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National Institute of Aquatic Resources

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Preface

This report presents the results from the project “COCKLE II: Bæredygtigt hjertemuslingefiskeri i Limfjorden” (ref. nr. 33113-B-20-172), which received financial support from the European Maritime and Fisheries Fund and the Danish Ministry for Food, Agriculture and Fisheries (“Ministeriet for Fødevarer, Landbrug og Fiskeri”) program “Hav- og fiskeriudvikling”.

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Content

Dansk resumé

Fiskeri af hjertemuslinger i Limfjorden (*Cerastoderma* spp.) er siden 2017 blevet det mest værdifulde fiskeri af toskallede bløddyr i Danmark med en værdi på 31,8 mio. kr. kr. pr. år svarende til 40% af værdien af alle landinger af toskallede bløddyr i hele Danmark (2017-2023, Fiskeristyrelsen). Hjertemuslingefiskeriet i Limfjorden er også det vigtigste europæiske hjertemuslingefiskeri og tegner sig for ca. 59% af de europæiske landinger siden 2017 (2017-2022, Eurostat).

På trods af, at hjertemuslingefiskeriet i Limfjorden er værdifuldt, forvaltes det stadig som bifangst i blåmuslingefiskeriet, selvom hjertemuslinger næsten udelukkende fiskes separat og ikke som en bifangst i fiskeriet af blåmuslinger. Selvom data og viden om Limfjordens hjertemuslingebestande og fiskeri er forbedret siden 2018, er fiskeriet stadig et datafattigt fiskeri, der sandsynligvis overgik fra ICES-kategori 5 til 4 eller 3 i 2023.

Det overordnede formål med dette projekt er at tilvejebringe ny viden om både hjertemuslingernes biologi og hjertemuslingefiskeriet i Limfjorden med henblik på at rådgive og understøtte en fremtidig bæredygtig og effektiv forvaltning af et selvstændigt hjertemuslingefiskeri.

Kapitel 2 rapporterer om udviklingen af en gyldig og omkostningseffektiv metode til bestandsopgørelse af hjertemuslinger i Limfjorden, hvor der er ringe tidevandsforskel og meget pletvis udbredelse af hjertemuslinger.

Den udviklede undersøgelsestilgang bruger en Day grab til nem, hurtig og pålidelig prøvetagning med 100% fangsteffektivitet, hvilket muliggør høj prøvetagningsintensitet og stationstæthed (11 til 16 stationer/km^2) i et regelmæssigt prøvetagningsdesign med 200 til 300 m afstand mellem prøvetagningspunkter, og med mulighed for stratificeret prøvetagning afhængigt af forventet eller fordeling af bestanden. Brugen af 10- eller 8 mm sigter sikrer opsamling af alle hjertemuslinger større end ca. 8-9 mm skalbredde, svarende til den del af bestanden, der bundslog den foregående sommer eller tidligere. Præcisionen af estimater af biomasse med denne metode varierede mellem ca. 9 og 57%.

Den foreslåede metode tager tre måneder og omfatter: i) en 3-ugers undersøgelse på ca. 60 km^2 i slutningen af foråret til forsommeren, når hjertemuslingefiskeriet lukker; ii) bestemmelse af hjertemuslingebestandenes størrelse og aldersstruktur; og iii) analyse af landingsdata, fiskeri og fangstmønstre. I 2023 omfattede en sådan tilgang de fire vigtigste fiskeriområder, der historisk set har stået for 86% af landingerne af hjertemuslinger i Limfjorden siden 2017-2018.

Kapitel 3 præsentererden første kvantitative beskrivelse af hjertemuslingens udbredelse og forekomst samt størrelse og aldersstruktur, vækst og dødelighed i de vigtigste fiskeriområder i Limfjorden i foråret 2021 og 2023.

I både 2021 og 2023 havde bestandene af hjertemuslinger en meget klumpet rumlig fordeling. I forhold til historiske landinger og 2021 (kun opmåling af Kås Bredning) vurderes hjertemuslingeforekomsten i 2023 (opmåling af fire områder, Kås Bredning, Salling Sund syd og nord og Sønder Bredning) til at være meget lav. Der er ikke observeret nogen signifikant rekruttering til hjertemuslingebestandene siden 2019, og derfor har rekruttering og vækst ikke kompenseret for naturlig dødelighed og fiskeridødelighed i de sidste 2-3 sæsoner.

Hjertemuslinger var små og viste reduceret vækst, med en negativ effekt af tæthed på størrelse på væksten, hvilket tyder på intraspecifik konkurrence om utilstrækkelige føderessourcer.

Den samlede dødelighed blev anslået til 78% om året, hvoraf den naturlige dødelighed udgjordeP 50 % om året, svarende til rapporterede rater i andre europæiske hjertemuslingebestande.

Kapitel 4 beskriver fiskerimønstre, fangster, fiskeriindsats og områdepåvirkning af hjertemuslingefiskeriet i sæsonen 2021-2022, hvor der ikke var forvaltningsmæssige begrænsninger i fiskeriet i forhold til landingsmængde mm. bortset fra de bestemmelser, der følger af at fiskeriet anses for at være en bifangst i blåmuslingefiskeriet og restriktioner vedrørende N2000-områder.

Fiskeriets frivillige fangstrapporter om fiskeriindsats, fangster og fangstprocenter viste sig ikke fuldt ud valide med det anvendte format, da de var biased, hvad angår fiskeriindsats og fangster, når der sammenlignes med Black Box systemet. Fiskeri genererede data kan dog stadig bidrage med valide data (f.eks. fangprøver for størrelse og alder) og oplysninger om fiskeri og hjertemuslingebestande, som kan indgå i forvaltning af hjertemuslingefiskeriet.

I fiskesæsonen 2021-2022 foregik hjertemuslingefiskeriet i 121 dage ud af potentielt 302 kalenderdage, svarende til 815 båddages fiskeri. I gennemsnit blev der i Limfjorden dagligt påvirket 52.600 ±2.600 m^2 (95% CI) pr. båd.

Fangstraterne (CPUE) varierede mellem 0,25 kg/m^2 og 0,30 kg/m^2 i henholdsvis hovedfiskeriområdet Kås Bredning og alle de fiskede områder i Limfjorden og varierede betydeligt mellem fartøjer, hvilket indikerer forskelle i fartøjernes fangsteffektivitet. I 2021-2022 blev udnyttelsesgraden i to forsøgsområder anslået til 40,4% og 29,5% af den samlede biomasse af hjertemuslinger før fiskeri, mens høst raten (andel af høstbar biomasse større end 16 mm skalbredde, der fjernes ved fiskeri) i forsøgsområderne blev anslået til at være hhv. 55,4% og 48,4%.

Hjertemuslingefiskeriet resulterede i et samlet befisket areal på 42,9 km^2 med en bundpåvirkning (ekskl. overlap af flere spor) på 10,3 km2 i Limfjorden, mens det i Kås Bredning var henholdsvis 25,6 km2 og 5,5 km^2. Hjertemuslingefiskeriets påvirkning på bunden udgjorde 9,6% af det potentielt fiskbare areal i Limfjorden og 13,6% i Kås Bredning. Fiskeintensiteten også kaldet swept area ratio (SAR, antal gange bunden blev fisket) var 4,2 i alle fiskeområder, men højere i Kås Bredning med 4,6.

Kapitel 5 beskriver hjertemuslingefiskeriets potentiale samt den potentielle områdepåvirkning af hjertemuslingefiskeri i et ikke-fisket område, N2000-området Nissum Bredning. Fiskeeffektiviteten af muslinge- og østersskrabere i Nissum Bredning blev også vurderet.

I sommeren 2022 havde hjertemuslinger en begrænset rumlig fordeling i Nissum Bredning i forhold til tidligere år, og forekom næsten udelukkende i én stor banke i den nordlige-midterste del af Nissum Bredning. Den samlede hjertemuslingebiomasse blev estimeret til 13.951 tons og høstbar biomasse til 12.765 tons, hvilket er relativt lavt i forhold til Nissum Brednings størrelse og sammenlignet med de vigtigste hjertemuslingefiskeriområder. Med en almindeligt anvendt fangstprocent på 33% havde Nissum Bredning potentiale til at levere 4.213 tons hjertemuslinger i 2022, hvilket er lidt lavere end gennemsnittet for landinger pr. sæson fra hovedhjertemuslingefiskeriområdet Kås Bredning (2017-2022).

Den generelle mangel på signifikant rekruttering af hjertemuslinger i Limfjorden 2019-2022 blev understøttet af den kohorte, der bundslog (settlede) i 2019, og som også dominerede hjertemuslingebestandene i Nissum Bredning.

Bundarealpåvirkninger forårsaget af potentielt fiskeri af hjertemuslingebiomassen i Nissum Bredning i 2022 blev estimeret ved at anvende en fangstandel på 33% og de fiskemønstre, der blev observeret i de andre fiskeriområder i sæsonen 2021-2022 (fangstareal pr. høstet og SAR). Bundarealpåvirkningen vil ligge mellem 3,7 og 4,1 km^2 svarende til mellem 2,2 og 2,4% af arealet af N2000-arealet i Nissum Bredning, og dermed under de accepterede grænser fastsat i Muslinge- og Østerspolitikken for fire økosystemkomponenter: ålegræs, makroalger, bundfauna og blåmuslinger. Det samlede påvirkede areal (inkl. overlappende skrab) vil ligge på mellem 15,6 km^2 og 19,0 km^2.

Fiskerieffektiviteten for muslinge- og østersskrabere var henholdsvis 18,0% (±3,3; 95% CI) og 16,0% (±1,6; 95% CI). Fiskeeffektiviteten for begge skrabere steg betydeligt med på hinanden følgende skrab i samme skrabespor, især med muslingeskraberen.

Kapitel 6 rapporterer foreløbig viden om hjertemuslingens konnektivitet i Limfjorden opnået gennem modellering af larvespredning og transport.

Det meste af Limfjorden, især langs den centrale akse, viste sig at være relativt godt forbundet, hvor de vestlige (Nissum Bredning) og de centrale dele (Kås Bredning og Løgstør Bredning) overvejende var forbundet ensrettet fra vest til øst. Selvrekrutteringen langs de centrale hovedaksebassiner (dvs. Kås Bredning, Salling Sund og Løgstør Bredning) er lav.

Det vigtigste fiskeriområde, Kås Bredning, er stærkt (og muligvis udelukkende) afhængig af rekruttering via larveimport fra hjertemuslingebestande andre steder i andre delbassiner (Nissum Bredning, Venø Bugt og Visby Bredning). Et af donorområderne er den største kendte sammenhængende og p.t. uudnyttede bestand af hjertemuslinger i Nissum Bredning. Fraværet af fiskeri af hjertemuslinger i Nissum Bredning kan forklare, hvorfor Kås Bredning opretholdt en relativt stabil rekruttering af hjertemuslinger, hvilket tillod regelmæssige og store hjertemuslingelandinger hver sæson, indtil den seneste generelle mangel på rekruttering i fjorden mellem 2019 og 2022.

Sidebassiner (Venø Bugt, Lovns Bredning og Skive Fjord) udgør spredningsbarrierer i forhold til Limfjordens midterakse. Isolerede dele af Limfjorden har relativt høj selvrekruttering og får meget få hjertemuslingelarver gydt andre steder (Venø Bugt, Visby Bredning, Thisted Bredning, Skive Fjord og Lovns Bredning). Variationerne i rekrutteringen fra år til år var begrænsede.

Løgstør Bredning blev identificeret som et primært drænområde, med potentielt høj tilførsel af larver fra andre dele af Limfjorden samt fra selvrekruttering, men uden at store og tætte hjertemuslingebestande er blevet observeret i de senere år. En hypotese er, at en eller flere miljømæssige/økologiske faktorer kan begrænse rekrutteringen af hjertemuslinger i disse områder.

Denne undersøgelse beskæftigede sig udelukkende med potentiel konnektivitet, som i modsætning til realiseret konnektivitet ikke tager højde for den nuværende fordeling af hjertemuslinger og faktorer som fertilitet, larvedødelighed, vækst, bosættelses- og rekrutteringssucces osv.

Denne undersøgelse giver således et udgangspunkt for fremtidige undersøgelser, hvor analyse af potentiel konnektivitet i kombination med data fra årlig bestandsvurdering og fiskeriovervågning kan understøtte forudsigelser af den fremtidige bestandsudvikling under forskellige forvaltningsstrategier.

Kapitel 7 rapporterer DTU Aquas råd og anbefalinger til den fremtidige forvaltning af hjertemuslingefiskeriet i Limfjorden.

Fiskeriet er stærkt afhængigt af nogle få fiskeområder, her især Kås Bredning. Nye hjertemuslingefiskepladser vil forbedre fiskeriets bæredygtighed og levedygtighed på lang sigt, men kan sandsynligvis kun findes i N2000-områder.

Anbefalinger:

- Hjertemuslingefiskeriet bør forvaltes som et selvstændigt fiskeri med sin egen forvaltningsplan, enten som et blandet fiskeri eller som et nyt særskilt selvstændigt fiskeri.
- Hjertemuslingebestandene og fiskeriet i Limfjorden bør overvåges og forvaltes i overensstemmelse med hjertemuslingerne specifikke biologi og bestandsdynamik og forholdene i Limfjorden.
- Et overvågnings-/bestandsvurderingsprogram bør følge den model, der er beskrevet i kapitel 2 i denne rapport.
- Hvis der er behov for rådgivning senere end september-oktober (f.eks. på grund af en senere start på fiskeriet), bør undersøgelsen af hjertemuslingebestandene foretages tættere på fiskeriets start og slutningen af hjertemuslingernes vækstsæson, hvilket vil forbedre bestandsvurderingen og biomassevurderingerne.
- Hjertemuslingens kønsmodenhed i relation til størrelse og alder i Limfjorden bør evalueres for at fastlægge en minimumstørrelse af hjertemuslinger, der må landes, hvilket vil sikre, at en tilstrækkelig del af hjertemuslingebestanden formerer sig mindst én gang.
- Fiskeri i N2000-områder er problematisk og skal overholde bevarings- og beskyttelsesregler for N2000-områder og den danske muslinge- og østerspolitik, der afvejer flere faktorer:
    - På den ene side kravene til beskyttelse af N2000-arter og naturtyper, potentielle miljøpåvirkninger fra hjertemuslingefiskeri og kræver endvidere grundlæggende biologisk viden om hjertemuslingebestande og rekrutteringsdynamik andre steder i fjorden.
    - På den anden side opretholdelse af et af de få levedygtige danske kystfiskerier med væsentlig økonomisk og social betydning for lokale/regionale samfund.

English summary

The Limfjorden cockle fishery (*Cerastoderma* spp.; Figure 1.1) has become the most valuable bivalve fishery in Denmark since 2017 at 31.8 mio. kr. per year equivalent to 40% of all bivalve landings per value in Denmark (2017-2023, Fiskeristyrelsen). The Limfjorden cockle fishery is also the main European cockle fishery accounting for ca. 59% of European landings since 2017 (2017-2022, Eurostat; Freitas et al., 2023).

Despite being valuable, cockle fishing in the Limfjorden is still managed as a by-catch species to the blue mussel fishery, even though cockles are almost entirely fished at different locations than blue mussels. Even if data and knowledge on the Limfjorden cockle populations and fishery are improving, particularly since 2018, the fishery is a data-poor fishery likely transitioning from ICES Category 5 to 4 or 3 in 2023.

The overall aim of this project is to provide new knowledge on both cockle biology and fishery in the Limfjorden to advise and support a future sustainable and efficient management of an independent cockle fishery.

Chapter 2 reports the development of a valid and cost-effective survey method and approach adapted to the subtidal, highly patchy distribution and infauna nature of cockles in the Limfjorden.

The developed survey approach uses a Day grab for easy, fast and reliable sampling with 100% efficiency of cockles in the sediment, allowing high sampling intensity and station density (11 to 16 stations/km^2) on regular sampling grids with 200 to 300 m spacing, with eventual stratified sampling depending on expected or known cockle spatial distribution. The use of 10- or 8-mm sieves ensures collection of all cockles larger than ca. 8-9 mm shell width, which settled in the previous summer or earlier. Expected error/precision of cockle biomass under usual cockle spatial distributions and abundances ranged between ca. 9 to 57%.

The proposed stock assessment approach requires three months to deliver advice before the new fishing season in September and includes: i) a 3-week survey covering ca. 60 km^2 in late spring to early summer once the cockle fishery closes; ii) determination of size and age structures of cockle populations; and iii) analysis of landing data, fishing and catch patterns. In 2023, such an approach covered the four main fishing areas historically responsible for 86% of cockle landings since 2017-2018.

Chapter 3 reports the first quantitative description of cockle distribution and abundance, as well as the size and age structure, growth, and mortality, in the main fishing areas of the Limfjorden in the spring of 2021 and 2023.

In both 2021 and 2023, cockle populations had a highly clumped spatial distribution. Relative to historical landings and 2021 (survey only of Kås Bredning), cockle abundance observed in 2023 (survey of four areas, Kås Bredning, Salling Sund syd and nord, and Sønder Bredning) is considered very low. No significant recruitment into cockle populations was observed since 2019 and thus recruitment and growth did not compensate for natural and fishing mortality over the last two to three seasons.

Cockles were small and showed reduced growth, with a negative effect of density on size and growth suggesting intraspecific competition for insufficient food resources.

Total mortality was estimated at 78% per year and natural mortality at 50% per year, similar to reported rates in other European cockle populations.

Chapter 4 describes cockle fishing behaviour, catches, fishing effort, and area impact of the fishery in 2021-2022 season, which had no management regulations limiting the fishery except as a by-catch of the blue mussel fishery and restrictions pertaining to N2000 areas, to inform the future management of a separate cockle fishery in the Limfjorden.

Fishery voluntary catch reports on fishing effort, catches and catch rates were not valid under the format used, being biased towards higher fishing effort and catches relative to the black box system. Nevertheless, the fishery can still contribute valid data (e.g. catch samples for size and age) and information on fishing and cockle populations for the management of the cockle fishery.

Over the 2021-2022 fishing season, cockle fishing activity occurred in 121 days out of potential 302 calendar days, corresponding to 815 boat days of fishing. On average 52,600 ±2,600 m^2 (95% CI) were dredged daily per boat in the Limfjorden.

Catch rates (CPUE) ranged between 0.25 kg/m^2 and 0.30 kg/m^2 in the main fishing area Kås Bredning and the Limfjorden respectively and varied significantly between vessels indicating differences in vessel fishing efficiency.

In 2021-2022, exploitation rates in two trial areas were estimated at 40.4% and 29.5% of the pre-fishing total cockle biomass. While harvest ratios in the trial areas (proportion of harvestable biomass larger than 16 mm shell width removed by fishing), were estimated at 55.4% and 48.4%.

Cockle fishing resulted in a total fished area of 42.9 km^2 with a bottom footprint impact (excludes overlap of multiple tracks) of 10.3 km^2 in the Limfjorden, whereas in Kås Bredning it was 25.6 km^2 and 5.5 km^2 respectively. Cockle fishing footprint impact on the bottom represented 9.6% of potential fishable area in the Limfjorden and 13.6% in Kås Bredning. Fishing intensity also referred to as swept area ratio (SAR, number of times the bottom was fished) was 4.2 in the Limfjorden, but higher in Kås Bredning at 4.6.

Chapter 5 describes the cockle fishing potential as well as the potential area impact of cockle fishing in a non-fished area, the N2000 area Nissum Bredning. The fishing efficiency of the mussel and oyster dredges in Nissum Bredning was also assessed.

In summer 2022, cockles had a limited spatial distribution relative to previous years, occurring almost exclusively in a single large bed in the northern middle of Nissum Bredning. Total cockle biomass was estimated at 13,951 tonnes and harvestable biomass at 12,765 tonnes, relatively low considering the size of Nissum Bredning relative to the main cockle fishing areas. With a commonly used harvest ratio of 33%, Nissum Bredning had the potential to supply 4,213 tonnes of cockles in 2022, slightly lower than mean landings per season from the main cockle fishing area Kås Bredning (2017-2022).

The general lack of significant cockle recruitment in the Limfjorden between 2019 and 2022 was supported by the cohort settled in 2019 also dominating cockle populations in Nissum Bredning.

Fishing efficiency of the mussel and oyster dredges was 18.0% (±3.3; 95% CI) and 16.0% (±1.6; 95% CI) respectively. Fishing efficiency of both dredges increased significantly with consecutive dredging, particularly with the mussel dredge.

Bottom area impacts caused by potential fishing of the cockle biomass in Nissum Bredning in 2022 were estimated by applying a harvest ratio of 33% and the fishing patterns observed in the Limfjorden in the season 2021-2022 (area fished per tonne harvested and swept area ratio). Bottom area impact would range between 3.7 and 4.1 km^2, corresponding to between 2.2 and 2.4% of the Nissum Bredning N2000 area, and below the accepted limits set in the Danish Mussel and Oyster Policy for four ecosystems components eelgrass, macroalgae, benthic fauna and blue mussels. The total cumulative fished area (i.e. including track overlap) would range between 15.6 km^2 and 19.0 km^2.

Chapter 6 reports preliminary knowledge on cockle demographic connectivity in the Limfjorden obtained through modelling larval dispersal and transport.

Most of the Limfjorden, particularly along the central axis, was found to be relatively well connected, with the western (Nissum Bredning) and central parts (Kås Bredning and Løgstør Bredning) predominantly connected unidirectionally from west to east. Self-recruitment along the main central axis basins (i.e. Kås Bredning, Salling Sund and Løgstør Bredning) is low.

The most important fishing area, Kås Bredning, relies heavily (and possibly solely) on recruitment via larval import from cockle populations elsewhere in other sub-basins (Nissum Bredning, Venø Bugt and Visby Bredning). One of the donor areas is the largest known contiguous, and currently unexploited population of cockles in Nissum Bredning. This may explain why Kås Bredning sustained relatively stable recruitment of cockles allowing regular and large cockle landings every season, until the recent general lack of recruitment in the fjord between 2019 to 2022.

Lateral side basins (Venø Bugt, Lovns Bredning and Skive Fjord) present dispersal barriers relative to the central axis of the Limfjorden. Isolated parts of Limfjorden have relatively high self-recruitment and receive very few cockle larvae spawned elsewhere (Venø Bugt, Visby Bredning, Thisted Bredning, Skive Fjord and Lovns Bredning). Year-to-year variations in recruitment were limited.

Løgstør Bredning was identified as a primary sink area, with potential high input of larvae from other parts of Limfjorden as well from self-recruitment, but with no large and dense cockle populations observed in recent years. A hypothesis is that one or more environmental/ecological factors may limit the recruitment of cockles in these areas.

This study addressed exclusively potential connectivity, which in contrast to realized connectivity does not account for the present distribution of cockles and factors such as fecundity, larval mortality, growth, settlement and recruitment success, etc.

This study thus provides a baseline for future studies, where analysis of potential connectivity in combination with data from annual stock assessment and fisheries surveillance can support the prediction of future stock development under different management strategies and scenarios.

Chapter 7 reports DTU Aqua’s advice and recommendations for future management of the cockle fishery in the Limfjorden.

The fishery is highly dependent on a few fishing areas, particularly on Kås Bredning. New cockle fishing grounds would improve the long-term sustainability and viability of the fishery, but likely may be only found in N2000 areas.

Recommendations:

- The cockle fishery should be managed autonomously from blue mussels according to its own management plan, either as a mixed fishery or as a new separate independent fishery.
- Cockle stocks and fishing in the Limfjorden should be monitored and managed according to the specific biology and population dynamics and the conditions of the Limfjorden.

- A monitoring/stock assessment program should follow the template described in Chapter 2 of this report.
- If advice is required later than September-October (e.g. due to a later start to fishing), the survey of cockle populations should be done as closer to the start of fishing and to the end of the cockle growth season, which will improve the stock assessment and biomass estimates.
- Cockle maturity at size and age in the Limfjorden should be evaluated to define an appropriate minimum landing size that ensures sufficient fraction of the cockle population reproduces at least once.
- Fishing N2000 areas is problematic and must abide by conservation and protection regulations for N2000 areas and the Danish Mussel and Oyster Policy, balancing several factors:
    - On one side, the requirements for protection of N2000 species and habitats, potential environmental impacts from cockle fishing, and also required basic biological knowledge of cockle populations and recruitment dynamics elsewhere in the fjord.
    - On the other side, maintenance of one of the few viable Danish coastal fisheries with significant economic and social importance for local/regional communities.

1. Rationale and aims

The Limfjorden cockle fishery (*Cerastoderma* spp.; Figure 1.1) has become the most valuable bivalve fishery in Denmark since 2017 at 31.8 mio. kr. per year equivalent to 40% of all bivalve landings per value (2017-2023, Fiskeristyrelsen). The Limfjorden cockle fishery is also the main European cockle fishery accounting for ca. 59% of European landings between 2017-2022 (Eurostat; Freitas et al., 2023).

Cockle fishing in the Limfjorden is managed as a bycatch of the blue mussel fishery, even though cockles are almost entirely fished at different locations than blue mussels (see ICES 2020 for a definition of target and bycatch species). Blue mussel and cockle fishing in the Limfjorden is thus done with limited by-catch of either of the two species. Recently in 2023, further regulations on cockle fishing imposed catch limits (TAC) based on cockle specific stock assessment. Cockles have at least a similar value – in most years higher – as blue mussels to the fishery, and when cockle fishing occurs, this species rather than blue mussels drives fishing patterns and behaviour of the fishery. Cockle fishing in the Limfjorden mostly occur in only a few fishing areas (produktionsområder for muslinger, MO 9, 11 and 15; Figure 1.2) particularly since 2017, with very irregular fishing in a few other fishing areas (e.g. MO 7, 25, 13; Figure 1.2; Freitas et al., 2023; Fiskeristyrelsen).

Even though data and knowledge on cockle populations and fishery in the Limfjorden has significantly improved since 2018, the cockle fishery is still a data-poor fishery. The fishery is in a transition since 2023 between a ICES Category 5, with only data on landings or a short time-series of catch data, with fishing patterns and activity often not separated from blue mussel fishing (Black Box and Elogs) to likely a ICES Category 3 with survey and trends-based assessment, life history information available for reliable indication of trends in stock metrics such as total mortality, recruitment, and biomass (ICES 2023).

Even though significant progress has been achieved in the last 6 years on the biology, assessment of cockle populations and the fishery itself in the Limfjorden (Freitas et al., 2023), knowledge is still lacking. Particularly, management of cockle fishing in the Limfjorden under a scenario in which cockles are no longer a bycatch of the blue mussel fishery but a separate target species, requires improved biological and fisheries knowledge to support its sustainability and improvement to ICES Category 4 or 3. Fisheries management requires collection of data, both dependent and independent from the fishery, to support the assessment of the stock (i.e. harvestable fraction) and population status and renewal, but also potential impacts from cockle fishing on habitats and other species. In addition, stakeholders require more information and research to support MSC certification of the cockle fishery in the Limfjorden.

The general purpose of the COCKLE II project was thus to provide new knowledge on both cockle biology and fishery in the Limfjorden to advise and support the sustainable and efficient management of this fishery. The main aim of COCKLE II project was to develop a valid and cost-effective monitoring program adapted to the specific subtidal conditions in the Limfjorden and cockle biology (infauna, patchy distribution). Such a monitoring program focuses on the most important and crucial area to the fishery, Kås Bredning, but was also implemented to assess cockle population abundance and distribution, size and age structure in other important cockle fishing areas of the Limfjorden. Secondary aims of the project were to increase our knowledge of cockle biology, larval dispersal and demographic connectivity and potential impact of expanding fishing grounds to other areas like the N2000 area Nissum Bredning (Figure 1).

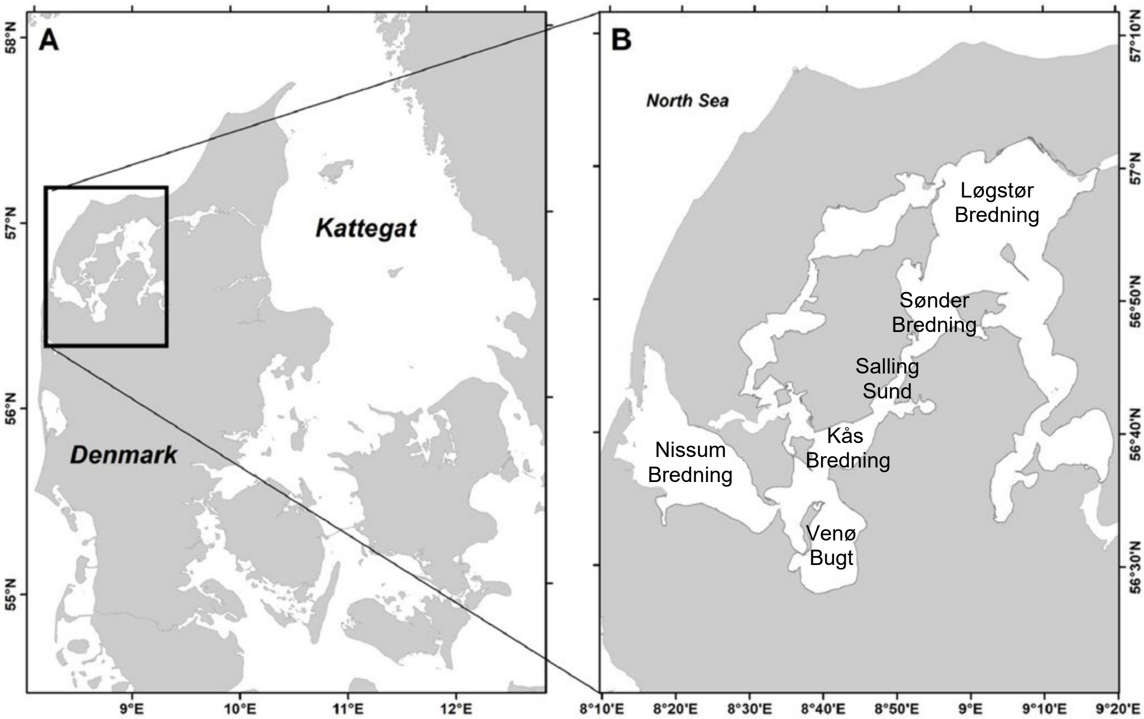

Figure 1.1. Map of Denmark (A) and the western part of Limfjorden (B) with selected broads (bredninger).

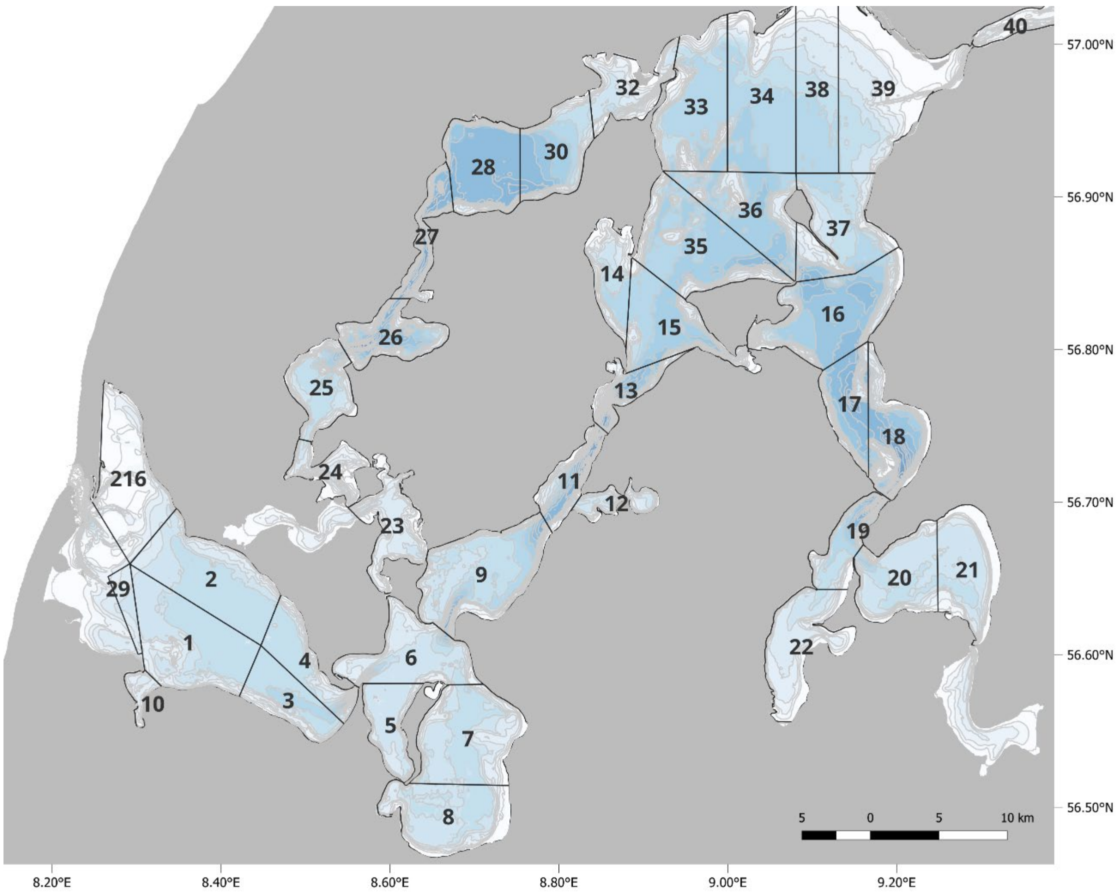

Figure 1.2. The Limfjorden with administrative fishing areas (produktionsområder for muslinger, MO) referred to in the text: Nissum Bredning – MO 1, 2, 3 and 4; Venø Bugt – MO 7 and 8; Kås Bredning – MO 9; Salling Sund Syd – MO 11; Salling Sund Nord – MO 13; Sønder Bredning (MO 15) and Visby Bredning – MO 25. Bathymetry in 1 m depth contours and blue shading.

