom trawling impacts and states of benthic macrofauna across Danish coastal areas (Chapter 6)
- Conclusions, key findings, and general management recommendations based on the findings of the report (Chapter 7)

In terms of dissemination, the report comprises 5 technical chapters (Chapter 2 – 6), as well as a number of published scientific papers and manuscripts in preparation provided as appendices. Chapters 3, 4 and 5 are provided as summaries of the appended scientific papers and manuscripts. Due to copyright limitations and publishing considerations these appendices are not enclosed with the online report but are available upon request.

2. Method development and data processing to improve estimates of coastal fishing pressure

Ole R. Eigaard, Karin J. van der Reijden & Jeppe Olsen

2.1 Overview

This chapter outlines steps taken to collate and process data for fishing effort with bottom-towed gears in Danish coastal waters and relevant WFD areas. The fishing effort data collated includes all fishing activities derived from black box system (BBS) data (from N2000 areas), as well as all Vessel Monitoring System (VMS) and Automatic Identification System (AIS) data. Special attention has been given to refining the current methodology for the processing of non-standard fishing gear types (i.e., Danish seines), thereby significantly improving the accuracy of gear footprint estimation based on vessel activity data. After being collated and processed, the data was filtered and cleaned to ensure that only fishing activities (and not steaming activities) were included in the final data set. The fishing effort data was subsequently used to estimate the extent, intensity, and total trawled area for the study area, and to provide specific predictor variables, required in the model-based analyses described in Chapters 3, 5 & 6.

2.2 Extent, intensity, and total trawled area for the study area

All data for fishing activity with bottom-towed gears (VMS, AIS, and BBS) in Danish nearshore areas for the years 2005–2017 was combined with logbook data. The three different sources of spatial fishing data comprise information on the vessels' position, speed, and heading, and the daily logbooks contain information on the gears used, their configuration, and the species retained. The logbook and spatial data were merged according to Hintzen et al. (2012). Gear-specific speed profiles were used to determine if a vessel was fishing, and only those recordings were kept in the analysed data set (Poos et al., 2013). The separation of vessel-positions into fishing or non-fishing activity is based on typical speed ranges of each fishery (defined by gear type and target species group), and this approach carries a risk of positions falsely being assigned as fishing activity when vessels slow down for other reasons than trawling (e.g. transiting into harbour, shallow water). Following the speed-filtering we reconstructed the fishing tracks by interpolating the fishing recordings of a vessel (Hintzen et al., 2012), combined with the modelled width of the fishing gear (Eigaard et al., 2016; Eigaard et al., 2017). Because of differences in the availability and recording frequency of the spatial data systems, we developed a hierarchical merging method, which prioritizes the most detailed data source (BBS, then AIS, then VMS).

For Danish seines, a deviating method was applied to compensate for the distinct fishing pattern and seabed footprint of this gear type. Demersal seines typically form a piriform shape (O'Neill & Noack, 2021), with multiple hauls from a single location, the so-called dhan. In line with the hierarchical merging method described above, AIS data were used to determine the exact piriform shapes where possible, and otherwise VMS data were used to locate the dhan position, after which standard piriform shapes were placed in the directions indicated by the VMS recordings. An example of estimated footprints of a demersal seine based on AIS is shown below, together with the footprint of the same gear when estimated from VMS data (Figure 2.1).

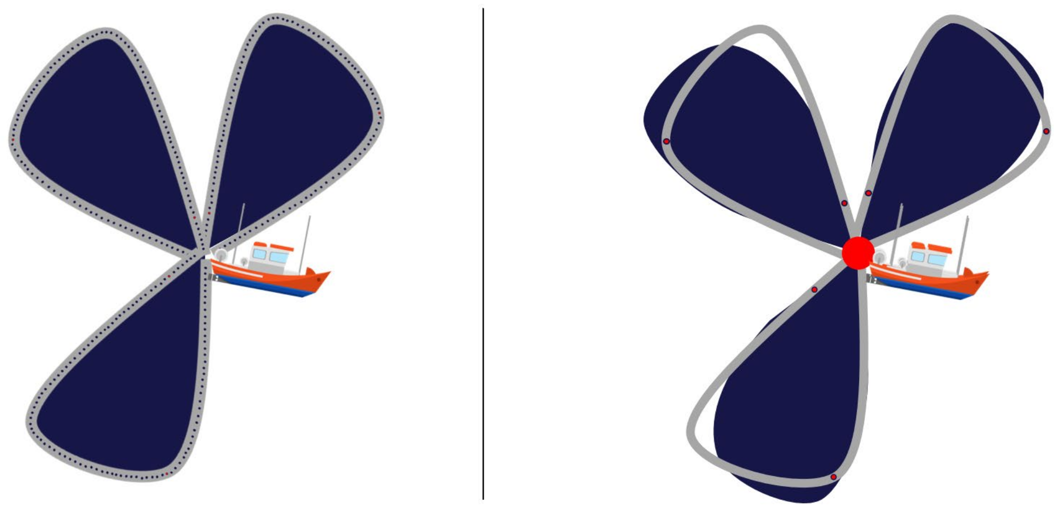


Figure 2.1: An example of estimated footprints of a Danish seine, based on AIS data (left) and VMS data (right). The predicted course of the fishing vessel is shown in grey, with the blue/red dots representing the recorded vessel positions by the AIS (left) and VMS (right), respectively. The actual footprint of the fishing gear is the area within the fishing track, depicted in dark blue. For AIS data (left), this gear footprint can be deducted directly from the estimated vessel track. For VMS data (right), the few vessel positions recorded do not allow for a correct estimation of the fishing track and gear footprint. Instead, the location of the dhan (large red dot) is determined, after which standard piriform-shaped footprints are placed in the direction of the observed VMS recordings.

Following the development and implementation of the hierarchical approach and new Danish seine footprint estimation method, the distribution and intensity of the total effort (all gears pooled) over the period from 2005 to 2017, was calculated and mapped as mean annual swept area ratios (SARs) in grid cells of 100 × 100 m (Figure 1.1). This methodology and data set of SAR values in 100 x 100 meters grid cells covering the entire Danish coastal area formed the basis of the subsequent work in WP4, with adapting and applying the ICES standard methodology for assessing benthic impacts from fishing to the Danish WFD areas.

For the Chapter 5 analyses, 5885 macrofauna and sediment samples extracted from the NOVANA program data, and covering the years from 2005 to 2017, were matched with 1 year of bottom trawling pressure data, estimated back in time from the day of sampling. The individual sampling positions of the NOVANA program are organized within monitoring sites/stations, where multiple replicate samples are collected in a grid pattern (e.g., Figure 5.1 inset). The number of stations per grid ranges from 5 to 45, although the vast majority of grids contain >40. The bottom trawling intensity was ascribed to each sampling position by creating circles with 100 m radius and aggregating the total surface of fishing tracks (swept area) within the circle over a 1-year period prior to sampling. The total swept area was then divided by the surface of the circle to determine the Swept Area Ratio (SAR year−1). A similar approach was taken for the model-based analysis of Chapter 3, where SAR values within a 100 m radius of the sampling position over the previous 1-year period were calculated and matched with 216 benthic samples that were collected in April 2017 and May 2021.

3. Relative impacts of trawling, organic enrichment, and natural pressures on coastal seabed fauna

Ciarán McLaverty, Esther Beukhof, Katrina Bromhall, Anders C. Erichsen, Grete E. Dinesen & Ole R. Eigaard

(McLaverty et al. *In prep*, Appendix 1)

3.1 Introduction

Coastal regions represent a zone of transition between marine and terrestrial systems. They support a range of biogeochemical and physical processes (Crossland et al., 2005), biological interactions (Griffiths et al., 2017), and are therefore often characterised by high environmental variability. Coastal systems are also among the world's most biologically productive (Costanza et al., 1995), and provide an array of ecosystem services (Agardy et al., 2005). In addition, coastal regions are heavily impacted by a range of anthropogenic pressures (Halpern et al., 2015), including the extraction of living and non-living resources, nutrient and chemical pollution, and marine development (Korpinen et al, 2019).

A particularly widespread human pressure on the worlds seabed is fishing with bottom-towed gears (otter trawls, beam trawls, seines, and dredges), hereafter 'bottom trawling' (Amoroso et al., 2018; Eigaard et al., 2017). Bottom trawling can physically alter seabed habitats (Bradshaw et al., 2021; O'Neill and Ivanović, 2016), and damage or kill seabed fauna (Collie et al., 2000). Bottom trawling therefore alters community composition (Hinz et al., 2009), functional composition (Tillin et al., 2006), trophic dynamics (Mangano et al., 2015), and size frequency composition of benthic fauna (McLaverty et al., 2020b; Queirós et al., 2006). A similarly noteworthy human pressure affecting coastal regions is that of nutrient enrichment and hypoxia. Their effects are typically more diffuse than those of bottom trawling and can arise from both natural processes and anthropogenic activities (Rabalais et al., 2010). Human sources of organic enrichment have greatly increased since the mid-20th century, and come chiefly via agricultural runoff, effluent, and coastal development (Diaz and Rosenberg, 2008). Nutrient enrichment in aquatic waters is associated with a range of environmental effects, such as eutrophication (the process whereby water bodies become overly enriched), increased primary production, reduced water quality, and ultimately hypoxia (oxygen concentrations <2mg/l).

While the benthic effects of pressures such as organic enrichment are relatively well understood for coastal areas, the environmental impacts of many coastal fisheries are unassessed or lacking data. Furthermore, there is a poor understanding of the potential cumulative effects of these pressures in the coastal zone (van Denderen et al., 2022), and how human pressures can be disentangled from natural stressors (Jac et al., 2022). These knowledge gaps therefore present a significant obstacle to the sustainable management of coastal resources (Forst, 2009; Sherman and Duda, 1999). In this study, we examine the relative influence of key human and natural drivers on benthic communities across a range of environmental settings. Benthic data were collected from 4 distinct regions of the Danish coastline, each experiencing differing bottom trawl fisheries and unique local environmental conditions. To elucidate potential relationships between benthic communities and their environment, we use two differing but complementary analyses; RLQ analysis and generalised linear mixed models (GLMMs). The RLQ analysis is a multivariate statistical approach designed to reveal associations between traits, species, environment variables, and sampling sites (Dray et al., 2014), while GLMMs are applied to examine community level responses to human and natural pressures. Each of the 4 regions are examined as separate case studies in this report. Each case study is then discussed in terms of species and trait relationships, followed by community responses. The study provides novel assessments of human and natural pressures at 4 of the most important coastal fishing grounds in Danish waters and provides new evidence regarding the context dependant responses of seabed communities to disturbance.

3.2 Materials and methods

A total of 216 benthic samples were collected from 4 of the main coastal fishing grounds in Denmark (Figure 3.1). Each area also represents a different coastal bottom trawl fishery: Danish seining in Jammer Bay, shrimp beam trawling in Wadden Sea, mussel dredging in Løgstør Broad, and otter trawling in the South Fyn strait. These areas were sampled across two time periods; May 2021 (Jammer Bay: 60, Wadden Sea: 60, South Fyn: 60) and April 2017 (Løgstør: 36).

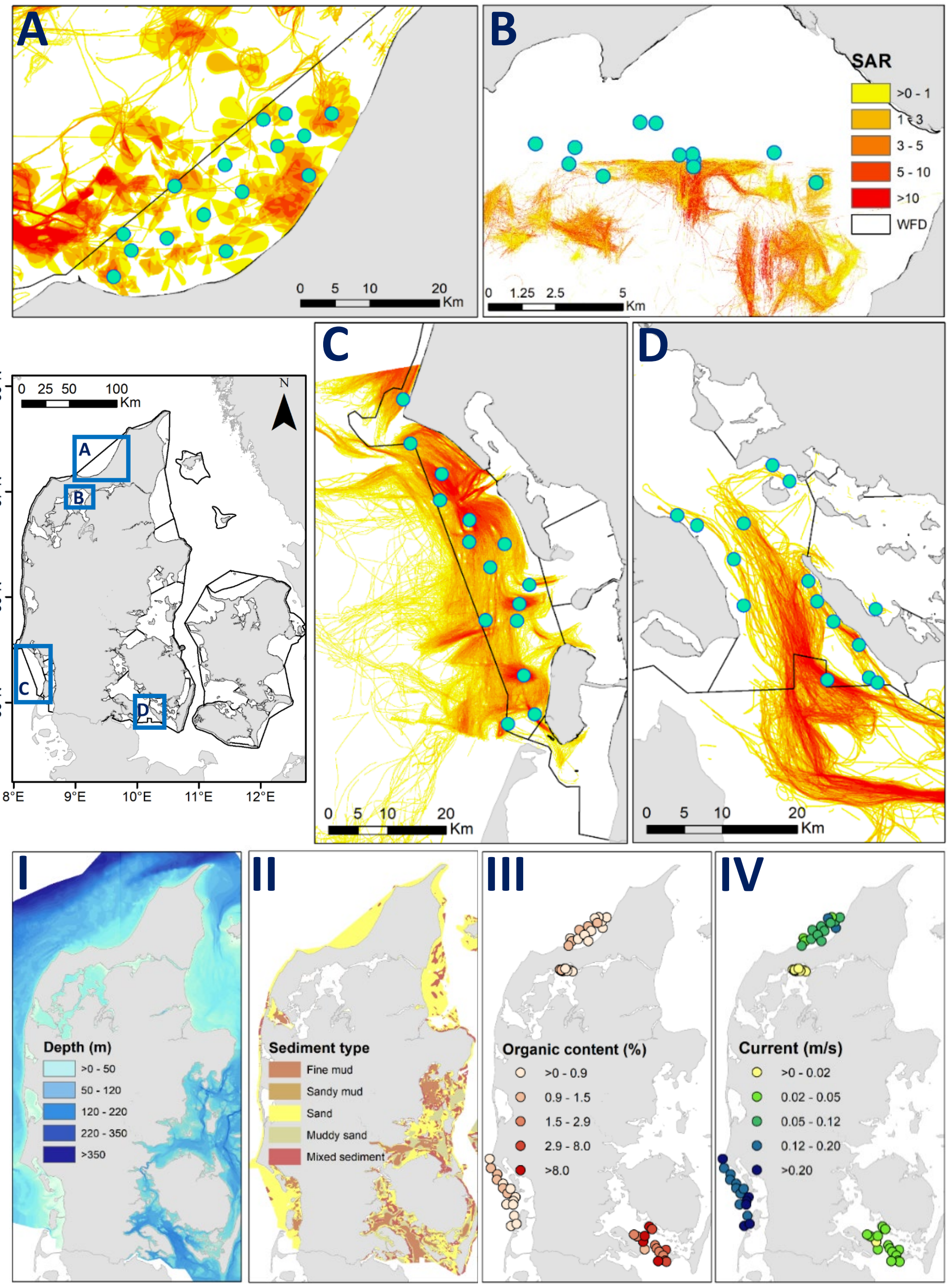


Figure 3.1: Location of sampling sites in relation to trawling pressure (A-D) and environmental variables examined (I-IV). (A) Jammer Bay – Danish seines (B) Løgstør Broad – mussel dredges (C) Wadden Sea – shrimp beam trawls (D) South Fyn – otter trawls. (I) Depth (II) broad scale sediment types (III) sediment TOC (sampled) (IV) bottom current speed (modelled). Bottom trawling pressure and bottom current speed are based on data for 2020.

In each case study, sampling sites were selected to represent the range of human and natural pressures. In the Wadden Sea and Jammer Bay, sampling sites were stratified by depth and bottom trawling effort to separate potential correlations between variables. Due to high levels of nutrient enrichment in South Fyn and Løgstør, gradients of hypoxia were also considered in these areas, in addition to depth and bottom trawling intensity, using maps of the estimated extent of seasonal hypoxia provided by the Danish Environment Agency. The data collection and sampling methodologies were consistent across the case studies.

We used 10 trait categories covering 44 descriptive modalities to characterise the range of life history types expressed by benthic species in each area. To represent human and natural pressures in each case study area, we gathered information on human activities that affect the seabed such as bottom trawling intensity and sediment total organic content, as well as natural parameters such as bottom current velocity, sediment grain size, and depth.

To investigate the associations between species, traits, environmental conditions, and human pressures, RLQ analysis was performed on each case study. RLQ analysis is a multivariate ordination technique that quantifies the structure between species abundances or occurrences per site (table L), species traits (table Q) and environmental variables per site (table R) (Dolédec et al., 1996; Dray et al., 2014). A combination of correspondence analysis and principal component analyses are performed on the data to summarise the main associations between species, traits, and their environment. Interpretation of the RLQ output is outlined in the following example. Two traits both exhibiting a highly negative score on a RLQ axis, indicates that they are strongly, positively associated. An environmental variable having a highly positive score on that same axis indicates that the two traits have a strong negative association to this variable. Similar interpretations can be made for how traits and environmental variables are associated with species and sites based on their ordination scores. Ordinations scores close to zero indicate no strong link to the respective RLQ axis. Generalised linear mixed models (GLMMs) were used to model 3 community metrics: abundance, biomass, and functional diversity, chosen based on their sensitivity to bottom trawling disturbance in Danish waters (McLaverty et al., 2020b).

3.3 Results

Jammer Bay: Results of the RLQ analysis revealed that sediment grain size (shown as sand %) and bottom trawling intensity were the strongest drivers of species and traits in Jammer Bay. Lower bottom trawling intensity and muddy sediments were associated with sites in the north and north-eastern areas (shown in blue/light blue) (Figure 3.2 d). These communities were associated with a higher biomass of suspension feeders (suspension), large body sizes (>100 mm), and benthic spawners (benthic eggs) (Figure 3.2 b). These traits were expressed mainly by the lancelet *Branchiostoma lanceolatum* and the phoronid *Phoronis muelleri* (Figure 3.2 c). In contrast, sites with negative scores (orange/red) experienced higher bottom trawling and sandier sediments and were generally located closer to shore. These communities were mainly composed of deposit feeders (surface deposit, subsurface deposit), and diffusive bioturbators (diffuse mixing), associated with the sea urchin *Echinocardium cordatum* and the annelid *Magelona alleni*. In terms of community level metrics (GLMMs), depth was a key driver exhibiting significant relationships with abundance, biomass, and functional diversity (Appendix 1 - Table 3). Bottom trawling did not exhibit a detectable effect at the community level.

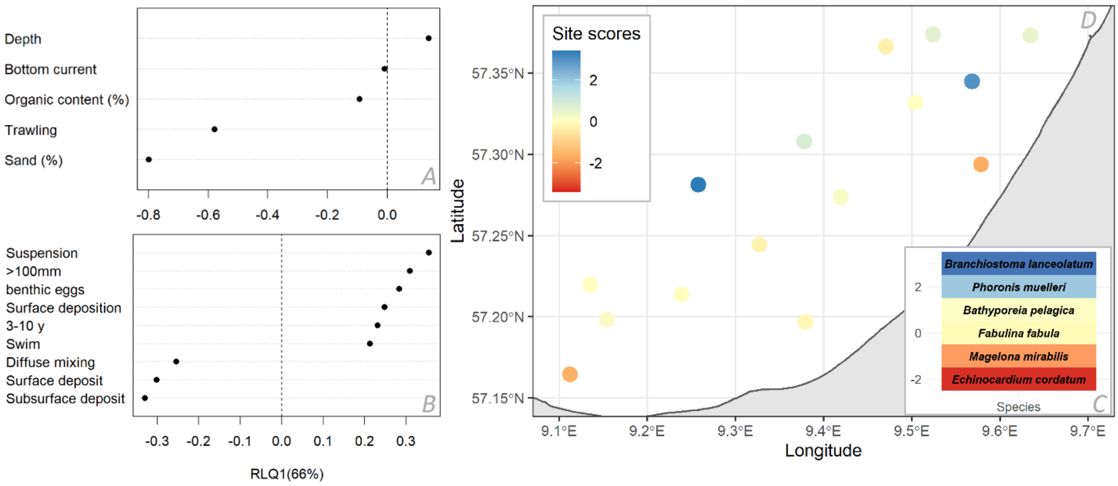


Figure 3.2: Results of the Jammer Bay RLQ analysis summarizing contribution of (A) environmental variables to spatial variations in (B) traits and (C) species according to their scoring along RLQ1. (D) Site scores illustrate relationships between variables across sampling sites.

