Forbedring af selektiviteten i trawl med henblik på beskyttelse af bestandene af torsk bedst muligt

DTU Aqua

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Forord

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Indhold

Sammendrag

Projektet er opdelt i tre separate delprojekter. Resultaterne fra forsøgene der er udført i Del 1, Del 2 og Del 3 kan være relevante for alle tre farvende. Mekanismerne og effekterne af de undersøgte designparametre har generel relevans for anvendelse, udvikling og lovgivning omkring fiskeredskaber i danske og internationale farvande.

Del 1: Østersøen

BACOMA-designet der anvendes i Østersøen består i dag af et 120 mm kvadratmaskepanel i fangstposens overside, mens undersiden er fremstillet af 105 mm diamantmasker. Resultater peger på at underpladen med 105 mm diamantmasker i BACOMA-designet i Østersøen i dag vil kunne ændres til 130 mm uden at der opnås et signifikant tab af torsk, hvorimod selektionen af rødspætter, og sandsynligvis også andre fladfisk som f. eks. skrubber og isinger, signifikant vil forbedres. I forbindelse med f.eks. et discard forbud, hvor en større fangst af små fladfisk vil være uhensigtsmæssigt, vil en sådan ændring i BACOMA designet signifikant kunne reducerer denne uønskede fangst.

Del 2. Kattegat/Skagerrak

Del 2 består af to separate del forsøg:

1: Aktiv stimulering af fisks adfærd med henblik på at forbedre kontaktsandsynligheden

Der er en observeret en tendens til at aktiv stimulering i panel sektionen kan forbedre et selektionspanels selektive egenskaber. Der blev dog ikke observeret en signifikant effekt for de undersøgte arter i dette forsøg. For at kunne vurdere potentialet i aktiv stimulering er det dog afgørende at kunne dokumentere stimuleringssystemets virke under fiskeriprocessen. I dette forsøg blev der monteret undervandskamera på selve fangstposen for at dokumentere dette. Undervandsoptagelserne var desværre så uklare grundet dårlig sigtbarhed i vandet samt mudderskyer genereret af trawlet at denne dokumentation ikke kunne indsamles.

Et effektivt stimuleringssystem i forbindelse med et selektionspanel vil potentielt kunne minimere effekten af panelsektionens geometri og dermed kunne bidrage til en mere ens effekt af selektionspaneler generelt. Et effektivt stimuleringssystem vil også kunne gøre panelets effekt uafhængigt af dettes placering i redskabet i forhold til bindestroppen, hvilket kunne være en fordel i de fiskerier hvori der opnås større fangster. I et eventuelt fremtidigt arbejde med at udvikle et stimuleringssystem med henblik på at opnå en signifikant forbedret kontaktsandsynlighed, kunne det være hensigtsmæssigt at henlægge dele af udviklingen til en

prøvetank således at systemets virke kan dokumenteres og tilpasses inden en kommerciel afprøvning.

2: Betydningen af panelsektionens geometri

Fangstposens geometri i panelsektionen påvirker i betydelig grad selektionen af fisk, herunder torsk. Er geometrien åben, er kontaktsandsynligheden lavere end hvis geometrien er mere kollapset (flad). Forskellen er betydelig og statistisk signifikant for flere arter. Ifølge resultaterne på f. eks. torsk var den samlede L50 på ca. 33 cm i et SELTRA 270 mm selektionspanel monteret i en 90 mm fangstpose med en åben geometri, mens L50 øget til over 90 cm da panelsektionen blev kollapset. Det betyder at to tilsyneladende ens selektionspaneler der er monteret lige langt fra redskabets bindestrop kan resultere i vidt forskellig selektion af torsk og andre marine organismer. Den kollapsede fangstpose resulterede også i et tab af jomfruhummere der dog ikke var signifikant.

Del 3: Nordsøen

Der anvendes i dag forskellige tråd tykkelser i dansk fiskeri. Generelt har der været en tendens til at der anvendes tykkere og mere stive tråde til fremstilling af specielt fangstposer. Både tråd tykkelsen og antallet af tråde der må anvendes er i dag reguleret i den tekniske regulering.