1.1 References

Freitas, P., Petersen, J.K., Madsen, L., Jensen, K.T., Nielsen, P., Joyce, P., Agüera, A., Olsen, J., Krause, K.E. & Saurel, C. 2023. Sustainable cockle fishery in the Limfjorden. DTU Aqua Report No. 439-2023. National Institute of Aquatic Resources, Technical University of Denmark. 108 pp.

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ICES. 2023. Advice on fishing opportunities. In Report of the ICES Advisory Committee, 2023. ICES Advice 2023, section 1.1.1. https://doi.org/10.17895/ices.advice.22240624

2. Survey and stock assessment of cockle (*Cerastoderma edule* and *Cerastoderma glaucum*) populations in the Limfjorden

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2.1 Introduction and rationale

The objective of fisheries management is to counter not only the impact of fishing mortality on exploited stocks, but also to encompass and act upon the effects/consequences of natural variations in growth, recruitment and natural mortality.

The sustainable and adequate management of fished stocks requires the collection of data for the assessment of abundance and distribution over time and space. Namely, catch data on the amount removed by fishing from a stock; abundance data (or an index) on the number of individuals or weight of the stock; and biological data on size, age, growth and maturity rates, natural mortality, genetics or movement.

While fishery dependent data can provide valid information and is essential to effectively manage all fisheries and often the only available data (e.g. Bradley et al., 2019). Fishery dependent data have however, significant limitations and biases, being influenced by variables specific to how fishermen harvest their catch (e.g. non-standardized, spatial and temporal gaps, lack of geographical information, dependent on and affected by changes in fishing strategies, activities, gear, etc). To determine quantitative changes in abundance, distribution or biological characteristics of exploited populations, fisheries independent data collected from research is required.

The cockle fishery is in a transition from a data-poor fishery ICES Category 5, but its status is not yet or at least only episodically an ICES 4 or 3 (see Chapter 1; ICES 2023).

Three factors impact and constrain the survey of cockle populations in the Limfjorden:

1. Cockles are an infauna species living just under the surface in sandy to muddy sediments and thus a sampling method that collects all cockles in the sediment is required.
2. Cockles are fished exclusively in subtidal areas deeper than 3 m in contrast to other cockle fisheries in Europe that are almost exclusively inter-tidal, and thus the use of boats for surveying is required, which is both expensive and slow.
3. The highly patchy distribution and spatially and temporally unstable populations (Ivell, 1981, Dare et al., 2004; Freitas et al., 2023) requires high-spatial resolution sampling and high sampling intensity to reduce the likelihood of missing dispersed and patchy high-density cockle beds, resulting in underestimation of the stock.

The use of data from surveys using surface dredges, such as done for blue mussel and European oyster populations in the Limfjorden, or even suction dredges (Freitas et al., 2023) is highly unreliable and not valid for monitoring cockle populations in the Limfjorden.

The aim of this study was thus to develop and evaluate an accurate, timely and cost-effective survey method and approach to support adequate fishery independent stock assessments for the Limfjorden cockle fishery based on the previous experience of DTU Aqua in surveying bivalve populations and on a review of monitoring programs in other cockle fisheries (e.g. Franklin and Pickett, 1979; Dare et al. 2004; Kater et al., 2006; Lancaster 2009; Bijleveld et al., 2012; Southall and Tully, 2014).

2.2 Methods

Survey

Sampling and sorting

Based on the constraints and review described above in section 2.1, a 0.1 m^2 and 15 l volume Day-grab that penetrates 10 cm into the sediment was chosen as sampling gear and samples were sieved through a 10 mm metal sieve that collects any cockle larger than 9 mm shell width or 14 mm shell length (Figure 2.1).

Once sieved, samples containing all live organisms and dead shells were placed in mesh bags and kept in water on-board. Samples were sorted and weighed for live cockles, other live organisms and dead shells either on board upon collection or taken to shore and kept in holding tanks with running water until sorting and weighing within 48h. Live cockles were then frozen for size and age measurements.

Sampling design and survey error

A sampling grid design with fixed spacing was chosen, as this is considered the best design to estimate temporal and spatial changes in abundance and mapping i.e. prediction of abundance at unsampled locations (Bijleveld et al., 2012).

The precision of grab sampling at individual stations was assessed by repeating all sampling operations including navigating to the station in 10 stations (7 to 12 replicate grabs per station), covering a range of densities from 150 to 1700 cockles/m^2 (Figure 2.2).

The impact of spatial resolution on the error of cockle biomass estimates, expressed as the 95% CI in % of mean estimates, to guide the choice of a sampling resolution adequate to the objectives of a given survey, was evaluated over a range of spatial resolutions (50 to 800 m) and surveyed areas (<1 km^2 to >100 km^2). All surveys done during the project were used in this exercise and occurred in several basins of the Limfjorden (Kås Bredning MO 9, Nissum Bredning MO 1-4, Salling Sund syd MO 11, Salling Sund nord MO 13) over three years, 2021, 2022, 2023 (Figure 2.4 and Table 2.1). Surveys were categorized by area size into small (<0.1 km^2), medium (8 to 30 km^2) and large (110 km^2) surveys (Table 2.1).

Cockle biomass (tonnes) estimated for the highest spatial resolution of each survey was assumed as the most accurate reference stock estimate for that survey. Cockle biomass was also estimated at lower spatial resolutions by resampling the original grid at reduced resolution (Table 2.1). For instance, in the large survey of Kås Bredning in 2021 done at 200 m resolution (Table 2.1), cockle biomass was also estimated at lower resolutions of 400 m (N = 4), 600 m (N = 9) and 800 m (N = 16). Cockle biomass was estimated by fitting a normal or exponential function for the area of cockle beds depending on data distribution. Biomass estimate errors are reported as 95% confidence intervals.

Figure 2.1. The 0.1 m2 Day grab (top) used in the cockle surveys and an example of a sample being washed and sieved through the 10 mm metal sieve (top photo: KC Denmark A/S).

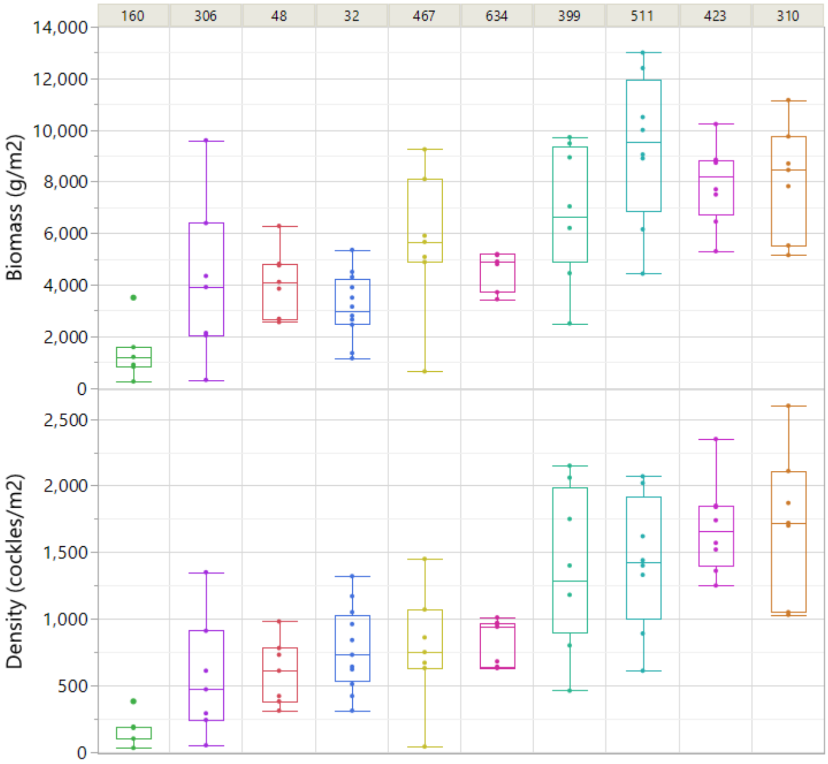

Figure 2.2. Box-plots of cockle density (bottom) and biomass (top) obtained from replicate grabs (7 ≤ N ≤ 12) at 10 stations over a large range of cockle abundance.

Size and age

Cockle size, shell height, length and width (Figure 2.3) were measured using a digital calliper to 0.01 mm. Cockles were aged based on the presence of annual winter lines on the shell surfaced (e.g. Richardson, 1980; Jones and Baxter, 1987).

In the large survey of Kås Bredning in 2021, a total of 6.792 cockles from 105 stations were analysed, while in the 2023 survey of Kås Bredning, Salling Sund and Sønder Bredning only 849 cockles from 49 stations were analysed due to the significantly lower cockle abundance, even if the surveyed area was larger than in 2023.

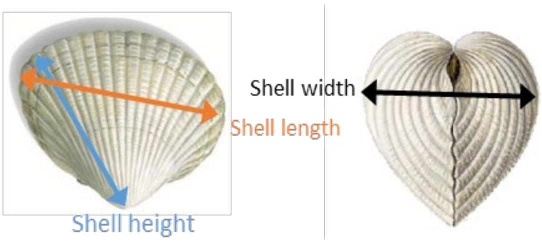

Figure 2.3. The three dimensions used to measure cockle shells: shell height, length, and width. Normally, minimum sizes refer to shell width or length.

Cockles in the Limfjorden commonly present disturbed growth (Freitas et al., 2023), which causes increased ageing uncertainty, particularly at ages of 4 and 5 years old. This is unavoidable as the precision of ageing is increasingly affected at older ages by the presence of secondary non-annual lines linked to reductions or disturbances in growth within a given year (e.g. Richardson, 1980; Ramon, 2003). Nevertheless, the presence of similar growth patterns (i.e. same sequence of large-small-large growth increments and the occurrence of secondary non-annual lines at the same location within that sequence) is also used to confirm and validate the age of individual cockles and provides assurances on the overall population age structure obtained.

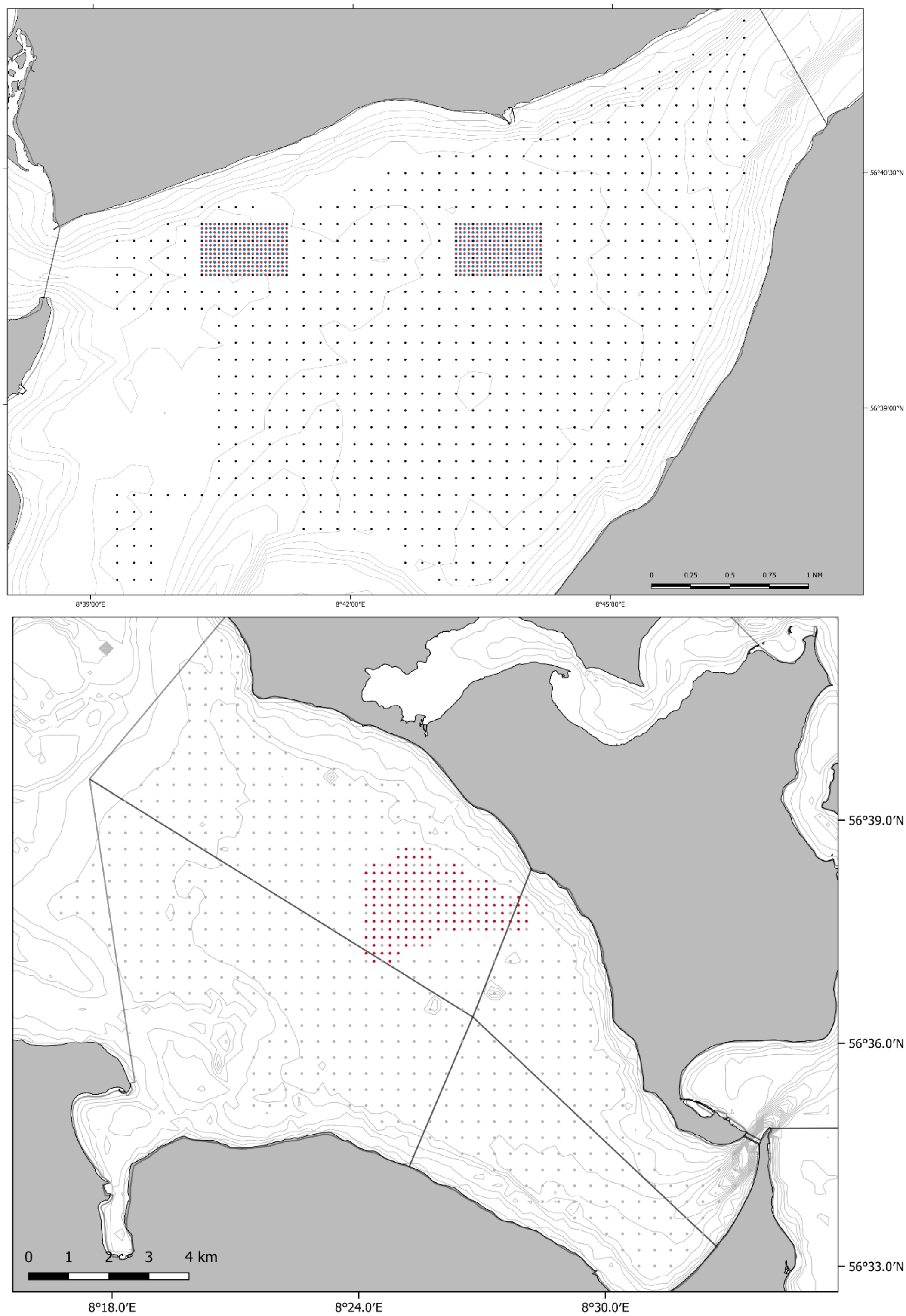

Figure 2.4. Surveys used in the cockle stock estimate error evaluation exercise. Top: Kås Bredning (MO 9) larger survey in 2021 (black, at 200 m) and small fishing trials surveys in 2021 (red at 50 m) and 2022 (blue at 70 m); Bottom: Nissum Bredning (MO 1, 2, 3 and 4) stratified survey in 2022 (grey at 400 m and red at 200 m).

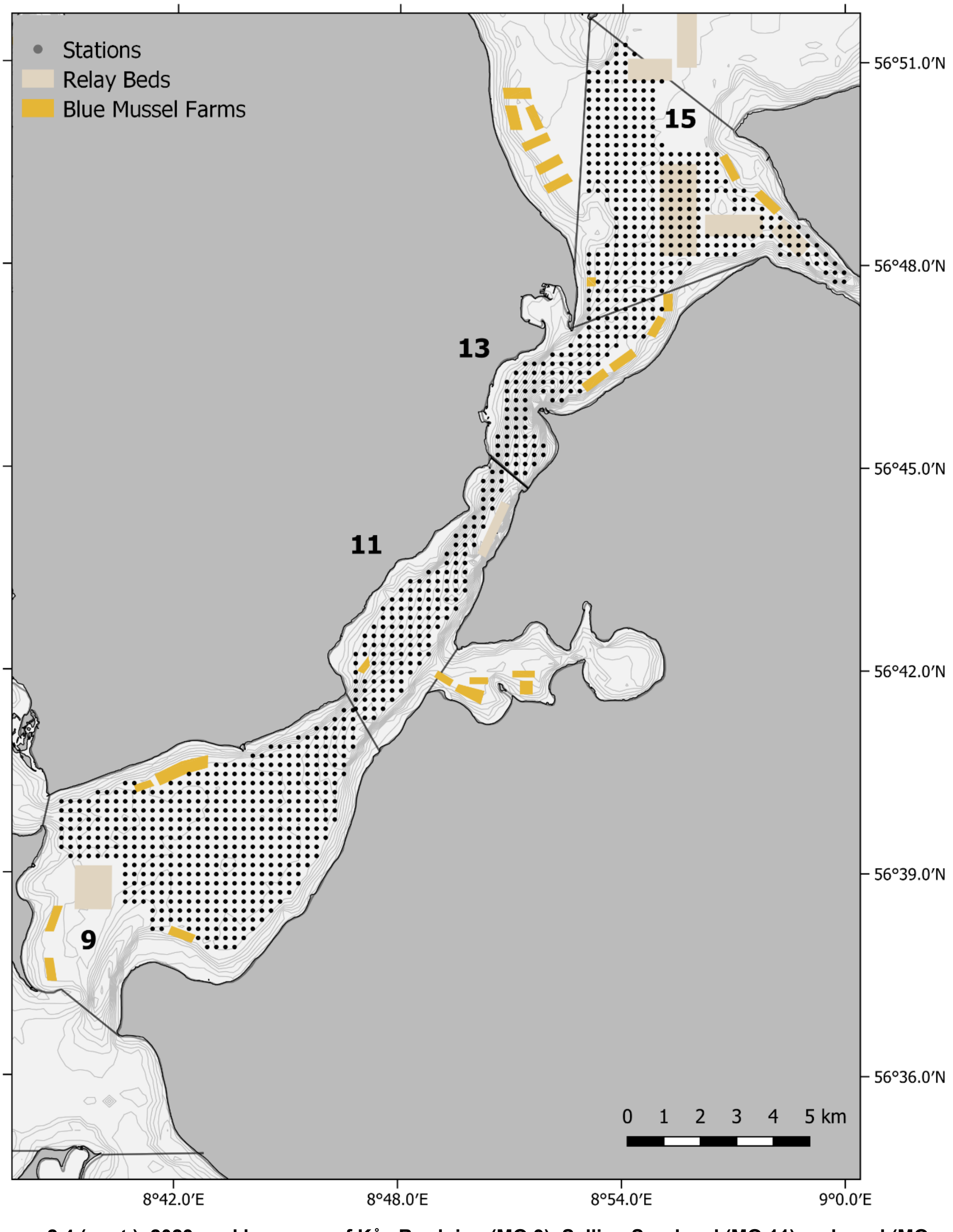

Figure 2.4 (cont.). 2023 cockle survey of Kås Bredning (MO 9), Salling Sund syd (MO 11) and nord (MO 13), and Sønder Bredning (MO 15) done at 250 m resolution (N = 473, 143, 112 and 348, respectively).

Table 2.1. Summary of survey data used in the evaluation of sampling spatial resolution impact on cockle biomass estimates error. Surveys were categorized in three size categories, small, medium and large. Station density is the number of stations per km² surveyed. Reference biomass is the biomass estimate at the highest sampling resolution in each survey. Error or precision are 95% confidence intervals.

Year	**Area** (km^2)	**Grid Spacing** (m)	**N**	**Number Stations**	**Stations /km²**	**Biomass Estimate** (tonnes)	**% Reference Biomass**	**% Estimate Error** (95% CI)
Kås Bredning (MO 9)								
2021	Small	50	2	273	455.0	1,596 – 2,011	100	6 - 8
	0.6	70	2	154	256.7	1,492 – 1,896	93 - 94	10 - 12
		100	2	77	140.0	1,718 – 2,073	103 - 108	15 - 16
		200	2	24	22.2	1,630 – 2,296	102 – 114	36 - 38
2022	Small	70	2	154	256.7	352 – 850	100	24 - 25
	0.6	100	2	77	140.0	307 – 891	87 - 105	34
		200	2	24	22.2	456 – 738	87 – 130	82
2021	Medium	200	1	738	24.6	27,061	100	14
	30	285	2	370	12.3	25,272 – 27,688	93 - 102	20 - 29
		400	4	189	6.3	24,445 – 29,935	90 - 111	30
		600	9	86	2.9	21,665 – 42,376	80 - 157	44 - 54
		800	16	50	1.7	12,307 – 38,125	46 - 141	63 - 93
2023	Medium	250	1	474	15.8	4,075	100	30
	30	350	2	239	8.0	2,811 – 5,176	69 - 127	44 - 46
		500	4	119	4.0	1,913 – 8,123	47 - 199	68 - 82
		750	9	54	1.8	1,237 – 11,334	30 – 278	97 - 302
Nissum Bredning (MO 2,4 and MO 1,2,3,4,29)								
2022	Medium	200	1	178	22.3	13,252	100	10
	7	400	4	66	8.3	11,470 – 15,987	87 - 121	17 - 32
		600	9	35	4.4	7,805 – 16,722	59 – 126	24 - 47
2022	Large	200+400	1	800	Mix	13,951	100	11
	110	400	1	670	6.1	16,686	120	21
		800	4	280	2.6	8,832 – 19,699	63 - 141	32 - 80
Salling Sund syd (MO 11)								
2023	Medium	250	1	143	15.9	1,750	100	41
	9	350	2	75	8.33	1,207 – 2,223	69 - 127	65
		500	4	40	4.44	1,137 – 2,850	65 - 163	93 - 133
Salling Sund nord (MO 13)								
2023	Medium	250	1	112	16.0	181	100	501
	7							
Sønder Bredning (MO 15)								
2023	Medium	250	1	348	15.8	553	100	65
	22							

2.3 Results

Sampling method

The Day grab worked very well in all soft-bottom sediments encountered during the surveys. Inspection of sediment samples using the lids in the grab together with videos collected during sampling confirmed that release of the grab resulted in consistent penetration of the grab shovels of 10 cm into the sediment. Occasionally the trigger mechanism misfired, i.e. no release and no sampling by the grab, in which case the station was repeated.

On all surveys, station sampling rate using the sampling protocol develop by DTU Aqua was at least 60 stations per day. Sampling processing, sorting and weighing of the 60 samples collected per day could be done by three persons in ca. 3 hours in the laboratory. Analyses of size and age of cockles took 1 day for ca. 5-8 samples with 60 cockles per sample.

Tests with different sizes showed the 10 mm sieve retained all cockles larger than 9 mm shell width and 14 mm shell length (Figure 2.3). In the Limfjorden, cockles of this size are younger than one year old (Freitas et al., 2023a) and therefore the 10 mm sieve retains all cockles slightly younger than one year old or older with 100 % efficiency.

The mean error of cockle biomass and density grab samples (i.e. 95% confidence intervals of mean) estimated from 7 to 12 replicate grabs at 10 stations was respectively 35.0% and 38.7% (Figure 2.5).

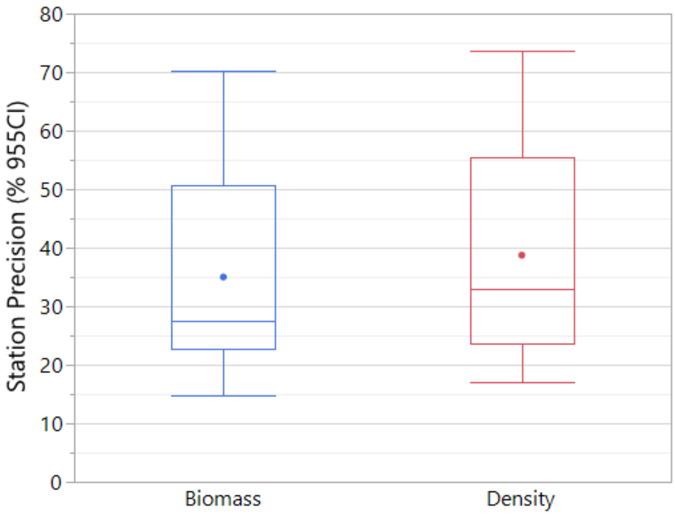

Figure 2.5. Box-plot of the error (i.e. precision) of cockle density and biomass obtained from grab samples, as the 95% confidence interval in 10 stations with 150 to 1700 cockles/m^2.

Survey spatial resolution and error

Cockle biomass estimates obtained at different spatial resolutions were compared in each survey to a reference biomass estimate obtained at the highest spatial resolution/station density (Figure 2.6 and Table 2.1).

Lower resolution biomass estimates deviated by up to 285 kg in small sized areas, up to 15,300 kg in medium sized areas and up to 5,750 kg in large areas (Table 2.1). In relative terms, lower resolution biomass estimates deviated from reference biomass by 2 to 30% in small sized areas, by 2 to 178% in medium sized areas and 20 to 41% in large sized areas (Figure 2.6 and Table 2.1).

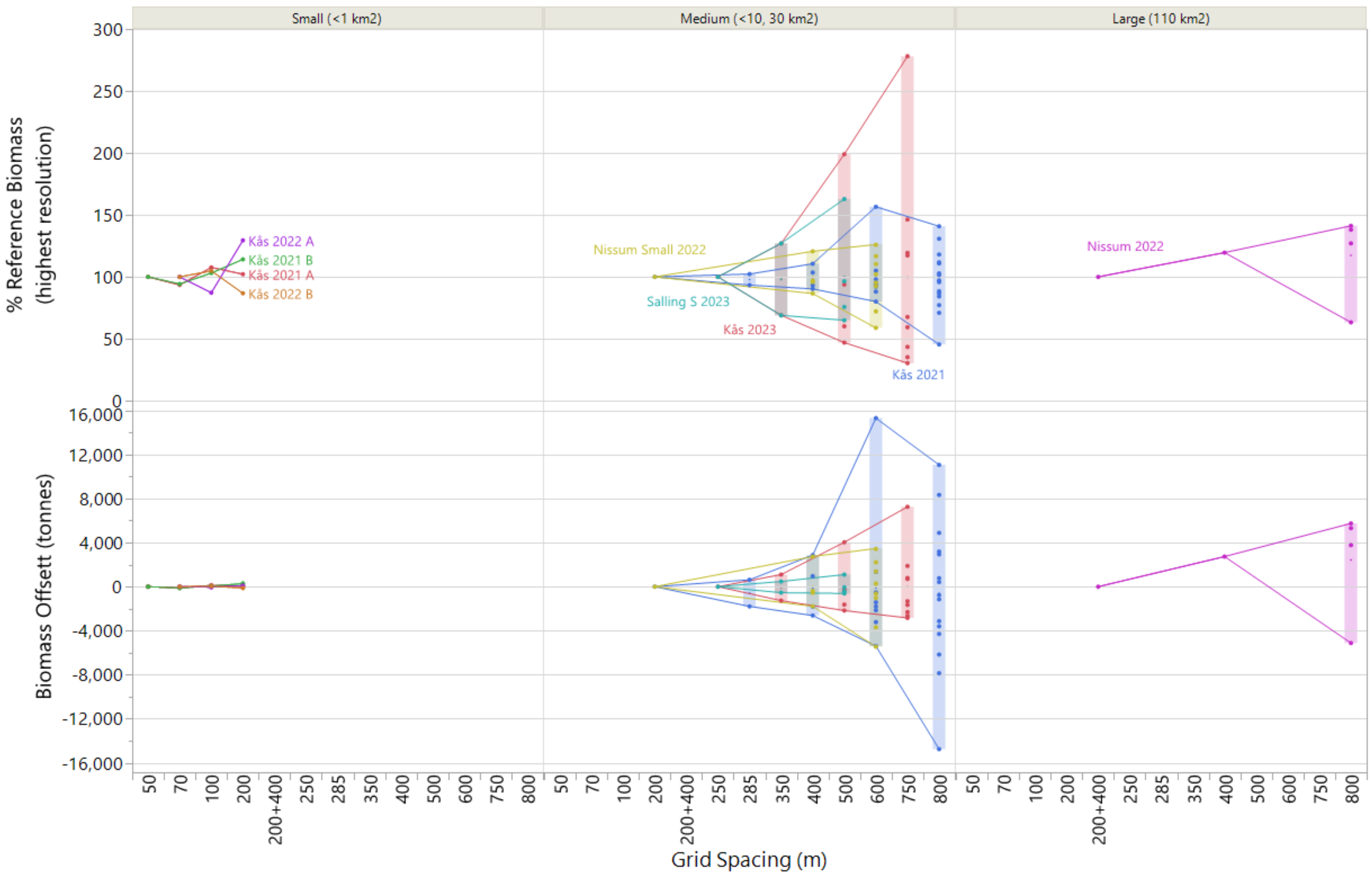

Figure 2.6. Impact of sampling spatial resolution on accuracy and error of cockle biomass estimates from surveys of areas with different sizes: small with <1 km², medium with 7 to 30 km² and large with 110 km² (surveys in Table 2.1.). Top: Offset in % of biomass estimates at different sampling resolution relative to reference biomass estimate of each survey (i.e. from highest sampling resolution); and Bottom: absolute offset of biomass estimates in tonnes from reference biomass of each survey. Sampling intensity/resolution decreases from left to right, as grid spacing and surveyed area (km²) increase. Bands and lines delimit minimum and maximum values. Salling Sund nord (MO 13) and Sønder Bredning (MO 15) are not shown due to low abundance of cockles.

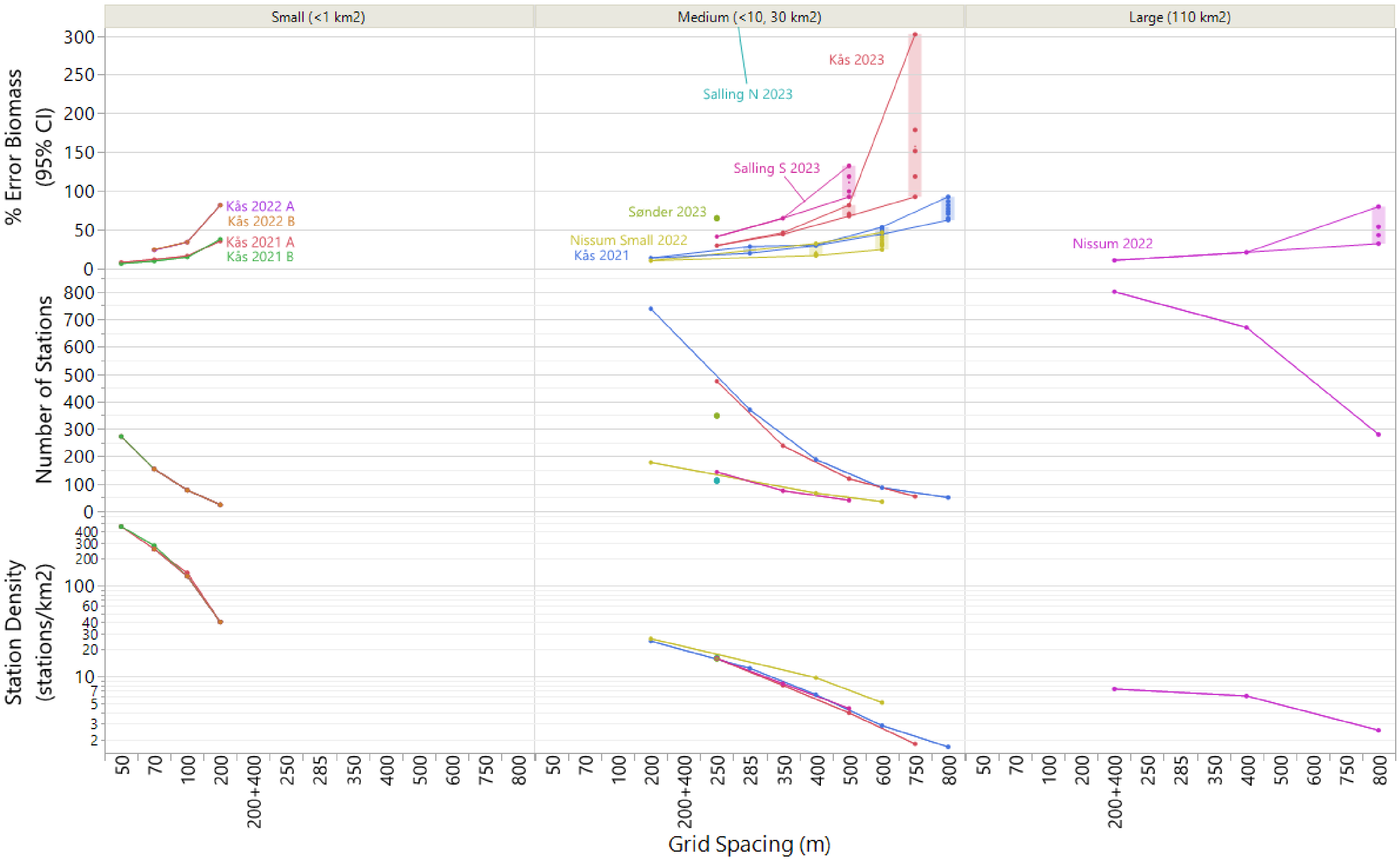

Figure 2.7. Changes in the error of cockle biomass estimates (i.e. precision) due to sampling spatial resolution in surveys of areas with different sizes: small with <1 km^2, medium with 7 to 30 km^2 and large with 110 km^2 (surveys in Table 2.1.). Top: % error of biomass estimates as 95% confidence interval of estimate; Middle: sampling intensity as number of stations; and Bottom: station density i.e. number of stations per km^2. Bands and lines delimit minimum and maximum values. Error for Salling Sund nord (MO 13) in 2023 was 501%.