Wadden Sea: The main environmental drivers in the Wadden Sea were organic content (positive scores), bottom current speed, and trawling intensity (negative). Stronger bottom currents, high bottom trawling, and low organic content are important in the south of the study area (Figure 3.3 d). Here, communities were characterised by egg brooders (brooding egg), swimmers (swim), and surface dwellers (surface), shallow living fauna (0-5 cm deep), predators (predator), and surface bioturbators (surface deposition). These traits were expressed mainly by brown shrimp *Crangon crangon* and shore crab *Carcinus maenus*. In contrast, high organic enrichment, weak currents, and low bottom trawling influenced communities in the north. These areas were characterised by deposit feeders (surface deposit, subsurface deposit), and pelagic spawners (pelagic eggs), and the sedentary annelids *Scoloplos armiger* and *Lagis koreni*. Bottom trawling intensity and bottom current speed were similarly important at the community level (Appendix 1 – Table 3), with bottom trawling leading to reduced community abundance and biomass. Total abundance and functional diversity decreased at higher current speeds and with sandier sediments. Biomass was also observed to increase in the presence of higher organic content.

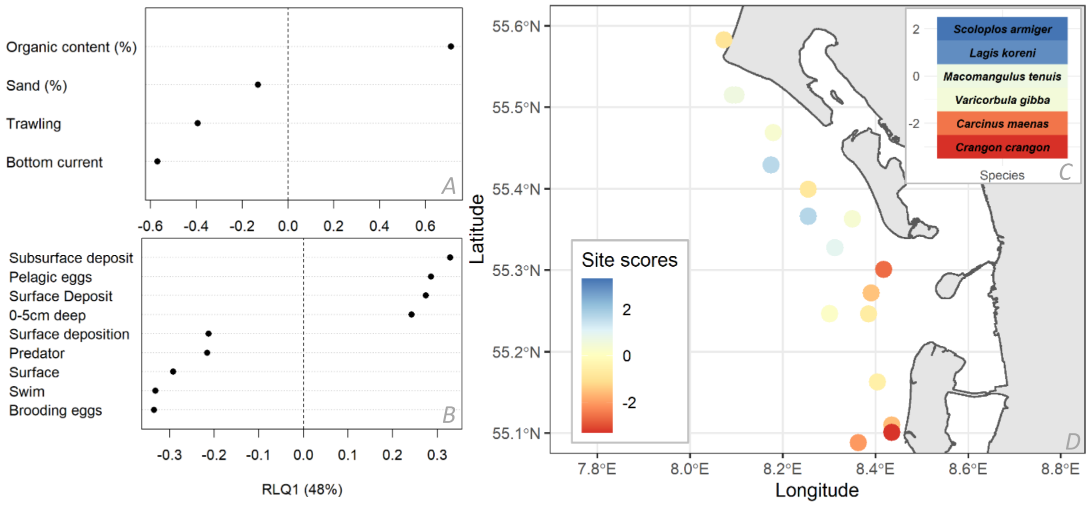


Figure 3.3: Results of the Wadden Sea RLQ analysis summarizing contribution of (A) environmental variables to spatial variations in (B) traits and (C) species according to their scoring along RLQ1. (D) Site scores illustrate relationships between variables across sampling sites.

Løgstør Broad: Sediment organic content and bottom currents (positive scores) were the main environmental drivers in Løgstør. High organics and strong currents influenced benthos in the west and central areas of the study site (Figure 3.4 d). These sites were characterised by stalked and tunic morphology, yolk feeding larvae (lecithotrophic), and ascidian species, such as *Styela clava* and *Ascidiacea* sp.. The remaining sites shown in red/orange (Figure 3.4 d) were mainly associated lower organic content and had a higher biomass of shelled (exoskeleton), crawling (crawl), and pelagic feeding larvae (planktotrophic) traits. Key species included the gastropods *Peringia ulvae* and *Nassa reticulata*. Organic content was similarly a key driver at the community level, with both total abundance and functional diversity reduced under high organic content (Appendix 1 - Table 3). Bottom current speed showed a significant positive relationship with biomass, while in contrast to the RLQ results, bottom trawling intensity has a significant negative effect on biomass.

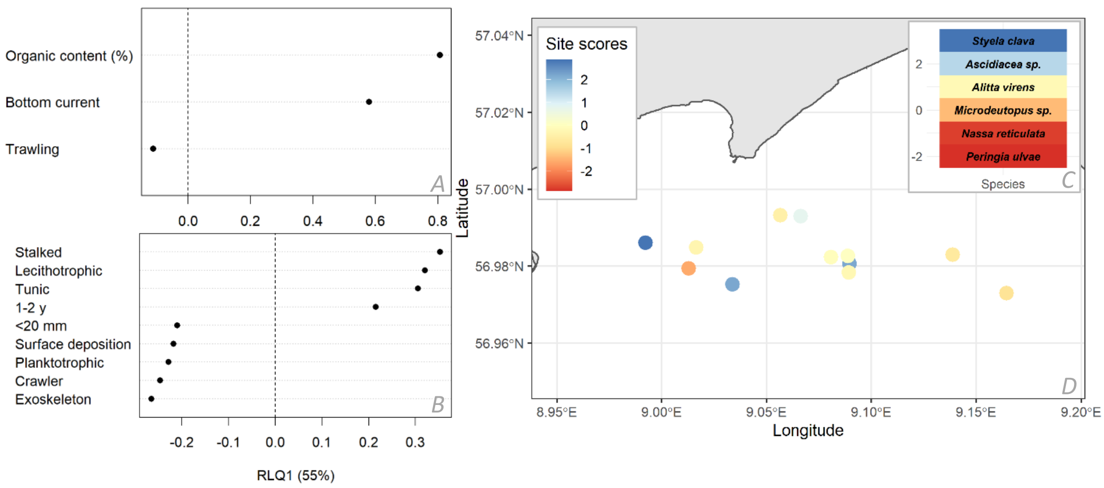


Figure 3.4: Results of the Løgstør RLQ analysis summarizing contribution of (A) environmental variables to spatial variations in (B) traits and (C) species according to their scoring along RLQ1. (D) Site scores illustrate relationships between variables across sampling sites.

South Fyn: Organic content (positive score) and depth (negative) were key drivers in South Fyn. Although bottom trawling intensity and bottom current speed were associated with negative scores, these factors were less important drivers (Figure 3.5 a). Deeper water was a stronger influence in the southern areas of the strait (Figure 3.5 d) between the islands of Als and Ærø. These sites had a high biomass of shelled (exoskeleton) traits, and were characterised by species such as the gastropod *Philine* sp. and brittle star *Ophiura albida*. Conversely, high levels of sediment organic content had a greater influence in the northern and shallower areas. These areas supported a high biomass of egg brooders (brooding egg), downward bioturbators (downward conveyer) and subsurface deposit feeders (subsurface deposit) and were associated with species such as *Arenicola marina* and *Scoloplos armiger* (both sedentary annelids). Compared to the other study areas, benthic communities in south Fyn were severely depleted. Of the 60 samples collected across the site, 9 were observed to be afaunal (composed of no macrofauna), with a further 4 samples containing only a single individual of the *S. armiger*. Organic content and current speed were also key drivers at the community level. Total abundance and functional diversity declined significantly under high organic content (Appendix 1: Table 3), while abundance and biomass increased with stronger bottom current speeds.

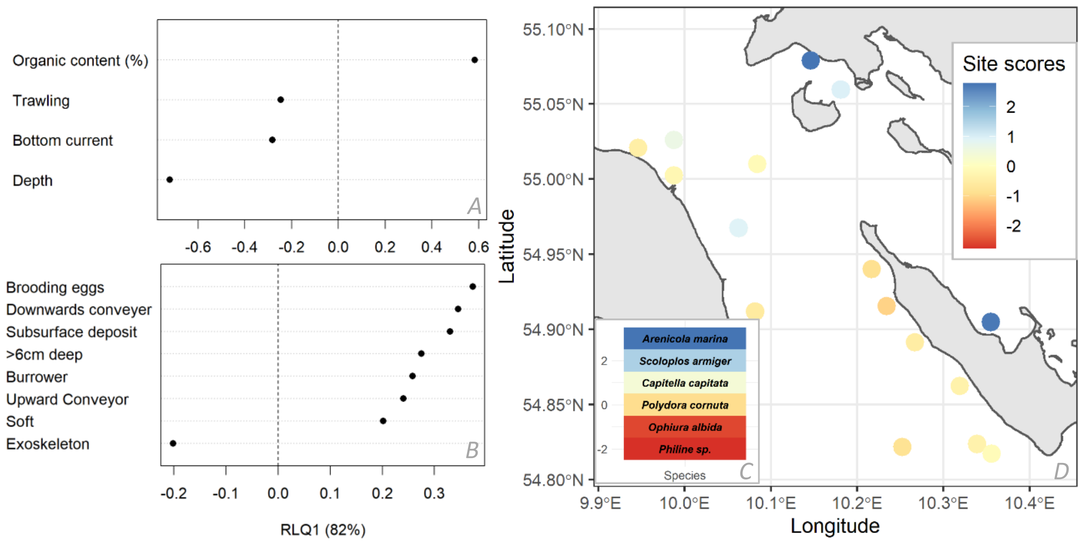


Figure 3.5: Results of the South Fyn RLQ analysis summarizing contribution of (A) environmental variables to spatial variations in (B) traits and (C) species according to their scoring along RLQ1. (D) Site scores illustrate relationships between variables across sampling sites. Sites with a white X comprised replicate samples that contained no benthic fauna.

3.4 Discussion

This study documents pronounced differences in the effects of human and natural drivers on benthic traits, species, and communities in different coastal settings. In the following sections, we elaborate these differences on a case-by-case basis, discuss their ecological implications, and outline the relevance of the results to the management of coastal resources.

Jammer Bay: The sandier habitats of Jammer Bay were associated with more intense fishing activity and were generally in shallow water, with communities found here dominated by deposit feeding fauna. This life history trait is common to shallow North Sea coasts (Bremner et al., 2006; Tillin et al., 2006), and is known to be relatively resistant to pressures such as bottom trawling (Van Denderen et al., 2015). Community biomass exhibited a negative relationship with depth, meaning that biomass was greater in the shallower areas. This relationship was mainly attributable to a single species of sea urchin *Echinocardium cordatum,* which is also characteristic of the sandier and more heavily trawled areas of Jammer Bay. This species has been thought to be sensitive to bottom trawling due to its fragile test (shell) (Dayton et al., 1995; Bergman & Santbrink, 2000), although this result would suggest that the relatively light ropes of the Danish seine do not negatively affect this species, especially as bottom trawling intensities of up to a SAR of 6 year^{-1} were observed at these sites. Pockets of lower bottom trawling effort were mostly associated with mixed sediments. Here, communities were characterised by large-bodied filter feeders, which are traits associated with low impact areas (Bremner et al. 2005, Tillin et al., 2006). These types of traits are generally less common in benthic communities (Shojaei et al., 2021), particularly in high energy environments (Gray & Elliot, 2009). This is thought to be due to the vulnerability of these traits to physical damage and high sediment re-suspension (Jennings & Kaiser 1998), and they are therefore more common in unfished or lightly fished areas (McLaverty et al., 2021).

This study represents the first examination of the effects of Danish seining on seabed fauna undertaken at the scale of the fishing fleet. Our understanding of the benthic effects of Danish seines has come from experimental bottom trawling studies and shows that passes of the Danish seine results in minor changes to species abundances and limited impact at the community level (Bromhall et al., *In Prep*; Chapter 4 of this report). The results of this study support these observations, with species and trait level changes taking place, but without any changes observed to community metrics. The relatively low benthic impacts of the gear likely reflect its shallow penetration depth, but also may reflect the dominance of generalist and stress adapted species across the bay. Given that the commonly deployed alternative fishing gear to Danish seines in these areas are beam trawls, which are associated with relatively high benthic depletion rates, these results may be of interest to those considering low impact gears in a fisheries conservation approach (Bromhall, 2022; Perry et al., 2022; Suuronen et al., 2012).

Wadden Sea: The influence of environmental drivers differed in northern and southern areas of the Wadden Sea. Communities to the north were chiefly influenced by organic content and were associated with shallow living deposit feeders. Characteristic species included the polychaetes *Scoloplos armiger* and *Lagis koreni*, both of which are known to thrive in the presence of high nutrient enrichment (Sampaio et al., 2010). The observed positive relationship between community biomass and organic content also suggests that elevated nutrients act as an important food supply for local benthic communities. To the south, bottom currents and bottom trawling were more influential, with bottom current speeds at these sites being some of the strongest observed in the study. Strong seabed currents can affect benthic fauna in a similar way to bottom trawling (Szostek et al., 2016; Van Denderen et al., 2015), and we similarly observed significantly reduced benthic abundance and functional richness at sites with the strongest current speeds. Bottom trawling intensity had significant negative impacts at the community level, with abundance and biomass declining with bottom trawling intensity, and reflecting observations from *Nephrops* fisheries in Kattegat (McLaverty et al., 2020b). The presence of intense bottom trawling and strong currents suggests a high-stress benthic environment in the southern Wadden Sea, and this was further reflected by the high biomass of mobile scavengers and predators at these sites.

Unlike some large bodied benthos, the brown shrimp *Crangon Crangon* and common shore crab *Carcinus maenus* are able to tolerate strong current and tidal regimes (del Norte-Campos and Temming, 1994; Seitz et al., 2014). The positive relationship between *C. crangon* and bottom trawling intensity would also suggest these areas represent optimal habitat for brown shrimp, which are typically associated with high levels of natural disturbance (Bergman et al., 2015). Furthermore, scavenging crab species are known to increase in response to beam trawling activities (Ramsay et al., 1998), due to their mobility and ability to utilise carrion and other organic matter provided by fisheries (Tillin et al., 2006). It has previously been assumed that impacts of shrimp trawling on benthic fauna were relatively minor, given that brown shrimp grounds are often naturally disturbed (Rijnsdorp et al., 2018). While we observed some positive relationships with bottom trawling, we also found that community abundance and biomass where significantly reduced. This would therefore suggest that shrimp trawling may result in more significant negative impacts than previously assumed.

Regardless, the influence of nutrients and bottom currents were greater than the influence from bottom trawling and natural drivers across the site. The Wadden Sea experiences long-term eutrophication (Beukema and Cadée, 1986), and reflecting the results of this analysis, long term data records have suggested a resulting overall increase in benthic biomass due to elevated nutrients (Beukema and Dekker, 2020). Nevertheless, current eutrophication levels are considered excessive and detrimental to the growth and distribution of ecological important benthic habitats such as seagrass beds (Philippart et al., 2020). This, and the widespread and intensive bottom trawling observed in this study, would suggest that large areas of the Danish Wadden Sea are strongly impacted by multiple human pressures. The potential cumulative impacts of these pressures should therefore be carefully considered in environmental management strategies for the area, particularly as the ecological communities of the Wadden sea are relatively sensitive to the effects of the pressures of climate change and sea level rise (Beukema and Dekker, 2005).

Løgstør Broad: Trait and species composition were chiefly influenced by organic content and bottom currents in Løgstør Broad. These two variables were strong drivers for roughly half the sites examined, located mainly to the west and centre of the basin. There was also a close association between these sites and ascidians (sea squirts), which are well adapted to exploit the elevated levels of nutrients and higher water movement in the areas. Ascidians are efficient benthic filter feeders that use cilia and mucus to trap sediment particles as they pass through their sac-like bodies (Petersen & Svane, 2002). Ascidians are also sensitive to bottom trawling (McConnaughey and Syrjala, 2014), and their abundance here may well also be linked to the lower bottom trawling effort in western areas. However, the RLQ scores for bottom trawling were relatively low, indicating a low overall influence of this variable. In contrast to this, bottom trawling showed a significant negative relationship with total biomass, indicating a stronger effect at the community level. Sites associated with lower organic content and weaker current speeds were not spatially aggregated and occurred in a more widespread distribution. The communities at these sites were associated with a high biomass of small-bodied mobile deposit feeders, such as netted dogwelk *Nassa reticulata* and mud snail *Peringia ulvae*. These species are highly characteristic of subtidal mussel beds (Conner et al., 2004), and therefore may be representative of mussel bed occurrence.

A key finding from this case study is that elevated levels of organic content have led to clear detrimental effects on benthic fauna. While increases in nutrients can benefit benthic fauna i.e.

as a food source, chronic nutrient loading can lead to reduced benthic diversity and biomass (Pearson and Rosenberg, 1978). We found that benthic abundance and functional diversity were significantly reduced under higher nutrient loads. This is despite TOC concentrations being relatively comparable to e.g., Jammer Bay and Wadden Sea. However, a clear difference between these areas relates to summer bottom water oxygen concentrations, which were generally hypoxic (~3.12 mg/l) in Løgstør. This is a long-running issue (Jørgensen, 1980; Schourup-Kristensen et al., 2023), and likely related to the combination of long-term nutrient inputs and high residence times. An additional consideration is that under regular disturbance, benthic communities will become stress-adapted over time irrespective of fishing effort (Kaiser et al., 2002). This aspect may explain why we did not observe a strong effect of dredging intensity on trait and species composition. It should also be considered that bottom trawling impacts was still measurable in Løgstør, despite long running oxygen depletion in the area. It is therefore likely the ultra-high resolution black box data used in the fishery enhances our ability to detect bottom trawling in disturbed environments such as in Limfjorden (McLaverty et al., 2020a). In view of this, management strategies that look to mitigate eutrophication and hypoxia should be a priority (Maar et al., 2021), as reducing these pressures would simultaneously improve the health of benthic communities and improve our ability to detect and manage dredging effects in these areas.

South Fyn: Although organic content was particularly high at all sampling sites in South Fyn, the influence of this variable on trait and species composition was greatest in the north. A potential reason for the elevated nutrient content of the sediment was a substantial liquid fertiliser spill that occurred ~40km north of the study area site in 2016. This spill has been associated with considerable ecological impacts (Olesen et al., 2020), although little is known about the impacts to benthic fauna. Of the 60 samples collected in south Fyn, 9 contained no benthic fauna, while another 7 contained only a single species. The scale of eutrophication here is such that total organic carbon was recorded at up to 15.7% in some areas, more than an order of magnitude higher than the maximum observed in Jammer Bay (1.2%), the Wadden Sea (1.3%), and Løgstør Broad (1.4%). At sites in the north, we observed a higher biomass of downward/upward conveyors, subsurface deposit feeders, and soft-bodied fauna. This particular combination of traits have been found in chronically polluted sediments from sewage discharge (Vesal et al., 2021). Characteristic species included the annelids *Arinicola marina* and S*coloplos armiger.* These polychaete species are both tolerant of elevated nutrients (O'Brien et al., 2009), and exhibit positive responses to organic enrichment (Longbottom 1970, Beukema 1991). Sites in the south of the study area were chiefly influenced by depth. Interpreting the ecological effects of depth can be challenging, as depth often relates to several environmental variables simultaneously (e.g., temperature, salinity, light attenuation, etc.). However, oxygen depletion maps provided by the Danish Environment Agency (table 1) reveal that the deeper areas of South Fyn are associated with minimal O_2 concentrations over large parts of the year. In this case, this would suggest that depth is acting as a proxy for oxygen concentrations. In addition, we found a greater biomass of exoskeleton traits, in line with observations from deep-water low oxygen sedimentary habitats (Pacheco et al., 2011), with *Philine* sp. and *Ophiura albida* particularly prominent. *Philine* sp. are a species often found under moderate levels of hypoxia (Nilsson & Rosenberg, 1994), while *O. albida* are considered resistant to severe hypoxia (Diaz & Rosenberg, 1995).