For en given tråd tykkelse vil selektionen af torsk forbedres ved at gå fra T0 til T90, mens selektionen reduceres ved at gå fra enkelttråd til dobbelttråd. Tykkere tråd reducerer selektionen. Størrelsen af denne reduktion bestemmes af om tråden er enkelt eller dobbelt, samt om nettets orientering er T0 eller T90. Generelt demonstrerer resultaterne fordelene ved at anvende en relativ tynd enkelttråd for at opnå god størrelsesselektion for rundfisk, samt at selektionen for rundfisk er bedst hvis der anvendes T90. Hvis man går fra en T0 til T90 orientering af nettet reduceres selektionen af rødspætter og sandsynligvis også andre fladfisk. En øgning i tråd tykkelsen reducerer også selektionen af rødspætter. Vores resultater demonstrerer at en meget forskellig selektion kan opnås med den samme maskestørrelse alene ved at variere tråd tykkelsen, antallet af tråde der anvendes (enkelt eller dobbelt) samt nettets orientering. Dette forsøg adresserer alene effekten på selektionen ved anvendelse af forskellige tråd tykkelser, antal tråde samt orientering af nettet og indeholder ikke styrkeberegninger eller lignende der kan dokumentere hvilket påvirkning fangstposerne skal kunne holde til under kommercielt fiskeri.

Generel introduktion

Bestandene af torsk i Kattegat, Skagerrak og Nordsøen har de sidste 10 år været historisk lave. Tiltag for at genoprette bestandene har omfattet lavere kvoter på torsk, reduceret samlet indsats, ændret teknisk regulering, etablering af lukkede områder mm. Disse tiltag har, i tillæg til at reducere fangsten af torsk, også påvirket fiskeriets muligheder for at udnytte de resterende bestande.

Der er de senere år udført en lang række forsøg med eksperimentelt forsøgsfiskeri i Østersøen, Kattegat/Skagerrak og i Nordsøen. De enkelte forsøgsfiskerier har ofte været rettet mod meget specifikke problemstillinger i disse fiskerier. Der er også internationalt udført et større arbejde med at forbedre selektionen af specielt torsk i de demersale fiskerier. Samlet set udgør de tilgængelige data et betydeligt informationsgrundlag til forbedring af de trawlredskaber der anvendes i disse fiskerier i dag.

Projektet er herunder inddelt i tre dele:

- Del 1 - *Østersøen*
- Del 2 - *Kattegat/Skagerrak*
- Del 3 - *Nordsøen*

Del 1 - *Østersøen* - drejer sig specifikt om at forbedre arternes selektionsintervaller (selection range - SR) i BACOMA fangstposerne der i dag anvendes i Østersøen. Del 2 - *Kattegat/Skagerrak* - består af to separate forsøg. Det ene forsøg beskriver effekten af aktiv stimulering af fisks adfærd i forbindelse med et selektionspanel med henblik på at forbedre kontaktsandsynligheden, samt undersøge muligheden for at gøre selektionspanelers selektive evne uafhængig af panelets placering i redskabet. Det andet forsøg undersøger betydningen af geometrien i panelsektionen på panelets kontaktsandsynlighed. Del 3 - *Nordsøen* - undersøger, med et meget omfattende datasæt baseret på afprøvning af 12 forskellige fangstposer, betydningen af tråd tykkelsen, hvorvidt der er anvendt enkelt eller dobbelt tråd i fangstposen samt nettets orientering (T0, T90).

Der er under nærværende projekts løbetid lavet en ny Skagerrak-aftale imellem Norge og EU. Dette har bevirket at der er kommet en ny situation i Skagerrak der blandt andet omfatter en ny teknisk regulering omkring anvendelse af slæbene redskaber i Skagerrak. Denne nye situation har under projektets løbetid påvirket udformningen af forsøgsdesignet i Del 2.