The offset of cockle biomass estimates relative to reference biomass, either absolute or relative, increased when sampling resolution/station density decreased and grid spacing increased in all three survey area sizes (Figures 2.6 and 2.7, Table 2.1).

Similarly, the error/precision of cockle biomass estimates (i.e. 95% CI of estimates), which ranged between 6 and 501%, increased with decreasing station density and increasing grid spacing (Figure 2.7 and Table 2.1).

Station density had a significant effect on the error of biomass estimates (least square regressions, $\log_{10}$ transformed, $F_{1,88} = 41.117$, $p < 0.0001$), which was different between small, medium and large surveyed areas (same slope, $F_{2,88} = 1.947$, $p = 0.149$, but different intercepts $F_{2,88} = 9.699$, $p = 0.0002$; Figure 2.7 and Table 2.1).

In all three survey area sizes, significant linear regressions with negative correlations between biomass estimate error and station density were observed (Figure 2.8; $\log_{10}$ transformed): Small area, $r^2 = 0.745$ ($F_{1,13} = 35.03$, $p < 0.0001$; $\mathrm{Log}_{10}\%error = 2.979 - 0.763 * \mathrm{Log}_{10}Station\ intensity$); medium area, $r^2 = 0.532$ ($F_{1,68} = 77.25$, $p < 0.0001$; $\mathrm{Log}_{10}\%error = 2.100 - 0.616 * \mathrm{Log}_{10}Station\ intensity$, excludes Salling Sund nord); and large area: $r^2 = 0.789$ ($F_{1,5} = 14.99$, $p = 0.018$; $\mathrm{Log}_{10}\%error = 2.218 - 1.281 * \mathrm{Log}_{10}Station\ intensity$).

2.4 Discussion

Sampling protocol

Operation of the Day grab in all surveys was simple, fast and highly reliable. The use of the Day-grab provides:

- A highly reliable sampling gear with a design (wide and flat main frame with adjustable weights) that ensures a stable and reliable contact with the bottom and digging into the sediment and consistent collection samples.
- Sampling with 00% efficiency of cockles in the sediment as the grab spade digs down to 10 cm.
- A light (55/75 kg to 165 kg), simple and fast sampling method that ensures high-station turnover of at least 60 stations per day.
- Sufficient sampled area per station of 0.1 m2, like surveys of other European cockle fisheries that commonly use between 0.06 to 0.5 m2 (e.g. Franklin and Pickett, 1979; Dare et al. 2004; Kater et al., 2006; Lancaster 2009; Southall and Tully, 2014).

Other cockle fisheries in Europe use sieves with smaller sizes than the current project surveys (down to 1 mm), but with the purpose of also sampling recently settled spat, i.e. settled during the year of the survey. A 10 mm sieve was used in the project surveys for several reasons:

- It retains any cockle with less than one year old and older, i.e. any cockle that has gone through the extremely high and variable post-settlement and first winter mortality.
- Smaller cockles will still be collected on the 10 mm mesh, but at less than 100% efficiency.
- Smaller size sieves can slowdown sampling operations due to increased washing times. Recent trials in 2024 indicate an 8 mm sieve can replace the 10 mm sieve without significant slowdown.
- Currently, to provide advice before the start of the cockle fishing season in the month of September, surveying precedes or coincides with the period of larvae settlement and thus cannot sample cockle spat.

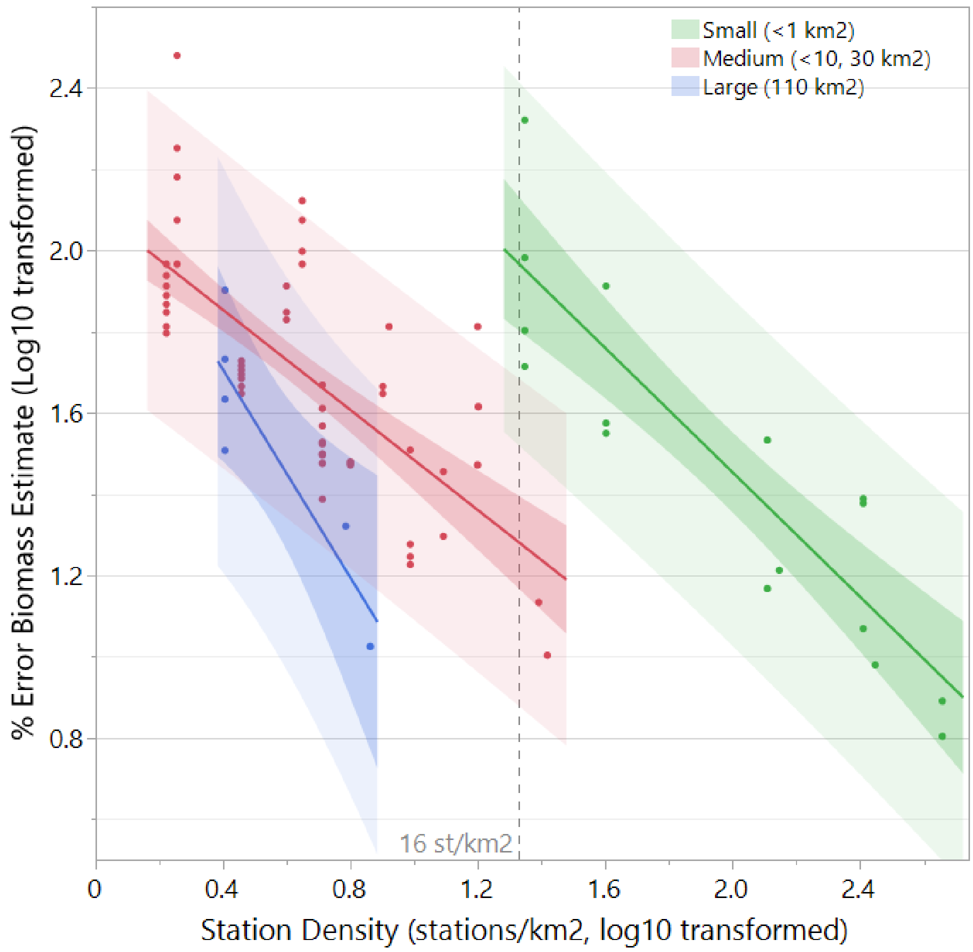

Figure 2.8. Linear fits between the error in biomass estimates and station density (both $\log_{10}$ transformed) for surveys of areas with different sizes (see Figure 2.7 and Table 2.1. All regressions were significant and different between areas (see text). Excludes Salling Sund nord (MO 13) in 2023. Shaded areas are 95% confidence intervals of fit (dark) and prediction (light).

Therefore, with the current objective of a cockle monitoring program in the Limfjorden, the use of sieves smaller than 10 mm is not required. A 10 mm sieve retains with 100 % efficiency all cockles that contribute to the stock biomass, both reproductive and harvestable biomass, including all young cockles that eventually contribute to new recruitment into the stock and may be related to future catches. With different stock assessment objectives, i.e. evaluation of recent settled spat in a survey later in the year, the use of smaller sized sieves is justified.

Cockle survey approach

The scale required for the assessment of cockle populations and stocks in the Limfjorden, ranges between medium and large areas from 7 to ca. 60 km^2 depending on the size and number of fishing areas to survey (Figure 2.4 and Table 2.1). Time and available resources inevitably constrain how large the surveyed area can be and the spatial resolution of surveys, which were 200 m in 2021, a stratified design of 200 and 400 m in the 2022, and 250 m in 2023 (Figure 2.4 and Table 2.1).

At such sampling resolutions, the error/precision of cockle biomass estimates ranged from 10% to 65% and were close to the error of the high-resolution surveys of small areas (<1 km^2 at 50 to 100 m), which ranged between 6 and 34% (Figure 2.7 and Table 2.1). However, factors other than sampling resolution and grid spacing may also influence the error of cockle biomass estimates, particularly cockle spatial distribution, i.e. how random, regular/homogenous or clumped/patchy, and obviously the size of cockle beds relative to grid spacing. For instance, a more homogenous or more clumped distribution is the likely explanation for the error in cockle biomass estimates from some surveys being lower or higher than other surveys with similar sampling resolution and intensity (Figure 2.7 and Table 2.1). Similarly, if the size of cockle beds is very small relative to the grid spacing, the probability that important cockle beds are missed in sampling is high and biomass estimate errors can become very large reaching up to several hundred %, as in Kås Bredning with a 750 m grid or Salling Sund nord with a 250 m grid in 2023 (Table 2.1).

Based on these findings, a monitoring program was developed to fulfil the current objectives of cockle stock assessment in the Limfjorden, i.e. to cover the main cockle fishing areas and provide advice before the start of the fishing season in September-October. In 2023, this approach was used to survey the four main fishing areas (MO 9, 11, 13 and 15) historically responsible for 86% of cockle landings since 2017-2018, including the cockle beds responsible for over 99% of landings in the previous season (DTU Aqua Notat 23-1009397).

The stock assessment and monitoring program require three months to be carried out and includes tasks such as survey design and preparation, a 3-week boat survey during spring, land-based sample processing, size and age analysis in the laboratory, analysis of survey data as well as of landings and black box data, with reporting in early September before the start of the following fishing season:

- A survey in late spring to early summer once the cockle fishery closes.
- Usage of a Day-grab and 10- or 8-mm sieves.
- High resolution sampling on a regular sampling grid (e.g. 200 to 300 m), with high station density (e.g. 16 stations/km2) and sampling intensity (e.g. 1.66 m2/km2).
- Eventual use of stratified sampling depending on expected or known cockle spatial distribution (i.e. smaller spaced grid over cockle beds).

Resulting in:

- Expected error in cockle biomass estimates under usual cockle distribution and abundance between 9 to 57% (from regression analysis).
- Survey of ca. 60 km2 in 15 days.
- Measurement of cockle size and age distributions of 60 to 80 stations in ca. 4 weeks.

If the objectives of the cockle stock assessment in the Limfjorden change, the monitoring program approach and design should be adapted to those changes to improve estimates of biomass, distribution and prospective catch rates. For instance:

- If advice is required later than September-October, a survey later in summer or early autumn closer to the end of the growth season will reduce the impact from growth and mortality between survey and the start of fishing and improve the accuracy of biomass estimates.
- If assessing the abundance and distribution of recently settled cockles becomes an objective, then a survey in early autumn using a smaller sized sieve (e.g. 6 or 2 mm) will collect recently settled cockles after they undergo early post-settlement mortality and grown to ca. 10 mm shell length.
- If the objective is no longer to assess fishing areas but only cockle beds, which then define catch limits for the fishing area where they are located, then sampling effort can be concentrated or limited to those beds to improve accuracy of the estimates. For instance, using a stratified design to concentrate most sampling intensity on essential areas to the cockle fishery, i.e. beds that historically have produced most landings or are important beds fished in the previous season that may still contain significant biomass.
- Even with unchanged objectives, a stratified design allows to increase sampling resolution and intensity on areas that contain cockles. Both in the survey of large fishing areas (e.g. as

done in Nissum Bredning 2022; Table 2.1) or of small cockle beds that reoccur at the same locations (e.g. Salling Sund syd, MO 11).

- The addition of a small percentage of random stations along the fixed grid of stations will improve the robustness of the stock assessment (Bijleveld et al. 2012).

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3. Cockle populations in the Limfjorden in spring 2021 and 2023

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3.1 Rationale

Apart from fisheries dependent data (e.g. landings, effort, fishing patterns), a stock assessment can include description of temporal and spatial trends, life history information (size, age, growth, mortality, maturity and reproduction) and how those relate to environmental factors (e.g. feeding, habitat, salinity, temperature, etc), population and fishery parameters (e.g. stock-recruitment relationships, exploitation rates, yield-production models and abundance indices), biological indicator/reference points, as well as advice on management objectives and actions.

The aim of this Chapter is to provide the first quantitative description of cockle (common cockle, *Cerastoderma edule*) distribution and abundance as well as the size and age structure, growth, and mortality, in the main fishing areas of the Limfjorden in the spring of 2021 and 2023.

3.2 Methods

Surveys

Two large surveys were done during the Cockle II project using the approach described in Chapter 2 covering Kås Bredning (MO 9) in both 2021 and 2023, and additionally Salling Sund syd and nord (MO 11 and 13) and Sønder Bredning (MO 15) in 2023.

In 2021, a 200 m grid was used at ca. 24.6 stations/km^2 for a total of 738 stations in Kås Bredning (Figure 3.1 and Table 2.1). While in 2023, a 250 m grid was used at 16 stations/km^2 with a total of 1,077 stations in four fishing areas responsible for 86% of cockle landings between 2017-2022 (Figure 3.2 and Table 2.1), the two main fishing areas of Kås Bredning (n = 474) and Sønder Bredning (n = 348) and two important areas in previous seasons Salling Sund syd (n = 143) and Salling Sund nord (n = 112).

Samples were collected, processed and cockle size and age measured according to the methods described in Chapter 2.

Cockle biomass was estimated in each fishing area by fitting a normal or exponential function to the stations in cockle beds depending on data distribution. Biomass estimate errors are reported for the 95% confidence intervals.

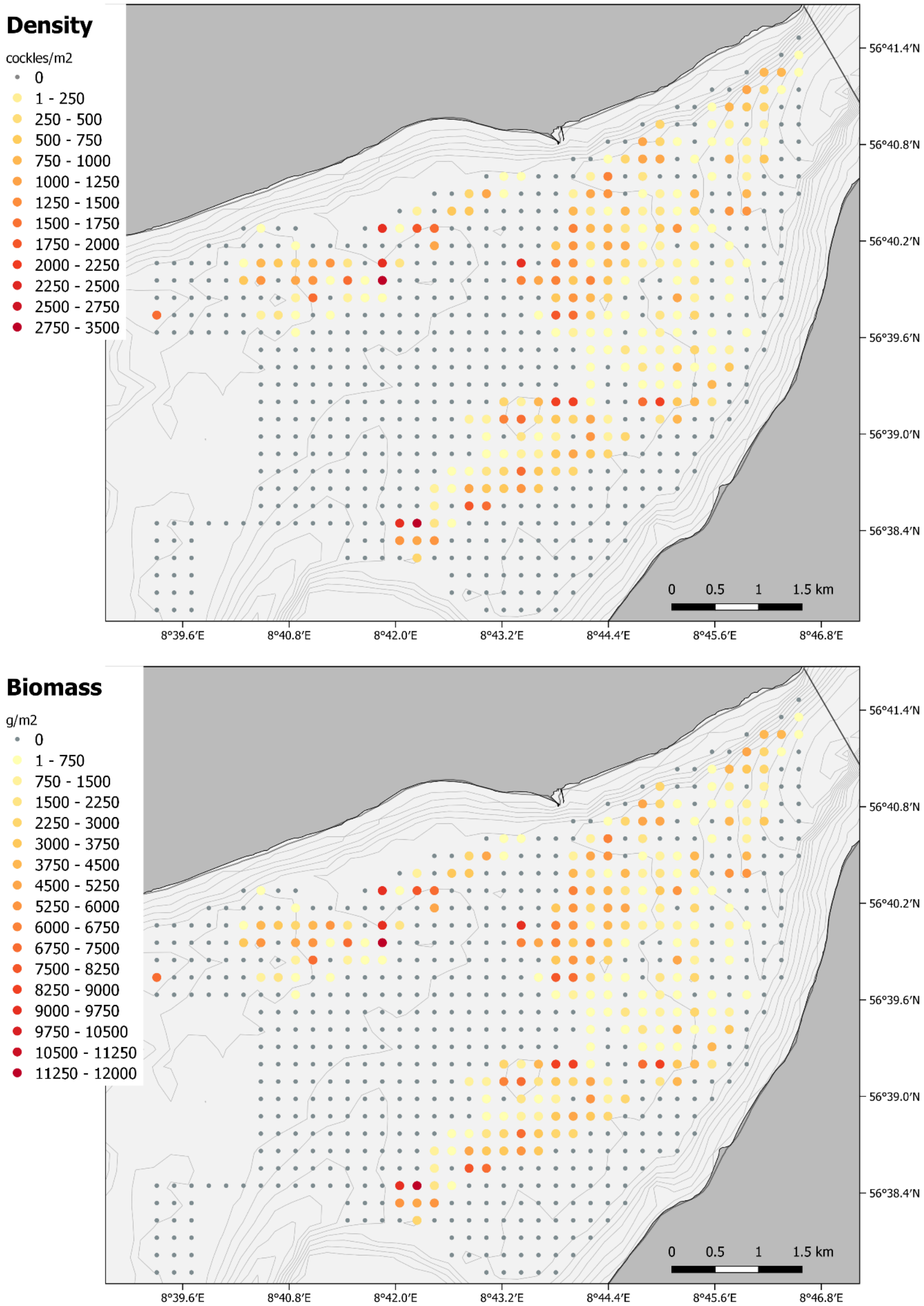

Figure 3.1. Spring 2021 survey of Kås Bredning (MO 9), density (top, cockles/m^2) and biomass (bottom, g/m^2).

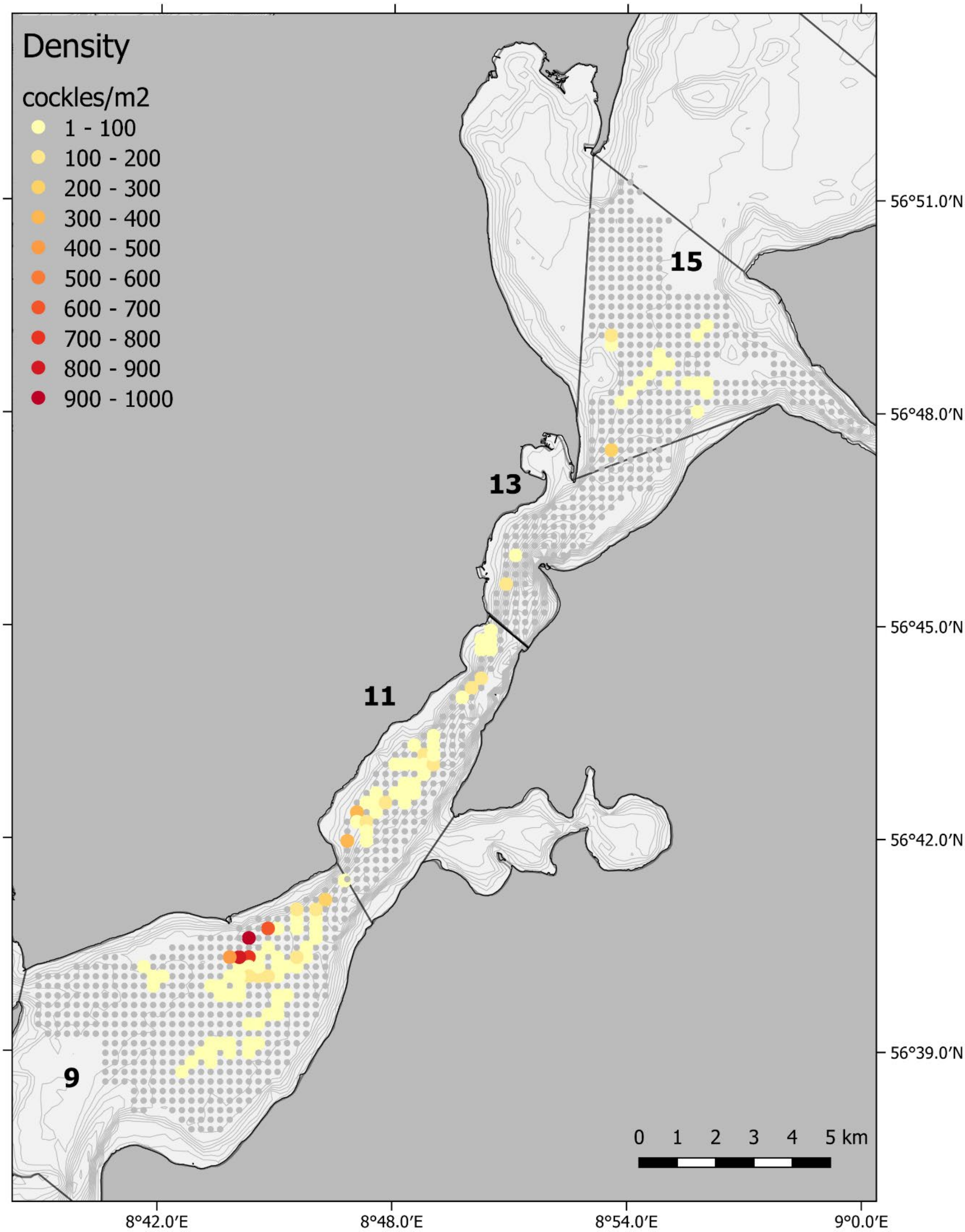

Figure 3.2. Density (cockles/m²) in the spring 2023 survey of Kås Bredning (MO 9), Salling Sund syd (MO 11) and Nord (MO 13), and Sønder Bredning (MO 15).

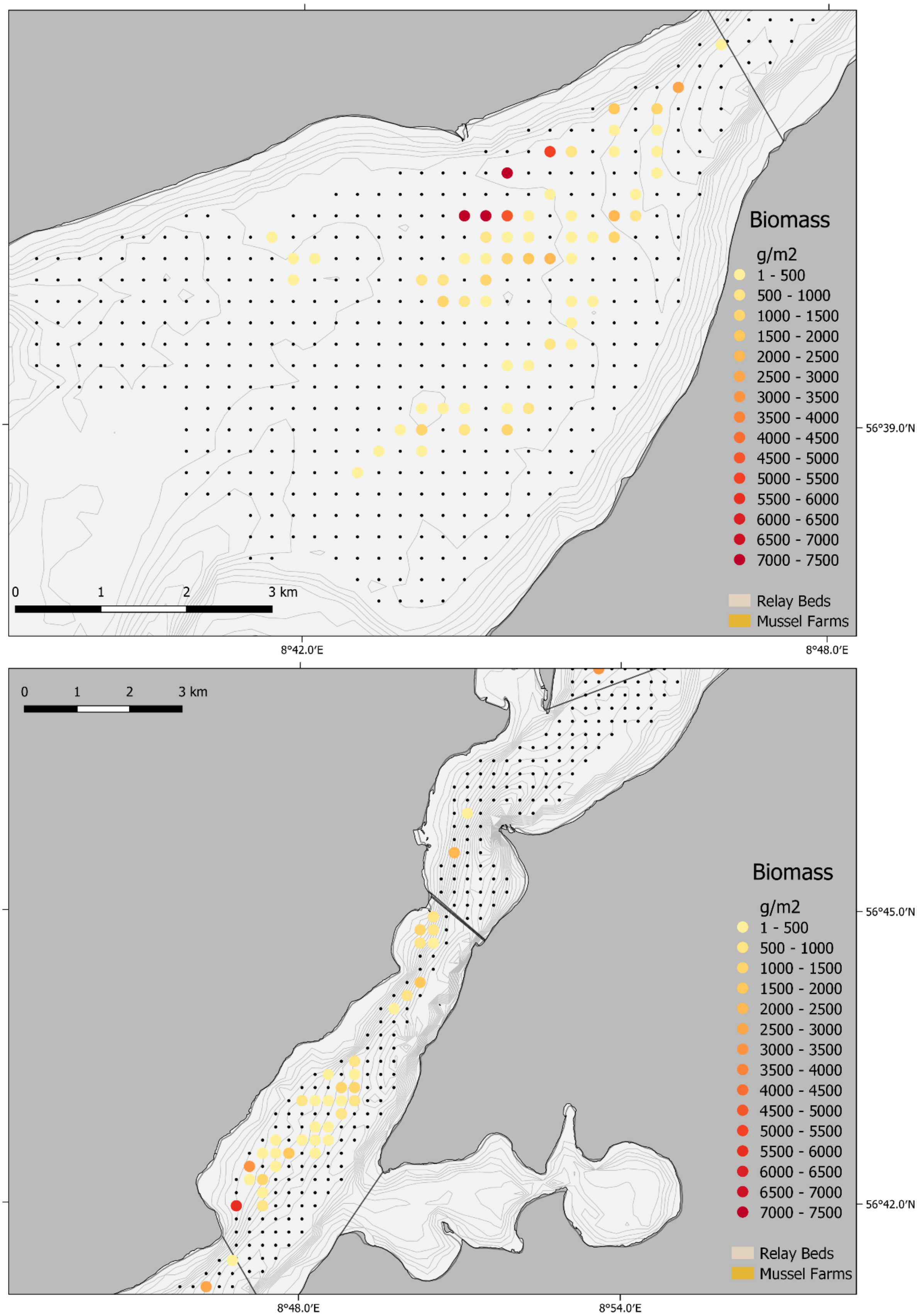

Figure 3.2 (cont.). Biomass (g/m^2) in spring 2023 survey of Kås Bredning (MO 9; top), Salling Sund syd and Nord (MO 11 and 13; bottom).

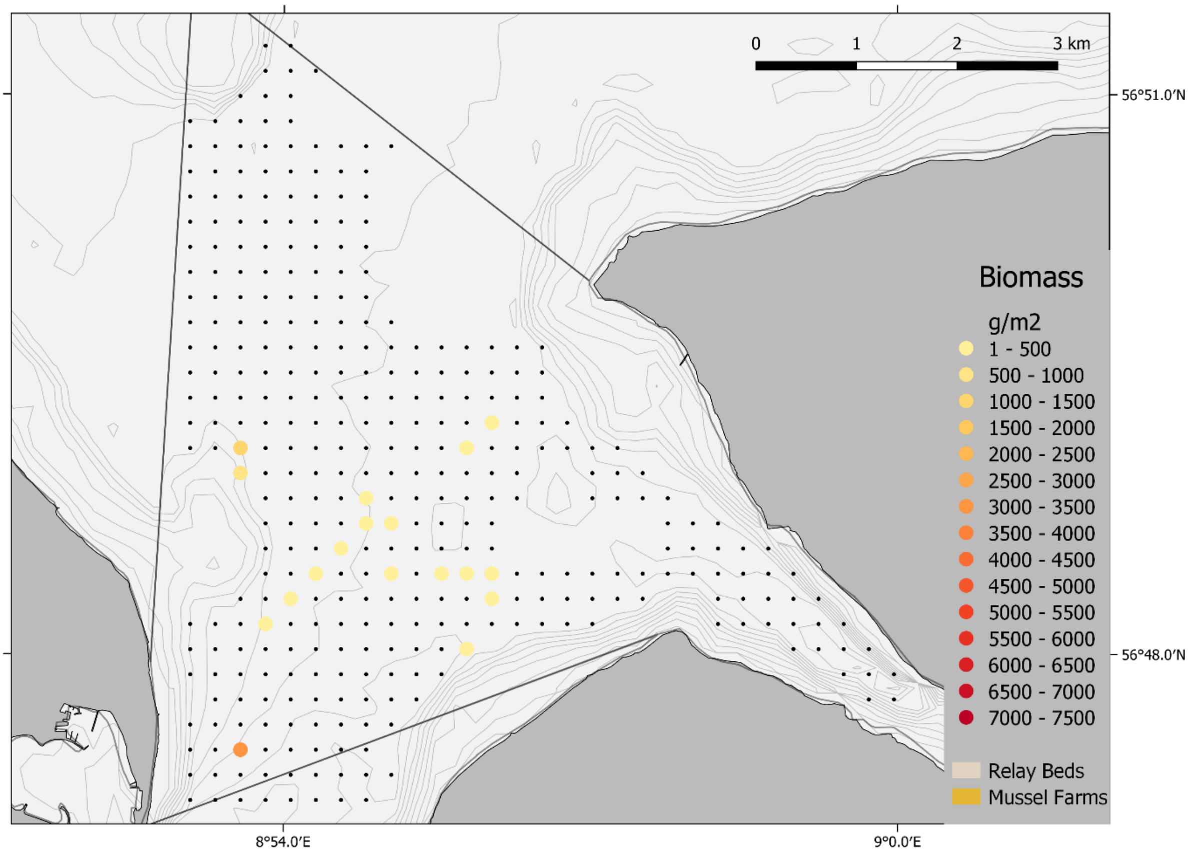

Figure 3.2 (cont.). Biomass (g/m²) in spring 2023 survey of Sønder Bredning (MO 15).

The spatial distribution of cockles was determined from the Morisita's index of dispersion I_d (Morisita, 1962), where if I_d < 1 indicates a uniform distribution, I_d = 1 indicates a random distribution and dispersion and I_d > 1 indicates an aggregated/clumped distribution:

$$I_d = n * \left[\frac{\sum x^2 - \sum x}{(\sum x)^2 - \sum x}\right]$$

Where I_d is the Morisita's index of dispersion, n is the total number of samples and $\sum x$ is the sum of x the individual grab sample counts. The significance of I_d was tested against the chi squared distribution by (Morisita, 1962):

$$X^2 = n * \frac{n * \sum x^2}{\sum x}$$

Cockle size is reported as shell width, length and height (mm) measured in the laboratory and cockle growth as the increase value.

For the 2019 cockle cohort in Kås Bredning, annual growth data (increment in shell size between annual winter lines) was obtained in 2022 as part of another task in this project (Chapter 4). Growth of the 2019 cohort was compared to growth from cockles collected in Kås Bredning in 2018, which ranged in age from 1 to 7 years (Freitas et al., 2023).

Annual mortality of the single 2019 cohort, which dominated the cockle population in Kås Bredning in 2021 and 2023, was determined as finite (%) and instantaneous mortality rates. For instantaneous mortality rates, total mortality (Z) = fishing mortality (F) + natural mortality (M). Z was obtained from the slope of a linear fit to Ln density and year, while % total mortality rate was 1 - e^Z. F and % fishing mortality were the proportion of the reduction in total biomass due to landings converted to density, while *M* and % natural mortality were obtained from the reduction in total biomass not due to fishing converted to density.

3.3 Results and discussion

Cockle distribution and abundance

In 2021, several large cockle beds were identified (Figure 3.1), covering an area of ca. 10 km^2 or 23,9% of the fishable area in Kås Bredning (excluding blue mussel farms and bottom culture areas).

Cockle beds fished in the season 2020-2021(not shown) before the survey, occurred in low density areas suggesting fishing in the previous season removed a significant fraction of the cockle population from those areas (DTU Aqua notat 21-1033607).

In 2021 (Figures 3.1 and 3.3; Table 3.1), cockle abundance in Kås Bredning was considered high, with a density of 226 cockles/m^2 (95% CI: 211 – 243) and a biomass of 914 g/m^2 (95% CI: 851 – 984). Total cockle biomass was estimated at 27,061 tonnes (95% CI: 23,941 – 30,182), and harvestable biomass at 8,660 tonnes (95% CI: 7,662 – 9,838), i.e. larger than the minimum reference size of 16 mm shell width.