While the benthic fauna recorded across South Fyn were generally well adapted to high levels of organic matter and low oxygen concentrations, communities were significantly depleted in terms of abundance and functional diversity. We observed no effect of bottom trawling on community indicators and little influence on trait/species composition, despite relatively high bottom trawling intensity. These finding are line with observations from oxygen depleted areas of the Baltic, where bottom trawling intensity has been shown to have no effect on communities exposed to chronic hypoxia (van Denderen et al., 2022). Considering this, reducing nutrient loads and mitigating the effects of hypoxia should therefore be prioritised in this area to improve the ecological condition of the seabed. This is particularly relevant as the South Fyn straight has been considered for inclusion in a 'no-trawl' marine protected area in the Belt Seas, which aims to improve marine biodiversity (Danish Environment Agency: https://fvm.dk/fiskeri/indsatsomraader/baeredygtigt-fiskeri/trawlfri-zone-i-baelthavet).The results of this study would suggest that any ecological benefits from reducing bottom trawling may be negated by the effects of chronic eutrophication in the area.

4. Experimental effects of a Danish seine on benthic fauna in sandy substrates of the southern Skagerrak

Ciarán McLaverty, Ole R. Eigaard, Thomas Noack & Grete E. Dinesen

(McLaverty et al. *In prep*, Appendix 2)

4.1 Introduction

In contrast to other commercial bottom trawls such as otter trawls and beam trawls, the Danish Seine is a relatively lesser-known bottom-towed gear. To date, there has been little empirical research regarding the impacts of Danish seines on seabed biota (although see Bromhall et al., *in prep*), despite its widespread use in coastal regions of Denmark (Dinesen et al., 2018; McLaverty et al., 2023) and in other coastal areas globally (Wijayanto et al., 2020). In the absence of empirical evidence, it has been assumed that Danish seines would be associated with relatively low ecological impacts (Eigaard et al., 2016), due to their design, and relatively light weight components (O'Neill and Noack, 2021).

Although classed as a demersal trawl (Council Regulation (EC) 850/98), the operation and gear components of the Danish seine differ considerably from standard bottom trawls. A Danish seine haul begins when the fishing vessel drops anchor and lays out two long lead-filled seine ropes (≤3 km long) in a pyriform or roughly triangular pattern (Figure 4.1 B). A seine net, attached to a ground gear, sits at the midpoint of the two ropes and is used to gather the fish as the main ropes come together during winching from the anchor point. The ground gear, which sweeps only ~1% of the Danish seine footprint, is thought to penetrate the top few centimetres of the sediments, while the ropes (the remaining 99%) pass over the sediment surface (Noack et al., 2019).

Methods such as experimental fishing studies, where an area of seabed is experimentally trawled with a defined gear and known fishing intensity, are particularly useful to quantify and risk assess the short-term and localised impacts of fishing on the seabed (Sciberras et al., 2018). In this chapter, we describe an experiment undertaken to observe the effects of a Danish Seine on benthic fauna in a low impact area of established Danish seine fishing grounds. Benthic samples were collected directly before and after fishing, and changes in the community were measured in terms of community composition, community indicators, and the response of common species. This study represents the first impact experiment undertaken in the Jammer Bay, the primary fishing grounds for this gear in Danish and European waters.

4.2 Materials and methods

Fishing took place within an area of roughly 2 x 1 km, located in approximately 7m water depth at 57.2°N and 9.4°E in June 2018 (Figure 4.1 A & B). The area was selected in agreement with the local fisherman's cooperative, as it provided a representative habitat of the larger fishing grounds and was considered to be subject to low levels of fishing. Sampling resulted in a total of 48 benthic samples collected from the experiment (24 before, 24 after fishing). Samples were collected using a 0.1m^2 Van Veen and preserved in 4% formalin/seawater solution buffered with borax (sodium borate).

Potential changes in the benthic community from fishing were examined using community indicators (abundance, species richness, and biomass), analysis of community composition, and the relative occurrence of common species before and after fishing. Differences in community composition before and after fishing were examined using a one-way permutational multivariate analysis of variance (PERMANOVA) design. PERMANOVA models were based on 999 permutations and on Bray-Curtis dissimilarity.

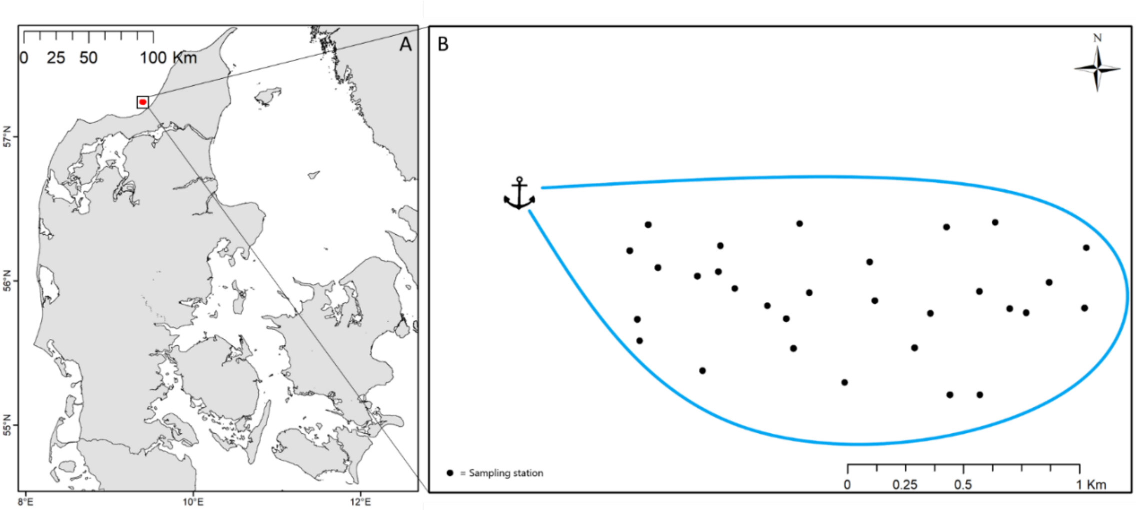


Figure 4.1: (A) Location of experimental fishing site in Jammer Bay off the northwest Danish coast (B) Location of sampling stations (black points) that were sampled before and after fishing. The estimated footprint of the Danish seine ropes is shown in blue, in relation to the anchor point of the seine.

4.3 Results

The results of the GLMs revealed no significant changes to mean abundance (β=-0.04, se=0.06, p=0.493), species richness (β=0.04, se=0.07, p=0.58) and biomass (β=-0.18, se=0.18, p = 0.327). Nevertheless, each of the indicators exhibited a relatively minor decline in values post fishing (Figure 4.2). Similarly, the composition of the benthic community as a whole did not vary significantly during the experiment. The results of the PERMANOVA analysis indicted that both abundance (pseudo-F = 1.28, p = 0.201) and biomass-based community composition (pseudo-F = 1.56, p = 0.146) were statistically similar before and after fishing.

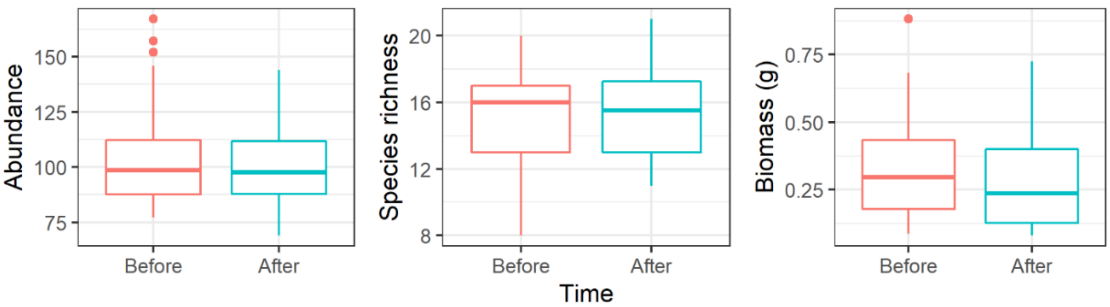


Figure 4.2: Comparison of benthic (A) abundance (B) species richness and (C) biomass before and after fishing.

Table 4.2 summarises changes in the 10 most abundant and highest biomass species recorded in the data. In terms of abundance, 6 of the 10 species declined after fishing, while 4 species increased in numbers. Two of these responses were statistically significant, and occurred for the annelid *Owenia fusiformis*, which increased by 69% after fishing, and the phoronid *Phoronis muelleri*, which decreased by 42%. Similarly, 6 species decreased and 4 increased in biomass after fishing, with three of these changes being statistically significant. These included the bivalve *Chamelea gallina* (82%) and brittlestar *Opuira ophiura* (85%) that declined after fishing, while the biomass of the annelid *Magelona mirabilis* was 30% higher.

Table 4.2: Differences in species abundance and biomass before and after fishing. Statistically significant changes (α= 0.05) are highlighted with an asterisk (*).

Abundance						
Class	Species	Before	After		% Change	Total
Bivalvia	*Fabulina fabula*	786	708	↓	9.9	1494
Bivalvia	*Mactra stultorum*	765	661	↓	13.5	1426
Annelida	*Magelona mirabilis*	315	392	↑	24.4	707
Annelida	*Chaetozone setosa*	104	89	↓	14.4	193
Annelida	*Owenia fusiformis*	62	105	↑	69.3*	167
Phoronida	*Phoronis muelleri*	86	50	↓	41.8*	144
Bivalvia	*Phaxas pellucidus*	66	57	↓	13.6	123
Annelida	*Sigalion mathildae*	54	59	↑	9.2	113
Annelida	*Spiophanes bombyx*	49	61	↑	24.4	110
Annelida	*Nephtys hombergii*	44	33	↓	25	77
Biomass (g AFDW)						
Class	Species	Before	After		% Change	Total
Echinodermata	*Echinocardium cordatum*	3.031	2.772	↓	8.5	5.803
Bivalvia	*Fabulina fabula*	1.476	1.304	↓	11.6	2.780
Bivalvia	*Chamelea gallina*	1.522	0.275	↓	81.8*	1.797
Bivalvia	*Mactra stultorum*	0.208	0.641	↑	207.9	0.849
Echinodermata	*Ophiura ophiura*	0.488	0.072	↓	85.1*	0.560
Annelida	*Magelona mirabilis*	0.214	0.279	↑	30.1*	0.494
Annelida	*Sigalion mathildae*	0.238	0.211	↓	11.2	0.449
Annelida	*Nephtys hombergii*	0.277	0.125	↓	54.7	0.403
Bivalvia	*Ensis ensis*	0.009	0.235	↑	2511	0.244
Gastropoda	*Euspira nitida*	0.11	0.112	↑	2.6	0.244

4.4 Discussion

While the results of this experiment did not show any community level responses of benthic fauna to Danish seining, we did observe some changes in the abundance and biomass of specific species. Prior to this study, Bromhall et al (in prep) provided the only other experimental impact study examining the ecological effects of the Danish seine. Their results are based on trials conducted in the western Kattegat, examining the seabed impact of both single and multiple passes of the Danish seine. Under both intensities, only minor reductions in community composition, abundance, species richness, and biomass were observed, closely corroborating our findings. Similarly, they observed some species-specific responses that were deemed to be attributable to fishing.

The absence of significant community level impacts in both studies from a single pass of the seine is likely due to fact that the Danish seine ropes (which constitute 99% of the gear footprint) only disturb the surface of the sediment surface. It is therefore unlikely that the gear can affect sediments to a depth that could result in large scale changes to the community. By comparison, commercial trawls such as otter trawls are estimated to penetrate sediments to an average depth of 2.5 cm and remove roughly 6% of biota with each pass (Hiddink et al. 2017). Furthermore, heavier gears such as beam trawls result in average penetration depths of 2.7 cm and depletion rates of ~14%. Changes in the occurrence of the most common species revealed a significantly reduced number of horseshoe worm *Phoronis sp.* after fishing. Interestingly, this is the same species observed to be sensitive to Danish seining in the studies of Bromhall et al., (in prep), and a comparative study of Danish seining gradients by McLaverty et al., (in prep). The reason why *Phoronis sp.* has been identified as sensitive to Danish seines across studies is likely due to the erect position of their fragile tubes at the sediment surface, and the dynamics of the Danish seine ropes, which primarily disturb the surface layer of sediment.

Due to a close proximity between areas fished by local Danish seiners and that by international beam trawlers, there has been considerable political debate regarding these fisheries and their relative sustainability in the Jammer Bay. Although beam trawls are known to be associated with high benthic depletion rates (Hiddink et al., 2017; Sciberras et al., 2018), it has previously not been possible to compare impacts due to a lack of quantitative impact studies for the Danish seine. Although this study focuses on the impacts of a single pass of a Danish seine, we consider it likely that benthic mortality will remain low under repeated impacts. This is as comparative studies have found little differences in community abundance and biomass between lightly fished areas and those impacted up to 6 times per year in the Jammer Bay (McLaverty et al., *in prep*). In view of this, Danish seines are likely to result in lower impacts to seabed fauna and benthic ecosystems than those arising from beam trawling and may be better suited to achieving the aims of an ecosystem approach to fisheries management.

5. An assessment of benthic indicators used to detect and monitor coastal bottom trawling impacts

Ciarán McLaverty, Ole R. Eigaard, Jeppe Olsen, Mollie E. Brooks, Jens Kjerulf Petersen, Anders C. Erichsen, Karin J. van der Reijden & Grete E. Dinesen

(McLaverty et al. 2023, Appendix 3)

5.1 Introduction

Benthic indicators developed under the WFD for use in coastal areas typically take the form of multi-metric indices i.e. single value metrics that use several separate indicators in their calculation. These indices are usually based on a combination of e.g. abundance, species richness, a diversity index (e.g. Shannon's diversity index), and species sensitivity scores. The inclusion of the species sensitivity scores are to incorporate estimates of the relative abundance of stress tolerant/sensitive taxa in a sample. As the WFD allows indicators to be developed on a country-by-country basis, a number of indicators are used across Europe (Van Hoey et al., 2010). In this regard, most nations (including Denmark), use indices that incorporate species sensitivity scores from AZTIs Marine Biotic Index (AMBI) (Borja et al., 2000), while some use scores from the Benthic Quality Index (BQI) (Rosenberg et al., 2004) or other metrics. Intercalibration studies have shown that many WFD indices are adept at monitoring pressures such as organic enrichment and chemical pollution, a key focus of the WFD (Borja et al., 2015). However, comparatively little attention has been given to examining the response of these indices to bottom trawling. This aspect merits further consideration, given that bottom trawling is widespread in coastal areas (Eigaard et al., 2017), and there is evidence from offshore areas that some WFD indices respond poorly to bottom trawling disturbance (Gislason et al., 2017).

Several issues have to date hampered research regarding the ecosystem effects of bottom trawling in coastal areas (see chapter 1). Nevertheless, it has been assumed that bottom trawling impacts in nearshore areas may be lesser than in deeper offshore areas. This is as natural forces are comparatively strong (e.g. tides, currents, seasonal changes, storms, salinity gradients), and cumulative human impacts are highest (Halpern et al., 2008) in coastal areas. Accordingly, coastal benthos can be naturally robust to disturbance (Szostek et al., 2016), and communities may be naturally less diverse (Josefson and Hansen, 2004) than those in offshore areas. In a Danish context, most coastal areas experience wide gradients of natural and manmade disturbance. Fishery effects have accordingly proven difficult to measure, particularly in the presence of high nutrient enrichment (eutrophication) and oxygen depletion (Bromhall et al., 2022; McLaverty et al., 2020a). However, studies to date examining the benthic impacts of coastal fisheries in Denmark have been fishery specific, and there is a lack of evidence at the scale of national and international fishing fleets.

In this study, we examine (i) the effects of chronic bottom trawling and natural drivers on coastal benthic macrofauna across Danish coastal areas, and (ii) the ability of widely used benthic indicators and WFD indices to detect bottom trawling impacts. We do this by combining VMS and AIS data to estimate high-resolution bottom trawling effort covering a national coastal area over a 12-year period. Using generalised linear mixed models, we model the response of 4 standard biodiversity indicators (abundance, species richness, Shannon diversity, biomass) and 4 multi-metric indices (AMBI, M-AMBI, DKI and BQI) to bottom trawling and environmental gradients. The study provides new evidence of the effects of bottom trawling on the seabed in coastal areas, and an appraisal of indicators best suited to evaluating benthic ecological status.

5.2 Materials and methods

Benthic macrofauna and sediment data were gathered from the ODA database (Surface Water Database, ODA - https://odaforalle.au.dk), provided by the Danish national environmental monitoring programme (NOVANA). The locations of the benthic samples are shown in Figure 5.1.

Environmental data were also included from several MIKE 3 HD Flexible Mesh (FM) models that provide high-resolution modelled data for 3 key physical water parameters; bottom current velocity (mean), bottom salinity (minimum), and bottom temperature (mean). In addition, each of the 5,885 macrofauna samples extracted from the ODA database were matched with 1 year of bottom trawling pressure data, estimated back in time from the day of sampling. This included effort from all bottom trawling gears using VMS, AIS, and Black box data with fishing tracks reconstructed via interpolation (Hintzen et al., 2010). For Danish seines, a deviating method was applied to compensate for their distinct fishing pattern (see Chapter 2).

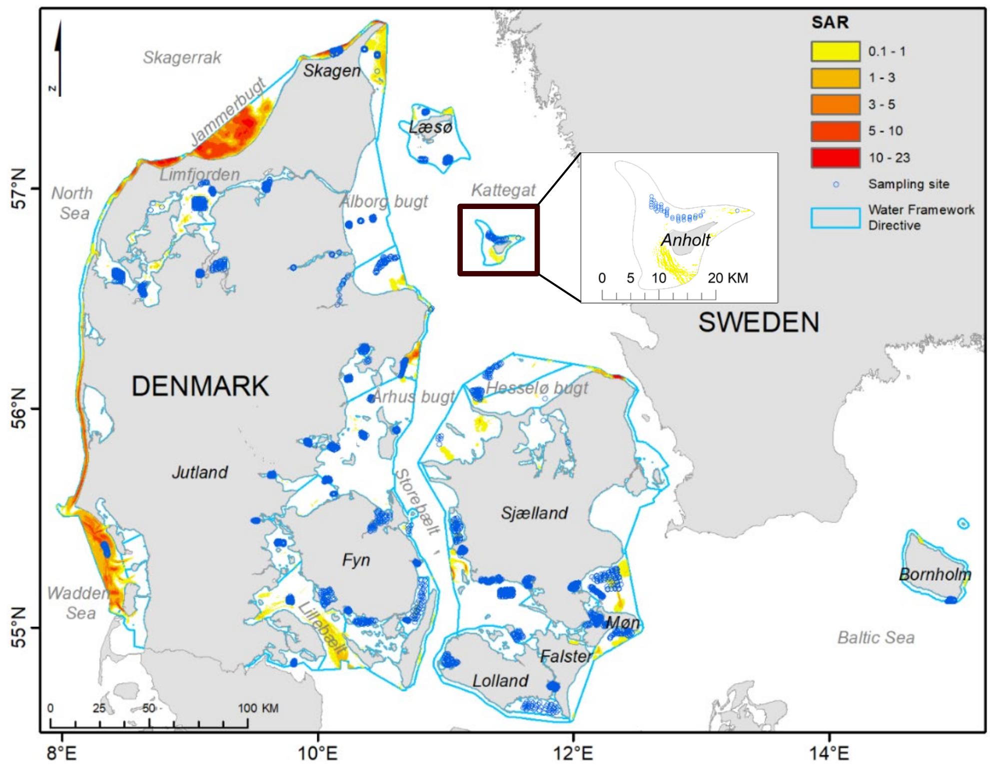


Figure 5.1: Location of benthic sampling stations (blue circles) in Danish Water Framework Directive (WFD) areas. Bottom trawling effort is shown as annual average swept area ratios (SAR) in grid cells of 100 x 100m for all gears pooled over the study period (2005 – 2017). Inset shows a grid of 41 individual sampling stations at the Anholt monitoring site. Note that because of the speed-filtering method grid cells can falsely be mapped as fished if vessels slow down for other reasons than trawling. This is especially the case close to some harbours (e.g., south of Anholt and south of Skagen).

The macrofauna data were used to calculate 8 benthic coastal monitoring metrics. These comprised 4 univariate indicators; total abundance (N), species richness (S), Shannon diversity (H'), and biomass, and 4 WFD multi-metric indices; AZTIs Marine Biotic Index (AMBI), the multivariate AMBI (M-AMBI), Benthic Quality Index (BQI), and the Danish Quality Index (DKI). To aid interpretation, we present the results for AMBI on an inverse scale, as unlike the other indicators in this study, AMBI describes high ecological quality using a low value (0 = high quality), while poor quality is reflected by high values (7 = poor quality). Generalised linear mixed effects models (GLMMs) were used to analyse the response of indicators to bottom trawling and environmental pressures. Each GLMM included bottom trawling intensity (SAR year-1), sediment type, water depth, bottom temperature, bottom salinity, bottom current speed, and latitude as fixed effects, and the monitoring site and sampling year as random effects. We quantified the importance of each predictor variable using Relative Variable Importance (RVI) scores, which estimates and quantifies predictor importance using multi-model inference and provides a score irrespective of statistical significance. Variables can thus be interpreted as highly important (RVI > 0.9), moderately important (RVI 0.9 - 0.6), or low to no importance (RVI < 0.6). We interpreted a RVI score of >0.6 as a clear indicator response to a predictor.

5.3 Results

Depth, latitude, sediment type, and bottom trawling intensity were particularly important across coastal areas, exhibiting RVI scores above 0.9 (Figure 2). Higher bottom trawling intensity was associated with lower values for all indicators except AMBI and DKI (Figure 5.2). Bottom trawling was particularly important for N (RVI 0.97), S (RVI 0.99), and BQI (RVI 0.77), but was of little to no importance for H' (RVI 0.45), AMBI (RVI 0.37), M-AMBI (RVI 0.3), and DKI (0.27). The degree of explained variance in the models ranged considerably, from high values of 72% (S) and 63% (N), down to values of 7% (DKI), and 4% (M-AMBI).

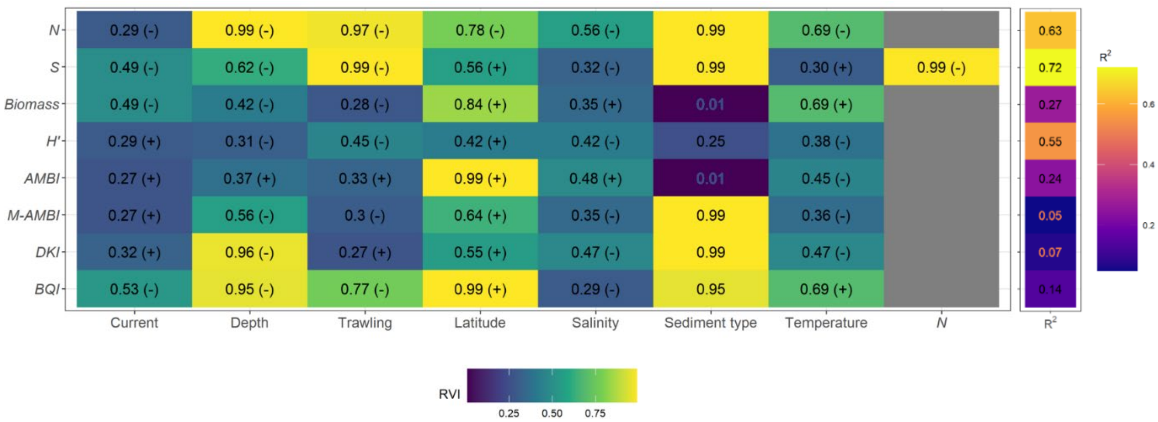


Figure 5.2: Relative variable importance (RVI) of environmental and fishing pressures on macrofaunal indicators. RVI scores can be interpreted as >0.9 = highly important, 0.9 - 0.6 = moderately important, <0.6 = low to no importance. Symbols indicate the direction of relationships between variables: positive (+) or negative (-). Note: *AMBI* values are reversed to aid interpretation, while sediment type is a categorical variable. R^2 values indicate variance explained by best fitting model.

Figure 5.3 reveals that N was markedly higher at non-trawled sites (Figure 5.3a), and reduced at heavily trawled sites (>20 SAR year^{-1}). Although the decline was not as sharp for S (Figure 5.3b), richness declined steadily from the non-trawled areas (max. 29 species) with increasing bottom trawling intensity (max. ~18 species at sites >20 SAR year^{-1}). Values of BQI also showed a clear negative relationship with bottom trawling (Figure 3e), despite a subset of sites with BQI values of ~12 recorded at high bottom trawling intensity. This group of sites were chiefly composed of samples from the Wadden Sea and Jammer Bay. Although most of the large biomass values were recorded in non-trawled areas (Figure 5.3c), the overall relationship with bottom trawling was weak (RVI 0.28). This is likely a result of the relatively low number of high biomass values recorded in the dataset. The majority of non-trawled biomass samples were <2g, which was generally comparable to biomass in the trawled areas. The indicators H' and M-AMBI exhibited no interpretable relationships with bottom trawling (Figure 3d/f). Conversely, AMBI (Figure 3e) and DKI (Figure 3g) exhibited positive trends (Figure 3e/g), although these were not found to be related to bottom trawling (RVI: 0.33 and 0.27, respectively).

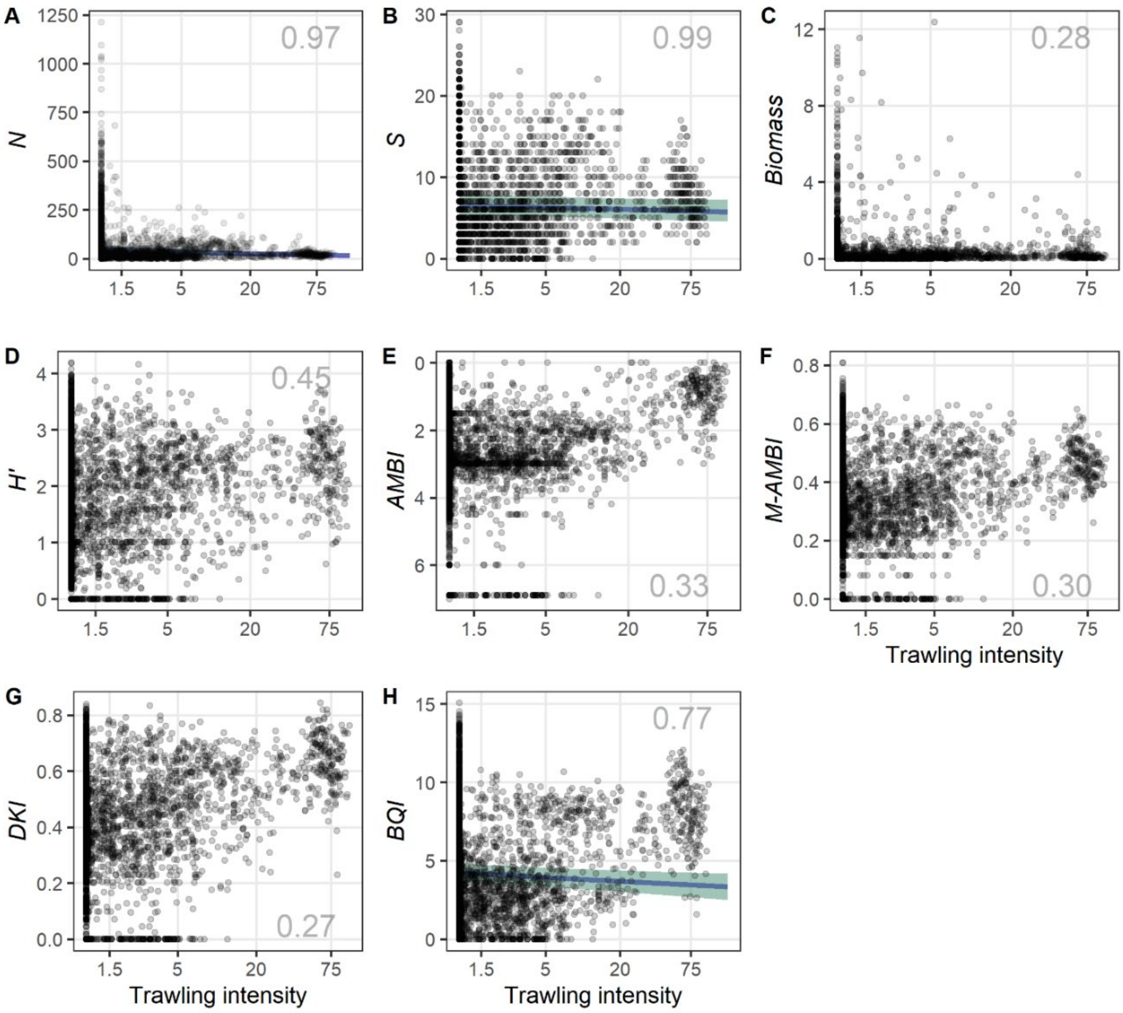


Figure 5.3: Relationships between monitoring metrics and bottom trawling intensity (SAR year^{-1}). Regression lines are shown for RVI scores >0.6. Greyed areas represent 95% confidence intervals. Inset values display the associated RVI score. Raw observations are overlaid as points. Bottom trawling intensity is presented on a logarithmic scale for presentation purposes. Note: *AMBI* values are reversed to aid interpretation. Biomass values are in grams.

A relatively clear and consistent relationship between high N (darker red colour) and lower bottom trawling intensity (smaller circles), and lower N (light red/white) and high bottom trawling (large circles) was evident across the study area (Figure 5.4a). The consistency of this relationship across sites would suggest that bottom trawling effects on N are consistent across environmental conditions. A similar relationship was observed for S and bottom trawling, albeit to a lesser degree (Figure 5.4b). Although some lightly trawled areas had higher BQI values (Århus Bugt, Ålborg Bugt, Anholt), areas such as Skagen and Wadden Sea were also associated with high bottom trawling (Figure 5.4h), and potentially explaining the lower RVI score for BQI. In addition, low BQI values were often associated with low salinity areas, irrespective of bottom trawling intensity (e.g. Sjælland, Fyn, Bornholm and in Limfjorden). This may suggest that BQI is better suited to detect bottom trawling impacts in open marine coasts, as opposed to smaller enclosed inlets, broads and fjords which are freshwater influenced. While AMBI, M-AMBI, and DKI values varied across the study area, there appeared little relationship with these indices and bottom trawling intensity.

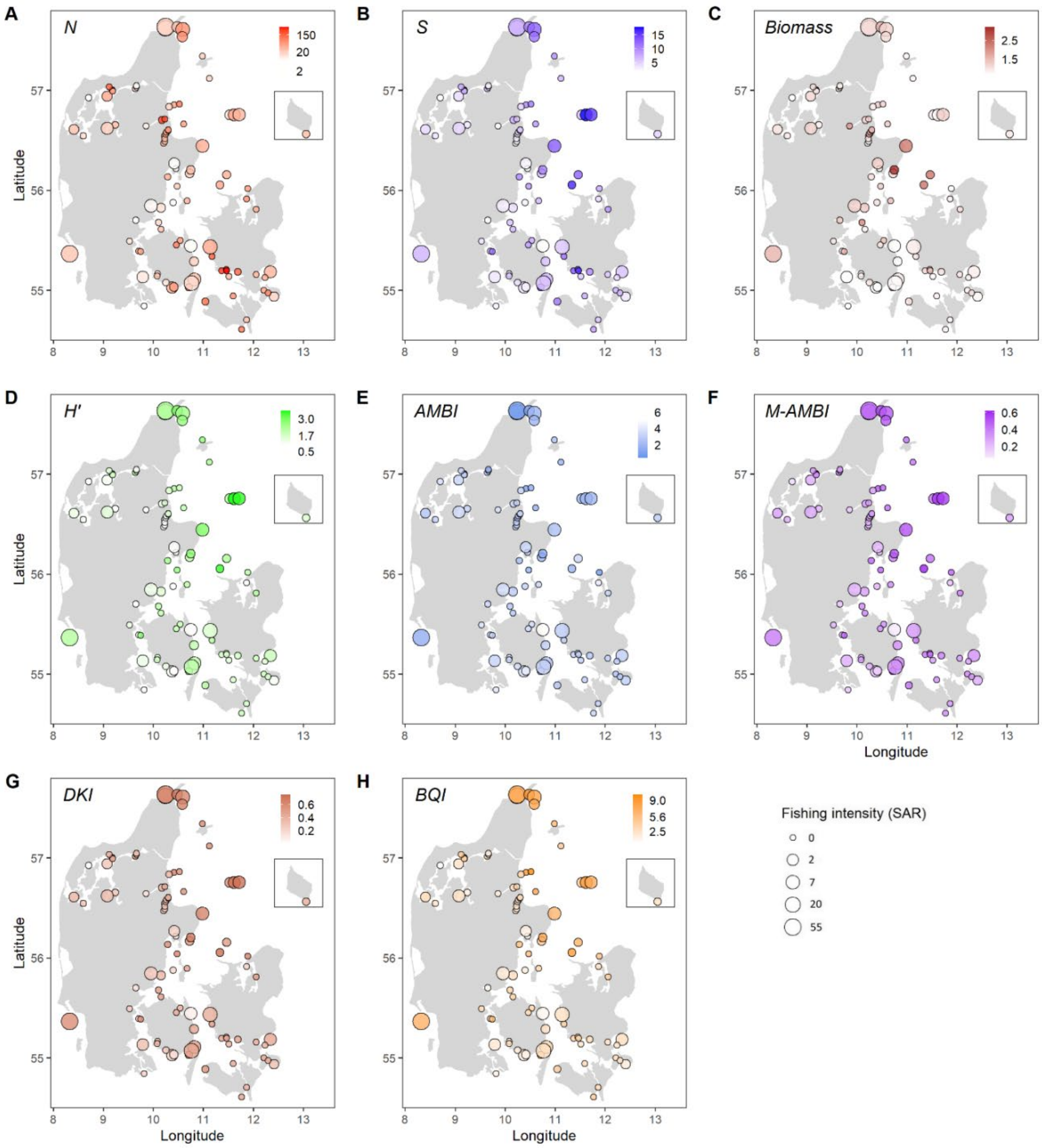


Figure 5.4: Spatial distribution of monitoring metrics as a function of bottom trawling intensity (SAR year^{-1}). The scale for *N*, *H'*, and *BQI* are log transformed to aid interpretation. The island of Bornholm is shown in the inset. Note: AMBI scale is reversed.

5.4 Discussion

Until now, studies investigating the impacts of bottom trawling in coastal areas have been hampered by poor data coverage for nearshore vessels. We used a hierarchical merging method in this study to combine complementary types of fisheries data (VMS, AIS, and BBS) and logbook information (see Appendix 3 for details), resulting in high resolution fishing pressure estimates for the entire Danish coastal area. This allowed us to observe, for the first time, that coastal bottom trawling has reduced benthic abundance (N) and species richness (S) across Danish nearshore water bodies. The BQI index, used to assess benthic quality in Swedish WFD areas, detected these changes to the community. However, the other WFD indices examined (DKI, AMBI, and M-AMBI) showed no response to bottom trawling, nor did H' or biomass, corroborating observations from offshore waters (Gislason et al., 2017). The results of this study highlight a considerable risk that WFD metrics used to monitor the health of coastal benthic ecosystems, and efforts towards Good Ecological Status (GES), may be unable to detect bottom trawling impacts on the seabed. Although the DKI is primarily used in Denmark, AMBI is used as a key component in the majority of European benthic monitoring indices (Borja et al., 2015). These findings are therefore highly relevant to coastal monitoring programs and national assessments of GES based on these metrics. Given the widespread nature of bottom trawling in European coastal areas (Eigaard et al., 2017), and the role of benthic macrofauna in seabed ecosystem function (Gammal et al., 2017; Kristensen et al., 2014), our results may also have implications for management of human pressures on coastal ecosystems.

The metrics N and S exhibited particularly clear negative relationships with bottom trawling across varying environmental conditions. N was markedly reduced in the trawled areas and showed a clear relationship with bottom trawling in most locations, indicating a generally high sensitivity. The responsiveness of N to bottom trawling is in line with previous studies in Danish waters (Bromhall et al., 2022; Gislason et al., 2017; McLaverty et al., 2020b) and other regions. In contrast, the literature regarding the sensitivity of S to bottom trawling is less conclusive (Hiddink et al., 2020). Biomass and H' did not exhibit changes attributable to bottom trawling. Although biomass is generally considered a highly effective bottom trawling indicator (Hiddink et al., 2020), its responsiveness to bottom trawling can be reduced in the presence of high environmental variation, particularly in eutrophic areas (McLaverty et al., 2020a). Indeed, the strong latitudinal gradient in biomass observed in this study may indicate that the sharp transition from marine conditions in the north, to more brackish conditions in the south, masked any responses to bottom trawling, particularly as biomass is often lower in brackish conditions (Edgar and Barrett, 2002).

Our results found no relationship between bottom trawling and AMBI, M-AMBI, or DKI. Given the prominent role of these indices in WFD monitoring, these findings are potentially significant. A likely explanation is that each of these indices were originally developed to monitor the effects of diffuse coastal pressures such as eutrophication and oxygen depletion (Borja et al., 2000; Josefson et al., 2009; Muxika et al., 2007). Accordingly, AMBI (and thus M-AMBI and DKI) are calculated using species sensitivity scores to eutrophication, based on expert-judgement (Borja et al., 2000). Benthic quality is then assessed by estimating the proportion of pollution tolerant species, relative to the proportion of pollution sensitive species. Given that the calculation of DKI is based on AMBI (Table S2), it is understandable why DKI and AMBI performed similarly, and why DKI has shown either mixed responses (Hansen & Blomqvist, 2018), or no response to bottom trawling in the past (Eigaard et al., 2020, Gislason et al., 2017). In either case, there is strong evidence here to suggest that pollution/eutrophication monitoring indices are poorly suited to identify benthic impacts from physical pressures such as bottom trawling. The other WFD index examined in this study, the BQI, exhibited a clearer response to bottom trawling. This may be due to the fact BQI chiefly uses N and S in its calculation (both sensitive to bottom trawling), and a different set of species sensitivity scores than AMBI/M-AMBI/DKI. In contrast, the BQI sensitivity scores are based on observed species responses to an artificial disturbance gradient, composed of several pressures such as hypoxia, physical disturbance, and toxic substances (Leonardsson et al., 2015). The scorings may therefore better reflect the multiple pressures (anthropogenic and natural) typically occurring in coastal and nearshore areas.

We demonstrate here that bottom trawling negatively impacts benthic macrofauna in nearshore areas, and that these impacts may go undetected by monitoring metrics commonly used to assess Good Ecological Status (GES). The DKI, used to assess benthic quality in Denmark, and AMBI, used in the calculation of many European benthic quality indices (Borja et al., 2015), were found to be unresponsive to bottom trawling. These indices are therefore potentially unsuitable to provide assessments of seabed quality in coastal areas, where multiple pressures are present. Moreover, we observed that some of the most heavily trawled sites were ascribed ‘high ecological quality’, by AMBI and the DKI. On the other hand, the BQI, used to monitor Swedish WFD areas, declined with increasing bottom trawling. The AMBI and DKI indices are tailored to monitor the effects of eutrophication and given that nutrient enrichment remains an enduring issue in all marine regions (Korpinen et al., 2019), these metrics are likely to remain important tools in benthic monitoring. We conclude that no single indicator can provide a ‘silver bullet’ for seabed monitoring, particularly in highly dynamic areas experiencing multiple pressures. It is likely that several metrics with complimentary properties, which can integrate aspects such as community structure, function, and sensitivity, are required to effectively track and measure coastal benthic health. In this regard, our results show N, S, and BQI to be effective indicators of bottom trawling impacts in coastal areas.

6. Bottom trawling impacts on benthic macrofaunal state in Danish WFD water bodies

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6.1 Introduction

Marine coastal systems are under pressure from increasing human resource demands and activities pertaining to fishery, agriculture, industry, and land and sea construction (EEA, 2020). Emissions of nutrients and pollutants, increasing water temperature and acidification combined with fish and aggregate extractions and underwater installations cause adverse effects or loss of seabed habitats and organisms in coastal waters. Benthic habitats of Danish inshore waters are adversely affected by these multiple pressures. While seabed constructions and aggregate extraction impacts locally, nutrient enrichment and derived oxygen depletion and fisheries using mobile bottom contacting gears (hereafter bottom trawling) impact extended coastal areas.