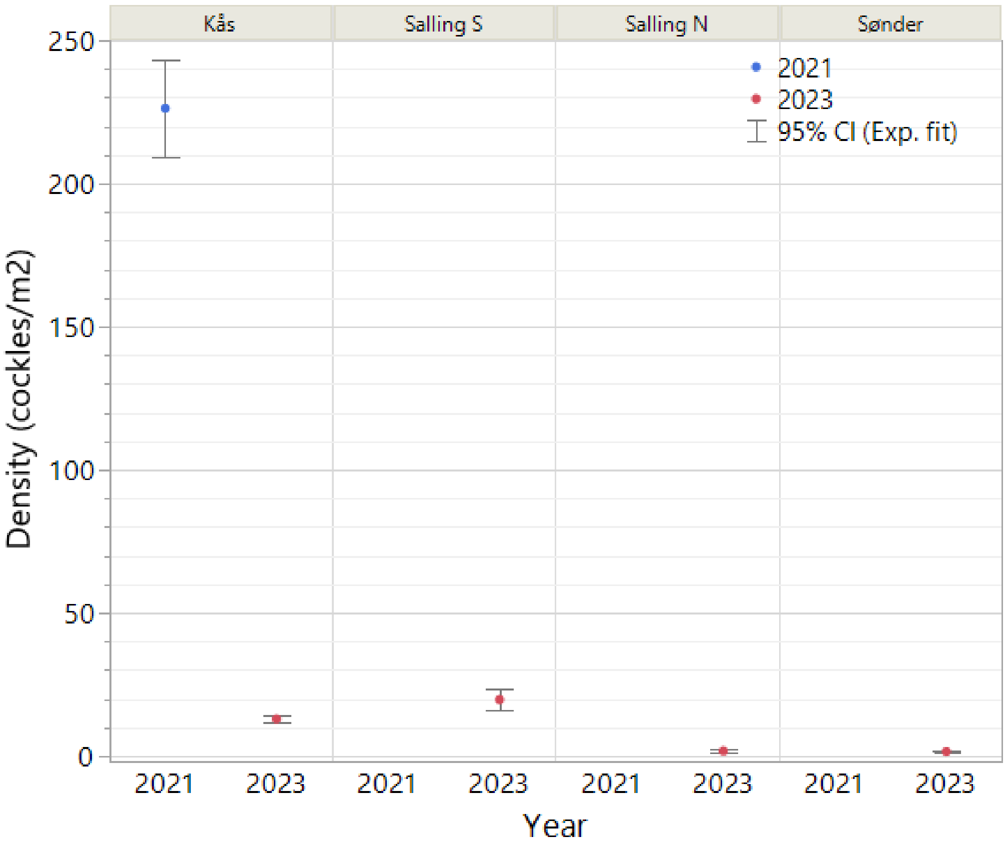

Figure 3.3. Cockle density (cockles/m^2) in the spring surveys in 2021 and 2023 in Kås Bredning (MO 9, only 2021), Salling Sund syd (MO 11) and Nord (MO 13), and Sønder Bredning (MO 15). Error bars are 95% confidence intervals from exponential distribution fits.

In 2023, cockle beds were observed in ca. 3.9 km^2 in Kås Bredning, ca. 1.4 km^2 in Salling Sund syd, ca. 0.1 km^2 in Salling Sund nord and ca. 1.1 km^2 in Sønder Bredning (Figures 3.2). However, cockle abundance was very low in all areas with density always lower than 20 cockles/m^2 (Figures 3.2 and

3.3; Table 3.1). Cockles occurred in previously fished cockle beds at low density and biomass with only a few exceptions (Figure 3.2; DTU Aqua notat 23-1009397).

Table 3.1. Cockle density (cockles/m²) and biomass (g/m²) in cockle beds only and all area surveyed in the 2021 and 2023 surveys. Intervals are 95% confidence intervals. N is number of stations.

			Density (cockles/m²)		**Biomass** (g/m²)	
	N	**Survey**	2021	2023	2021	2023
Kås Bredning (9)	247/62	Cockle beds	676 (598 – 768)	100 (78 – 129)	2,739 (2,423 – 3,112)	1,052 (828 – 1,363)
	738/474	All	226 (211 – 244)	13.0 (11.9 – 14.3)	914 (851 – 984)	138 (126 – 151)
Salling syd (11)	36	Cockle beds		79 (58 – 111)		778 (571 – 1,099)
	143	All		20 (16.9 – 23.4)		196 (167 – 232)
Salling nord (13)	2	Cockle beds		105 (34 – 631)		1,450 (470 – 8,720)
	112	All		1.9 (1.6 – 2.3)		26 (22 – 31)
Sønder Bredning (15)	18	Cockle beds		33 (21 – 54)		492 (320 – 811)
	348	All		1.7 (1.5 – 1.9)		25 (23 – 28)
Total	118	Cockle beds		83 (70 – 100)		889 (746 – 1,071)
	1077	All		9.1 (8.6 – 9.7)		97.4 (91.9 – 103.5)

In spring 2023, the majority of cockle biomass was found in Kås Bredning, while the other three fishing areas contained lower biomass:

- Kås Bredning: 4,075 tonnes (95% CI: 3,209 – 5,283)
- Salling Sund syd: 1,750 tonnes (95% CI: 1,284 – 2,472)
- Salling Sund nord: 181 tonnes (95% CI: 59 – 1,090)
- Sønder Bredning: 553 tonnes (95% CI: 360 – 912).

Relative to historical landings, as well as to Kås Bredning in spring 2021, total biomass in the four fishing areas surveyed in spring 2023 is considered very low at only 6,559 tonnes (95% CI: 5,505 – 7,900). For comparison, seasonal landings from the four surveyed areas were 6,572 tonnes/season since 2017-2018 and thus 13 tonnes higher than estimated cockle biomass in 2023.

Therefore, recruitment and growth in Kås Bredning, Salling Sund Nord and Sønder Bredning, did not compensate for natural and fishing mortality over the last two to three seasons.

As reported previously, cockle populations have a highly patchy, aggregated/clumped spatial distribution (e.g. Chapter 2; Ivell, 1981; Dare et al. 2004; Freitas et al., 2023). In both the 2021 and 2023 surveys, as expected, cockle populations were found to have highly aggregated/clumped distributions with Moritisa distribution indices I_d significantly higher than 1, ranging between 6.35 and 84.44 (all $p <$ 0.0001).

Cockle size and age

A single age cohort settled in 2019, i.e. 2 years old in 2021 and 4 years old in 2023, dominated cockle populations in all areas in 2021 and 2023 with between 80% to 95% of all cockles (Figure 3.4). The exception was Sønder Bredning in 2023 with the presence of several cohorts between 2 and 5 years old each with between 15% to 33% of all cockles.

No significant recruitment in cockle populations was observed in the four areas surveyed since 2019.

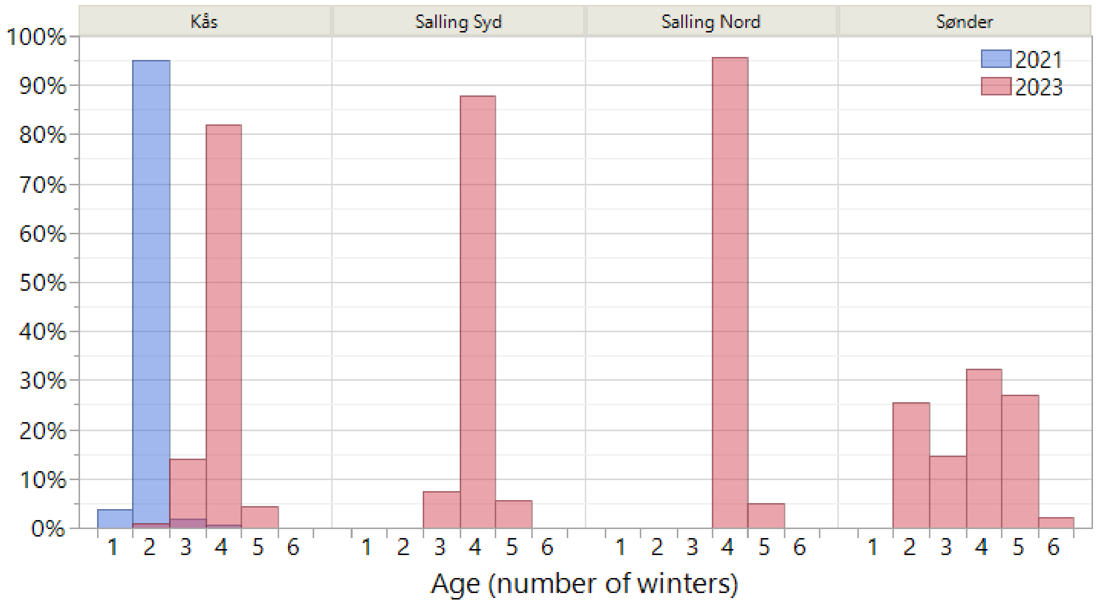

Figure 3.4. Histogram of cockle age (i.e. number of annual winter lines) in spring 2021 (blue) and 2023 (red) in Kås Bredning (MO 9; N = 6,122 and N = 570), Salling Sund syd (MO 11; N = 195) and nord (MO 13; N = 21), and Sønder Bredning (MO 15; N = 55). Note that sample size is very low in Salling Sund nord and Sønder Bredning.

Regarding cockle size, only shell width is described as shell height and length follow the same patterns (Figure 3.5).

In Kås Bredning in spring 2021, cockles were small with a mean shell width of 14.7 mm (±0.06 95%CI, n = 6630), with only 33% of cockles larger than the minimum reference size of 16 mm shell width (MRS) used to define the harvestable fraction (Figure 3.5).

In 2023, all cockles were larger than MRS (Figure 3.5). Mean shell width in Kås Bredning had increased to 20.6 ±0.2 mm (95%CI, n = 573), while in other areas, shell width was 21.8 ±0.3 mm (95%CI, n = 198) in Salling Sund Syd, 22.8 ±1.0 mm (95%CI, n = 21) in Salling Sund Nord and 24.2 ±0.5 mm (95%CI, n = 56) in Sønder Bredning.

In 2023, shell width differed between surveyed areas (ANOVA, $F_{(2,826)} = 30.32$, $p < 0.0001$), excluding Salling Sund Nord due to its small sample size (n = 21), increasing in size from Kås Bredning to Salling Sund Syd and to Sønder Bredning (post-hoc Tukey-HSD, p < 0.0003 for all).

In 2023, no juveniles or spat were observed in any of the surveyed areas (Figures 3.4 and 3.5).

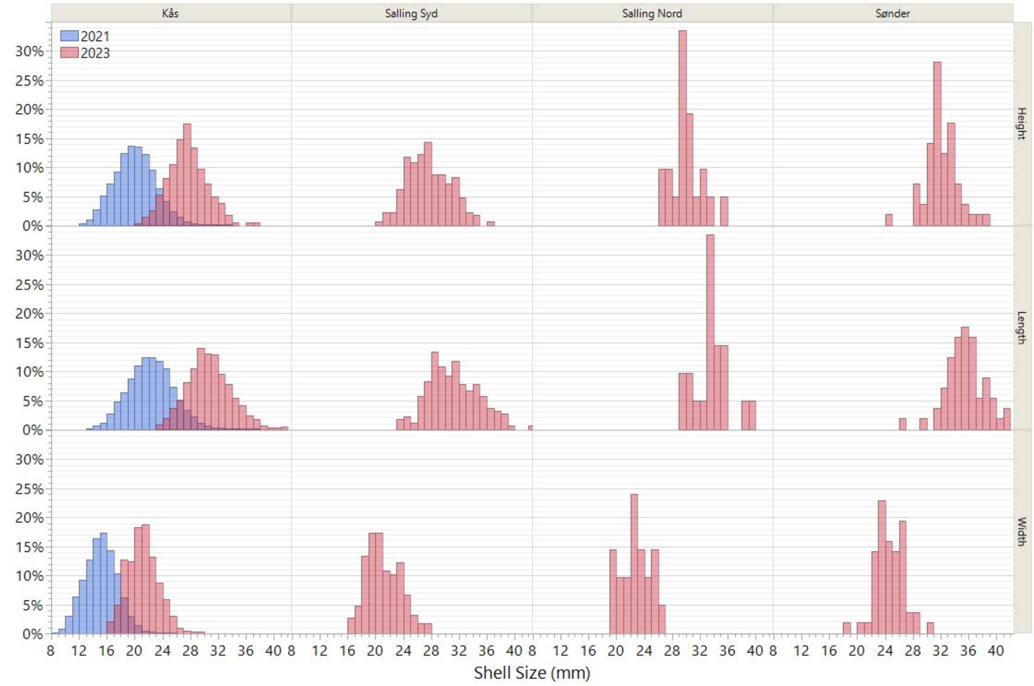

Figure 3.5. Histogram of cockle shell size (mm) in spring 2021 (blue) and 2023 (red) in Kås Bredning (MO 9), Salling Sund syd (MO 11) and nord (MO 13), and Sønder Bredning (MO15): height (top), length (middle) and width (mm). Minimum reference size used to define harvestable biomass/fraction is 16 mm shell width.

Density effects on size and growth

A clear effect of density on cockle size was observed in Kås Bredning in 2021 with shell width showing an exponential decrease with density (Figure 3.6): *Shell width* = 12.953 + 6.583 * $e^{-0.000942*Density}$, AICc = 368.4, RMSE = 1.46, r^2 = 0.41, N = 101). In 2023 after 2 years of growth and significant natural and fishing mortality, such an effect was weak (r^2 = 0.15, p = 0.0097), with a large variability in shell width at densities lower than 200 cockles/m^2 (Figure 3.6). It can be argued that an effect of density on cockle size can still be observed in 2023 at densities higher than ca. 180-200 cockles/m^2, with an offset in size relative to 2021 due to growth (Figure 3.6).

Regarding growth, the 2019 cockle cohort in Kås Bredning increased in mean shell width by 6.0 ±0.3 mm (95%CI) from 14.8 ±0.1 mm in spring 2021 to 20.8 ±0.2 mm in spring 2023 (Figure 3.5; ANOVA, $F_{(1, 6834)}$ = 1442.78, p < 0.0001, density weighed), an increase in size of 20.3% per year assuming a constant growth rate.

Considering the high cockle densities observed in Kås Bredning in 2021 of more than 2,000 cockles/m^2, (Figure 3.2 and 3.3) and that a single cohort almost entirely dominated the population (Figure 3.4), it can be deduced that settlement of the 2019 cohort was extremely strong and successful.

The 2019 cohort showed reduced annual growth at 1- and 3-years of age but similar growth at 2-years of age compared to the growth of cockles at similar ages collected in 2018 (Figure 3.7. Non-parametric Kruskal-Wallis H test, $\chi^2(1)$ = 701.6, p <0.0001, $\chi^2(1)$ = 174.9, p < 0.0001; and $\chi^2(1)$ = 2.37, p =0.124). Growth of cockles in Kås Bredning was thus low in 2019 and 2021, likely an indication of inadequate food supply. The negative density effect on cockle populations size and growth at the scale of Kås Bredning suggests cockle abundance was above the carrying capacity of this fishing areas at least occasionally in 2019 and 2022.

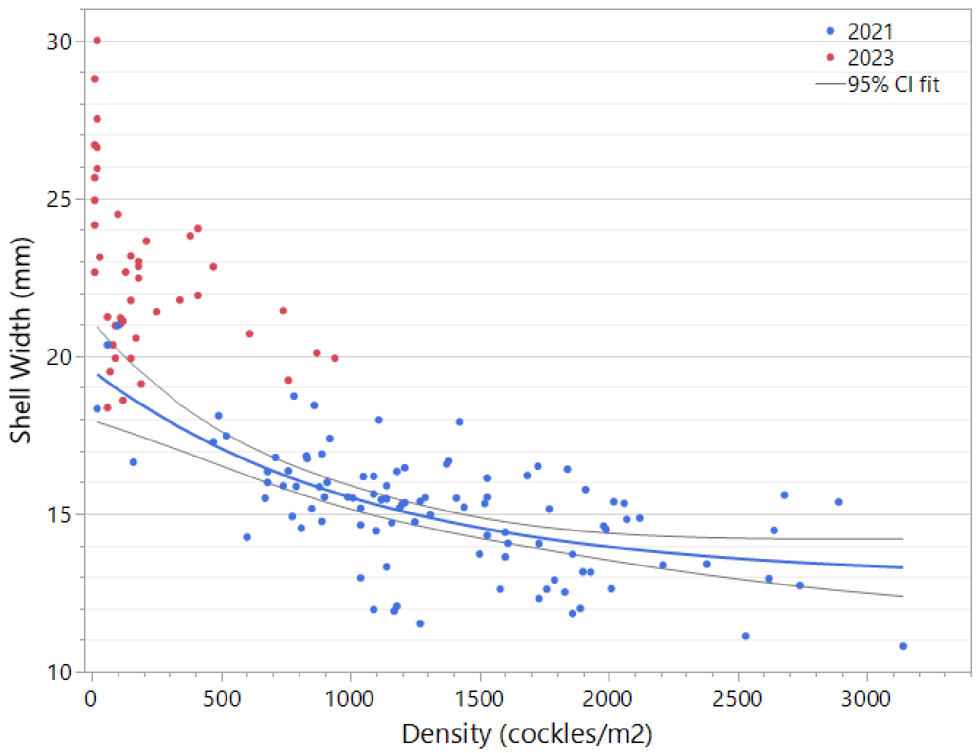

Figure 3.6. Shell width (mm) decrease with station density (cockles/m^2) of *C. edule* 2019 cohort in Kås Bredning (MO 9). For 2021 (blue), exponential fit with 95% confidence intervals: *Shell width* = 12.953 + 6.583 * $e^{-0.000942*Density}$, AICc = 368.4, RMSE = 1.46, r^2 = 0.41, N = 101). In 2023 (red), there was a weak negative correlation between shell width and density (r^2 = 0.15, p = 0.0097).

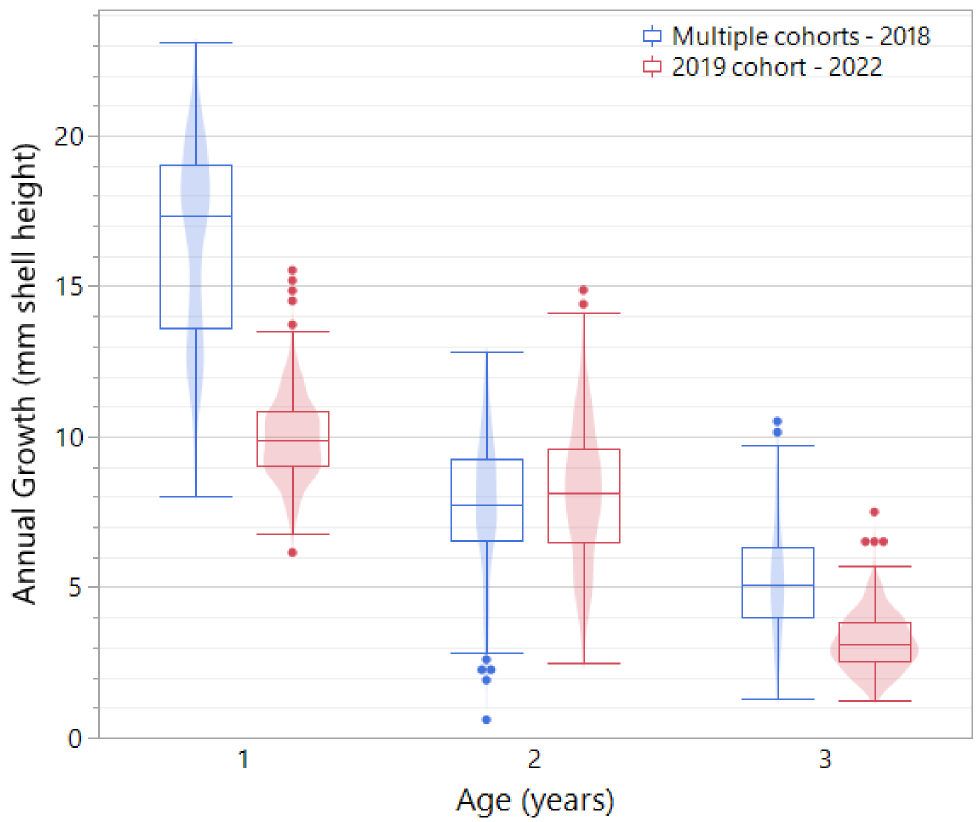

Figure 3.7. Annual shell growth (in mm shell height) of cockles in Kås Bredning (MO 9) from the 2019 cohort from (red) and from multiple cohorts collected in 2018 (blue). Cockles from the 2019 cohort collected in 2022, with 1-year of age corresponding to 2020, 2-years of age to 2021 and 3-years of age to 2022.

Spatfall survival, growth and production in cockles is negatively affected by adult cockle density (Hancock, 1973; Ivell, 1981; André and Rosenberg, 1991; Bachelet et al., 1992a, 1992b; Jensen, 1993; Beukema and Dekker, 2015; Beukema and Dekker, 2018; Mahony et al., 2022), either by larvaphagy (André et al., 1993) or competition for food and space (Hancock 1973; André & Rosenberg, 1991; Bachelet et al., 1992a, 1992b; Jensen, 1993; Beukema and Dekker, 2015; Mahony et al., 2022). Therefore, the highly successful settlement in 2019, resulting in high cockle abundance, may have had a negative effect on the subsequent growth, but also settlement and spatfall survival in the following years.

Mortality

The total mortality of the 2019 cockle cohort in Kås Bredning obtained from the decrease in density between the ages of 2 and 4 years was estimated at a finite mortality of 78.1% per year or an annual instantaneous mortality rate (Z) of -1.519 (Table 3.2). Fishing mortality was estimated at 28.1% per year with an annual instantaneous mortality rate (F) of -0.546. Natural mortality was estimated at 50.1% per year with an annual instantaneous mortality rate (M) of -0.973.

Table 3.2. Annual mortality of the 2019 cockle cohort estimated from the reduction in density between the ages of 2 and 4 years old from 2021 to 2023.

2019 Cohort	2021	2023	**Annual Mortality**	Total	Fishing	Natural
Biomass (tonnes)	25,979	3,260	Tonnes	22,179	8,159	14,560
Density (cockles/m^2)	217.3	10.4	cockles/m^2	206.8	74.3	132.6
			% per year	78.1	28.1	50.1
			Instantaneous	Z	F	M
				-1.519	*-0.546*	*-0.973*

The annual natural mortality rate of 50% estimated for the 2019 cockle cohort in Kås Bredning is similar to reported rates in intertidal areas (e.g. Bell et al., 2001; Parada and Morales, 2008), but almost twice the reported rate for the Limfjorden by Ivell (1981) of 26.2 ±12.7% per year. However, the approach used by Ivell (1981) underestimates natural mortality as it is based on changes in the assemblage of dead paired valves, which ignore dead single valves and the removal of cockles from their study site.

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4. Cockle exploitation patterns and impacts in Kås Bredning in 2021-2022

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4.1 Rationale

For the blue mussel fishery, Black box and Elogs (BB - BlackBox R2, Anchor Lab, Copenhagen; Fiskeristyrelsen) are used to register fishing activity and landings. However, it is not always possible to fully and accurately separate blue mussel and cockle (*Cerastoderma edule* and *Cerastoderma glaucum*) fishing activities and associated landings, because the cockle fishing is considered as a by-catch of the blue mussel fishery (see Chapter 1). For instance: 1) Cockle and mussel daily landings are reported together and not relative to specific fishing events or areas. Currently, landings are attributed to all fishing tracks of a given boat for each day proportionally to track length, regardless of these corresponding to cockle or mussel fishing; 2) Occasionally fishing tracks in the black box data are mislabelled with/without cockle landings or the wrong target species; and 3) Occasionally, separate cockle and mussel beds can occur in close proximity and can therefore be difficult to identify. Thus, information from fishermen and adequate tracking of cockle fishing areas and activity are essential to correctly identify cockle fishing tracks in the black box data.

The aim of this study was to describe cockle fishing behaviour, catches, fishing effort, and area impact of the fishery in 2021-2022 to support the transition to a management as an independent cockle fishery.

To achieve this, two trial areas with known cockle abundance were established in Kås Bredning (Figures 4.1 and 4.2). Independent surveys, voluntary catch reports from the fishery and black box monitoring systems provided information on cockle abundance, fishing activity and catches over the 2021-2022 fishing season in the trial areas, Kås Bredning and the Limfjorden. In addition, information was obtained from the fishery on how a bed is exploited and which factors determine the start and end of fishing (e.g. density, size, meat yield, condition, abundance of dead shells, size of bed, location).

4.2 Methods

Fishing trials

Two areas (each 600 x 1000 m, Figure 4.1) were defined based on the cockle abundance and distribution obtained from the DTU Aqua cockle survey in April 2021 at the end of the 2020/2021 fishing season. The two trial areas were chosen to provide high enough biomass to support cockle fishing, while having spatial heterogeneity in cockle and dead shells abundance (Figures 4.2 and 4.3). Note that cockle beds in both trial areas defined by stations with cockles (Figure 4.2), are not limited to the trial areas and extend outside, particularly to the NE, E and SE of area B (Chapter 3, Figure 3.1).

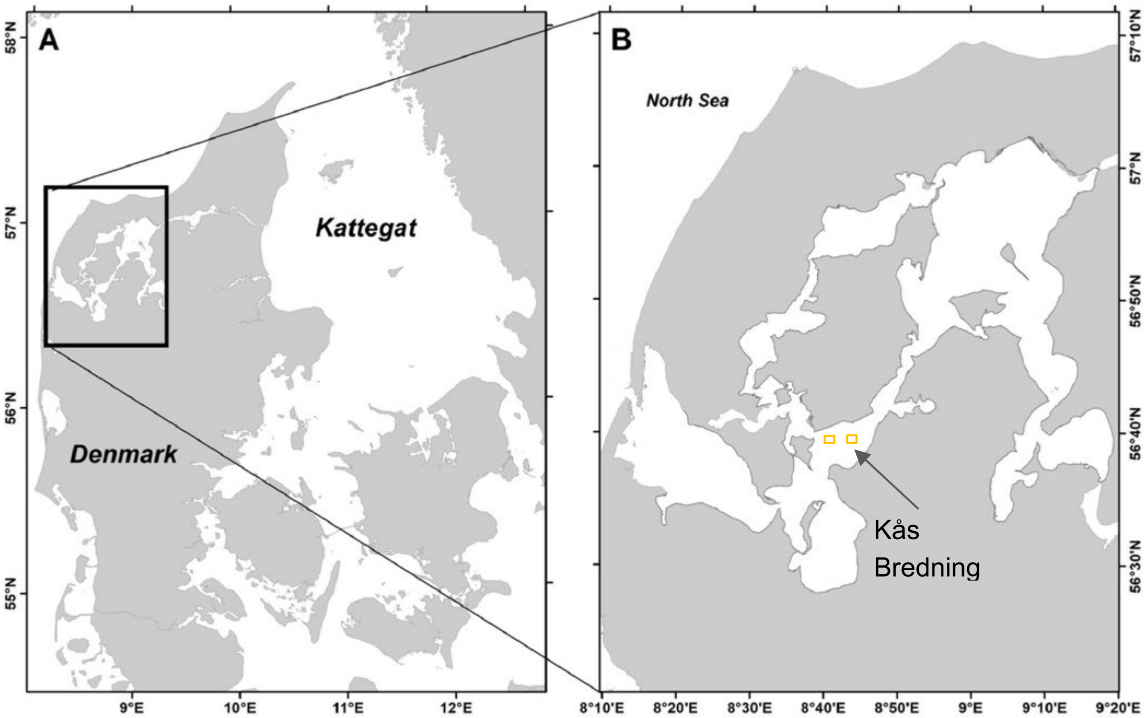

Figure 4.1. Map of Denmark (A) and the western part of Limfjorden (B) with Kås Bredning (MO 9) and the two trial areas.

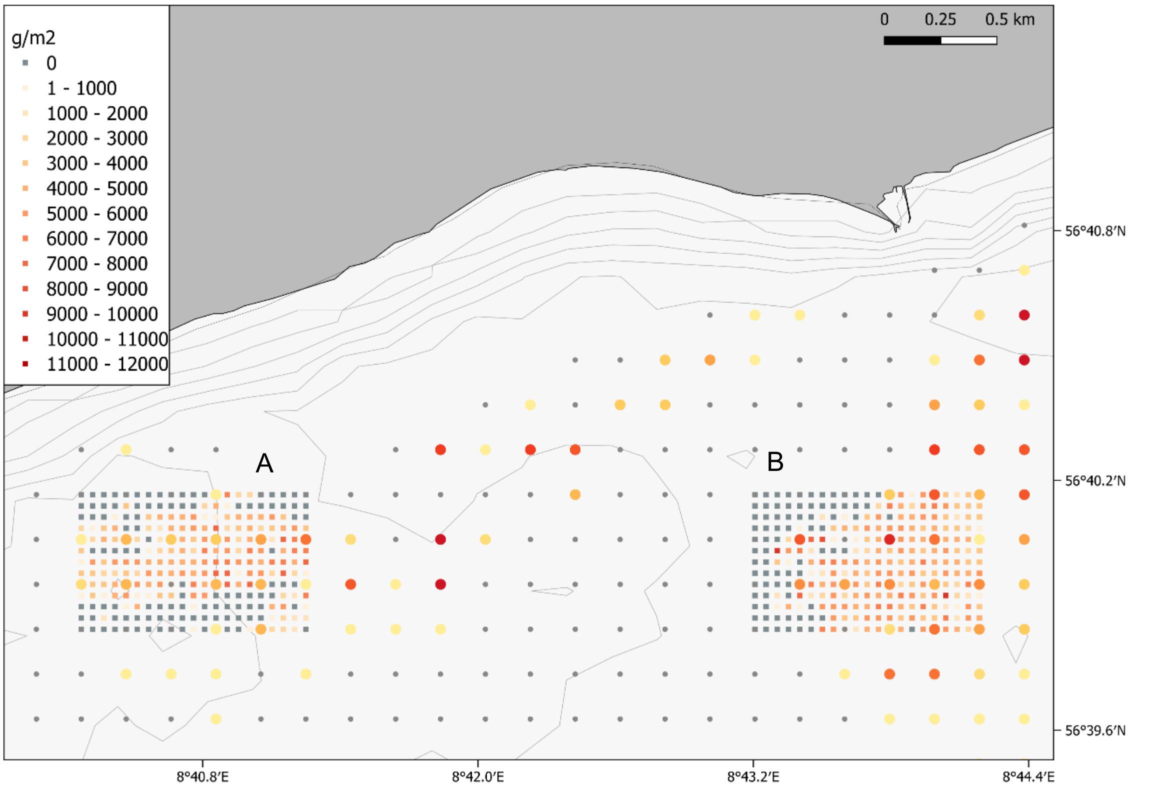

Figure 4.2. Location of the two trial areas in Kås Bredning (MO 9) and cockle biomass (g/m^2) at the start of the fishing season in September 2021 (50 m grid), overlayed on cockle biomass from April 2021 survey of all Kås Bredning (200 m grid).

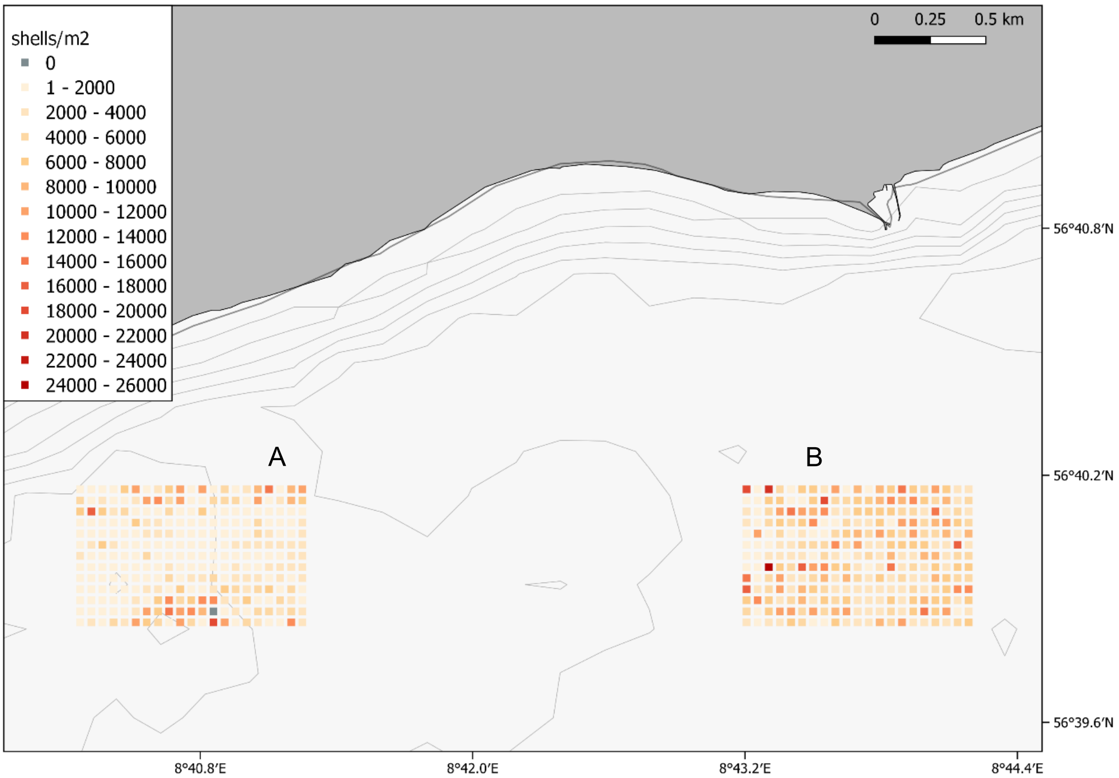

Figure 4.3. Dead shells biomass (g/m^2) in the two trial areas at the start of the fishing season in September 2021 (50 m resolution).