The Water Framework Directive (WFD) (2000/60/EC) focuses on water quality, chemical pollutants, nutrient enrichment and oxygen depletion. The policy aims toward achieving Good Ecological Status (GES) defined as a "slight variation from an undisturbed condition" for each of the European coastal WFD water bodies. The ecological status of a WFD water body is derived from using a lowest common denominator rule for the quality elements (i.e., applying the lowest scoring element state). This "one out – all out" assessment approach is regarded as a precautionary approach towards achieving the goal of GES. However, unidentified causal-relations between specific anthropogenic pressures and the responding biological state variables may prevent development of adequate management measures.

The WFD GES assessments are based on selected quality elements, of which one of the four biological elements is "macro invertebrates". Several indicators have been developed and applied at the national level (Borja et al., 2015). Whereas bottom trawling is the most extensive pressure causing physical disturbance to seabed habitats in coastal waters (Eigaard et al. 2017, Amoroso et al. 2018, McLaverty et al. 2023), Danish inshore waters suffer from high nutrient loadings causing frequent extended hypoxia events (Conley et al., 2007). The ecological state of benthic macro invertebrates in the Danish WFD water bodies are assessed by the indicator "Danish Quality Index" (DKI) (Josefson et al., 2009, Henriksen et al., 2014), whereas the indicator "Benthic Quality Index" (BQI) is used to assess Swedish WFD water bodies (Borja et al., 2015, Nygård et al., 2020). Both indicators rely on measures of density of individuals (N), density of species (S), and different qualitative indices of species-specific stress tolerance. However, recent studies have showed these indicators are insensitive to fishing pressure and, thus, may be inadequate for assessing impacts of bottom trawling on seabed habitats (Gislason et al., 2017, McLaverty et al., 2023).

Recently, the International Council for Exploration of the Sea (ICES) has developed the assessment approach, Fisheries Benthic Impact Tools (FBIT) with several functional indicators that are designed to estimate impacts of bottom trawling of benthic habitats over large spatial scales

(ICES, 2022 2023). The FBIT assessment approach builds upon empiric models of benthic faunal longevity biomass-distributions across different environmental conditions to predict functional responses of benthic habitats and associated communities. Benthic sensitivity, based on faunal longevity compositions, and correlated recovery times from bottom trawling are then related to bottom fishing intensity and gear specific depletion rates in a mechanistic model to estimate seabed state (Relative Benthic State, RBS) and impact (1-RBS) (e.g., Hiddink et al., 2017, Pitcher et al., 2017), and its application has been tested at regional (Rijnsdorp et al., 2018, 2020) and global scales (Pitcher et al., 2022). However, it should be noted that RBS values are designed to be reflective of bottom trawling impacts and does not directly inform of the effects of other pressures on the seabed.

The overall aim of this study was to apply the FBIT assessment approach and explore its robustness in detecting impacts of bottom trawling and state of seabed habitats in coastal areas. Moreover, RBS is compared with the state indicators DKI and BQI that are commonly used in the WFD GES assessment and is discussed relative to their potential application for GES assessment of the Danish WFD water bodies.

6.2 Materials and methods

Study area: The study area included the Water Framework Directive water bodies in the Danish Exclusive Economic Zone (EEZ). These inshore waters fringe the seas of two of the marine subregions as defined by the MSFD biogeographic regions, that is the Baltic Sea subregion in the south-east (incl. the Bornholm basin, western Baltic and the Belt seas), and the Greater North Sea subregion (incl. the Kattegat, Skagerrak, Eastern North Sea and northern Wadden Sea) (Figure 6.1). The transitional area between the two subregions is characterized by an outflowing meso- to polyhaline surface layer and a deeper euhaline inflowing layer. The Danish coastline is long (i.e., ~8,750 km) and convoluted surrounding multiple bays and fjord systems. The Danish coastal waters receive freshwater emission from small riverine systems and mainly agricultural uplands resulting in high nutrient enrichment and derived oxygen depletion of the seabed in many inshore areas.

WFD water bodies and regional subdivision: The WFD GES assessment is carried out for specific inshore water bodies within the Danish EEZ. Due to the hydrographic heterogeneity, we divided the 109 individual Danish WFD water bodies into six areas based on hydrographic characteristics of water salinity, energy (as classified by EMODnet), pycnocline and tidal regime (i.e., Danish area names: Bornholm, Bælthavet (og sydfynske øhav), Kattegat, Limfjorden, Vestkysten og Vadehavet) (Table 6.1). The geographic boundaries of these areas follow the HELCOM divisions for Bornholm, the Belt seas together with the Sound and western Baltic basins, separating them from the Kattegat, Skagerrak and North Sea. The Limfjorden follows boundaries set for the inner Danish waters. The west coast thus fills the gap between the HELCOM boundaries of the Kattegat in the North, and that of the Wadden Sea Conservation Area in the south as defined by the Wadden Sea World Heritage (i.e., with a northern boundary at Blåvands Hug) (Figure 6.1).

Table 6.1: The six areas to which the 139 Danish WFD water bodies were assigned for assessment of Relative Benthic State (RBS) and Impact (1-RBS).

Water area	WFD Water bodies	Salinity (ppt)	Energy	Pycnocline	Tidal regime
Bornholm	2	Mesohaline (5-18)	High	Rare	Microtidal
The Belt seas	103	Polyhaline (18-30)	Moderate-Low	Frequent	Microtidal
Kattegat	19	Euhaline (>30)	High-Low	Frequent	Microtidal
Limfjorden	3	Mesohaline to Pol-yhaline (5-18; 18-30)	Low	Common	Microtidal
The Danish west coast	7	Euhaline (>30)	High	Rare	Microtidal
Wadden Sea	5	Euhaline (<30)	High	Rare	Mesotidal

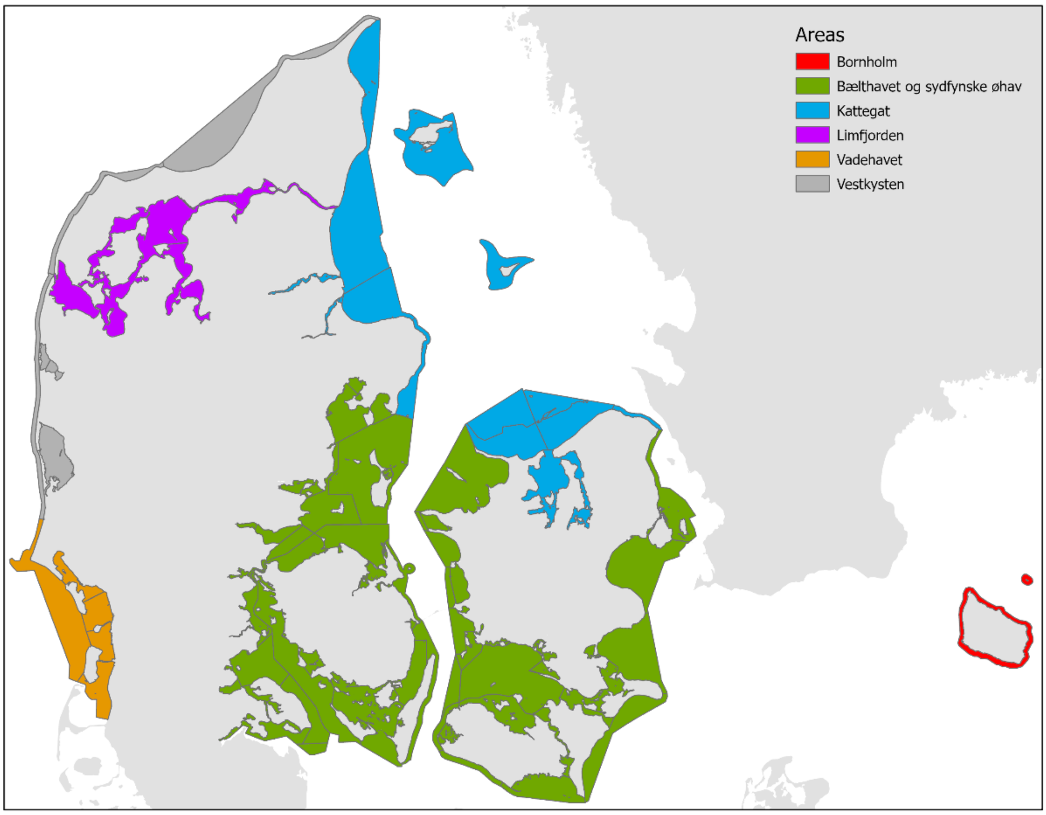

Figure 6.1: Map of the 139 WFD water bodies, divided into 6 areas within the Danish EEZ.

Spatial and temporal data resolution: All spatial data (i.e., categorical, continuous) were assigned to a raster grid following the 0.01 °E x 0.01 °N degrees, equal to grid cell size of ~0.66 km^2 at the geolocation of the Danish EEZ. Due to the annual sampling time of the response variable of benthic macrofauna from ultimo April through May, all pressure and environmental variables that are measured on a continuous scale were summed into an annual value covering the 12-month time period prior to sampling (i.e., from May y-1 to April y).

Depth data: The depth model applied herein was extracted from the EMODnet (Figure 6.2).

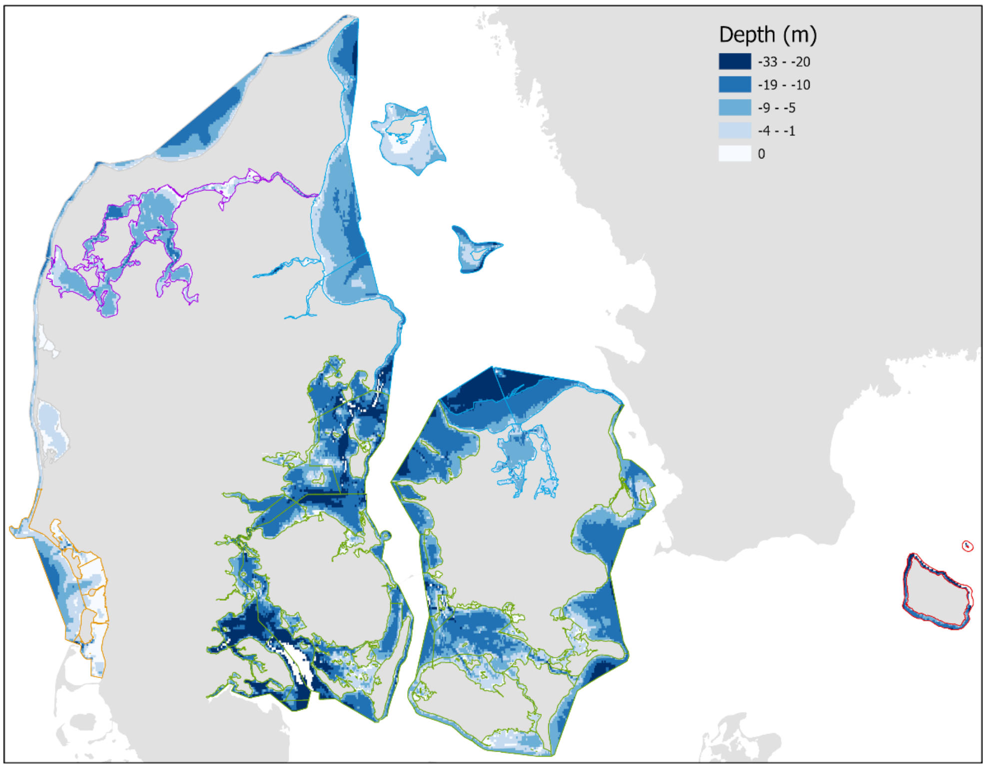

Figure 6.2: Spatial depth distribution in meters from the EMODnet.

Energy information: The data layer for energy was extracted from the EMODnet. The EMODnet energy classification was modified for the Limfjorden (i.e., set to "Low energy") and the Isefjord (changed from "High energy" to "Low energy") based on expert judgement (Figure 6.3).

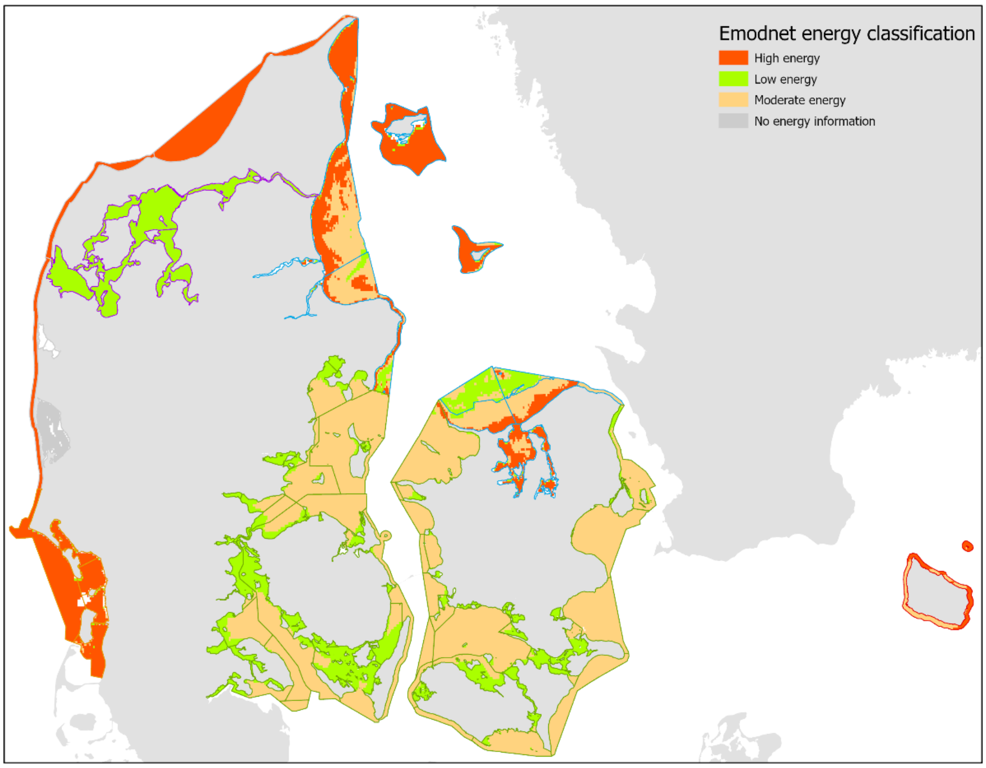

Figure 6.3: Spatial distribution of energy as classified by EMODnet.

Salinity and oxygen data: Salinity and oxygen data were retrieved from the hydrodynamic models Copernicus for the Atlantic region (www.copernicus.eu/da), and the BSIOM (Lehmann et al. 2014) for the Baltic region. From the available quarterly data (January, April, July, and September) data were extracted for the first date of each quarter for the period from 2009-2017. Both models suffer from boundary issues near the coast as well as in the Skagerrak transitional zone between the two biogeographic regions. To address this issue, interpolations were applied to smooth data, however the boundary issues were only partly resolved. Thus, the model was unsuitable for application for the fjords. Salinity data included minimum salinity, maximum salinity and salinity difference from May y-1 to April y (i.e., salinity 1st July y-1, 1st October y-1, 1st January y, 1st April y). The spatial distribution of salinity for May 2009-April 2010 is presented in Figure 6.4-6.6 (for annual salinity values of each quarter, see Figure S1-7, S1-8 and S1-9). Oxygen data included annual minimum oxygen ml/l from May y-1 to April y (i.e., mmol oxygen/m3 for 1st July y-1, 1st October y-1, 1st January y, 1st April y x 0.022391). Negative values were set to zero. The spatial distribution of minimum oxygen for May 2009-April 2010 is presented in Figure 6.7 (for annual salinity values of each quarter, see Figure S1-6).

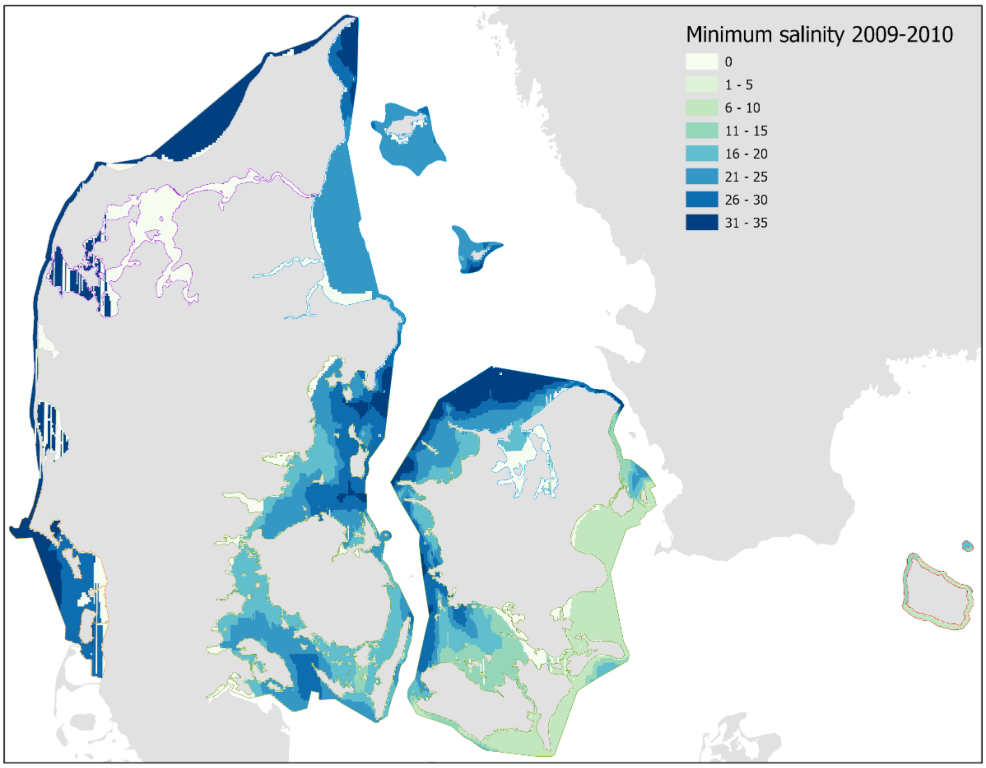

Figure 6.4: Spatial salinity distribution expressed as quarterly minimum for the period May 2009-April 2010.

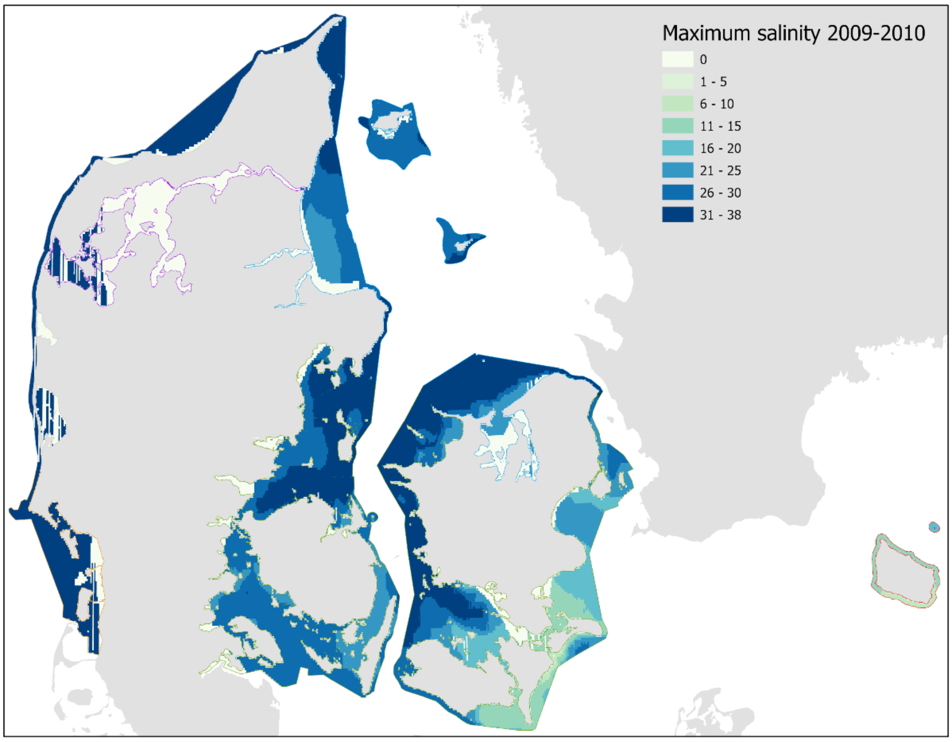

Figure 6.5: Spatial salinity distribution expressed as quarterly maximum for the period May 2009-April 2010.

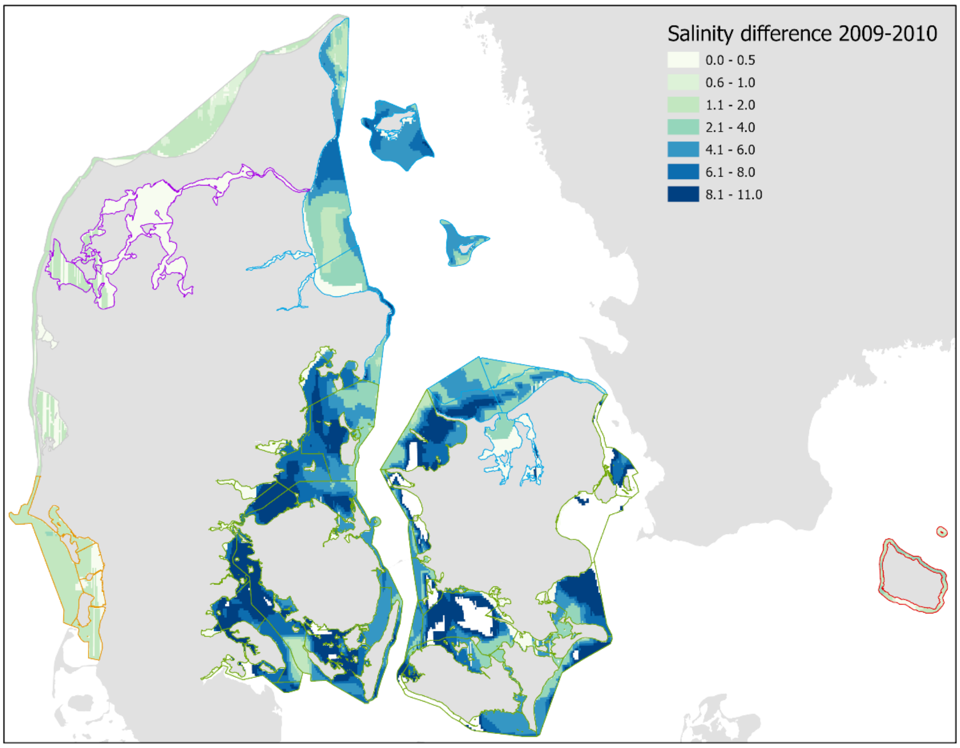

Figure 6.6: Spatial salinity distribution expressed as quarterly difference for the period May 2009-April 2010.

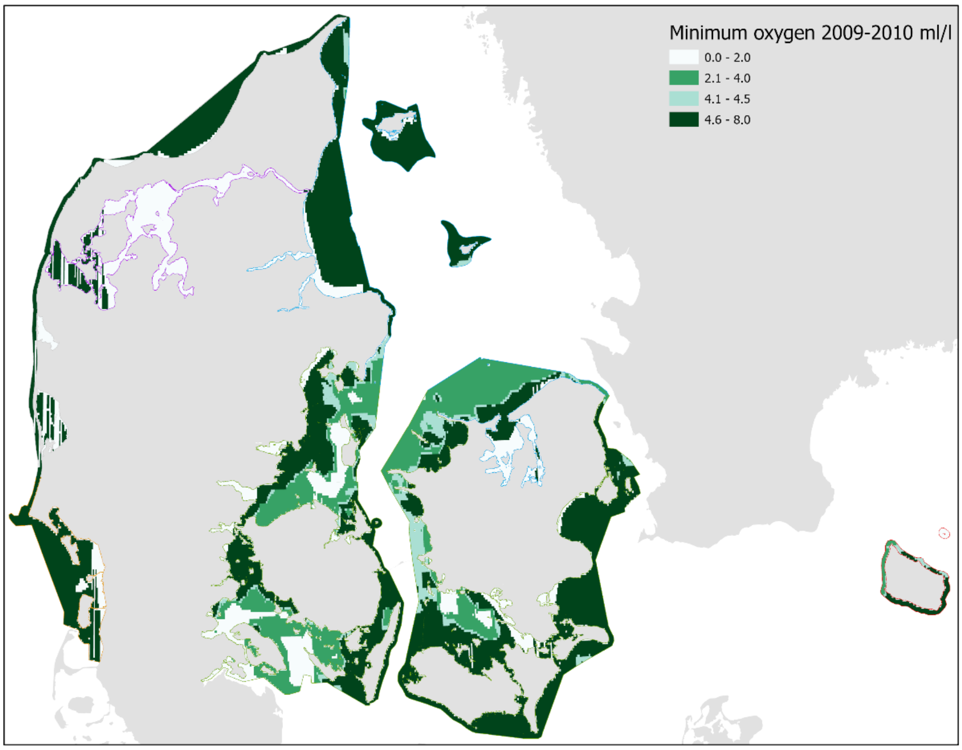

Figure 6.7: Spatial minimum oxygen distribution, mean of the quarterly minimum on ml/l for the period of 2009-2010.

Fisheries data: Pressure intensity and extent of trawling with bottom-contacting gears was estimated as the Swept Area Ratio (SAR) based on data from the Vessel Monitoring System (VMS) and high resolution Black Box data (BBD) combined with fisheries logbook information for each mobile bottom-contacting gear type, including the métiers: i), DRB_MOL; ii), OTT; iii), OTT_SPF; iv), SDN; v), SSC; vi), TBB_CRU; and vii), TBB_DMF (as per Eigaard et al., 2016, 2017; ICES, 2019b). Where appropriate, high-resolution data from the Automatic Identification System (AIS) were joined with VMS data to increase the temporal and spatial accuracy of the fishing footprint. For the period May 2009 – April 2010, daily surface SAR values were modelled, and data were extracted at a temporal scale of 12 months prior to each state indicator sampling event (i.e., in April-May). Thus, the annual spatial distribution of SAR comprises the period from May y^{-1} to April y^{0}, for examples from May 2009 – April 2010 (Figure 6.8) (see Appendix 4 - Supplementary material 1: Figure S1-5 for maps of the spatial distribution of SAR of all 12-months intervals).

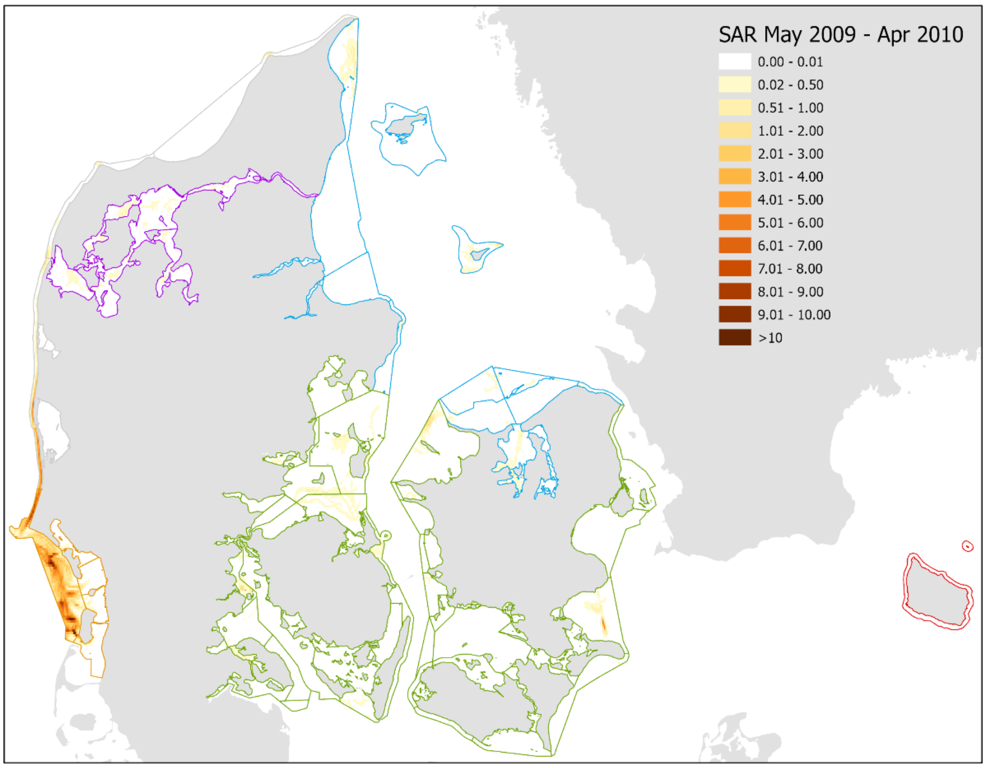

Figure 6.8: Spatial distribution of fishing pressure expressed as SAR for the period May 2009-April 2010.

Correlations between the aforementioned explanatory variables were used to identify the variables selected and tested in the longevity models.

Habitat data: The spatial distribution of the MSFD Benthic Broad Habitat Type data (ver. EUSeaMap2021) were retrieved from the data portal EMODnet (https://emodnet.ec.europa.eu/en/seabed-habitats). The EUSeaMap2021 shows gaps in smaller areas of Danish inshore waters. Thus, a separate data layer was produced to fill these gaps in 7 areas based on sediment data information from the Danish monitoring programme, NOVANA (see a detailed description of habitat mapping methods and results in the document "Supplementary material 2 for RBS analyses" provided in Appendix 4). This new BBHT data layer was included as an add-on to the official EUSeMap v. September 2021 data layer.

Each of the BBHTs was spatially assigned to a raster grid of 0.01 °E x 0.01 °N, equal to grid cell size of ~0.66 km^2. The BBHT that overlaid the central point of each grid cell was assigned to the entire cell. The spatial distribution of all BBHTs in the Danish WFD water bodies are shown in Figure 6.9. For BBHT maps of each of the subregional areas, see Appendix 4 - Supplementary material 1: Figure S1-4. The total coverage of each BBHT is shown in Table 2.1 (and per subregion in Table S1-3).

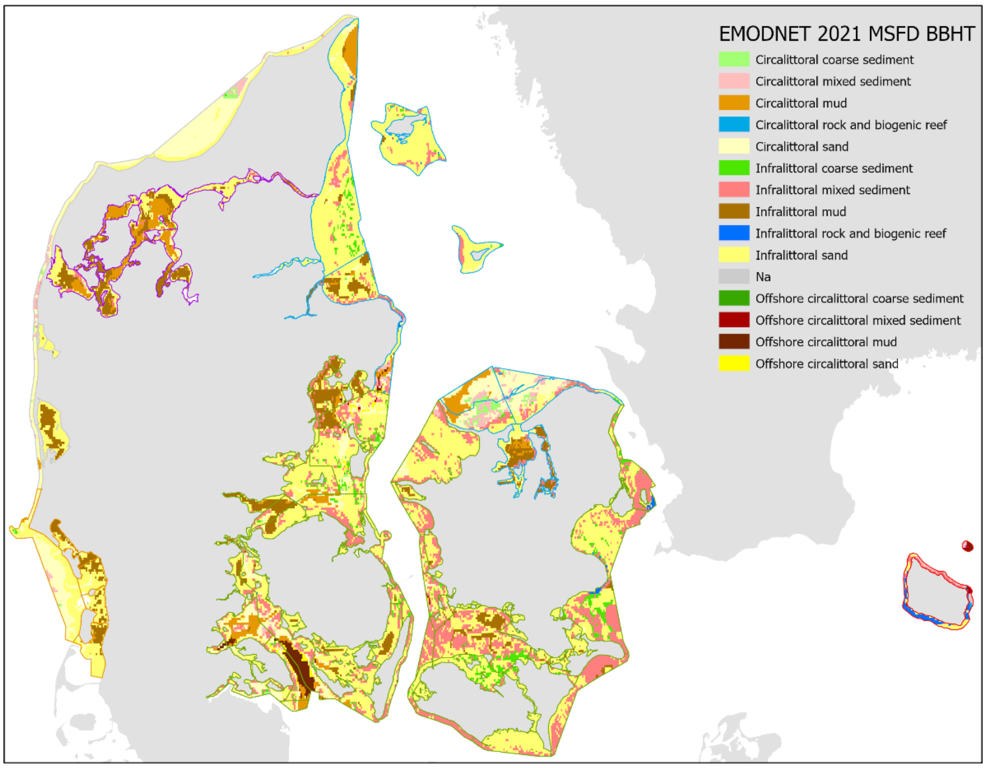

Figure 6.9: Spatial distribution of the data layer EUSeaMap v. September2021 of the MSFD Benthic Broad Habitat Types within the Danish WFD water bodies of the Danish EEZ.

Benthic macrofaunal data: As part of the Danish national environmental monitoring programme, NOVANA, benthic macrofaunal samples are collected from the 139 WFD water bodies. The NOVANA sampling of benthic macrofauna is conducted in April-May prior to the peak period of reproduction and larval settlement. For this study, we retrieved data from the ODA database (Surface Water Database). These data are now available at the new database, Danmarks Miljøportal (https://miljoedata.miljoeportal.dk/).

We included a total of 4,980 quantitative samples collected (Figure 6.10) by a HAPS corer that covers an area of 0.0143 m^2 of the seabed during the period from 2010-2017. The HAPS corer is developed for quantitative sampling of level bottom substrates, including mud, sand, and fine gravel. The sampler is unsuitable for deployment on mixed and hard substrates (Kanneworff and Nicolaisen, 1973).

In the field, all samples are rinsed for sediment over a sieve with a 1 mm mesh size, and the residual is stored in 96% ethanol. In the laboratory, all macrofaunal individuals are identified to the lowest taxonomic level possible (preferably to the species level), and the individuals enumerated for each taxon and weighed jointly (see protocol procedures in Josefson and Hansen, 2014). Since the weighing method varied between years, all the biomass estimates (of wet weight or dry weight) were standardised to ash-free dry weight (AFDW) using the conversion factors provided by Ricardi and Bourget (1998).

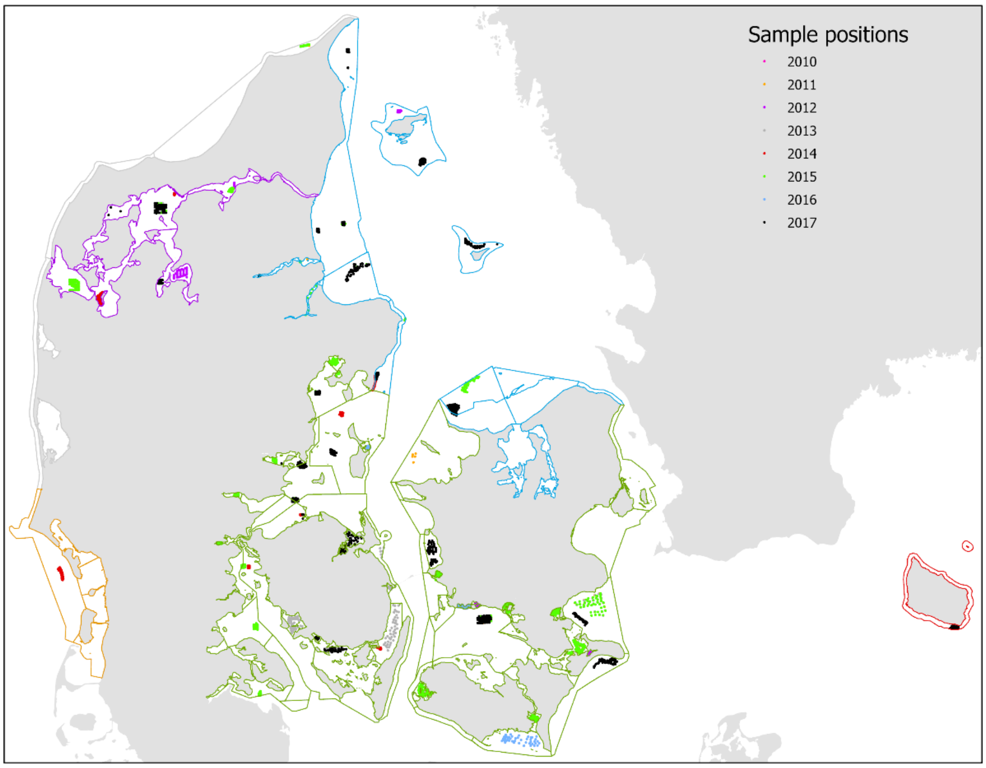

Figure 6.10: Spatial distribution of the samples collected in the 139 Danish WFD water bodies 2010-2017 using a HAPS corer covering an area of 0.0143 m2). The six subregional divisions are indicated by different line colours of the individual WFD water body boundaries: Red), Bornholm; Green), Belt seas; Blue), Kattegat; Purple), Limfjord; Grey), west coast; and Orange) Wadden Sea.

WFD multi-metric indicators for macro invertebrate: The WFD biological quality element "macro invertebrates" GES assessment of the Danish inshore waters is based on the DKI (Henriksen et al. 2014), whereas the WFD GES assessment of Swedish western inshore waters uses the BQI (Leonardsson et al., 2009, 2015). Both indices build on measures of density of individuals (N) and density of species (S), combined with a diversity index (e.g., the Shannon diversity index, H', as used for the DKI) and species specific sensitivity values (e.g., from the AZTIs Marine Biotic Index as used for the DKI) (for details on AMBI, see Borja et al. 2000, Borja and Dauer 2008), or calculated from observations in reference samples (e.g., as used for the BQIo). The indicator calculations used herein for DKI and BQI followed that of Gislason et al. (2017; DKI, BQI). For further details on indicator calculation of N, S, biomass (B) and the two multi-metric indicators, see Chapter 5 – McLaverty et al. (2023).

The FBIT approach - RBS and Impact: The Fisheries Benthic Impact and Trade-offs (FBIT) approach was developed by ICES for assessment of impact from fisheries using mobile bottom-contacting gears (ICES, 2019a, c). The FBIT assessment approach comprises four steps: 1) Assign the area of interest and acquire and model all relevant spatial data layers, such as geographic and management boundaries, MSFD BBHTs, environmental variables, and pressure layers (e.g., fishing pressure); 2) Estimate relations of benthic longevity and environmental variables, based on faunal biomass longevity distribution from samples from representative (and preferably undisturbed) seabed habitats; 3) Predict seabed sensitivity (i.e., extrapolate longevity distributions) for each grid cell; and 4) Estimate seabed state and impact (see detailed guidelines to the FBITver2 methodology in ICES, 2022). The outcomes of step 1 are presented in the Material and Methods section (see the Figures 6.1 to 6.10 above) together with the methods and data preparation for step 2-4 (see the text below). The outcomes of the steps 2-4 are presented in the Results section. We applied the relevant components for each of the FBIT steps using the FBIT R-Script available on GitHub (updated by P. Daniel van Denderen, available at https://github.com/ices-eg/FBIT/tree/dev). Spatial and statistical modelling was carried out using R-studio (version R-4.1.2 and the packages “sf”, “dplyt”, “data, table”, “lme4”, “readxl”, and “corrplot”).

Longevity trait coding: The biological trait “Maximum Longevity” was coded for 548 taxa. Coding was conducted at the Genus or higher taxonomic level, depending on available information. We used the BENTHIC trait data table (CEFAS/BENTHIS longevity table by Bolam et al., 2017) together with additional BT-coding of non-coded taxa, to assign four maximum longevity modalities: i), <1 year; ii), 1-3 years; iii), 3-10 years; and iv), >10 years; to the macrofaunal biomass of the HAPS corer samples collected under the NOVANA programme from 2010-2017 (Figure 6.10). We expect the use of these four modalities as adequate for the HAPS corer data, as the selectivity of this core sampler favours small-bodied and short-lived species. Thus, individuals of species with a maximal longevity >20 years are relatively few and under-represented in the dataset.