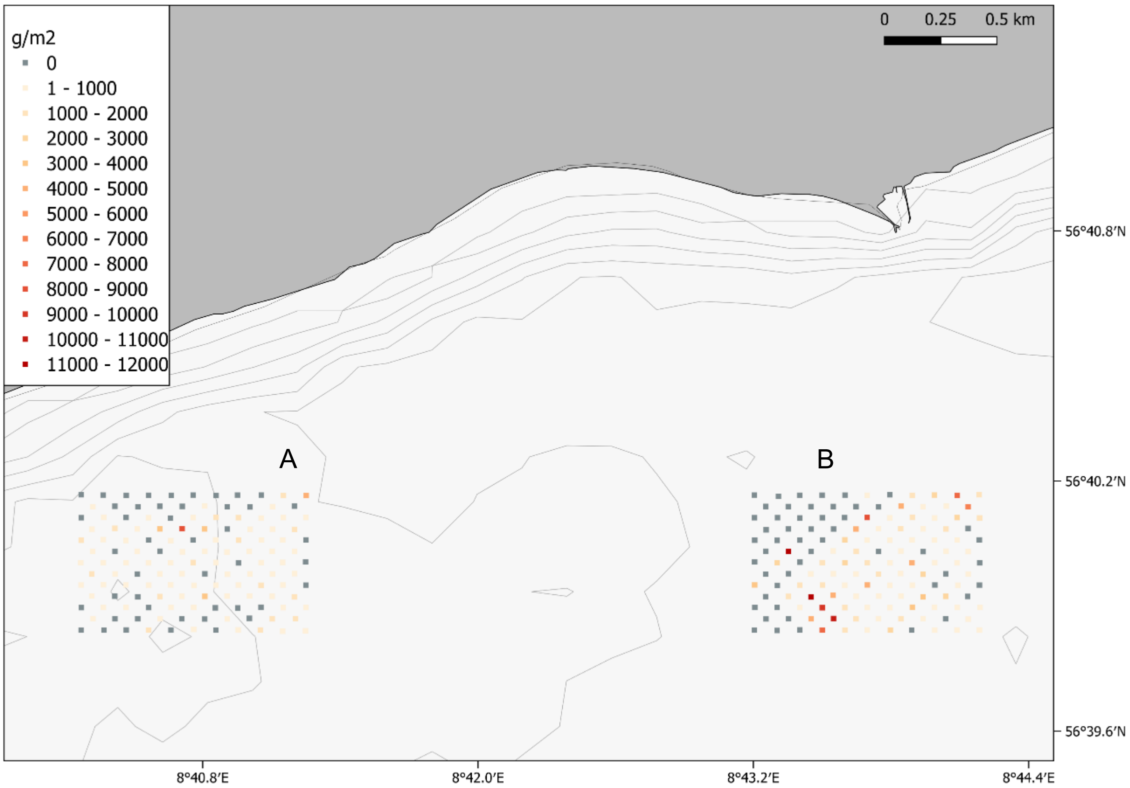

Figure 4.4. Cockle biomass (g/m^2) in the two trial areas at the end of the fishing season in April 2022 (70 m resolution).

Cockle abundance

Cockle abundance was surveyed at the start and end of the fishing season, respectively in September 2021 and April 2022 on 50 and 70 m station grids, (Figures 4.2 and 4.4). Samples were collected and processed as described in Chapters 2 and 3. A sub-sample of cockles were measured and aged (see Chapter 2). The prevalence of the lagoon cockle *C. glaucum* was very low in the two areas, averaging 0.5 % in area A and 0.3% in area B. Therefore, all results are presented for the common *C. edule*.

Fishing activity and patterns

Fishing activity and catches of cockles and blue mussels inside the two trial areas were followed during the 2021/2022 fishing season from fishermen catch reports and electronic monitoring of fishing activity.

Fishermen provided voluntary catch reports when fishing in the two trial areas, reporting the number and length of tracks, % of track length inside the trial areas, estimated catch and dead shells fished inside the trial areas, and provided a sample of the catch. However, not all boats provided catch reports or at least not for all fishing trips inside the trial areas. Thus, catch reports only provide a partial sample of fishing activity and catches inside the trial areas (see below, Tables 4.4 and 4.5).

The electronic monitoring systems of fishing activity Black Box and Elogs (BB - BlackBox R2, Anchor Lab, Copenhagen; Fiskeristyrelsen) provided information on any boat fishing inside the trial areas, with georeferenced fishing tracks. Figure 4.5 shows all fishing tracks that took place inside the two trial areas. Black box data was processed and analysed using QGIS.

Fishing effort in the two trial areas was calculated as the fished area inside trial areas. Cockle fishing areal impact was assessed as: the total fished area (i.e. cumulative area of all fishing tracks including overlaps), and the bottom “footprint” fished area (i.e. excludes overlaps between tracks). Fishing intensity was calculated as the swept area ratio (SAR) which is the number of times a m^2 was fished (i.e. total fished area divided by the bottom footprint area). A SAR of one means that an area (e.g. m^2 or a cell) was fully fished once.

Black box fishing track data contains associated cockle landings that are calculated as the proportion of the total daily landings of each boat from track length. Track landing data may thus contain cockles captured in areas other than the trial areas.

Cockle catches of each track segment inside the trial areas were calculated as a proportion of track landing relative to track length inside the trial areas.

Catch rates (catch per unit effort, CPUE) of each track inside the trial areas were then calculated as kg of cockles landed per area fished.

The spatial distribution of fishing effort, bottom impact and CPUE was determined by splitting the black box data into 25 by 25 m grid cells. Since cockle catches are reported for entire tracks, the catch of each track segment inside a cell were proportional to the catch and area of each entire track. Thus, CPUE is the same for all segments of each track and may reflect catches that come from other cells covered by those tracks.

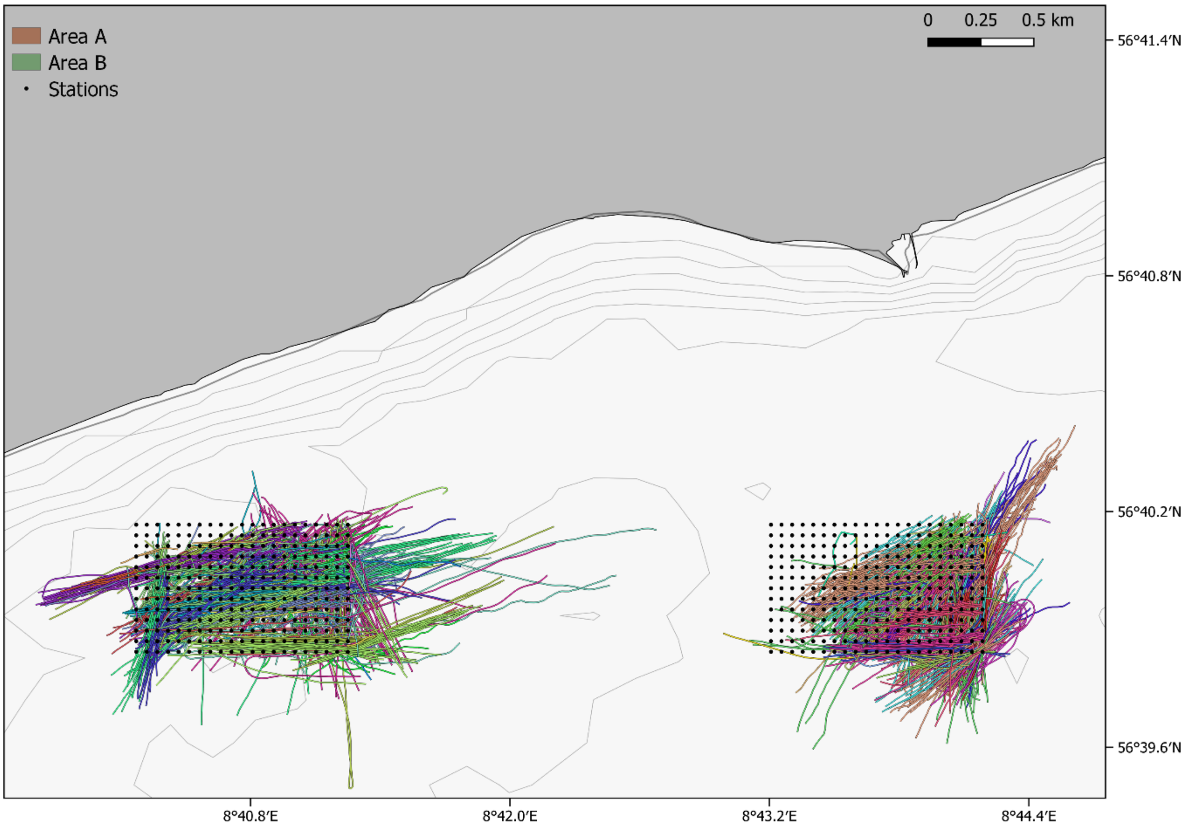

Figure 4.5. Cockle fishing tracks that took place inside trial areas A (brown) and B (green) in the 2021-2022 fishing season with a different colour for each boat. Stations from the September 2021 survey delimit the trial areas (50 m resolution).

Exploitation rate is defined as the proportion of total cockle biomass at the start of the fishing season removed by fishing during the fishing season between September and June, although fishing usually only occurs in 7 months from October to April.

Total mortality (i.e. natural and fishing mortality) was calculated as the difference in abundance between the start and the end of the fishing season, from September 2021 to April 2022. The annual natural mortality determined in Chapter 3 of 50.1% per year or 5.6% per month were used.

4.3 Results and discussion

Cockle populations in the trial areas

Abundance

At the start of the 2021-2022 fishing season, the two trial areas showed clearly identifiable, high abundance cockle beds, which extended outside the two trial areas (Figure 4.2). Mean abundance in these cockle beds was larger than in the entire Kås Breding (Table 4.1 and Chapter 3).

The two trial areas showed significant differences in cockle abundance and size, even though cockles in both areas were almost exclusively from the same 2-year-old cohort (Table 4.1 and Figure 4.6). Area A had higher cockle density, but biomass was not significantly different between the two areas (Zero inflated negative exponential correlation, Wald test $\chi^2 = 20.23$, $p < 0.0001$ and Wald test $\chi^2 = 1.27$, $p = 0.260$), since cockles were larger in area A and compensated for the lower density (Table 4.2). The abundance of dead shells was twice as high in area B (Table 4.1 and Figure 4.6; log-transformed, ANOVA, $F_{(1,271)} = 103.84$, $p < 0.0001$).

At the end of the fishing season, density and biomass decreased significantly in both trial areas (Table 4.3 and Figure 4.6; Zero-inflated negative binomial correlation, Wald test $\chi^2 > 57.35$, $p < 0.0001$ for both areas).

Density was still lower in area A (Zero inflated negative exponential correlation, Wald test $\chi^2 = 45.03$, $p < 0.0001$), but biomass was now lower in area A than area B (Zero inflated negative exponential correlation, Wald test $\chi^2 = 30.82$, $p < 0.0001$). In area A, density and biomass decreased by 307 cockles/m^2 and 1,697 g/m^2, while in area B, density and biomass decreased by 401 cockles/ m^2 and 1,579 g/m^2 (Table 4.3 and Figure 4.6).

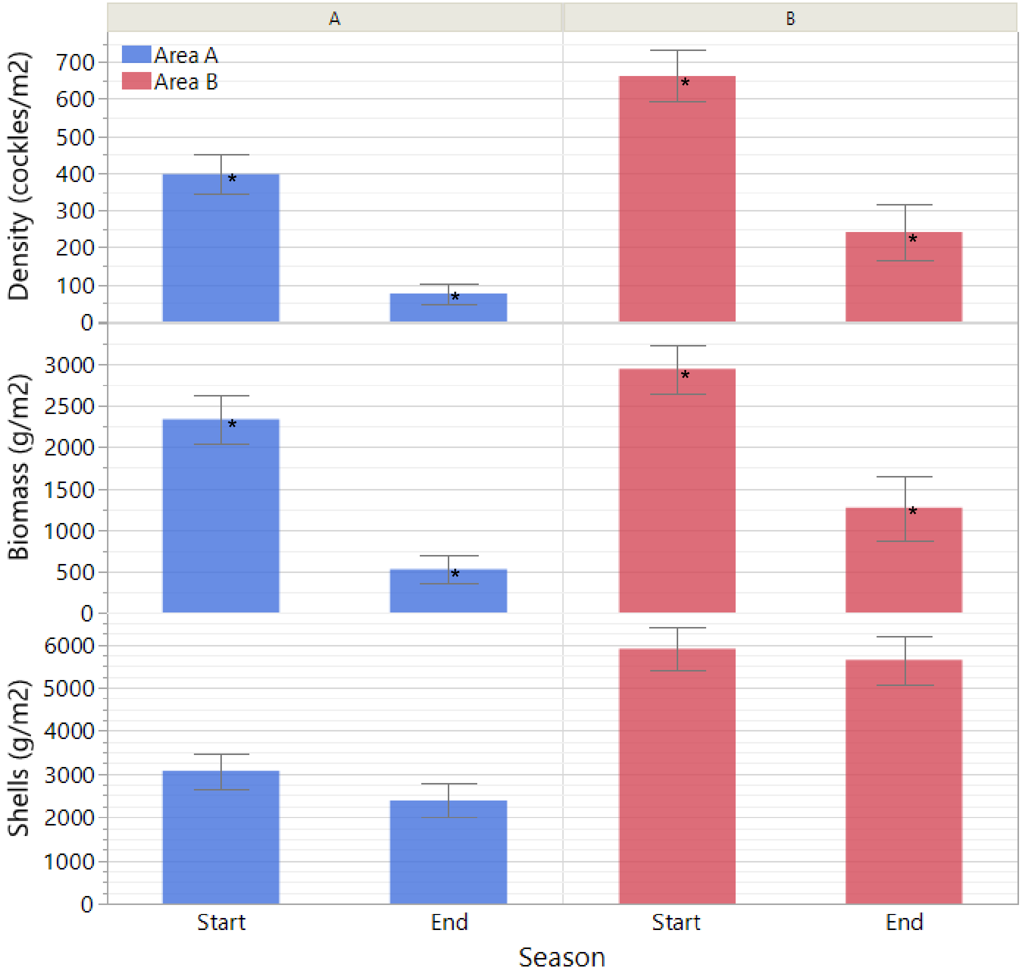

Figure 4.6. Cockle density and biomass in the trial areas at the start and end of the 2021-2022 fishing season. Shells is the abundance of dead shells. Errors are 95% confidence intervals. Significantly different between start and end of fishing season: * at $p < 0.0001$.

Total mortality (natural and fishing reduction in density) between the start and end of the fishing season over 8 months, was 80.2% and 62.4% in areas A and B, respectively (Table 4.3). Natural mortality in the same period was estimated at ca. 37.0% based on the annual natural mortality reported for the entire Kås Bredning between 2021 and 2023 (Chapter 3, this report). The reduction of total cockle biomass of 76.4 and 55.5 %, respectively in areas A and B, reflects both mortality (fishing and natural) and growth (Tables 4.2 and 4.3).

Table 4.1. Cockle density and biomass in the trial areas at the start and end of the 2021-20222 fishing season. Abundances in the entire trial areas, but also only in the cockle beds (i.e. excluding areas with no cockles). N is the number of stations sampled. Errors are 95% confidence intervals; Significantly different between start and end of fishing season * at p < 0.0001.

	Total Trial area					Cockle Beds only				
	N	Density (cockles/m^2)	Biomass (g/m^2)	Stock (tonnes)	Dead shells (g/m^2)	N	Bed area (km^2)	Density (cockles/m^2)	Biomass (g/m^2)	Dead shells (g/m^2)
Area A										
Start	273	*397 (298–546)	*2,338 (1,709–3,319)	1,403 (1,230–1,576)	3,073 (2,741–3,461)	166	0.415	*653 (591–715)	*3,846 (3,547–4,145)	1,862 (1,619–2,105)
End	137	*76 (54–111)	*525 (359–812)	315 (215–487)	2,384 (2,064–2,773)	90		*115 (76–155)	*799 (558–1,040)	1,829 (1,559–2,098)
Area B										
Start	273	*662 (521–859)	*2,947 (2,278–3,904)	1,768 (1,593–1,943)	5,905 (5,448–6,414)	194	0.485	*932 (866–997)	*4,147 (3,883–4,441)	5,643 (5,169–6,116)
End	137	*242 (163–381)	*1,266 (827–2,080)	760 (496–1,248)	5,640 (5,079–6,288)	86		*385 (273–497)	*2,017 (1,443–2,590)	5,161 (4,495–5,828)

Table 4.2. Cockle size as shell width and age (number of winter lines) at the start and end of the fishing season (September 2021 to April 2022), and growth in shell width (mm) and total fresh weight (g/cockle) during the fishing season. Errors are 95% confidence intervals.

		Shell Width	**Age**	**Growth**	
Trial Area	N	mm	Years: %	mm	g/cockle
Area A					
Start	491	17.10 ±0.17	2: 99.8%		
End	240	17.91 ±0.21	3: 97.5%	0.81	1.1
Area B					
Start	698	15.62 ±0.11	2: 99.3%		
End	371	16.53 ±0.19	3: 97.5 %	0.90	0.8

Table 4.3. Reduction in cockle density and biomass between the start and the end of the fishing season (September 2021 to April 2022).

	Reduction Density	**Mortality**	**Reduction Biomass**	**Reduction Stock**	
Trial Area	cockles/m^2	%	g/m^2	Tonnes	%
Area A	307	80.2	1,697	1,018	76.4
Area B	401	62.4	1,579	947	55.5

Cockle stocks

At the start of the fishing season, total cockle stock biomass present was 1,403 tonnes (1,230 – 1,576, 95% CI) in area A and 1,768 tonnes (1,593 – 1,943, 95% CI) in area B (Table 4.1 and Figure 4.6). While at the end of the fishing season, the cockle stock present was 315 tonnes (215 – 487, 95% CI) in area A and 760 tonnes (496 – 1,248, 95% CI) in area B.

The decrease in total cockle stock during the fishing season was 1,018 tonnes and 947 tonnes respectively in areas A and B (Table 4.3).

At the start of the fishing season, 73% and 61% of the cockle population belonged to the harvestable fraction (i.e. larger than the minimum reference size of 16 mm shell width). At the end of the fishing season, that proportion was 87% and 67%, respectively in areas A and B, due to the increase in cockle size.

Age, size and growth

Cockles in the two areas, both at the start and end of the fishing season, belonged almost entirely to the same single age cohort (Table 4.2). Almost all cockles were two years old at the start and three years old at the end of the fishing season (Table 4.2).

At both the start and end of the fishing season, cockles were larger in area A than in area B (ANOVA Welch tests unequal variances, $F_{(1/1,1815/609)}$ = 206.17/96.19, p < 0.0001 for both), respectively 17.10 ±0.17 mm and 15.62 ±0.12 mm shell width at the start and 17.94 ±0.21 mm and 16.64 ±0.18 mm shell width shell width at the end (Table 4.2).

During the fishing season 2021-2022, cockles from the 2019 cohort grew significantly in both areas by 0.81 mm and 0.90 mm shell width respectively in areas A and B (density weighed, ANOVA Welch test unequal variances, $F_{(723)}$ = 34.85.76, p < 0.0001 and $F_{(1,053)}$ = 67.04, p < 0.0001 for area A and B; Table 4.2). The increase in cockle size during the fishing season was observed despite the expected size selectivity of fishing preferentially removing larger sized cockles.

Cockle fishing activity

In the season 2021-2022, of a potential of 302 fishing days (i.e. 1st of September to 30 of June), cockles were fished in the Limfjorden on 121 days corresponding to 815 boat days of fishing that occurred regularly throughout the season, with a weekly cycle and no fishing during the Christmas and new year holidays (Table 4.4 and Figure 4.7).

The trial areas A and B were fished for significantly shorter periods of 41 days and 30 days at 82 and 97 boat days of fishing, likely due to the small size of the trial areas limiting how much cockle biomass could be fished (Table 4.4). Area A was fished earlier in the season from December 2021 to mid-February 2022, while area B was fished later in the season from mid-February 2022 to early April 2022. However, both trial areas were fished intermittently throughout the fishing season, likely ‘test fished’ to evaluate catch rates, quality of cockles and abundance of dead shells (Figure 4.7).

Table 4.4 Summary of cockle fishing black box data and catch reports submitted voluntarily by the fishery in the entire Limfjorden (LMF) and in the two trial areas during the fishing season 2021/2022: number of days and number of boats and catch reports.

	Fishing - Black Box					Catch Reports				
Area	First Day	Last Day	Days	Boats	Boat Days	N	Days	% BB	Boats	% BB
LMF	25/10/2021	09/04/2022	121	24	815					
Area A	25/10/2021	22/03/2022	41	18	82	33	19	46.3	11	61.1
Area B	25/10/2021	09/04/2022	30	19	97	24	12	40.0	8	42.1

The start of fishing season in both areas likely reflects the time when fishing became advantageous relative to other cockle beds, which considering the high cockle biomass in both areas, must have depended on factors other than cockle abundance. In area B, the fishery clearly waited until close to the end of the season for fishing to become advantageous relative to other cockle beds likely to compensate for the small size of cockles and high abundance of shells (Table 4.2).

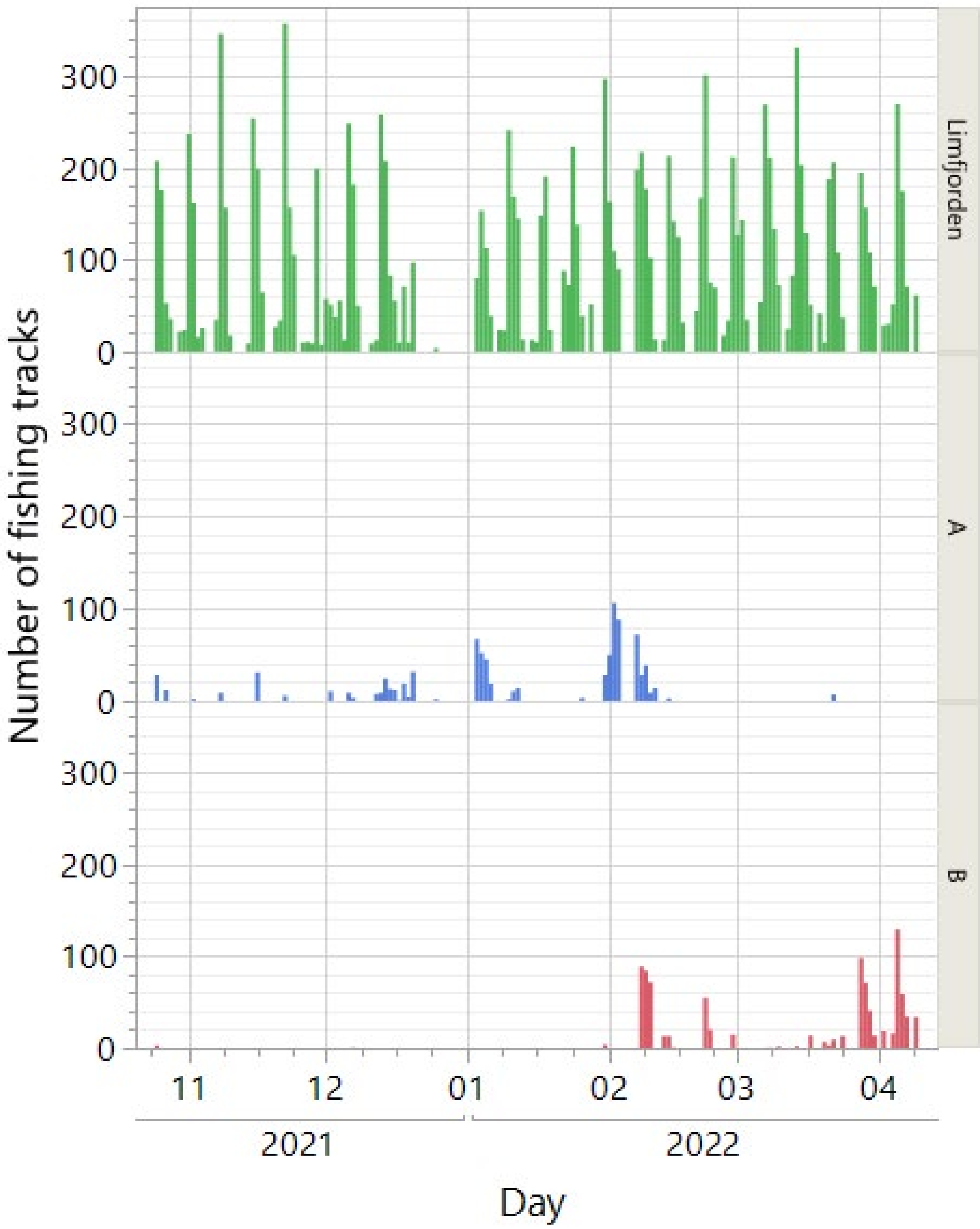

Figure 4.7. Timeline of cockle fishing activity (number of fishing tracks) in all Limfjorden (top) and in the two trial areas A (middle) and B (bottom) from black box data.

The low cockle biomass in area A at the end of the fishing season (Table 4.1) suggests fishing in this area stopped when biomass became too low, and fishing was no longer advantageous or economically viable. In contrast to area A, fishing in area B stopped when cockles became mature and meat quality dropped in early April (information from the fishery, FME) which is also the beginning of the spawning season (Freitas et al., 2023a;), which also determined the end of the fishing season (Figure 4.7).

Catch rates (CPUE) did not appear to determine neither the start nor the end of fishing in both trial areas, showing no clear temporal trend (Figure 4.10).

Patterns of fishing activity in the two trial areas thus showed examples of fishing behaviour related to cockle abundance, size, shell abundance, but also meat content and quality.

Catch reports

The voluntary catch reports of fishing activity in the trial areas A and B provided by fishermen during the fishing season 2021-2022, covered only a fraction of fishing activity recorded in black box data (Tables 4.4 and 4.5). Catch reports in areas A and B respectively covered, 61% and 42% of the fishing fleet, 46% and 40% of fishing days, 65% and 43% of fishing tracks, 86.0% and 56.7% of total fished area and 93.0% and 97.1% of cockle landings registered in black box data (Tables 4.4 and 4.5).

The size of cockles caught by the fishery in the two trial areas varied significantly during the fishing season and relative to the grab surveys at the start and end of the fishing season (Figure 4.8). Several factors likely influenced the observed variation in cockle size: Firstly, size will not be homogenous and will vary across both trial areas and, thus depending on where fishing occurred size will vary. Secondly, the mussel dredge preferentially removes cockles larger than a gear specific minimum size, which will shift the remaining unfished population to smaller sizes and biases catches to larger sizes. Finally, growth during the earlier part of the fishing season (no shell growth occurs in the winter months) increases the size of unfished cockles despite the preferential removal of larger cockles by fishing (Figure 4.8).

Importantly, catch reports were clearly biased relative to black box data, often with more than 2- or 3-times higher fishing effort and catches, i.e. more tracks, longer track length and larger fished area, but also higher daily catches, and for area B higher catch rate (Table 4.5 and Figure 4.9). Catch reports were based on the fishermen subjective evaluation of their fishing effort and catches. Thus, the cause of catch reports biases may come from an overestimation of the proportion of tracks and catches from inside the trial areas, since 49.4% and 57.4% of dredge tracks in areas A and B had on average 20.0% and 21.8% of the total area outside the trial areas.

Fishing effort from black box data

Fishing in trial areas A and B represented a small fraction of the total cockle fishing activity in the Limfjorden in 2021-2022, 5.7% and 4.4% of the total fished area in the Limfjorden at respectively 2.44 km^2 and 1.91 km^2 (Table 4.5). A total of 901 and 938 cockle fishing dredge tracks were reported in trial area A and B respectively, representing 6.9% and 7.2% of the total 12,999 cockle fishing dredge tracks in the Limfjorden (Table 4.5 and Figure 4.9). On average, 29,367 ±5,572 m^2 (95% CI) and 19,649 ±2,991 m^2 (95% CI) were dredged daily per boat in trial areas A and B and 52,612 ±2,590 m^2 (95% CI) for the Limfjorden (Table 4.5 and Figure 4.9).

Cockle fishing in the two trial areas had fewer and shorter tracks and smaller fished area per track than in the whole of the Limfjorden (Table 4.5; non-parametric Kruskal-Wallis and Dunn-comparison tests, $p < 0.0001$ for all). This is explained by both the relatively small size of the trial areas but also by the fact that most fishing tracks inside the trial areas were a fraction of longer tracks that extended outside the trial areas as cockle beds were not restricted to the trial areas (Chapter 3, Figure 3.1).

However, fishing effort was similar between the two trial areas (Table 4.5 and Figure 4.9; number of tracks per day, track length and area per day; Dunn-comparison tests, $p > 0.05$ for all). Therefore, fishery operations showed a similar effort when fishing in the two trial areas, which may have been driven by similar cockle biomass, despite other differences between the cockle populations of the two trial areas (density, shells, size; see above Table 4.1).

Table 4.5. Summary of fishing effort and catch per boat in the two trial areas from black box data and the limited catch reports of fishing activity. All dredge tracks or fraction of dredge tracks inside the trial areas were accounted for. Limfjorden and Kås Bredning (MO 9) include the two trial areas. * Calculated from daily CPUE per boat, excludes outliers (Limfjorden = 3, Kås Bredning = 4, Area A = 1 and Area B = 2) and thus differs from CPUE calculated from total landings and total fished area. + Dockside landings include landings not associated with fishing tracks in the black box data (e.g. likely due to filtering of travelling tracks that have an associated catch) of 1,871,188 kg in 2021/2022. In the trial areas, dockside landings were estimated from the proportion of black box catches. Errors are 95% confidence intervals.

	Fishing Effort									Catches				
	Number of Tracks		Tracks per day	Track length (m)	Track area (m^2)	Daily Track length (m/boat/day)	Daily Fished area (m^2/boat/day)	Total Fished area (km^2)		Total Catch (tonnes)	Dockside+ Landings (tonnes)		Daily Catch (kg/boat/day)	CPUE* (kg/m^2)
Black Box		% LMF							% LMF			% LMF		
Limfjorden	12,999	100	16.0	551	3,299	8,783	52,612	42.9	100	8,653	10,524	100	10,618	0.298
			±0.5	±5	±28	±432	±2,590						± 403	±0.018
Kås Bredning	7,989	61.5	16.1	535	3,203	8,631	51,693	25.6	59.7	5,106	6,250	59.4	10,443	0.246
			±0.6	±6	±34	±444	±2,663						± 511	±0.016
Area A	901	6.9	10.9	452	2,705	4,908	29,367	2.44	5.7	466	567.2	5.4	5,687	0.257
			±1.9	±15	±108	±1,081	±5,572						±1,360	±0.060
Area B	938	7.2	9.7	339	2,032	3,281	19,649	1.91	4.4	429	522.4	5.0	4,521	0.238
			±1.3	±13	±76	±659	±2,991						±945	±0.028
Catch Reports		% BB							% BB			% BB		
Area A	584	64.8	17.7	587.9	3,527	10,591	63,545	2.10	86.0	433	527	93.0	15,486	0.272
			±3.1	±70.6	±408	±2,102	±13,108						±3,639	±0.053
Area B	400	42.6	16.7	445.8	2,675	7,502	45,010	1.08	56.7	416	506	97.1	18,107	0.442
			±3.3	±85.3	±484	±1,917	±12,138						±4,494	±0.084

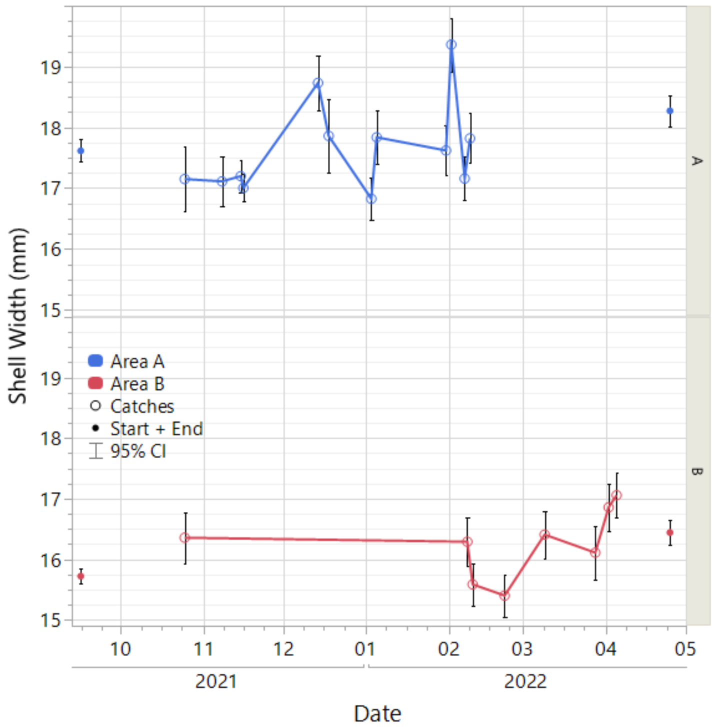

Figure 4.8. Cockle size (shell width, mm) in catch samples provided by fishermen (open circles) during the fishing season and from surveys at the start and end of the fishing season (dots) in trial areas A (blue) and B (red). Errors are 95% confidence intervals.