Benthic sensitivity: It is assumed that the cumulative biomass proportion in each sample is a sigmoidal (logistic) function of longevity, which starts at 0 and approaches 1 when longevity becomes high. Thus, longevity is log transformed, and a binomial distribution is applied to the GLMMs (Brooks et al. 2017), with samples as a random variable (normal distribution). Model selection was based on the Akaike information criterion (AIC) (Akaike, 2011). The best longevity distribution model was selected to predict benthic sensitivity, that is, to estimate the longevity distribution for each grid cell based on the cell-specific environmental data. In this study, this was done at a global scale (i.e., using the same model) for all the 139 Danish WFD water bodies. However, where sufficient data are available for the response variables (i.e., a sufficient number of macrofaunal samples) different longevity compositions could be established for individual subregions with highly different environmental conditions. Moreover, where sufficient data are available for each MSFD BBHT, longevity compositions tend to differ not only between ecoregions and subregions, but also between BBHTs in relation to e.g., substrates, as has been shown for BBHTs in the greater North Sea (Rijnsdorp et al., 2018, 2020). However, to include this in the assessment requires that baseline data (i.e., macrofaunal species and biomass data) are available from a sufficient number of undisturbed sites representative of each habitat and substrate, and spatial habitat and substrate data are available at the required grid scale.

The PD model: The population dynamic (PD) model is a mechanistic model that estimates the decrease in biomass of benthic fauna in response to bottom trawling intensity and longevity dependant recovery time (Hiddink et al., 2017, 2019, Pitcher et al., 2017, Rijnsdorp et al., 2018, 2020, van Denderen et al., 2019). In a comparison of three models (i.e., L1, L2 and PD) to estimate bottom trawling impact and state of benthic biota, the PD model was found to perform best over a broad range of bottom trawling intensities (Rijnsdorp et al., 2020). We applied the FBIT approach using the PD model (ICES, 2020) to estimate the Relative Benthic State (RBS) and Impact of bottom trawling on the BBHTs in the Danish WFD water bodies. The RBS equation is as follows:

RBS = B/K = 1 – FP x d/r

where RBS is the Relative Benthic State, B is observed biomass, K is carrying capacity, FP is bottom trawling intensity, d is the depletion rate (gear dependent) and r is the recovery rate (i.e., population growth rate, which is species and habitat dependent). The Impact is the reciprocal value of RBS:

Impact = 1 - RBS

Depletion rates: Depletion rates are defined as the proportion of the biomass killed with each passage of the gear, and the depletion rates are gear type dependant (Hiddink et al. 2016, 2017). For the SARs of bottom-contacting fishing gear types we thus applied the metier based depletion rates provided by Rijnsdorp et al. (2020, Table 1), d: i), 0.2 for Dredges (DRB for mussels); ii), 0.06 for Otter trawls (OTBs combined of 0.1 for OT_CRU for Nephrops and mixed fish; 0.026 for OT_DMF for cod, plaice; and 0.075 for OT_MIX1 for mixed fish); iii), 0.009 for Danish seine (SDN, plaice, cod); v), 0.06 Beam trawl (TBB_HRJ for brown shrimp) and vi), 0.14 for Beam Trawl (TBB for flatfish).

Recovery rates: We applied a recovery rate that is longevity dependant (Hiddink et al., 2017). This approach estimates the biomass (B) recovery time t (years) from the impacted state (B0) as Bt = 0.9 K (Pitcher et al., 2017). The recovery rate was calculated as:

r = H/years of longevity

where r is the recovery rate, H = 5.31 (or alternatively H = 0.57) based on experimental recovery studies after fishing events (Hiddink et al. 2017) and years of longevity is based on the longevity distributions estimated from the benthic biomass composition of the undisturbed samples and the corresponding environmental condition.

6.3 Results

Longevity distribution model selection: Pairwise correlation models showed low or moderate correlations between most explanatory variables (Figure 6.11). However, the correlation between minimum and maximum salinity was high. We therefore included only minimum salinity, as well as salinity difference, depth, and minimum oxygen as environmental variables in the exploration of the best longevity model across all samples from undisturbed sites.

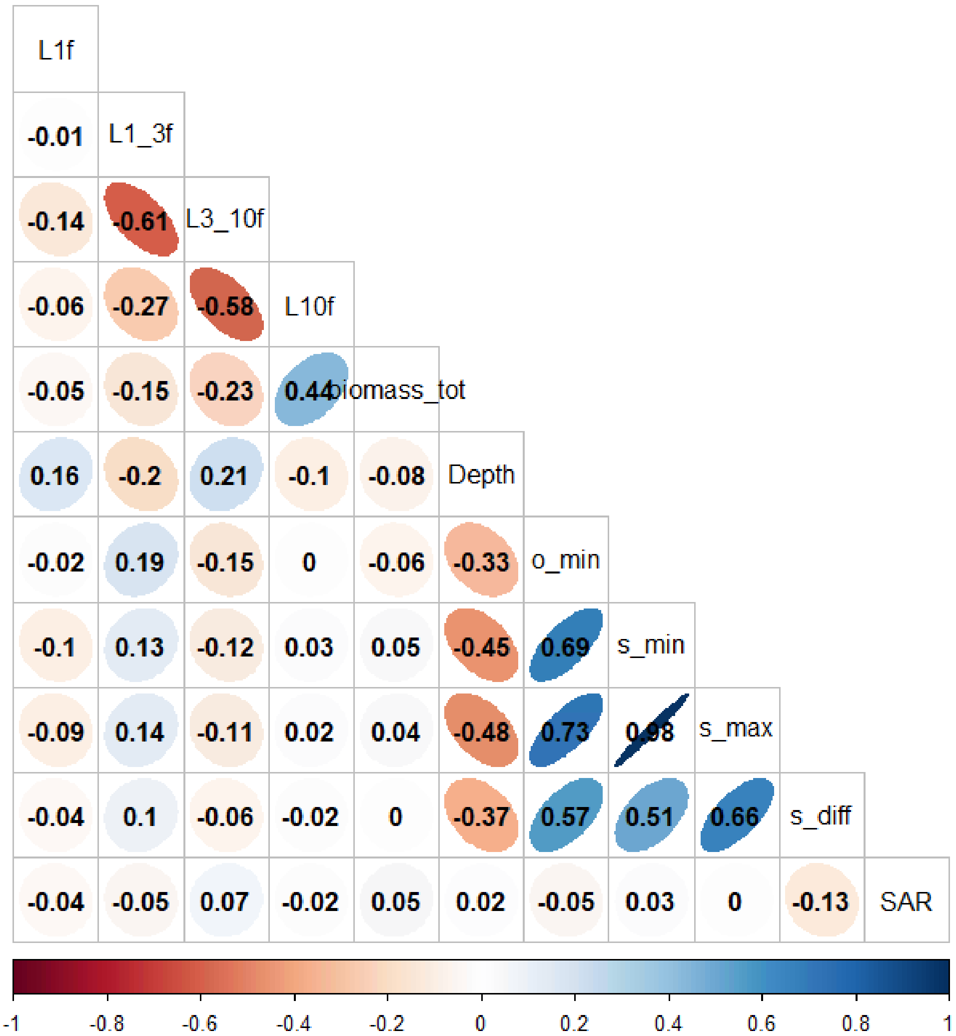

Figure 6.11: Correlation plot between environmental variables (depth, salinity min. and max., oxygen min.), fishing pressure (SAR) and response variables (biomass, longevity modality L1F, L1-3f, L3-10f, and L10f).

Undisturbed sites were characterised as having low or no fishing pressure, equal to values of SAR <0.1 (after which 4408 samples remained) and good oxygen conditions, equal to Oxygen min. >4.0 ml/l (after which 2691 samples remained).

The best global longevity distribution model was (AIC = 4088):

mod <- glmer(Cumb ~ ll + Oxygen_min + Salinity_min + Salinity_diff + Depth + (1 | ID)

with the following model parameters:

	lower 2.5	upper 97.5	mean	
(Intercept)	-11.98328737	-9.2036895	-10.5934885	
Llog		2.72266406	2.9474945	2.8350793

Oxygen_min	0.58737711	0.9344915	0.7609343	
Salinity_min	0.45137524	0.7569728	0.6041740	
Salinity_diff	0.04162954	0.7586986	0.4001641	
Depth		0.04567227	0.2468317	0.1462520

Estimation of benthic sensitivity: Seabed habitat sensitivity was estimated for each year from 2010-2020 based on the longevity composition predicted for each grid cell using the spatial data layers of the environmental variables. The spatial median longevity distribution for 2010 is shown in Figure 6.12 (see additional years in Figure S1-10). The estimated median longevity (i.e., of 50% of the biomass) is moderate in the northern inshore parts of the Kattegat and in the Wadden Sea. The highest modelled median longevities are seen in the southern parts of the Kattegat and in the deep parts of the Belt seas. This result appears mainly to be driven by the relative greater depth and lower minimum salinity of those areas, which would both correspond well ecologically with a higher median longevity of the benthic fauna. However, these areas frequently experience hypoxia events which could argue for an opposite effect. However, the hydrographic models (i.e., of the variables of oxygen, salinity, temperature, and bottom current show severe boundary issues in almost all the near-coastal area, also in the southern parts of the Belt Seas. However, the most pronounced boundary issues of the hydrographic data are seen in the fjords and in the near-shore waters in the Wadden Sea. Due to these severe boundary issues of the hydrographic models, the results herein for the near-coastal areas may have low credibility and need to be re-assessed when these issues have been resolved in the existing hydrographic models.

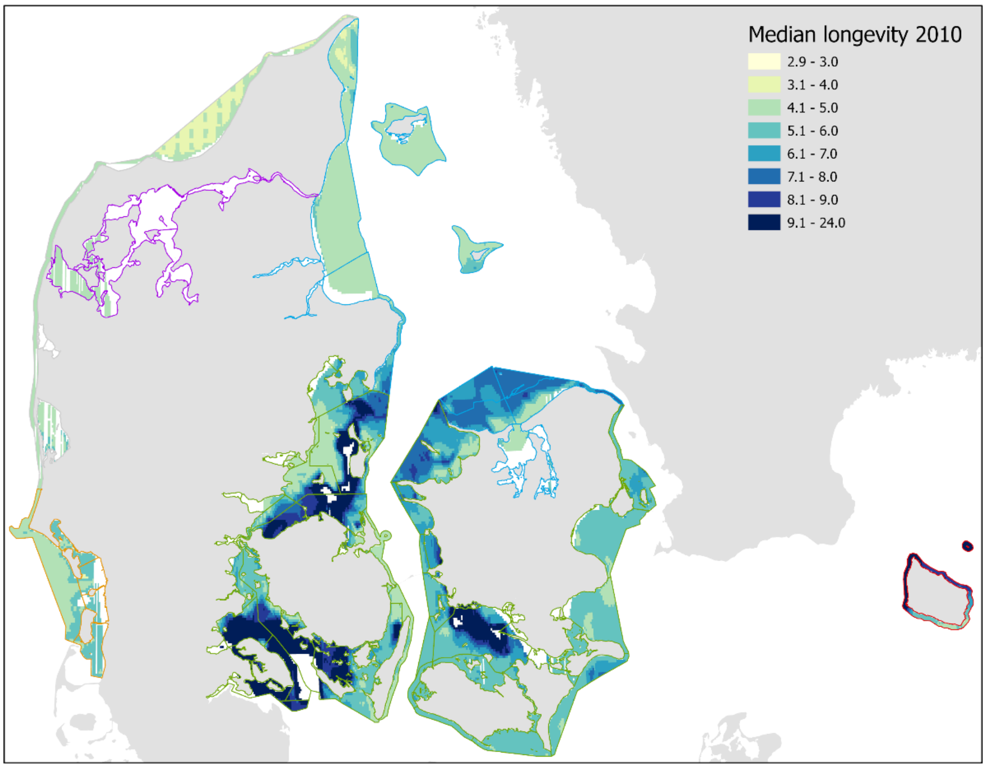

Figure 6.12: Median longevity estimated from May y-1 to April y for the period 2010-2020.

Estimation of RBS and Impact: The correlation between depletion and state was calculated for each cell per year. As an example, see the diagram for 2010 in Figure 6.13 (see additional years in Figure S1-11). The spatial distribution of the Relative Benthic State (RBS) was estimated and mapped for each year from 2010-2020 (see Figure S1-12). Here, the spatial RBS estimates averaged for the entire period from 2010-2020 are mapped in Figure 6.14. The spatial distribution of the Impact (1-RBS) was similarly estimated for each year from 2010-2020 (for the Impact distribution of individual years, see Figure S1-13). The average Impact distribution for the entire period from 2010-2020 is shown in Figure 6.15.

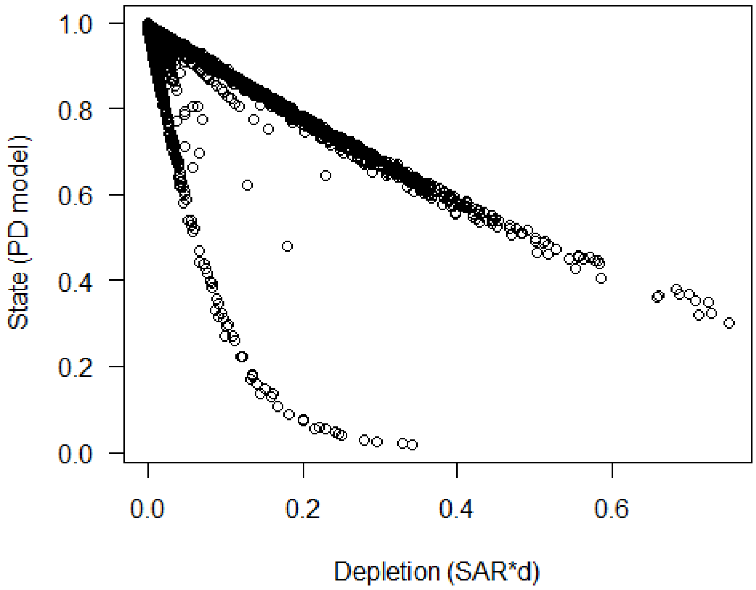

Figure 6.13: The relationship between Depletion (SAR x d) and State (derived from the PD model) per annual period from May y-1 to April y for the year 2010. The correlation shows the depletion contribution from the individual mobile bottom-contacting fishing gears.

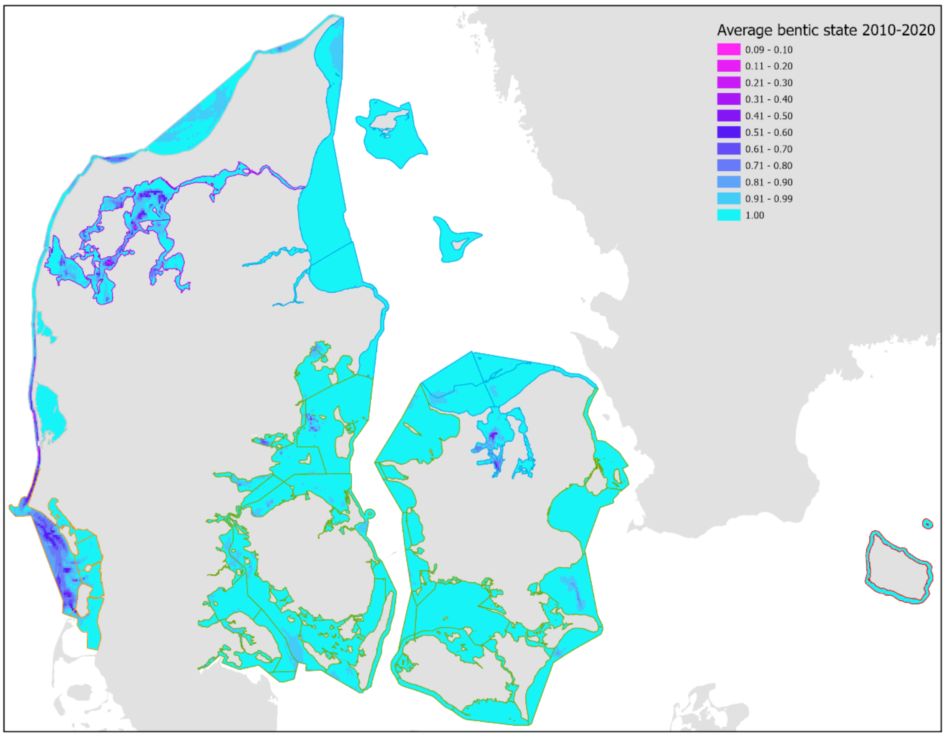

Figure 6.14: Spatial distribution of the average of the Relative Benthic State (RBS) estimated for the individual years for the period 2010-2020.

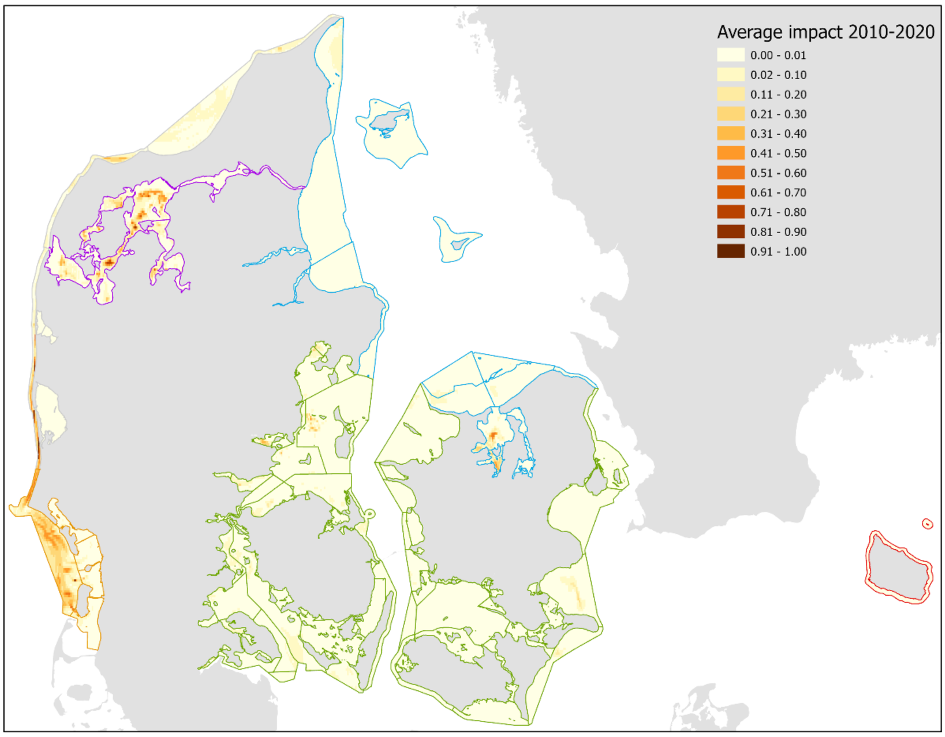

Figure 6.15: Spatial distribution of the average of Impact (1-RBS) estimated for the individual years for the period 2010-2020.

Due to the NOVANA benthic faunal sampling design, the RBS (and Impact) indicator values are only representative for the benthic macrofaunal communities associated with the MSFD BBHTs with substrates of mud and sand and, to some extent, coarse sediment. The values are, thus, not reliable for the BBHTs of mixed sediments, rock or biogenic reefs. These BBHTs are therefore marked by grey in Table 2.1. The indicator value of RBS calculated for each BBHT for each of the six subregions is available in Appendix 4 - Supplementary material 1: Table S1-3.

Table 2.1: The area of each MSFD BBHT (in km2) within the WFD water bodies of the Danish EEZ, with a summary of the Relative Benthic State (RBS) (i.e., Impact = 1 - RBS) as estimated for each year and as an average for the period 2010-2020 (NA = areas not assigned to a MSFD BBHT). RBS Values >0.8 are considered in GES, whereas values <0.8 are considered in subGES by Pitcher et al., 2022).

MSFD BBHT	Area km^2	RBS av 2010-2020	RBS state 2010	RBS state 2011	RBS state 2012	RBS state 2013	RBS state 2014	RBS state 2015	RBS state 2016	RBS state 2017	RBS state 2018	RBS state 2019	RBS state 2020
Circalittoral coarse sediment	154.98	0.99	0.99	1.00	0.99	0.99	0.99	0.99	0.99	0.98	0.98	0.99	0.99
Circalittoral mixed sediment	462.46	0.99	0.99	1.00	1.00	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.97
Circalittoral mud	644.28	0.98	0.99	0.99	0.99	0.98	0.99	0.98	0.98	0.98	0.98	0.98	0.95
Circalittoral rock and biogenic reef	5.46	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99
Circalittoral sand	2398.84	0.95	0.96	0.97	0.99	0.96	0.95	0.95	0.94	0.94	0.93	0.94	0.96
Infralittoral coarse sediment	501.19	1.00	1.00	1.00	1.00	0.99	1.00	0.99	0.99	1.00	1.00	1.00	1.00
Infralittoral mixed sediment	3032.31	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Infralittoral mud	1103.89	0.99	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.99	0.99	0.98
Infralittoral rock and biogenic reef	102.05	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Infralittoral sand	8134.77	0.99	0.99	1.00	1.00	1.00	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Na	1.23	0.98	0.97	0.99	1.00	0.99	0.99	0.97	0.97	0.99	0.96	0.98	0.99
Offshore circalittoral coarse sediment	1.39	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Offshore circalittoral mixed sediment	21.85	0.97	1.00	1.00	1.00	1.00	0.99	0.97	1.00	0.99	0.94	0.91	0.90
Offshore circalittoral mud	60.73	0.96	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.68	0.86
Offshore circalittoral sand	67.03	0.99	1.00	1.00	1.00	1.00	1.00	0.99	1.00	1.00	0.99	0.93	0.96

6.4 Discussion

Pitcher et al. (2022) conducted a global assessment in which they suggested that the threshold between GES and subGES specifically related to bottom trawling impacts should be set at the RBS value 0.8, thus, RBS >0.8 could be considered in GES. If we apply this suggested threshold to our overall results for all the WFD water bodies combined, all muddy, sandy and course BBHTs appear to be in GES in all years from 2010-2020, except for Offshore circalittoral mud in 2019 when the RBS value is 0.68 (Table 2.1). However, if instead, we were to look at the RBS values of each BBHT with mud, sand or gravel within each subregion, several habitats in more years appears to be adversely affected by bottom trawling (see Appendix 4 Supplementary material 1: Table S1-3 values of RBS <0.8). In the Wadden Sea, the BBHTs Circalittoral course sediment (RBS as low as 0.64), Circalittoral sand (RBS as low as 0.86) are adversely effects in several or most years (Table S1-3). This is related to beam trawling for brown shrimp. On the east coast, the BBHT Circalittoral mud (RBS as low as 0.58) is affected in most years, which is ascribed to bottom trawling for *Nephrops* and mixed fish. In in the Belt seas, Offshore circalittoral mud (RBS as low as 0.42) is adversity affected in 2019-2020, most likely due to bottom trawling for cod and flat fish. The results of each subarea suggest that at least one BBHT in several years would be in subGES, due to adverse effects of bottom trawling if the GES assessment is conducted individually for each WFD water body. However, due to the severe boundary issues of the hydrographic models in near-coastal areas, the results from these areas should be treated with caution until more robust hydrographic models become available.

In this dataset, density of individuals (N) and species (S) are highly correlated at a logarithmic scale (Figure 6.16). A similarly high correlation between log N and log S was also found in the NOVANA data from offshore stations (mainly in the Kattegat) by Gislason et al. (2017). Gislason et al. (2017) emphasised that the density of species depends on the density of individuals in any given sample. Furthermore, this correlation becomes more pronounced at small sampling sizes, and the fraction of the total density that is collected will vary between sites with different densities of individuals and species. Multi-metric indicators that incorporate both density of individuals and density of species could be used for comparisons within sites but not across large spatial scales with different faunal densities of individuals and species (Gislason et al., 2017). As mentioned above, several indicators proved unsuitable for detection of fishing impact (e.g., DKI, BQIo). However, the multi-metric indicator, BQI_E, addresses the logN to logS autocorrelation by using rarefied samples, and, importantly, this indicator is sensitive to bottom trawling (Gislason et al., 2017). Our analyses therefore supports that BQI_E is currently the best available multi-metric state indicator for overall GES assessment of the quality element ‘macro invertebrates’ in the Danish WFD water bodies.

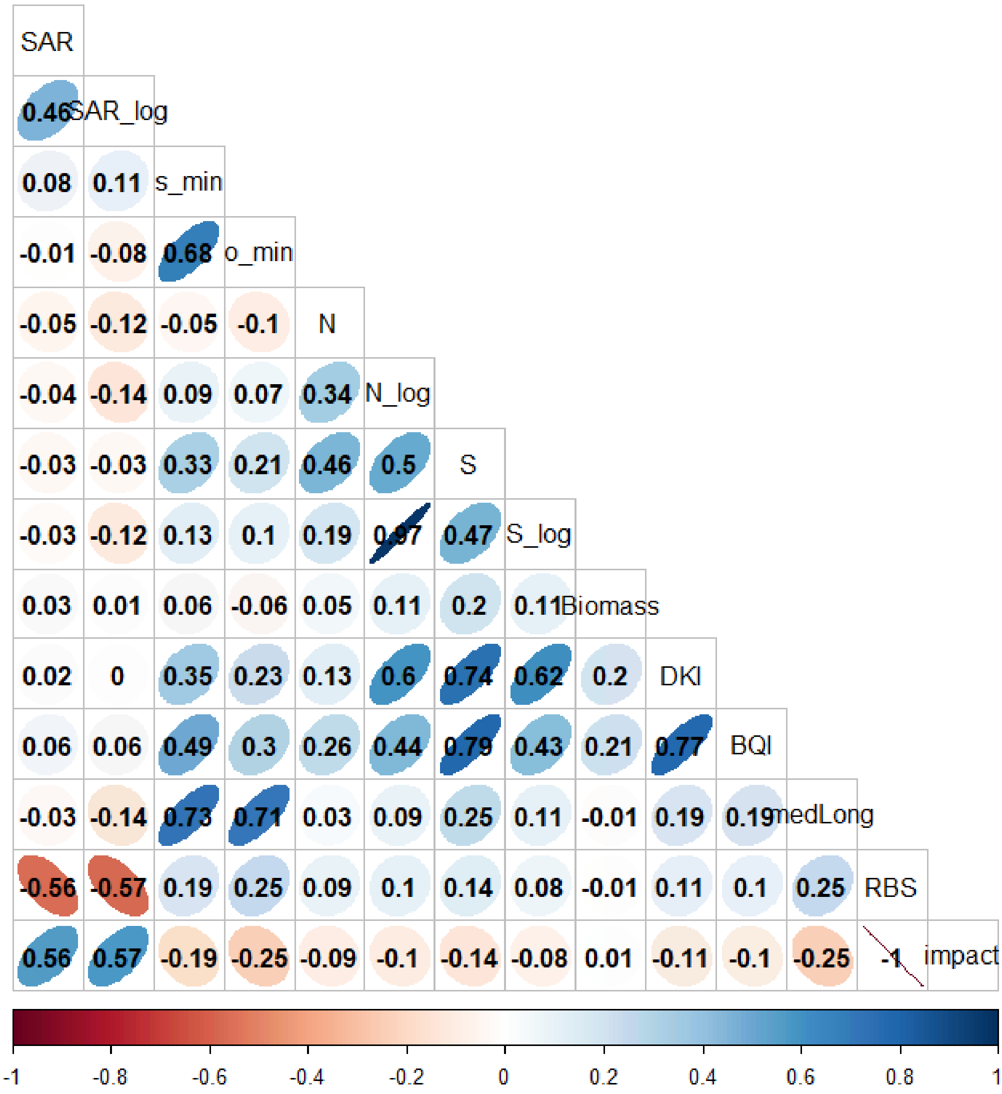

Figure 6.16: Correlation plot of all model input variables as well as of the indicators N, logN, S, logS, and B, the WFD multi-metric indicators DKI_{v3} and BQI_o, and the ICES FBIT state indicator RBS, and impact indicator Impact (1-RBS).

The FBIT RBS provides an alternative state indicator for GES assessment that is linked directly to specific pressures variables, such as bottom trawling, and considers environmental conditions, such as temperature, salinity and oxygen. The RBS and Impact indicators are developed to detect and quantify the ecological state of seabed fauna in response to bottom trawling across large spatial scales and environmental conditions.

The PD model uses biomass-based longevity distributions as a proxy for ecosystem processes, such as nutrient cycling and food web energy flows (Pitcher et al., 2017). It builds upon the theory of Pearson and Rosenberg (1978) and others, that highly disturbed areas are dominated by short-lived (and small-bodied) benthic fauna whereas long-lived (and large-bodied fauna) dominates areas of low or no disturbance, such as nutrient enrichment and oxygen depletion. Physical disturbance from bottom trawling appears to follow the same pattern in coastal and offshore waters, and the FBIT approach allows for including environmental and pressures variables in the indicator estimation if they are available at the spatial scale of the grid applied. The estimation of longevity compositions, and the distribution of median longevity, RBS and Impact is designed for use across large spatial scales and covering large ranges of environmental and pressure variables. Estimation of RBS and Impact thus depends on high-resolution models of the most important variables. For Danish inshore waters, these variables comprise the pressures of bottom trawling and oxygen depletion, as well as salinity and bottom substrate. Since the hydrographic model of oxygen and salinity show severe boundary issues in the Danish near-coastal areas, this introduces errors in the sensitivity layers of the RBS approach in these areas of the WFD water bodies. Moreover, as some of the deeper (circalittoral, offshore circalittoral) BBHTs are only represented by very small areas within individual WFD water bodies, data from the same BBHTs adjacent to the WFD water bodies should be included in the longevity models underlying the RBS assessment.

Future work will undertake RBS-based GES assessment for the entire Danish EEZ and identify and apply suitable data to establish the most robust longevity models for undisturbed sites within each of the two marine subregions (i.e., Greater North Sea, Baltic Sera) as the baseline for the RBS and Impact estimation. Further, the longevity models will be established individually for each of the BBHT and these results will supplement the wider assessment and aid in the development of sustainable fisheries management in WFD water bodies and offshore Danish waters.

7. Conclusions and recommendations

This report presents several novel findings regarding the ecological impacts of coastal bottom trawling. These include new evidence regarding the effects of bottom trawling relative to other coastal pressures, a range of concerns regarding several ecological metrics used widely in Europe, as well as applied and field-based trials of theoretical impact indices and alternative fishing gears. These findings are expected to contribute directly to the evidence base of human impacts in coastal areas and potentially aid in the development and improvement of ecosystem-based fisheries management for coastal areas. Some of the main findings, outputs, and conclusions of this report include:

- We observed that bottom trawling has a significant overall negative effect on benthic abundance and species richness in Danish coastal areas. A further key finding was that these impacts were not detected by most commonly applied benthic indices, including several of those used to monitor the health of benthic communities in European coastal areas. The exception to this was the BQI index, which responded effectively to bottom trawling impacts. Our results therefore highlight the considerable risk that the metrics used to assess Good Ecological Status (GES) under the WFD in costal areas may fail to identify bottom trawling impacts.

- The effects of coastal bottom trawling on benthic communities were highly dependent on background levels of natural and human disturbances at a given location, as well as the dynamics (size and weight) of the fishing gear. Deeper penetrating gears were associated with greater benthic impacts (e.g., shrimp beam trawls in the Wadden Sea vs. Danish seines in the Jammer Bay). However, in areas affected by oxygen depletion, this relationship was disrupted significantly. Bottom trawling impacts were undetectable in areas experiencing chronic eutrophication (e.g. South Fyn), while the effects of fisheries were weaker under moderate eutrophication (Løgstør), regardless of gear penetration depth.

- Using the Relative Benthic State (RBS) indicator developed by ICES, we observed that a number of benthic habitat types fall below thresholds for Good Ecological Status (GES) in coastal areas due to bottom trawling. These included shallow subtidal sands and course sediments in the Wadden Sea, shallow muds on the east coast, and heavily dredged areas of Limfjorden and Isefjorden. In contrast, RBS scores over >0.8 were observed in many areas and years, indicating that good ecological status was not adversely affected by bottom trawling. However, the hydrographic models that forms the basis for the longevity model and, thus, the RBS value estimations, were found to have severe boundary issues in near-coastal areas. This suggests the effects of hypoxia were underestimated. As a result, this initial examination of RBS in coastal areas should be considered with caution, and we suggest that improved hydrographic models for near-coastal areas are required to successfully model RBS and impact estimation of bottom trawling and other pressures in such areas.

- A detailed examination of the gear impacts of Danish seines via a field-based impact experiment found no detectable changes to benthic fauna at the community level from a pass of the gear. Conversely, some individual species were observed to be significantly reduced in abundance. This included *Phoronis* sp., a tube-building horseshoe worm that inhabits surface sediments. Based on this, we conclude that fishing with Danish seines is of considerably less impact to benthic communities than other bottom-towed gear types used in similar areas and habitat types, but that fishing with this type of gear likely results in strong negative impacts to specific species.

- The project also resulted in the development of a novel hierarchical model that integrates Black Box (BB), Automated Identification System (AIS), and Vessel Monitoring System (VMS) data with logbook data, and a deviating method that accounts for the distinct fishing pattern and seabed footprint of coastal fishing gears (Danish seines). These steps represent a significant development regarding the accuracy of fishing pressure estimates in the coastal zone, and were used to produce high-resolution coastal fishing pressure maps at the scale of 100x100 meters grid cells across the Danish coastal zone.

Based on the findings of the report, the following recommendations for the future development of sustainable coastal bottom trawl fisheries are suggested:

- Bottom trawling comes at an environmental cost, but some types of trawl gear are less damaging than others. We found that bottom-contacting gears such as Danish seines, which do not penetrate deeply into the sediment, are associated with lower ecological impacts then heavier gears. It is therefore suggested that low impact gears such as these are favoured for use in coastal bottom trawling grounds, where possible, to reduce impacts to benthic fauna, and enhance the integrity of coastal habitats.

- While the methods used to estimate bottom trawling intensity in coastal areas have been improved in this project, there are still some issues pertaining to using VMS and AIS data to estimate bottom trawling intensity. In contrast, black box devices used in Danish coastal mussel fisheries provide ultra-high resolution, and information to register the start and end of hauls. Black box data therefore do not require modelling/interpolation to estimate fishing pressure, and result in a much-improved ability to assess seabed impacts. It is therefore suggested that applying black box devices to all coastal vessels would greatly improve the understanding of bottom trawling impacts in these areas and provide documentation of the exact magnitude and location of impacts, which may be useful for fisheries and environmental management, as well as for the fishers themselves. This recommendation may be particularly pertinent in relation to our observations from multiple pressure environments such as Løgstør Bredning and Lillebælt, where the detectability of bottom trawling impacts become obscured by other pressures. Furthermore, black box data would be particularly suited to the typically non-standard fishing behaviour of coastal fishing vessels (e.g. Danish seiners and mussel dredgers).

- Some of the ecological indicators widely used in management to track and monitor coastal benthic health are not designed for pressures such as bottom trawling, and therefore may not be fit for purpose to monitor the range of human pressures present in the coastal zone. This was demonstrated by the inability of the DKI and AMBI based indices to detect bottom trawling impacts in our analysis. We therefore suggest that other indices (e.g., abundance or BQI) are used in conjunction with current standard indicators to ensure that also changes to benthic communities caused by bottom trawling are detected.

- Our analysis shows that some in coastal areas (e.g. Løgstør and Lillebælt), bottom trawling impacts are masked or undetectable due to high levels of eutrophication and/or oxygen depletion. From a fisheries management perspective, this indicates that when multiple pressures are present simultaneously, the relative impacts of fishing must be carefully considered. At present, management plans are being proposed across Europe to improve the health of coastal environments by e.g. removing physical pressures such as bottom trawling (via Marine Protected Areas (MPAs)). However, some of the areas proposed for protection in Danish coastal waters are known to also experience chronic poor oxygen conditions. Our findings would suggest that well intentioned conservation plans can be potentially undermined by other human stressors. Based on our case studies, it is unlikely that coastal areas significantly impacted by eutrophication will benefit from the exclusion of bottom trawling or other physical disturbance of the seabed. On the other hand, MPAs, or no-trawl areas, should be prioritised in areas that are less impacted by diffuse pressures e.g. eutrophication, and/or areas of biological importance where the ecological quality of the system may benefit from the exclusion of specific pressures.

Acknowledgements

We thank the technical staff and the student assistants from DTU Aqua for assistance with laboratory analyses of the sampled benthic material. We also thank the staff and crew of R/V *Egon P* and R/V *Havfisken* who assisted during the field experiments.

The research outlined in this report and the project 'KYSTEFFEKT - det kystnære fiskeris effekter på bundfauna' (COASTEFFECT - Effects of coastal fisheries on benthic fauna) - (Grant Agreement No 33113-B-20-178) was funded by the European Maritime and Fisheries Fund (EMFF) and the Danish Fisheries Agency. In addition to this funding, the work described in Chapter 4 (Experimental effects of a Danish seine on benthic fauna in sandy substrates of the southern Skagerrak) was part-funded by the VELUX Foundation through the project 'Bæredygtighed i danske farvande – Kortlægning af danske farvande for miljøbeskyttelse'. Similarly, the work carried out in Chapter 6 was also part-funded by the EMFF project "GESseabed" - Udvikling af indikatorer og tærskelværdier for god miljøtilstand af havbunden og fiskeripåvirkning til direkte implementering af MSFD og Natura 2000 – grant agreement number 33113-B-20-182.

European Union
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Project Dissemination (Appendices)

The main outcomes of the project are the report chapters described herein, as well as the scientific papers and manuscripts listed below as separate appendices of this report. Chapters 3, 4 and 5 of this report are summarised versions of the key findings of these appendices (Appendices 1, 2 and 3). Due to copyright limitations and publishing considerations, Appendices 1 and 2 are not enclosed within this report. Appendix 3 is available via open access through the link provided below. Appendix 4 is available on request.

Appendix 1: Relative effects of trawling, organic enrichment, and natural pressures on coastal seabed fauna
Ciarán McLaverty, Esther Beukhof, Katrina Bromhall, Anders C. Erichsen, Grete E. Dinesen, Ole R. Eigaard. *Relative effects of trawling, organic enrichment, and natural pressures on coastal seabed fauna.* Manuscript (In preparation).

Appendix 2: Effects of a Danish seine on benthic fauna in the southern Skagerrak
Ciarán McLaverty, Ole R. Eigaard, Thomas Noack, Grete E. Dinesen. *Effects of a Danish seine on benthic fauna in the southern Skagerrak.* Manuscript (In preparation).

Appendix 3: European coastal monitoring programmes may fail to identify impacts on benthic macrofauna caused by bottom trawling
Ciarán McLaverty, Ole R. Eigaard, Jeppe Olsen, Mollie E. Brooks, Jens Kjerulf Petersen, Anders C. Erichsen, Karin J. van der Reijden, Grete E. Dinesen. *European coastal monitoring programmes may fail to identify impacts on benthic macrofauna caused by bottom trawling*. Journal of Environmental Management (2023) 334: 117510. DOI: 10.1016/j.jenvman.2023.117510 (https://www.sciencedirect.com/science/article/pii/S0301479723002980)

Appendix 4: Bottom trawling impacts on benthic macrofaunal state in Danish WFD water bodies – Supplementary material S1 & Supplementary material S2
Grete E. Dinesen, Josefine Egekvist, Ciarán McLaverty, Mollie E. Brooks, P. Daniel van Denderen, Alexandros Kokkalis, Jeppe Olsen, Karin J. van der Reijden, Jonathan Stounberg, Ole R. Eigaard.

More information and complete appendices can be provided upon request via cimc@aqua.dtu.dk (Ciaran McLaverty) or jekjp@aqua.dtu.dk (Jens Kjerulf Petersen).

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