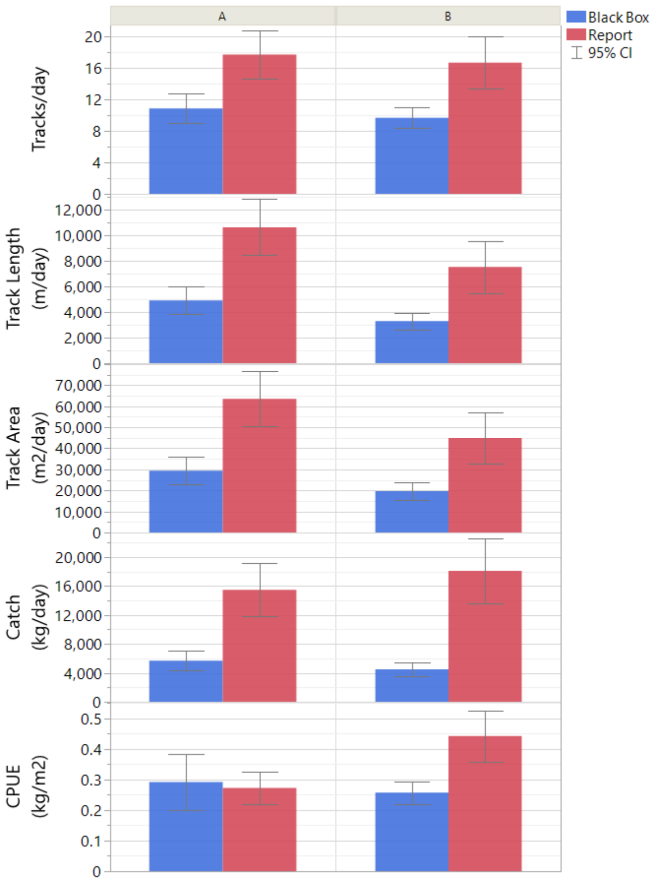

Figure 4.9. Fishing effort, catches and catch rate per boat and per day (catch per unit effort, CPUE) in trial areas A and B from black box data (901 and 938 tracks) and catch reports (584 and 400 tracks). Errors are 95% confidence intervals.

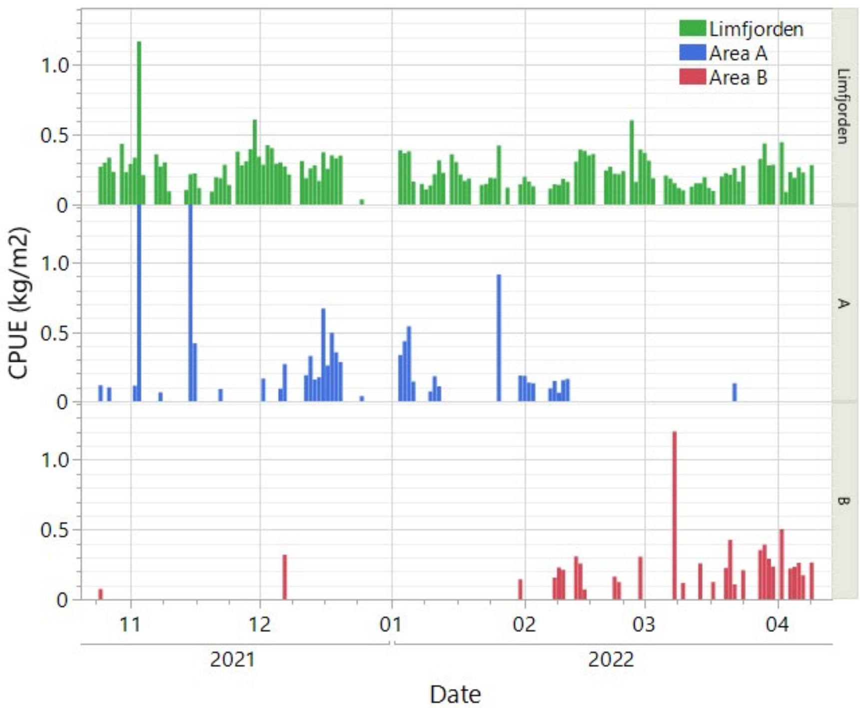

Figure 4.10. Timeline of catch rates (CPUE) as kg/m² fished in trial areas A and B and Limfjorden during the fishing season from black box data.

Cockle catches from black box data

Total cockle catches in trial areas A and B represented 5.4% and 5.0% of catches the Limfjorden in 2021-2022, respectively at 567 and 522 tonnes (Table 4.5 and Figure 4.9).

Daily cockle catches in trial areas A and B were ca. half of those in all Limfjorden at 5,687 and 4,524 kg/day respectively, likely due to the size of the trial areas being smaller that the areas normally fished in a day (Table 4.5 and Figure 4.9).

The exploitation rates were estimated at 40.4% and 29.5% of the pre-fishing total cockle biomass in trial area A and B respectively (Tables 4.3). The harvest ratios in trial areas A and B, corresponding to the proportion of harvestable cockle biomass (i.e. larger than 16 mm shell width) at the start of the season removed by fishing were estimated at 55.4% and 48.4% respectively. Thus, larger than harvest ratios between 20 to 44%, commonly 33%, used in several cockle fisheries in Europe (Dare et al. 2004; Hervas et al, 2008; Southall and Tully, 2014; MII and BIM, 2018; IFCA, 1992, 2017). High harvest ratios in the two trial areas were expected as cockle abundance was high, and the fishery was expected fish these areas intensively (see below sections on spatial patterns and bottom impact)

Catch rates (i.e. catch per unit effort, CPUE) were 0.26 and 0.24 kg/m² in areas A and B, 0.25 kg/m² in Kås Bredning and 0.30 kg/m² in the Limfjorden (Table 4.5 and Figure 4.9). CPUE in trial areas A and B were 11.0% and 8.1% of the pre-fishing total cockle biomass (kg/m²; Table 4.1) providing a rough estimate of fishing efficiency. However, it must be considered that cockle biomass changed from the start of the season to the time of fishing reflecting not only natural mortality but also growth.

CPUE was not significantly different between the trial areas or relative to Kås Bredning and the Limfjorden (log-transformed ordinary least squares with area and vessel (nested) as fixed effects, day as random effect, $F_{(3,80)} = 0.60$, $p = 0.615$).

However, CPUE differed between vessels (log-transformed ordinary least squares with area and vessel as nested fixed effects and fishing day as random effect, $F_{(3,80)}$ = 13.00, $p \leq 0.0001$), ranging in different boats between 0.05 and 0.83 kg/m^2.

Cockle CPUE in the trial areas A and B, similarly to all Limfjorden, did not show any clear temporal trend during the fishing season (Figure 4.10). Other factors than CPUE likely determine fishing behaviour decisions as to when to start or stop fishing a bed, e.g. cockles too small or in poor condition, or if a bed contains too many shells.

Spatial patterns of fishing effort and catches from black box data

Fishing effort was not spatially homogenous and focused on areas with higher cockle abundance, with 50% of total impact area coming from only 27.4% and 24.7% of fished cells in trial areas A and B (Figure 4.11).

The level of fishing effort per cell meant most cells were fully fished more than once resulting in fishing intensity (i.e. SAR; Figure 4.12) being focused on a small fraction of the trial areas and cockle beds (Figure 4.13). In areas A and B, 90.8% and 77.1% of fished cells were fully fished at least once and half of the fished cells were fished more than 3.9 and 3.7 times, respectively (Figure 4.12).

The spatial distribution of fishing effort and intensity matched well the biomass distribution of cockles observed at the start of the fishing season (Figures 4.11, 4.12 and 4.13). A few exceptions were observed, namely on the southern and northeastern edges of the cockle bed in Area A and the northern edge of the cockle bed in area B (Figures 4.11 and 4.12).

Therefore, fishing behaviour and intensity targeted locations with higher cockle abundance in the two trial areas, avoiding the edges of what fishermen perceive as cockle beds, and higher cockle catches occurred at locations with higher cockle abundance (Figures 4.13). 50% of cockle catches originated from a small fraction of 27.3% and 25.0% of all fished cells, respectively in areas A and B (Figure 4.13).

The spatial distribution of CPUE, and its link to cockle abundance (i.e. density) was more complex than fishing effort and cockle catches (Figure 4.14). Likely because fishing for cockles is not random (i.e. fishing occurs on known immobile beds with “unvarying” biomass). Thus, above a minimum abundance threshold fishing effort likely occurs independently of catches and density and focuses on the middle of cockle beds, leading to a fishing behaviour dissociating CPUE from cockle abundance. In addition, the highest CPUE values in both trial areas occurred in bordering areas with very low fishing effort and is likely an artifact from catches originating from other cells outside the trial areas (Figures 4.11 and 4.14).

Bottom area impact

Bottom area impact of cockle fishing was assessed as the total fished area, the bottom footprint fished area (i.e. excluding overlaps of dredge tracks), and the swept area ratio SAR, i.e. number of times a m^2 or cell was fished (Table 4.6 and Figure 4.14).

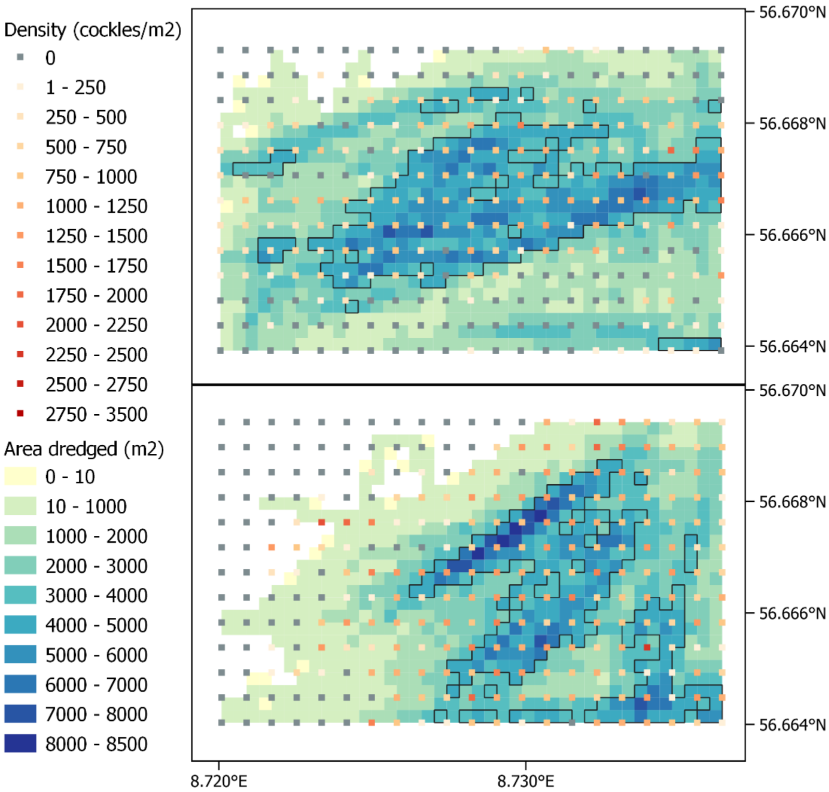

Figure 4.11. Fishing effort as total fished area (fished m²/cell) and density (cockles/m²) at the start of the 2021-2022 fishing season in trial areas A (top) and B (bottom). Black lines encompass 50% of fished area.

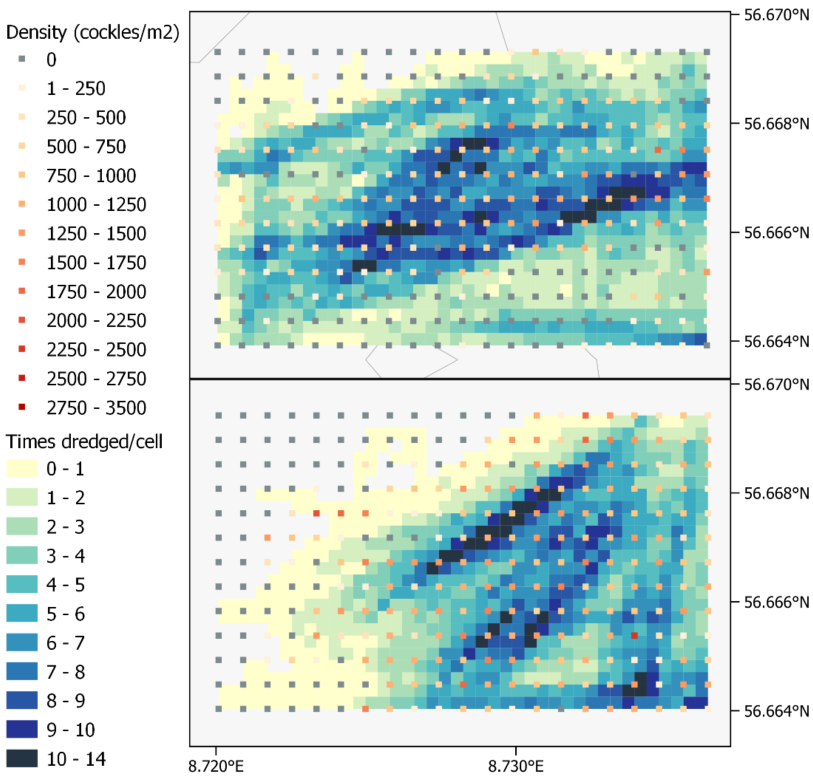

Figure 4.12. Fishing intensity or swept area ratio (SAR, i.e. times a cell was fished) and density (cockles/m²) at the start of the 2021-2022 fishing season in trial areas A (top) and B (bottom). Scale not linear in the largest class.

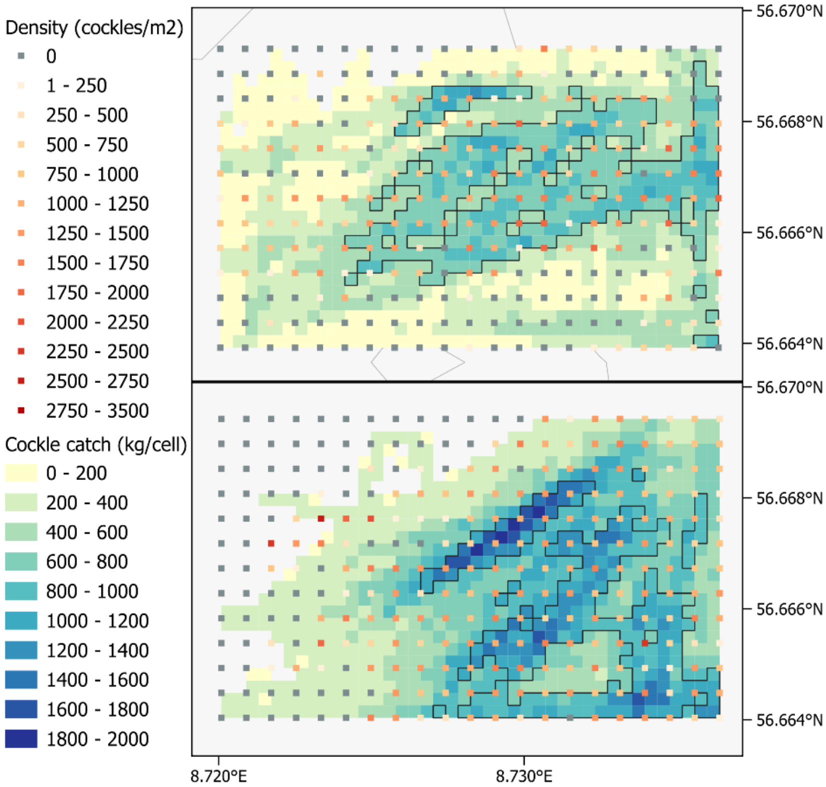

Figure 4.13. Cockle catches per fished cell as (kg/cell) and density (cockles/m²) at the start of the 2021-2022 fishing season in trial areas A (top) and B (bottom). Black lines encompass 50% of catches.

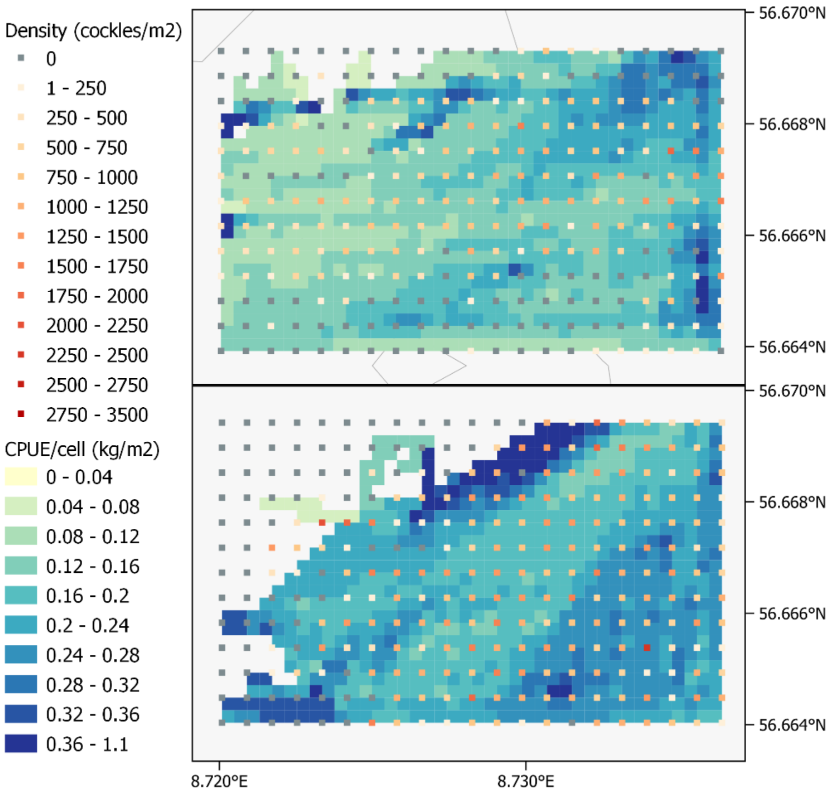

Figure 4.14. Catch rate (CPUE) per cell (kg/m²/cell) and density (cockles/m²) at the start of the 2021-2022 fishing season in trial areas A (top) and B (bottom). Scale not linear in the largest class.

In trial areas A and B, total fished area was ca. 2.4 km^2 and 1.9 km^2, respectively, equivalent to 4 and 3 times the trial area surface and ca. 6 and 4 times the area of cockle beds in the trial areas (Table 4.6). The bottom footprint fished area was 0.51 km^2 and 0.40 km^2 in areas A and B (Table 4.6). The bottom footprint fished area corresponded to 86% and 66% of the total trial area surface, area A and B, respectively and 124% and 82% of the area of cockle beds present in the trial areas A and B respectively (Table 4.6).

In the Limfjorden, total fished area was 42.9 km^2 with 60% or 25.6 km^2 in Kås Bredning (Table 4.6). The bottom footprint fished area in the Limfjorden was 10.3 km^2 with ca. 50% or 5.5 km^2 in Kås Bredning (Table 4.6).

The proportion of potential fishable area (i.e. area of fished MO areas deeper than 3 m and excluding N2000 areas and closed areas) and impacted by cockle fishing was much larger in the trial areas than in the Limfjorden and Kås Bredning, as indicated by either total or bottom footprint fished area. For instance, bottom footprint fished area was 9.6% and 13.6% of the potential fishable area in the Limfjorden (i.e. fishing areas MO 7, 9, 13 and 15) and Kås Bredning in 2021-2022 (respectively 107.7 and 40.9 km^2), it reached 86% and 66% in the two trial areas (Table 4.6). However, this was the result of the trial areas being small (0.6 km^2) and deliberately placed on dense cockle beds.

The level of fishing effort meant most of the bottom area was fished more than once in the trial areas, Kås Bredning and the Limfjorden (Table 4.6; Figures 4.11 and 4.15). In trial area A and B, fishing intensity (SAR) was 4.74 and 4.80 respectively, a difference of only 0.06 indicating similar fishing intensity in the two trial areas (Table 4.6). Fishing intensity in the Limfjorden and Kås Bredning were 0.64 and 0.19 lower than in the two trial areas (Table 4.6).

Fishing intensity was thus higher in the trial areas and in Kås Bredning than in all the fishable areas in the Limfjorden. This was not surprising as Kås Bredning, where the trial areas are located, provides ca. 64% of cockle landings (Freitas et al., 2023b) and is assumed to usually have higher cockle abundance than other areas in the Limfjorden.

The bottom area fished per tonne of cockles harvested ranged between 760 m^2/tonne in area B, 906 m^2/tonne in area A and 981 m^2/tonne in all Limfjorden (Table 4.6), with lower values indicating lower bottom impact rates of cockle fishing.

Fishing patterns showed lack of spatially homogeneity, as fishing effort focused on areas with higher cockle abundance in the two trial areas as well as in Kås Bredning (Figure 4.15). 50% of the fishing intensity and thus bottom impact was only on 27.4% and 24.7% of fished cells in trial areas A and B (Figures 4.12 and 4.14). In Kås Bredning (Figure 4.14) and the Limfjorden (not shown), 19.3% and 17.4% of fished cells respectively sustained 50% of the fishing intensity.

4.4 Conclusions

This study established the first description of cockle fishing activity and behaviour in the Limfjorden over a full fishing season in 2021-2022 when cockle beds contained significant biomass, which can be used as reference for the management of the fishery in future seasons.

Table 4.6. Bottom area impact by cockle fishing. Area is the trial area and fishable areas in Kås Bredning (MO 9; deeper than 3 m and excludes mussel farms and bottom culture plots), while cockle bed is fraction of trial area with cockles. Total fished area is the total cumulative area fished, while footprint area ignores overlap of dredge tracks. SAR is swept area ratio, i.e. total area fished divided by footprint area or cell area (e.g. Figure 4.11). LMF refers to all fishing areas fished for cockles in the Limfjorden (MO 7, 9, 13, 15) in the season 2021-2022.

Trial Area	Fishable Area (km^2)	Cockle Bed Area (km^2)	Tracks	Total Fished Area (km^2)	% Fishable Area	% Bed Area	Footprint Area (km^2)	% Fishable Area	% Bed Area	% Total Area	SAR	Area fished per tonne (m^2/tonne)
LMF	107.666	-	12,999	42.9	46.1	-	10.320	9.6	-	24.1	4.16	980.6
Kås	40.857	9.880	7,989	25.6	62.6	259	5.545	13.6	56.1	21.7	4.61	887.2
A	0.600	0.415	901	2.44	406.3	587	0.514	85.7	123.9	21.1	4.74	906.2
B	0.600	0.485	938	1.91	317.7	393	0.397	66.2	81.9	20.8	4.80	760.0

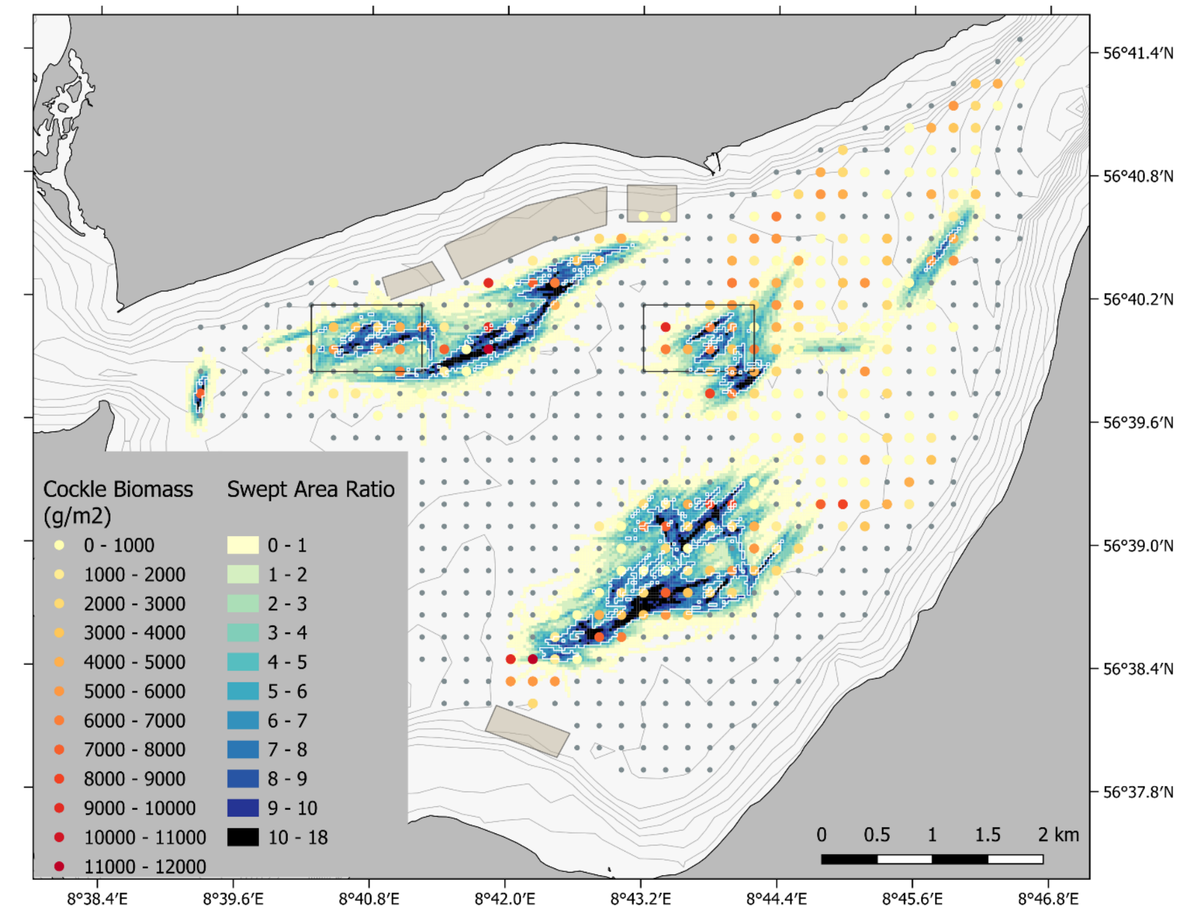

Figure 4.15. Fishing intensity as swept area ratio (SAR, total fished area/cell area = number of times a 25 m cell was dredged) in Kås Bredning (MO 9) in 2021-2022 season. Overlayed is cockle biomass in June 2021. Black rectangles are trial areas A (left) and B (right), and white lines encompass 50% of total area fished. Polygons are blue mussel farm or bottom culture units. SAR scale is not linear in the last class.

Cockle fishing occurred over 121 days corresponding to 815 boat days, with boats fishing on average 16 tracks per day per boat, dredging an area of 52,600 m^2 and producing 10,600 kg of cockles. Cockle catches, fishing effort, and thus fishing impact were not spatially homogenous, and focused on areas with higher cockle abundance avoiding the edge of cockle beds. In the trial beds, fishing removed between 40% and 30% of total cockle biomass providing an estimate of exploitation rates of high abundance beds.

Fishing activity patterns in the two trial areas and in the Limfjorden, together with information from the fishery provided examples of fishing behaviour decisions on where and when to fish reflecting multiple factors that affect profitability, fishing operations and efficiency, and which may vary between fishermen and during the season: 1) Cockle abundance and catch rates: if below a certain level will make fishing not economically viable, but it is likely that above a certain level other factors will influence fishing behaviour. 2) Shell abundance will affect fishing, possibly by reducing dredge fishing efficiency and reducing net landings of live cockles. 3) Cockle size, as it can affect sale price and preferences of the processing industry. 4) Cockle condition, as the sale price varies with meat content and quality. The processing industry is not interested in mature pre-spawning cockles which have poor meat quality in spite of high meat content, and cockle maturity and spawning can determine fishing stops in specific cockle beds or the end of the fishing season. 5) Operational factors, as fishermen may choose to minimize travel distances between cockle beds, mussel beds (as cockle is a by-catch), to home and landing harbours.

4.5 References

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5. Cockle populations, fishing efficiency and potential impacts in Nissum Bredning, a Natura 2000 area

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5.1 Rationale

Over the last 10 years and in particular since 2017, cockle fishing in the Limfjorden has occurred in only a few basins with irregular fishing activities in additional areas. Currently, no cockle fishing occurs in Natura 2000 areas, other than residual catches together with blue mussel fishing (Fiskeristyrelsen). However, the investigation of the potential for cockle fishing in Natura 2000 areas where cockle beds have previously been recorded, informs management options to reduce the dependence of the fishery on a few areas, particularly on Kås Bredning (MO 9), and reduce the risk of recruitment fluctuations and low fishable stock.

This study had multiple aims: 1) assessing cockle populations of Nissum Bredning (Figure 5.1), a Natura 2000 area known to have had significant cockle populations (Freitas et al., 2023) and described to have a significant role in the supply of cockle larva and potentially recruitment/ donor area to some of the main cockle fishing areas of the Limfjorden (see Chapter 6). 2) Evaluate the fishing efficiency in Nissum Bredning of the mussel and oyster dredges used in the blue mussel and oyster fisheries, as these are dredges potentially used in an independent cockle fishery. 3) Estimate the area impact of cockle fishing in Nissum Bredning, based on the area impact of cockle fishing in Kås Bredning (Chapter 4).

To achieve these aims, an assessment of cockle populations in Nissum Bredning was done in August 2022, followed by fishing efficiency trials with mussel and oyster dredges from the fisheries in March 2023. Fishing data from Kås Bredning in 2021-2022 was then used to estimate fishing impact on cockle beds found in the 2022 survey of Nissum Bredning.

5.2 Methods

Cockle survey 2022

A survey of cockle populations in Nissum Bredning was carried from 9 August to 2 September 2022 following the sampling design and approach developed in Chapter 2, using a 0.1 m^2 Day grab and 10 mm sieve with size and age measurements in the laboratory.

Considering the large size of Nissum Bredning, a stratified design was chosen to maximise the survey area and minimise error of biomass estimates, and the survey was limited to areas deeper than 5 m depth. First a regular 400 m grid (635 stations) was sampled in the fishing areas MO 1, 2, 3, and 4, followed by a smaller 200 m grid (129 stations) on cockle beds found on the 400 m grid for a total of 764 stations (Figure 5.2). Cockle stocks of observed cockle beds were estimated excluding stations with no live cockles.

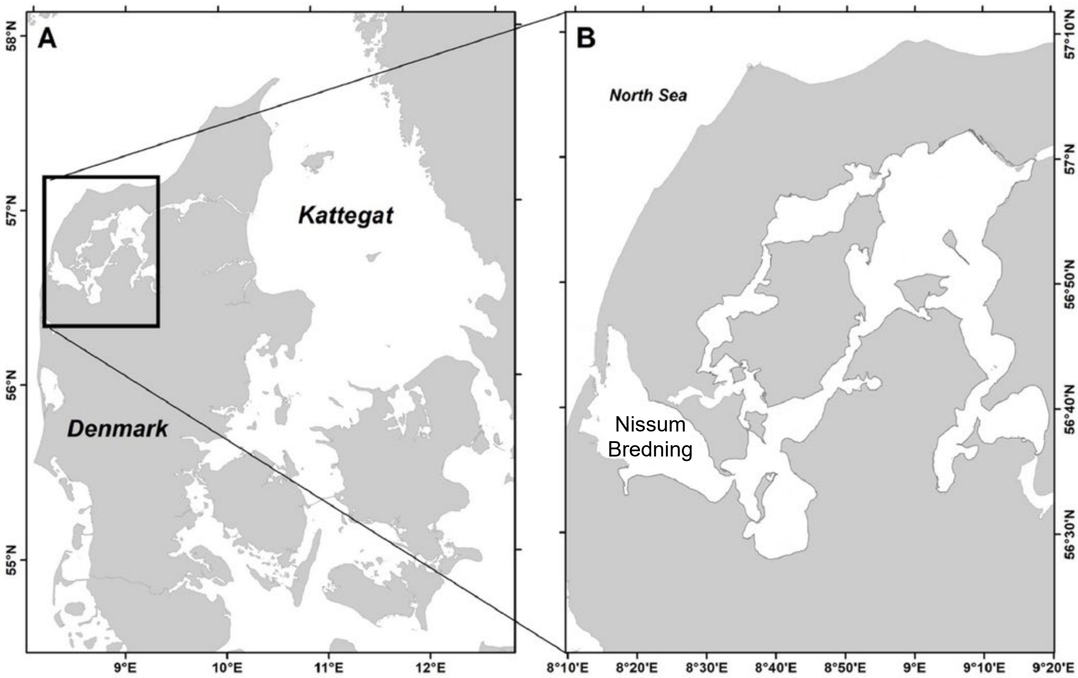

Figure 5.1. Map of Denmark (A) and the western part of Limfjorden (B) with Nissum Bredning.

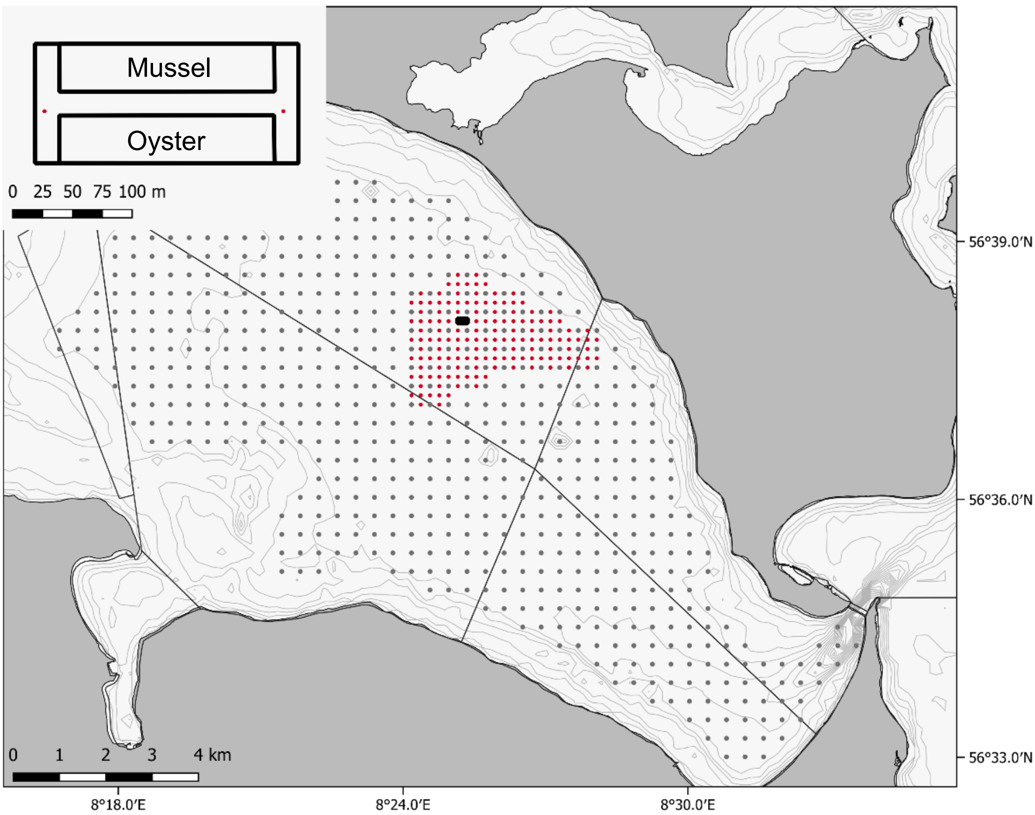

Figure 5.2. Location of stations and fishing trials in the Nissum Bredning (MO 1, 2, 3 and 4) August 2022 survey: 400 m grid (grey), the 200 m grid (red) and fishing trial area (black). Inset show the two fishing efficiency trial areas for the mussel (top) and oyster (bottom) dredges.

Fishing trials

The cockle fishing efficiency of the mussel and oyster dredges used in the blue mussel, cockle and oyster fisheries was determined within the large cockle bed found at 6.5 water depth during the Nissum Bredning survey (Figure 5.2). Fishing efficiency was tested in two trial areas with 40 x 180 m with 7,200 m^2 of area oriented on a west-east axis, the northern area for the mussel dredge and the southern area for the oyster dredge (Figures 5.2 and 5.3).

To simulate the normal behaviour of the cockle fishery by making multiple overlapping passes, 33 dredge consecutive tracks were fished inside each of the mussel and oyster dredge areas (Figure 5.3). Dredging was done on either west-east or east-west directions inside each trial area, with 70 m of cable at 3-4 knots, with mean track length of 166 and 169 m respectively for the mussel and oyster dredges (range: 150-196 m and 160-184 m, respectively (Figure 5.4).

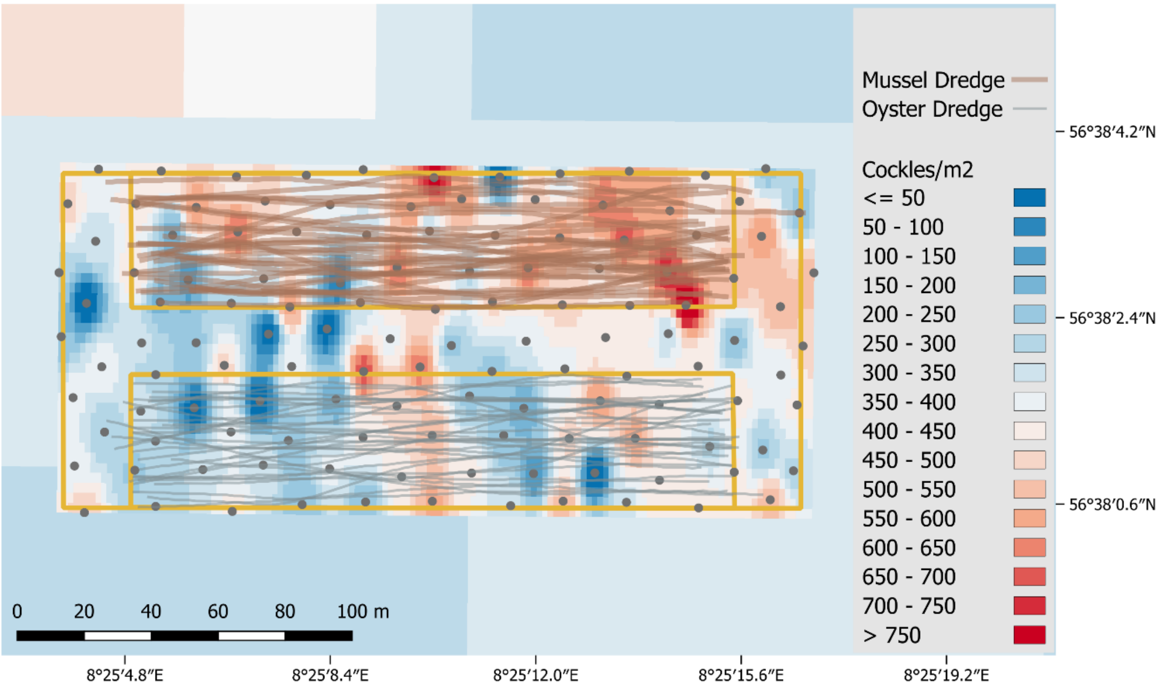

Figure 5.3. Dredge tracks (N = 33) of the mussel dredge (top) and oyster dredge (bottom) in the trial areas overlayed on cockle density before the fishing trials.

The mussel dredge was provided by the fishing industry (Foreningen Muslingeerhvervet, FME), weighing 165 kg including the net and metal rings bag and with an opening of 1.5 m. The oyster dredge was the one used by DTU Aqua for European oyster surveys and is the same as the one used in the oyster fishery, weighing 44 kg including the net and metal rings bag with an opening of 1.0 m (Figure 5.4). An inner net of smaller mesh size of 35 mm was used in both dredges as normal in cockle fishing to increase the retention of cockles that are smaller than mussels and oysters.

Fishing efficiency

Fishing efficiency was determined using a catch-based approach. The control-impact approach used in a previous study to estimate cockle fishing efficiency of the mussel dredge (Freitas et al., 2023a) was not used in this study. This was due to the objective of the current trials being to evaluate fishing efficiency of the dredges with multiple consecutive overlapping dredge tracks as per normal behaviour of the blue mussel and cockle fishery.

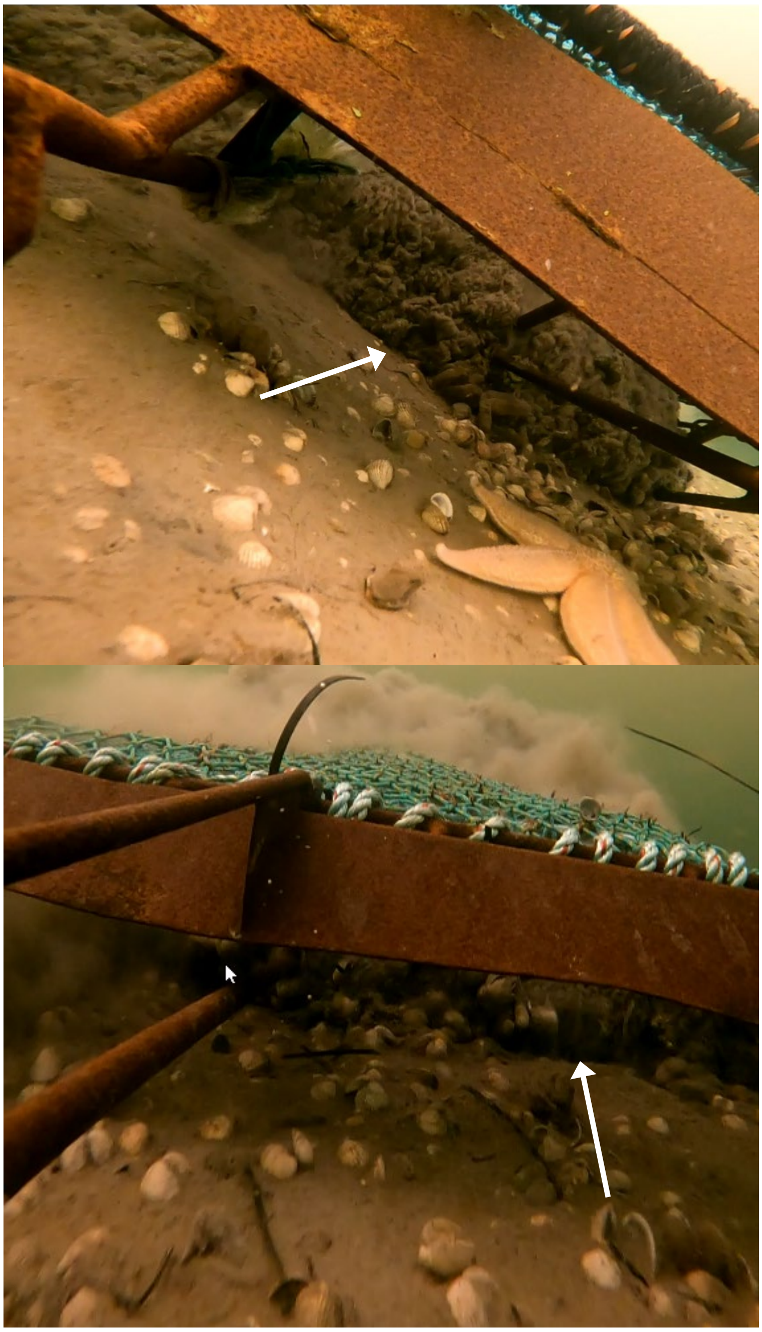

Figure 5.4. Video stills of the mussel (top) and oyster (bottom) dredges fishing cockles. Note how the horizontal bars of the mouth frame of both dredges scrape the top of the sediment (white arrows).

Cockle abundance was surveyed before the fishing trials at high-resolution on a 14 m grid (Figure 5.3; N = 23), on 16-18 January, with the approach developed in Chapter 2. Cockle density was 475 cockles/m^2 (±76, 95% CI) and 316 cockles/m^2 (±78, 95% CI), respectively in the mussel and oyster dredge trial areas, while biomass was 3,210 cockles/m^2 (±514, 95% CI) and 2,261 g/m^2 (±573, 95% CI), respectively in the mussel and oyster dredge trial areas.

The total number and weight of live cockles caught in each dredge track was determined. Catch rates (number or weight of cockle per m^2 dredged) were calculated from the area dredged by each track.

Fishing efficiency was determined for each individual track as the proportion of the cockle population or density (cockle/m^2) removed by each dredge catch (cockle/m^2 dredged). Cockle abundance before each dredge track was recalculated to account for the removal of cockles by previous dredge tracks.

Fishing impact

To provide an estimate of the potential area impact of cockle fishing in Nissum Breding, cockle fishing impacts and patterns determined for Kås Bredning and Limfjorden in 2021-2022 (Chapter 4 of this report) were applied to the observed cockle biomass in Nissum Bredning in 2022. Namely, the area fished per tonne of harvested cockles to estimate bottom footprint impact area and the swept area ratio (SAR) to estimate total cumulative fished area, if the area were to be open for fishing.

5.3 Results and discussion

Cockle population and potential landings from Nissum Bredning in 2022

Previously, cockle populations were observed over most of Nissum Bredning although with fewer observations in its southwestern part, in surveys monitoring the European Flat oyster between 2018 and 2021 and also cockles in 2018 (Figure 5.5).

In 2022, however, cockle populations occurred almost exclusively in the northern middle part of Nissum Bredning (MO 2), both in the August cockle survey and the March 2022 European flat oyster survey (Figure 5.5). The distribution of cockles in Nissum Bredning in 2022 was thus spatially limited relative to previous years occurring mainly in a single large, delimited bed with ca. 4.5 km^2 area (Figure 5.5). For comparison, cockle beds in the main fishing area Kås Bredning (MO 9) occupied ca. 10 and 3.9 km^2 in 2021 and 2023 respectively (Freitas et al., 2021 and 2023b; Chapter 3 this report)

The mean biomass of cockle beds in Nissum Bredning in 2022 of 3,601 ±363 g/m^2 (Table 5.1 and Chapter 3; Freitas et al., 2021 and 2023b) was different from the one in the main cockle fishing area Kås Bredning in 2021 and 2023 (non-parametric Kruskal-Wallis test, $\chi^2_{(2)}$ = 65.90, p < 0.0001), being higher than 2,738 ±316 g/m^2 in 2021 and 1,052 ±437 g/m^2 in 2023 (Dunn pairwise multiple test, p < 0.0001 for all).

The mean density of the main cockle bed in Nissum Bredning in 2022 of 444 ±59 cockles /m^2 (Table 5.1 and Chapter 3; Freitas et al., 2021 and 2023b) was different from the main cockle fishing area Kås Bredning in 2021 and 2023 (non-parametric Kruskal-Wallis test, $\chi^2_{(2)}$ = 77.66, p < 0.0001). Being similar to the 676 ±90 cockles /m^2 observed in 2021 but larger than the 100 ±51 cockles /m^2 observed in 2023 (Dunn pairwise multiple test, p = 1.000 for 2021 and p < 0.0001 for 2023).

Total cockle biomass in Nissum Bredning in 2022 was estimated at 13,951 tonnes (95% CI: 12,473 – 15,029; Table 5.1). Relative to Kås Bredning, it was approximately half the total cockle biomass in 2021 of 27,061 tonnes (95% CI: 23,941 – 30,182; Freitas et al., 2023b) and ca. three times higher than total cockle biomass in 2023 of 4,075 tonnes (95% CI: 3,209 – 5,283; Freitas et al., 2023b and Chapter 3).

Considering that the four fishing areas surveyed in Nissum Bredning (MO 1, 2, 3 and 4) are approximately three times larger than Kås Bredning, cockle abundance in Nissum Bredning in 2022 was relatively low.

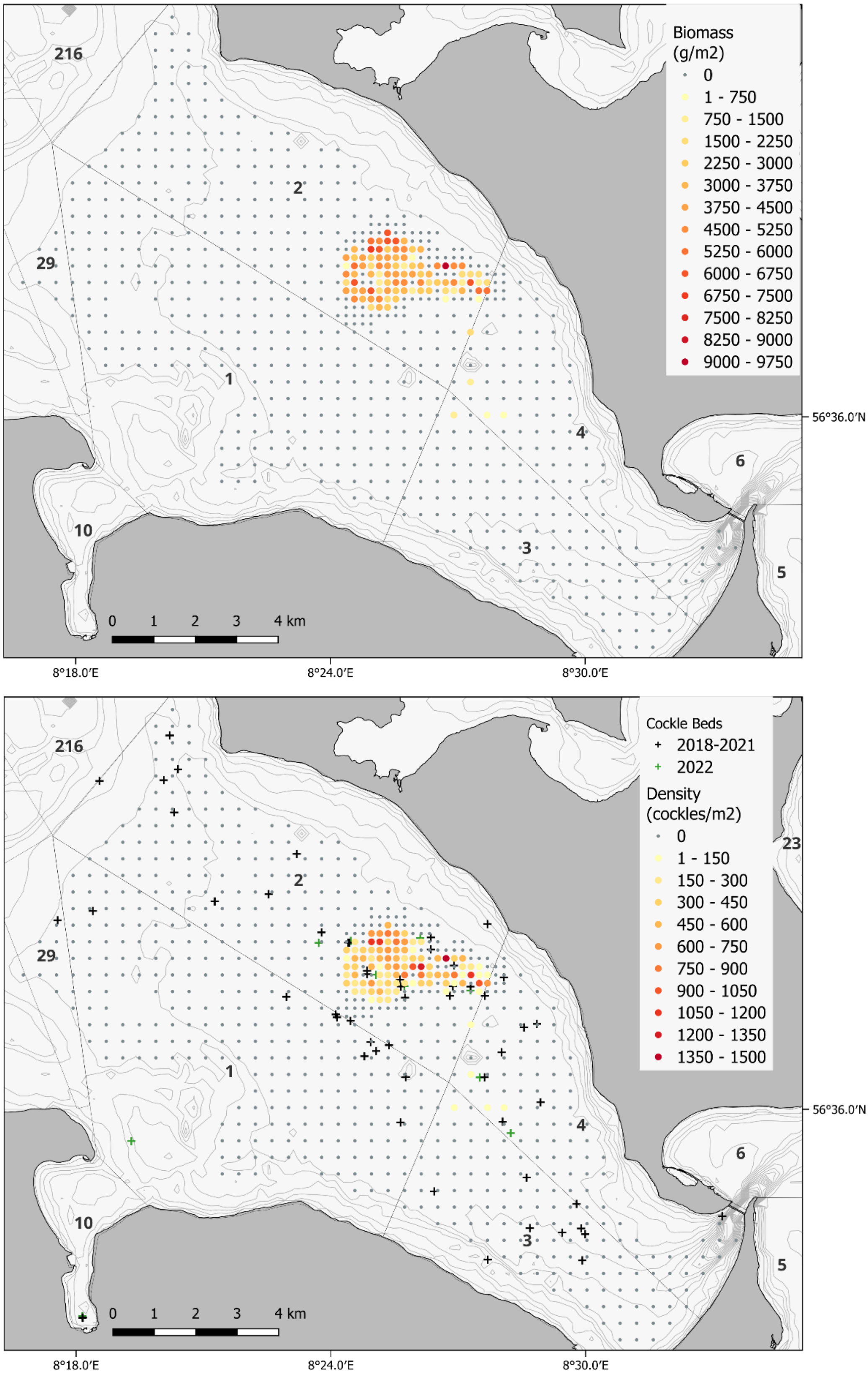

Figure 5.5. Cockle biomass (top) and density (bottom) distribution in Nissum Bredning (MO 1, 2, 3 and 4) in August 2022. Locations of previous cockle beds found between 2018 and 2021 (black crosses) and in March 2022 (green crosses) in monitoring surveys of the European flat oyster. Mussel fishing areas (Muslingeproduktions områder) are shown by grey lines.

Table 5.1. Cockle density, biomass and estimated stock in Nissum Bredning in August-September 2022. Errors are 95% confidence intervals of mean.

Area	N	**Density** cockles/m²	**Biomass** g/m²	**Stock** tonnes
Nissum Bredning	764			
400 m Grid	588	0.44 ±0.47	7.43 ±7.78	
200 m Grid	176	232.0 ±45.1	1,882 ±328	
Cockle beds only	97			13,951 ±1,478
400 m Grid	5	52.0 ±50.0	874.0 ±790.9	699 ±633
200 m Grid	92	443.9 ±59.1	3,601 ±363	13,252 ±1,336

A single age cohort with three years of age dominated cockle populations in Nissum Bredning in 2022 representing 77% of all cockles (Figure 5.6). This age cohort is the same that settled in the summer of 2019 and was observed to dominate cockle populations in other areas of the Limfjorden in 2021 and 2023 (Chapter 3 and Figure 5.6).

The present study provides further evidence that 2019 was a year with an exceptional successful settlement in the Limfjorden with little recruitment occurring since, at least from Nissum Bredning in the west, through Kås Bredning and Salling Sund and to a lesser extent in Sønder Bredning in the east (MO 9, 11, 13 and 15; Chapter 3 and Figure 5.6).

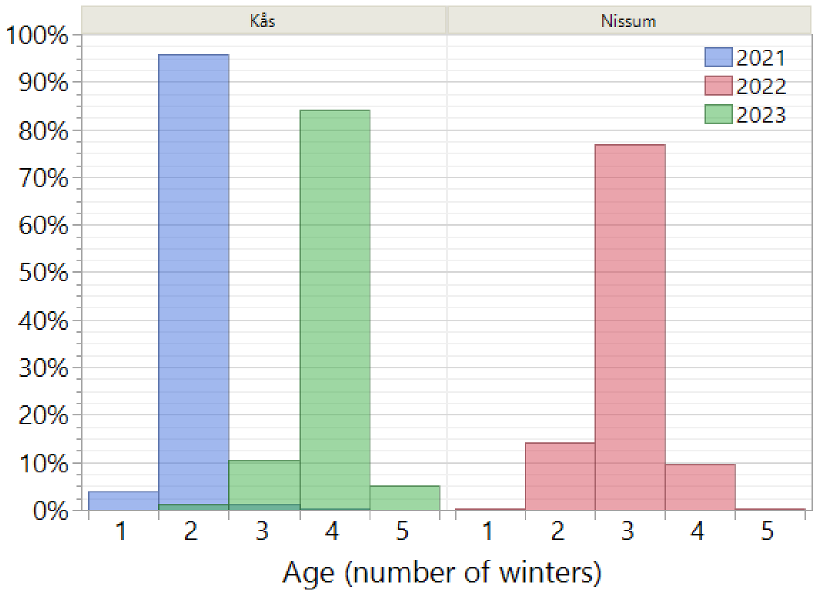

Figure 5.6. Histogram of cockle age (i.e. number of annual winter lines) in Kås Bredning (MO 9) in spring 2021 (blue; N = 6,122) and 2023 (green; N = 570) and Nissum Bredning (MO 1-4) in 2022 (red; N = 1,026).

Regarding size structure, the cockle population in 2022 in Nissum Bredning had a mode of 18 mm shell width and a mean of 18.9 ±0.2 mm (Figure 5.7). In 2022 in Nissum Bredning, cockle populations had mid-sized distribution in between the distributions in Kås Bredning in 2021 and 2023 (Figure 5.7), likely reflecting differences in age of the 2019 cohort at the time of surveys (Figure 5.6).

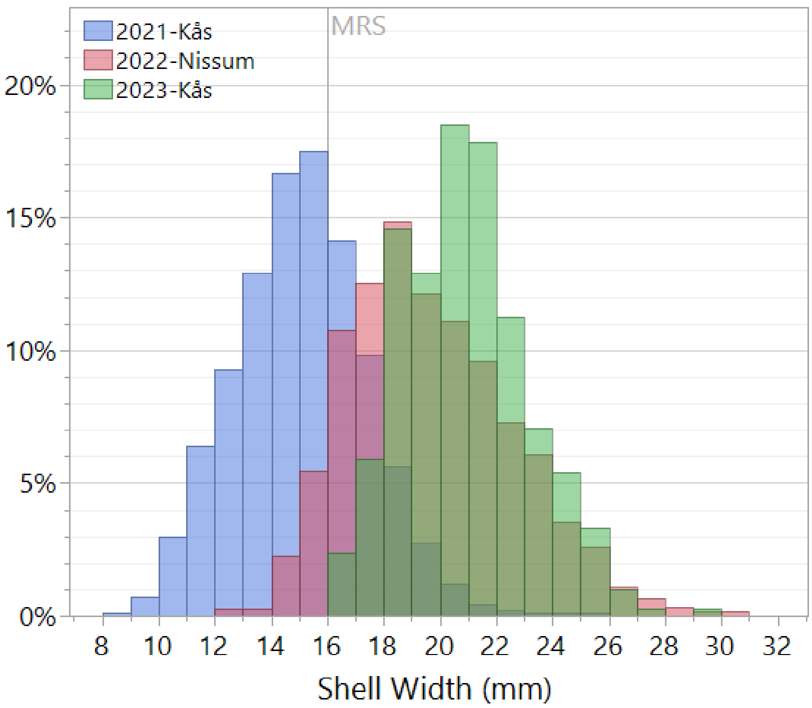

Figure 5.7. Histogram of cockle shell width (i.e. in % of 1 mm size bins) in Kås Bredning (MO 9) in spring 2021 (blue) and 2023 (green; N = 6,122 and N = 570) and Nissum Bredning) MO 1, 2, 3 and 4) in 2022 (red; N = 1,026). MRS is the minimum reference size of 16 mm shell width.

In 2022 in Nissum Bredning 91.5% of cockles were larger than the minimum reference size (MRS) of 16 mm shell width (Freitas et al., 2021 and 2023b). Therefore, the harvestable biomass (i.e. the fraction of the total biomass larger than MRS and thus available to the fishery) was 12,765 tonnes.

With a commonly used harvest ratio of 33% (Freitas et al., 2023b), in 2022 Nissum Bredning had the potential to produce 4,213 tonnes of cockle landings additional to what the fishery landed from other areas. Such value is 677 tonnes lower than mean landings of 4,880 tonnes/season obtained by the fishery from the main cockle fishing area Kås Bredning in the previous seasons 2017-2022 (Freitas et al., 2023b).

Cockle fishing efficiency

On average, each dredge track removed 131 kg/track (±24, 95% CI) and 54 kg/track (±5, 95% CI) of cockles, with the mussel and oyster dredge, respectively (Table 5.2). Live cockles represented 50% and 40% of the total gross catch of each dredge track with the mussel and oyster dredge, respectively.

In total, fishing removed a total of 4,310 kg and 1,794 kg of cockles, respectively with the mussel and oyster dredge (Table 5.2). Fishing removed 19% and 9% of a cockle population biomass estimated at 22,061 kg (±2,325; 95%CI) and 18.563 kg (±2,279; 95%CI) respectively in the two trial areas (Table 5.2).

Cockle catch rates were 73 cockles/m^2 (±12, 95% CI) and 53 cockles/m^2 (±5, 95% CI) respectively with the mussel and oyster dredge (Table 5.2), from cockle beds with densities of 475 cockles/m^2 (±76, 95% CI) and 316 cockles/m^2 (±78, 95% CI).

Table 5.2. Cockle fishing efficiency of the mussel and oyster dredges. Cockle catches, % of cockle biomass in the population removed by fishing, cockle catch rates per track and per area dredged and fishing efficiency. Error is 95% confidence interval of mean.

	Cockle Catch				Fishing Efficiency
Dredge	kg	% Population Biomass	kg/track	cockles/m^2	%
Mussel	4,310	18.7	130.6 ±23.6	73.4 ±11.5	18.0 ±3.3
Oyster	1,794	9.1	54.4 ±5.3	53.2 ±5.1	16.0 ±1.6

Mean cockle fishing efficiency of the 33 tracks, accounting for the number of cockles removed by each consecutive dredge track, was 18 % (±3.3, 95% CI) and 16% (±1.6, 95% CI), respectively with the mussel and oyster dredge, and thus similar between the two dredges (Table 5.2). Fishing efficiency of both dredges varied over a wide range, between 4% and 40% with the mussel dredge and between 6% and 23% with the oyster dredge (Figure 5.8).

Different methodologies make comparisons between cockle fishing efficiency of the mussel dredge determined in this study and a previous project (Freitas et al., 2023) unreliable, as the latter used a pairwise control-impact approach in single dredge tracks. Nevertheless, cockle fishing efficiency estimated from both approaches with a similar set up (inner net) was not significantly different considering the variability observed (ANOVA, Welch test unequal variances, $F_{(1,10.56)} = 2.72$, $p = 0.1282$), 18 % (±3, 95% CI) and 34 % (±21, 95% CI, N = 7) respectively.

Importantly, fishing efficiency of both dredges showed increasing trends with consecutive dredge tracks (Figure 5.8). Particularly with the mussel dredge, where cockle fishing efficiency on the first few tracks was 4 to 7.5% and in the last tracks it was 28 to 40%, while with the oyster dredge fishing efficiency the increase is smaller from 10 to 17% in the first few tracks to 12 to 22% in the last tracks (Figure 5.8).

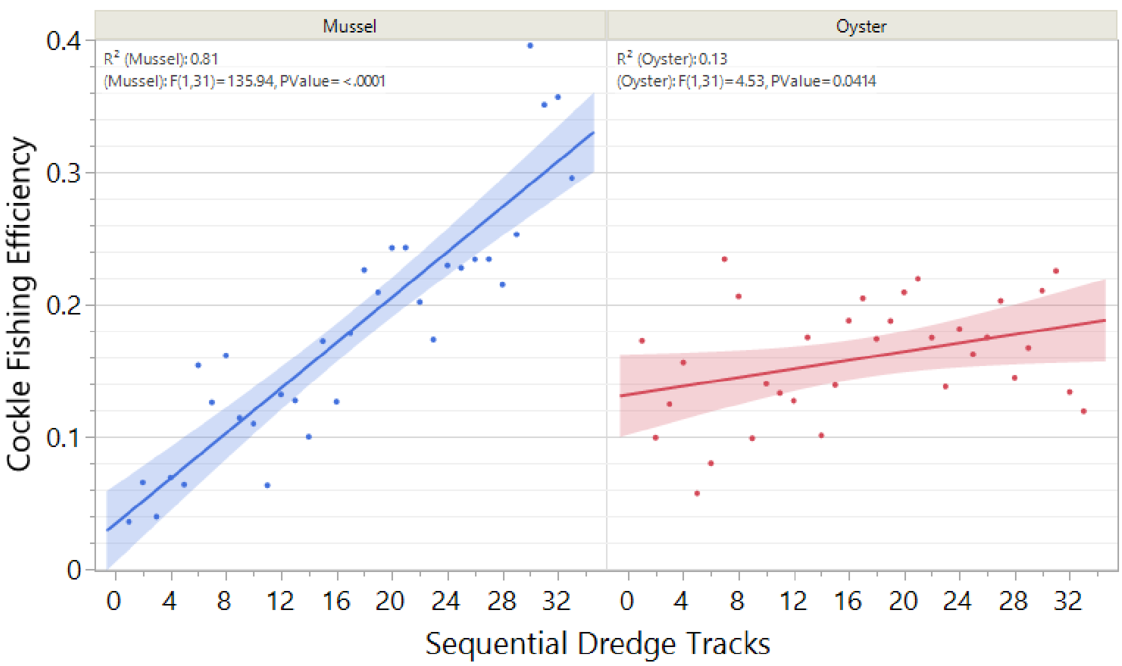

Figure 5.8. Linear regressions of cockle fishing efficiency of the mussel dredge (left) and oyster dredge (right) with track sequence. For the mussel dredge, fishing efficiency increased significantly with track sequence, but not with the oyster dredge. Shaded areas are 95% confidence intervals of fit.

The linear regression between mussel dredge cockle fishing efficiency and sequential number of tracks was significant (GLM least-squares, $F_{(1,31)}$ = 135.94, p < 0.0001; Figure 5.8) and explained 81.2% of the variance. While for the oyster dredge, the relationship was weaker even if significant (GLM least-squares, $F_{(1,31)}$ = 4.53, p = 0.0414; Figure 5.8) and only explained 12.7% of the variance.

Therefore, cockle fishing efficiency of both dredges did not vary randomly but increased linearly with the number of dredges done, with no sign of reaching a peak, plateau or decreasing (Figure 5.8).

A possible explanation for the increase in cockle fishing efficiency with consecutive dredge tracks of both dredges, may derive from two factors: track overlap and bottom disturbance. These factors are known to induce the surfacing of cockles to or near the sediment surface (Richardson et al., 1993; Freitas et al., 2023), which would then increase availability of cockles to both dredges and thus increase its fishing efficiency.

A stronger increase in cockle fishing efficiency with consecutive dredge tracks of the mussel dredge than of the oyster dredge, may thus derive from a larger track overlap, higher bottom disturbance and also higher cockle density in the mussel trial area.

Firstly, the mussel dredge is wider (1.5 m relative to 1.0 m) than the oyster dredge, which resulted in larger dredged area and higher overlap between tracks than with the oyster dredge (Figure 5.3 and Table 5.3). The total cumulative dredged area was 8,146 m^2 and 4,315 m^2 with an overlap between dredge tracks of 38.4 and 27.0 % respectively (Table 5.3). Secondly, disturbance of bottom sediment and thus of its cockle population is expected to be higher with the heavier mussel dredge than with oyster dredge. Finally, cockle density was higher in the mussel trial area, resulting in a stronger “crowding effect” with reduced available space in the sediment for cockles favouring physical contact and increased disturbance of cockles.

Table 5.3. Cockle fishing efficiency of the mussel and oyster dredges. Track length and % overlap, total dredged area, bottom footprint dredged area and swept area ratio (SAR).

	Track			Total Area		Footprint Area		
Dredge	N	Length (m)	% Overlap	m^2	% Trial Area	m^2	% Trial Area	**SAR**
Mussel	33	166 ±3.1	38.4	8,146	113	5,017	69.7	1.62
Oyster	33	169 ±2.1	27.0	4,315	59.9	3,148	43.7	1.37

Potential impact from cockle fishing in Nissum Bredning

Applying an area impact per tonne of harvested cockles of 887.2 m^2/tonne and 980.6 m^2/tonne from Kås Bredning and all Limfjorden in 2022 (Chapter 4) to the potential cockle harvest of 4,213 tonnes (i.e. a harvestable ratio of 33%), the estimated bottom area impact in Nissum Breding in 2022 would range between 3.74 and 4.13 km^2.

Since Nissum Bredning is a protected Natura 2000 area, the Danish Mussel and Oyster Policy is based on an ecosystem-based approach to ensure that the management of fisheries in the N2000 sites are a balance between opportunities to develop the bivalve fishing industry, and the advancement of environmental conservation using scientific tools. Any new fishing activity of cockles in Nissum Bredning, will thus be regulated by a cumulative area impact of 15% over the regeneration time of the components blue mussels, benthic fauna, and macroalgae (Udenrigsministeriet, 2019; Eigaard et al., 2020; Nielsen et al., 2020). Impacts on the eelgrass ecosystem component must be zero as eelgrass must not be adversely affected by fishing (e.g. Udenrigsministeriet, 2019; Nielsen et al., 2021a and 2023).

The potential bottom area impact of between 3.74 and 4.13 km^2 from cockle fishing in Nissum Bredning in 2022-2023, would be larger than the annual area impact from oyster and starfish fishing that ranged between 0.01 to 3.0 km^2 since 2017-2018 (Nielsen et al., 2021b and 2023). Cockle fishing area impact would represent between 2.17 and 2.40% of the habitat area H28 in Nissum Bredning used to calculate area impacts from bottom fishing in Nissum Bredning (Udenrigsministeriet, 2019; Nielsen et al., 2021, 2021b and 2023).

Using the calculated fishing impacts in Nissum Bredning in 2022-2023 of 0.16 km^2 or 0.09% area impact from starfish fishing (Nielsen et al., 2023), cockle fishing would increase fishing area impact to between 3.90 to 4.29 km^2 and between 2.26 to 2.56% area impact. In addition, the contribution of cockle fishing impact on the four ecosystem components, eelgrass, macroalgae, benthic fauna and blue mussels to the cumulative area impact must be determined (e.g. Eigaard et al., 2020; Nielsen et al., 2021, 2021b and 2023).

Impacts on the eelgrass ecosystem component would be zero as any cockle fishing would occur outside potential eelgrass areas.

The cumulative area impacts with the contribution from potential cockle fishing in 2022-2023 were estimated at: 0% for eelgrass, 4.08 to 4.26% for macroalgae, 4.09 to 4.32% for benthic fauna and, albeit unknown (e.g. Nielsen et al., 2021a and 2023) it would only add 0.20 to 0.22% to the cumulative impact on blue mussels. Therefore, if cockle fishing was allowed in Nissum Bredning in 2022-2023 under the scenario described above, the cumulative area impact on the four ecosystems components would remain below the accepted limits of 0% for eelgrass and 15% for the other components.

Obviously, changes in the abundance and distribution of cockle populations (size and biomass of cockle beds), as well as in cockle fishing patterns (i.e. fished area/tonne harvested, SAR and track overlap), will vary from year to year and bed to bed and will result in corresponding increases or decreases in bottom area impact. However, the approach used here is constrained and anchored by real, observed cockle abundance and distribution in Nissum Bredning, and bottom area impacts and fishing patterns from cockle fishing in the Limfjorden over a whole season. Therefore, this approach provides valid if approximate estimates of potential bottom area impact from cockle fishing in Nissum Bredning, which can be updated with new available data.

5.4 Conclusions

In the summer of 2022, cockles had a limited spatial distribution relative to previous years, occurring almost exclusively in a single large bed with ca. 4.5 km^2 in the northern middle part of Nissum Bredning (fishing area 2).

In 2022, a single age cohort with 3 years of age dominated cockle populations in Nissum Bredning, which is the same cohort that settled in the summer of 2019 and dominated cockle populations in other areas of the Limfjorden from 2021 to 2023. Such observation is further evidence of exceptional successful settlement in 2019 with little recruitment occurring since in the Limfjorden.

Total cockle biomass was estimated at 13,951 tonnes (95% CI: 12,473 – 15,029; Table 5.1), which considering the size of Nissum Bredning relative to other fishing areas of the Limfjorden, is relatively low. However, 91.5% of cockles were larger than the minimum reference size (MRS) of 16 mm shell width and harvestable biomass was 12,765 tonnes. With a commonly used harvest ratio of 33%, Nissum Bredning had the potential to supply 4,213 tonnes of cockles in 2022, slightly lower than mean landings from the main cockle fishing area Kås Bredning (2017-2022).

Fishing efficiency averaged 18% (±3.3, 95% CI) and 16% (±1.6, 95% CI) respectively of the mussel and oyster dredge. Fishing efficiency of individual tracks ranged between 4% and 40% and the oyster dredge between 6% and 23%, respectively for the mussel and oyster dredge. Fishing efficiency of both dredges increased significantly with consecutive dredge tracks, particularly for the mussel dredge where 81%% of the fishing efficiency variance was explained by dredge track sequence, while the oyster dredge showed a weaker increase (Figure 5.8).

A possible explanation for the increase in cockle fishing efficiency with consecutive dredge tracks, may derive from track overlap, bottom disturbance and a "crowding effect" that favours physical contact and disturbance of cockles. In this scenario, increased repeated fishing at the same locations by increasing disturbance and physical contact of cockles would induce the surfacing of cockles, resulting in increased availability of cockles to the dredges and higher fishing efficiency.

Potential Impacts
In 2022, the estimated cockle fishing bottom area impact in Nissum Breding would range between 3.74 and 4.13 km^2, corresponding to between 2.2 and 2.4% of the habitat area H28 in Nissum Bredning. The total cumulative fished area (i.e. including track overlap) would range between 15.6 km^2 and 19.0 km^2.

The approach used in this study provided valid if approximate estimates of potential bottom area impact from cockle fishing in Nissum Bredning, which can be updated with new available data. The implementation of catch limits (e.g. TAC) or area restrictions (e.g. fishing boxes) are two management measures that if required can be used to constrain area impacts to below allowed cumulative limits.

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6. Reproductive connectivity of cockles in the Limfjorden

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6.1 Summary

In this section, a summary is presented of the Hansen et al., 2024 study: Hansen FT, Erichsen AC, Saurel C, Freitas PS (2024) Assessing the demographic connectivity of common cockles in a shallow estuary as a basis for fisheries management and stock protection efforts. Marine Ecology Progress Series, 731:293-313. https://doi.org/10.3354/meps14297. Additional information is made available as supplementary files to the article (https://www.int-res.com/articles/suppl/m731p293_supp/), and as two annexes at the end of this report.

6.2 Rationale

Most marine populations are connected via dispersal of pelagic larval stages and renewal and recruitment to these populations reflects an ever-shifting balance between key factors that will determine adult abundance (e.g. Armsworth, 2022; Yau et al., 2014 and references therein). On one hand, the supply of larvae, which are related to the biomass, fecundity, distribution and connectivity of spawning adults. On another hand, the highly variable and unpredictable biological processes and environmental conditions that affect larvae and post settlement survival and growth (e.g. Armsworth, 2022; Yau et al., 2014 and references therein). The dominance of the latter, often results in recruitment being largely uncoupled from spawning biomass, resulting in the absence of clear stock-recruitment relationships (e.g. Szuwalski et al., 2015; Canales et al., 2020).

Demographic connectivity contributes to the understanding of the spatial scales over which population dynamics operate, are connected, and interact, and thus the spatial scales over which exploited populations should be managed and/or protected (e.g. Cowen et al., 2006, 2007; Leis et al., 2011). In marine species with pelagic larval stages, connectivity between populations is usually dominated by transport and dispersal processes of larvae (e.g. Gawarkiewicz et al., 2007; Pineda et al., 2007), which define the degree of how closed or open populations are, that is the degree of local self-recruitment or external recruitment from or to other areas (e.g. Cowen et al., 2000; Hixon et al., 2002). Fisheries or conservation management objectives and actions can differ depending on whether a local population is considered to be open vs. closed, and should consider potential impacts of local harvest not only on self-recruitment but also on larval export and thus recruitment elsewhere (e.g. White et al. 2013; Yau et al., 2014).

The use of larval dispersal modelling and connectivity analysis has previously been proposed as a tool to support marine management: marine protected areas (e.g. Shanks et al. 2003, Balbar & Metaxa 2019; Jonnson et al. 2020), marine spatial planning (e.g. Jonnson et al. 2021), coastal ecosystem services (e.g. Ospina-Alvarez et al. 2020); Management (Hansen & Christensen 2018) and monitoring of marine invasive species (Lindegren et al. 2022), and also for fisheries management (e.g. Fogarty and Botsford, 2007; Yau et al., 2014; Berger et al. 2021).

The Limfjorden, a microtidal enclosed estuarine system in northern Denmark, is home to significant cockle populations supporting the main Danish and European cockle fishery, which accounted for

59% of European landings between 2017-2022 (Freitas et al., 2023; Eurostat). Fishing patterns vary greatly among different basins in the Limfjorden, which suggests different population and recruitment dynamics. Only the main fishing area of Kås Bredning produces significant regular landings every season, while smaller secondary side basins produce highly variable and irregular landings (Freitas et al., 2023). Variations of these cockle subpopulations, particularly in Kås Bredning as observed in 2023, either from recruitment failure or natural and fishing mortality can compromise the Limfjorden cockle fishery, risking significant economic and social impacts on fishermen and industry stakeholders. This suggests a fragility in the sustainable exploitation of cockle populations that needs to be addressed by reliable stock estimates, but also by understanding the local reproductive and recruitment dynamics of cockle.

6.3 Objectives

The aim of this study was to evaluate cockle demographic connectivity and how the most important fishing grounds in the Limfjorden may be replenished, but also address the general patterns of the potential larval dispersal and connectivity in the whole of Limfjorden through modelling of potential larval dispersal and transport (Hansen et al, 2024).

The objectives and rationale were: 1) Improve the understanding of cockle population dynamics. Namely, the regular renewal and high production of cockle populations in the main fishing area Kås Bredning, as the significant dependence on a single fishing area may pose risks for the sustainability and viability of the cockle fishery. 2) Assess the connectivity among and within different basins to understand the degree of self-recruitment and of external recruitment. Historical fishing patterns suggest differences in population and recruitment dynamics within the Limfjorden. Differences in circulation patterns occur among basins with a residual circulation from west to northeast, from the opening to the North Sea in the west to the opening to the Kattegat in the east. Therefore, some basins may likely function as open systems, relying on external recruitment from other areas and/or supporting recruitment elsewhere, while others likely rely mainly on self-recruitment. 3) Derive preliminary knowledge on cockle population connectivity within the Limfjorden to inform management of the cockle fishery in a transition to becoming a new independent fishery. Namely potential impacts of opening to fishing currently unexploited areas/grounds (e.g. N2000 areas), as well as the potential effects of TACs and changes in exploitation patterns in different basins, including the main fishing area of Kås Bredning.

6.4 Approach

The potential cockle larval dispersal and settlement patterns in the Limfjorden were predicted using biophysical modelling, which combines hydrodynamic models simulating the direction and speed of ocean currents, and agent-based modelling (ABM) which simulates the Lagrangian drift trajectories and settling of individual larvae with a defined pelagic larvae duration (PLD; Hansen et al., 2024). Agents were released in a 1x1 km grid covering the extent of Limfjorden, every 6 hours for the 2 months spawning period. Simulations were run for an additional 35 days for all agents to settle after the end of the spawning period.

Results from larval dispersal simulations, i.e. of start and end positions of individual simulated agents, were further analysed to understand the connectivity within and between both known subpopulations of cockles and other potential cockle habitats in Limfjorden, reporting both larval export and import probabilities from connectivity probability matrices. Probabilities of larvae export can provide valuable information for management to identify cockle beds, which may potentially serve as an important larvae supplier to other sites. This study addresses exclusively potential connectivity, and thus the probability of a larvae being release in a cell of the model is the same for all cells and thus independent if any or how many cockles actually occur and how many larvae are produced in each cell.

Connectivity export and import probability maps were extracted for 15 known major cockle beds, but connectivity export and import probability maps for all grid cells are included as additional annexes at the end of this report (Chapter 9: Annexes A and B). Cluster analysis was performed to identify the general patterns of potential connectivity of cockles in the whole of Limfjorden, and the location and strength of possible dispersal barriers. In addition, the graph theory metrics referred to strength and transitivity were extracted. Several standard sensitivity analyses were carried out to test robustness of results regarding alternative PLDs, spawning period, alternative horizontal and vertical dispersion coefficients.

A detailed description of the method used can be found below in this chapter, the manuscript that resulted in the article Hansen et al. (2024).

6.5 Results and discussion

In this study, results show that most of Limfjorden, particularly along the central axis, is relatively well connected with the western (Nissum Bredning) and central parts (Kås Bredning and Løgstør Bredning) being connected predominantly unidirectionally from west to east, but with only limited exchange of larvae from east to west. Self-recruitment along the main central axis basins (i.e. Kås Bredning, Salling Sund and Løgstør Bredning) is low (Table 1 in Hansen et al., 2024), and the primary sink areas (in-strength, Figure 6 in Hansen et al., 2024) are the central basins of the Limfjorden (central and southern Løgstør Bredning, northern Salling Sund and the strait of the island of Mors).

Lateral side basins (Venø Bugt, Lovns Bredning and Skive Fjord) present dispersal barriers with the larger clusters of the central Limfjorden, even though these barriers still allow for some exchange of larvae particularly unidirectional dispersal towards the central basins and anticlockwise dispersal dominates around the island of Mors (Tables 3 and 4; Figures 1, 3, 4 and 5 in Hansen et al., 2024). Cockle beds in more isolated parts of Limfjorden have relatively high self-recruitment and receive very few larvae spawned elsewhere (Venø Bay, Visby Bredning, Thisted Bredning, Skive Fjord and Lovns Bredning; Figures 1, 4 and 5 in Hansen et al., 2024). Results indicate that year-to-year variations are limited.

The most important fishing area, Kås Bredning, relies heavily (and possibly solely) on recruitment via larval import from multiple cockle populations elsewhere in other sub-basins, transported by the dominant west-to-east circulation pattern (Nissum Bredning, Venø Bugt and Visby Bredning; Figures 1 and 4 in Hansen et al., 2024). One of the donor areas is the largest known contiguous, and currently unexploited population of cockles in the western part of the fjord system (Nissum Bredning). This can explain why Kås Bredning sustains a relatively stable recruitment of cockles allowing regular and large cockle landings every season.

While demographic connectivity patterns found between existing subpopulations of cockles are supported by observations from survey data and cockle landings, other demographic connectivity predictions are not supported by empirical data. For instance, the large central basin of Løgstør Bredning was identified as a primary sink area, with a potential high input of larvae from other parts of Limfjorden as well as from self-recruitment, but no large and dense cockle populations have been observed in its central and northern parts. A hypothesis is that one or more environmental/ ecological factors may limit the recruitment of cockles in these areas. This decoupling between adults spawning biomass, larval supply, settlement and recruitment has been found for cockles in other studies (e.g., Dankers 1993, Andresen et al. 2014), since for cockles, environmental drivers dominate settlement, survival, and recruitment processes (Dankers 1993). Often high larval production (~1 mill. eggs per female, Dare et al. 2004) and supply does not necessarily translate into high settlement and/or recruitment success and future adult abundance.

For species with high reproductive outputs (like cockles and blue mussels) and high population densities, even low calculated dispersal probability may be sufficient to supply a minimum of larval settlement to support a large recruitment, as larval dispersal and settlement have a secondary importance relative to environmental and ecological factors. One of the most challenging topics in marine connectivity studies, is the criteria for when a connection between sites can be considered strong or weak and such criteria is not trivial (e.g., Treml et al. 2012, Jacobi et al. 2012) and remains unresolved. Such criteria or thresholds need to be addressed in future research on demographic connectivity e.g., aiming at examining statistical correlations between observations of abundances and annual recruitment successes, and environmental and ecological explanatory variables. and larval dispersal and connectivity metrics.

This study addressed exclusively potential connectivity, which does not account for the present distribution of cockles and factors such as fecundity, larval mortality, growth, settlement and recruitment success, etc. In contrast, realized connectivity accounts for cockle biomass distribution to determine probabilities of larvae being produced in an area and probabilities of being dispersed and settled in the same/other areas. Thus, potential connectivity may lead to biased conclusions on sink-source and self- to external recruitment dynamics, as some source cells may produce none or few larvae while others produce significant amounts, with cascading effects to the number of larvae received by sink cells. Nevertheless, potential connectivity provides a baseline and a useful insight to population dynamics that can be expected or predicted within and between subpopulations of marine organisms.

The present study emphasizes that analysis of potential connectivity based on biophysical modelling alone without data on the present distribution of the species studied and/or habitat quality, may lead to biased conclusions on sink-source dynamics and ultimately misguidance of management practices, particularly when recruitment processes are not well understood.

Nevertheless, for the management of the cockle fishery in Limfjorden, the study provides a baseline for such future assessment, where analysis of potential connectivity in combination with data from annual stock assessment and fisheries surveillance can support the prediction of future stock development under different management strategies and scenarios. This includes potential consequences from opening non-fished areas (e.g. Nissum Bredning) to fishing in a new independent cockle fishery, which may impact not only local self-recruitment but also significant larval export and thus recruitment elsewhere in other important fishing areas (Kås Bredning), or potential consequences of closure of fished areas that may be heavily reliant on self-recruitment.

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7. Fishery management recommendations

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7.1 Rationale

The Limfjorden cockle fishery (*Cerastoderma* spp.) has become the most valuable bivalve fishery in Denmark since 2017 at 31.75 Mio. kr. per year and 39.5% of all bivalve landings per value (2017-2023, Fiskeristyrelsen). The Limfjorden cockle fishery is also the main European cockle fishery accounting for ca. 59% of European landings since 2017 (2017-2022, Eurostat; Freitas et al., 2023).

Nevertheless, despite its economic and social importance, cockle fishing in the Limfjorden is not an independent fishery and is managed as a by-catch fishery of the blue mussel fishery, which can lead to both poor management and inefficient or overexploitation of the resource. Until recently (2023), no population monitoring or management program existed for cockle fishing in the Limfjorden, and thus essential and crucial components for a sustainable management are missing. Bivalve populations are especially susceptible to overexploitation as they form local sessile, sedentary populations, demographically connected by the dispersal of planktonic larvae (e.g. Hansen et al., 2024; Chapter 6, this report), which can be efficiently harvested with targeted non-random fishing (Meyer et al., 1981; Chapters 4 and 6, this report).

Even though a previous EMFF project (Freitas et al., 2023) has provided valuable missing knowledge on both cockle biology and the fishery, there is still a significant lack of knowledge on cockle biology and population dynamics in the Limfjorden, as well as on the fishing patterns and impacts of the fishery at habitats and species level.

The aim of this chapter was to compile results from the project to provide recommendations and advice to the fishery management agency on future management options and scenarios for the Limfjorden cockle fishery. Namely: 1) cockle fishing becoming an independent fishery, managed autonomously from blue mussels considering cockle biology (e.g. infauna, highly patchy distribution, population and recruitment dynamics) and conditions in the Limfjorden (e.g. microtidal and subtidal habitat).; 2) a valid, cost-effective cockle monitoring/stock assessment program adapted to the cockle biology and subtidal conditions of the fishery; 3) the potential and consequences of cockle fishing in a N2000 area; 4) implications for management of a cockle fishery in relation to population connectivity within the Limfjorden; 5) cockle fishing efficiency of mussel and oyster surface dredges; 6) future knowledge needs.

7.2 Recommendations

Future management of cockle fishing

The Limfjorden cockle fishery is managed as by-catch that can constitute up to 49% of total gross daily landings per boat outside N2000 areas and 10% inside N2000 areas. However, cockles are almost entirely fished in spatially separate beds and are specifically targeted by the fishery, as they are more valuable than blue mussels (Freitas et al., 2023). Thus, blue mussel and cockle fishing in the Limfjorden are mainly done with limited by-catch of either of the two species.

Fishing inefficiency will increase from unnecessary daily travel between mussel and cockle grounds because of the obligation to fish one species (mussels) to capture the other (cockles) even when the physiological condition and meat quality of blue mussels is poor.

Managing cockles as a target species would improve not only a sustainable resource utilization but would also improve the accuracy and quality of fishery dependent data by separating blue mussel from cockle fishing in fishing patterns and effort, and associated ladings (i.e. electronic monitoring systems Black Box and Elogs).

Therefore, with the considerations described above, it is DTU Aqua recommendation that cockle fishing in the Limfjorden should be managed autonomously from the blue mussel fishery according to its own management plan. DTU Aqua recommends that cockle stocks and fishing in the Limfjorden should be monitored and managed according to the specific biology and population dynamics of cockles, which are different from blue mussels, as well as the conditions of the Limfjorden.

Management of cockle fishing could be implemented either as a mixed fishery with blue mussels and cockles as co-target species, captured in spatially offset areas, or as a completely new separate independent fishery. In both options, the two species should have separate stock assessments and monitoring programs, regulations and catch limits/quotas, and the by-catch of either species even if expected to be low should be landed and accounted for on the respective quota (i.e. landing obligation).

Monitoring program

Fisheries management requires the collection of data, dependent and independent from the fishery, to support the assessment of fishing impacts, as well as the stock (i.e. harvestable fraction) and population renewal. Whichever the model chosen for the future management of cockle fishing the Limfjorden, a valid cost-effective stock assessment/monitoring program specific to cockle populations should be used. Such stock assessment/monitoring program should be adapted both to the cockle biology and population dynamics and the conditions of the Limfjorden, which are different from blue mussels and other European cockle fisheries.

Chapters 2, 3 and 6 of this report present respectively an evaluation and development of a stock assessment and monitoring program (Chapter 2) and the potential impact of an implementation of such program in 2021, 2022 and 2023 (Chapters 3 and 6).

DTU Aqua recommendations for a monitoring and stock assessment program are summarized here (see also Chapter 2):

1. A stock assessment comprising both fishery dependent data (fishing activity and patterns, landing data and catch samples for size and age, and ad-hoc input on cockle distribution or new recruitment) and fishery independent data (monitoring survey, evaluation of biomass estimates and spatial distribution, size and age structure and dynamics).
2. The stock assessment requires approximately a 3-month period to deliver a report before the fishing season starts in September.
3. The large area of the Limfjorden makes the survey of all potential cockle fishing areas (i.e. produktionsområder for muslinger, MOs) in the western and central Limfjorden an unrealistic task. A compromise is thus required with fishery independent data obtained on the most important cockle fishing grounds based on historical data and up to date information from the fishery (fishery dependent data).

4. A monitoring survey after the cockle fishery closes in late spring (e.g. covering up to ca. 60 km^2 in 15 survey days; Chapters 2 and 3, this report).
5. If the start of the fishing season is moved later, management should consider a later survey in autumn instead of late spring-early summer. The time limit is when information on the stock status and advice on catch limits (i.e. TAC) is required by the fishery management body. The loser the survey is to the end of the growing season and the start of the fishing season, the smaller the changes in cockle biomass/stock estimates will be between the survey and the start of fishing. Thus, the more accurate the stock assessment and advice on catch limits (i.e. TAC) will be.
6. Use of a sampling tool (e.g. Day grab) which has a 100% sampling efficiency of the buried cockle population. The Day grab is reliable, easy and fast to operate ensuring high sampling intensity.
7. High resolution sampling on a fixed grid (e.g. 200 to 300 m) with high station density and sampling intensity to address the highly patchy cockle distribution and ensure sufficiently sampling of significant cockle beds by the survey.
8. An adaptable survey design (e.g. stratified, from season to season) to concentrate sampling intensity on the main cockle beds and on essential areas to the cockle fishery, and to improve accuracy of biomass estimates.
9. Determination of cockle population size and age structure to follow cockle population dynamics, define harvestable biomass and catch limits.

Minimum landing size

The management of fisheries of species with episodic and variable recruitment, such as cockles, requires the incorporation of uncertain recruitment by guaranteeing an adequate abundance of mature individuals whenever conditions are adequate for successful spawning and recruitment to occur. This is defined as the "storage effect" where the potential for strong successful recruitments is stored in the presence of sufficient mature adults in the population capable of contributing to reproduction when favourable conditions occur (e.g. Warner & Chesson 1985).

Minimum landing sizes define the fraction of the total cockle population that is considered adult/mature, thus recruited into the stock and available for exploitation. European cockle fisheries commonly use minimum legal or reference sizes between 14 to 22 mm shell width (the smallest dimension of a cockle shell) to protect spawning potential and ensure a significant proportion of cockles reach maturity and reproduce (e.g. Dare et al. 2004; Southall and Tully, 2014; Hervas et al, 2008). Currently, there is no legal minimum landing size for cockle fishing in the Limfjorden. DTU Aqua uses a minimum reference size of 16 mm shell width to define the harvestable fraction of total cockle biomass (Freitas et al., 2021, 2022, 2023b). However, the size and age at which cockles became mature in Limfjorden, as well as if cockles reproduce in their first or second spring-summer after settlement, is unknown. Sexual maturity in cockles depends more on the size rather than age (in Dabouineau and Ponsero, 2011).

Data obtained since 2018 on cockle population structure in the Limfjorden indicates that the cockle fishery normally does not target cockles younger than 2-years of age (i.e. two winters; Freitas et al., 2023a; Chapters 3 and 4, this report). More recently, with the lack of older and larger cockles, in the 2023-2024 season the fishery will likely target 1-year old cockles that settled in summer 2023 (unpublished data, HjertFisk project).

Therefore, DTU Aqua recommends that cockle maturity in relation to size and age is evaluated for the Limfjorden to define an appropriate minimum landing size that ensures sufficient cockles reach maturity and contribute to the reproductive potential and safeguard of the adult cockle spawning biomass.

Cockle fishing potential in unfished N2000 areas in the Limfjorden

Cockle fishing in the Limfjorden has mostly occurred in only a few fishing areas, particularly since 2017, with very irregular fishing in a few other fishing areas (Freitas et al., 2023; Fiskeristyrelsen). The occurrence of significant cockle populations in N2000 areas of the Limfjorden, such as Nissum Bredning, Venø Bugt or Løgstør Bredning, has previously been reported both from blue mussel surveys (Nielsen et al., 2018; Eigaard et al., 2020; Nielsen et al., 2020, 2021a, 2021b, 2023) and cockle surveys (Freitas et al., 2023a; Chapter 5, this report). Contrary to blue mussels and European flat oysters, no targeted cockle fishing has occurred in Natura 2000 areas in the Limfjorden, and thus these areas may provide potential new cockle fishing grounds. However, any cockle fishing must abide by conservation and protection regulations for N2000 areas. The Danish Mussel and Oyster Policy aims to balance the opportunities to develop the bivalve fishing industry, and the advancement of environmental conservation using scientific tools. Any new fishing of cockles in N2000 areas would require estimation of the cumulative areal impacts over the regeneration time of four ecosystem components: eelgrass, macroalgae, blue mussels and benthic fauna in accordance with the Danish Mussel and Oyster Policy.

In 2022, DTU Aqua found significant cockle populations in the N2000 area, Nissum Bredning, with the potential to supply significant landings (> 4,000 tonnes). The corresponding cumulative area impact on the four ecosystems components, estimated by applying cockle fishing patterns elsewhere in the Limfjorden, would remain below the currently accepted limits (Chapter 5 of this report). Harvest control rules as implemented for blue mussel and European flat oyster fishery, such as N2000 specific catch limits or area restrictions (e.g. fishing boxes) are two management measures that, if required, can be used to constrain area impacts below the allowed cumulative limit.

However, factors other than cockle abundance must be considered if Nissum Bredning or other N2000 areas were to be open to cockle fishing. For instance, demographic connectivity studies (Hansen et al., 2024; Chapter 6, this report) identify Nissum Bredning as the source of significant larval export and recruitment to important fished areas (e.g. Kås Bredning, Salling Sund and Sønder Bredning), while in other non-fished N2000 areas (e.g. Løgstør Bredning) recruitment is mainly external originating elsewhere in the Limfjorden. In addition, no significant recruitment to cockle stocks in the Limfjorden occurred between 2020 and 2022, including in Nissum Bredning (Chapter 5, this report), with spawning potential based on a single and ageing cohort from 2019. Thus, opening Nissum Bredning to cockle fishing could potentially have a significant impact on cockle settlement and recruitment elsewhere in the Limfjorden.

For cockles to be fished in N2000 areas of the Limfjorden, even if these areas contain significant cockle biomass and environmental impacts remain below the currently accepted limits, management and political decisions are required that must consider and balance several factors, including:

- N2000 species and habitats protection regulations.
- Potential environmental and areal impacts from cockle fishing.
- Approaches to eliminate or mitigate negative factors.
- Required biological knowledge, such as cockle abundance, size and age population structure and/or potential impacts from fishing on cockle recruitment dynamics elsewhere in the fjord.

- Support to one of the few remaining viable Danish coastal fisheries, the most valuable Danish bivalve fishery and the main European cockle fishery, with significant economic and social importance for local/regional communities and associated industries.

Biological knowledge

Even though significant progress has been achieved in the last five years on the biology and assessment of cockle populations in the Limfjorden (Freitas et al., 2023a, this report), DTU Aqua recommends the improvement of cockle biological and fishery knowledge. In addition, management of cockle fishing in the Limfjorden under a scenario in which cockles are no longer a bycatch of the blue mussel fishery but an independent fishery, requires improved biological knowledge. Such knowledge (e.g. size-age at maturity, growth, mortality, connectivity, size and age structure, cockle habitat and recruitment dynamics in the Limfjorden) will form key parts of a management plan for the cockle fishery but can also contribute to management decisions relative to situations as the recent lack of successful recruitment. Improved fishery knowledge from further evaluation of cockle fishing patterns and impacts can provide important knowledge on cockle fishing impacts on benthic communities and habitats.

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9. Annexes

Two online annexes are provided to Chapter 6 “Reproductive connectivity of cockles in the Limfjorden”. These present connectivity export and import probability maps extracted from the model for all grid cells. Each annex is provided in two files due to its size.

9.1 Annex A: Downstream (export) connectivity probability maps

Part 1 of Annex A
https://www.aqua.dtu.dk/-/media/institutter/aqua/publikationer/rapporter-451-500/468-2024-COCKLE-II-Annex-A-Part-1.pdf

Part 2 of Annex A
https://www.aqua.dtu.dk/-/media/institutter/aqua/publikationer/rapporter-451-500/468-2024-COCKLE-II-Annex-A-Part-2.pdf

9.2 Annex B: Downstream (export) connectivity probability maps

Part 1 of Annex B
https://www.aqua.dtu.dk/-/media/institutter/aqua/publikationer/rapporter-451-500/468-2024-COCKLE-II-Annex-B-Part-1.pdf

Part 2 of Annex B
https://www.aqua.dtu.dk/-/media/institutter/aqua/publikationer/rapporter-451-500/468-2024-COCKLE-II-Annex-B-Part-2.pdf

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