Del 1 – Østersøen

Forsøg i Østersøen med henblik på reduktion af Selektion Range for torsk og forbedring af selektion af fladfisk

Til trawlfiskeriet i Østersøen efter torsk anvendes i dag af de fleste fiskere trawl hvor fangsten akkumuleres og opsamles i en BACOMA fangstpose bagerst i trawlen. Med den nuværende BACOMA fangstpose, der består af et UltraCross panel som overpanel med maskevidde 120 mm i enkelt tråd (5 mm) anvendt som kvartrat maske og med et underpanel bestående af diamant masker i 4 mm dobbelt tråd med maskevidde 105 mm, er der for torsk observeret en ret flad størrelsesselektion. Dette resulterer blandt andet i et stort selektions range (SR). Årsagen til det menes at skyldes at ikke alle torsk der i løbet af en fiskeriproces opsamles i fangstposen bagerst i trawlen er i stand til at komme i kontakt med det mest selektive UltraCross panel og derfor vil få deres selektion bestemt af det mindre selektive underpanel. Resultatet bliver en såkaldt dual-selektion hvor nogle af fiskene får deres størrelsesselektion bestemt af selektionsegenskaberne for et panel mens den resterende del får deres størrelsesselektion bestemt af de selektive egenskaber af et andet panel. Hvis der er stor forskel i de selektive egenskaber mellem de to paneler kan den resulterende selektionskurve blive ret flad og have et ret karakteristisk forløb der adskiller sig væsentligt fra de selektionskurver der ellers benyttes til at beskrive størrelsesselektion i fangstposer til trawl. I 2010 blev maskevidden for UltraCross panelet lovgivningsmæssigt ændret fra 110 mm til 120 mm uden at der blev indført ændringer i lovgivningen omkring specifikationerne for underpanelet. Denne lovgivningsmæssige ændring har medført en større ubalance i de størrelsesselektive egenskaber mellem over og underpanel i BACOMA fangstposen. Et andet problem med den nuværende BACOMA fangstpose er at kvartrad maskerne i UltraCross overpanelet er mindre velegnet til at tillade små fladfisk som skrubbe og rødspætte undslippe grundet deres meget anderledes kropsfacon sammenlignet med torsk som panelet er valgt ud fra. Samtidigt er maskevidden i den diamant maskede underpanel med sine 105 mm så lille at det også tilbageholder mange undermåls fladfisk.

På baggrund af ovenstående problemstillinger blev der fortaget et forsøgsfiskeri hvor størrelsesselektionsegenskaberne for tre forskellige trawlfangstposer blev sammenlignet. Det første design var den traditionelle BACOMA 120mm kvadrat/105mm diamant. Mens det andet design var tilsvarende baseret på det traditionelle BACOMA design men hvor nettet i den diamant maskede under plade var ændret til maskevidde 130 mm i stedet for 105 mm og at der blev anvendt net med enkelt tråd i stedet for dobbelt tråd. Dette design benævnes BACOMA120/130. Da det udover BACOMA 120/105 er lovligt at benytte en såkaldt T90 fangst pose med maskevidde 120 mm til trawl fiskeriet efter torsk i Østersøen indeholdt det udførte forsøgsfiskeri en sådan fangstpose som det tredje design. Forsøgsfiskeriet blev gennemført af det tyske institut ”Thünen-Institute of Baltic Sea Fisheries” med et internationalt samarbejde herunder med DTU AQUA.

De 3 forskellige fangstposer afprøvet ved eksperimentelt fiskeri. Forsøgsfiskeriet foregik fra det tyske forskningsfartøj ”FRV Solea” i september 2011 i den vestlige Østersø. De forskellige fangstposer blev fisket enkeltvis monteret i enden af det samme trawl. Mellem enkelt slæb var den anvendte fangstpose den eneste ændring. Der blev anvendt forsøg med små masket dæknet over fangstposen under fiskeri. Torsk og rødspætte fangsten blev opmålt på længde grupper (1 cm) i både dæknet og fangstpose. Fangstdata i dæknet og fangstpose blev på slæbniveau for hver af de to arter anvendt til at estimere selektionskurven som udtrykker den størrelsesafhængige sandsynlighed for en fisk der under fiskeri kommer ned i fangstposen bagerst i trawlen også bliver tilbagehold der. Selektionen blev i de enkelte slæb kvantificeret i form af parametrene L50 og SR. L50 er i selektionsanalyse defineret som total længden af fisk med 50 % sandsynlighed for at blive tilbageholdt i fangstposen. Mens SR udtrykker forskellen i længde på fisk med henholdsvis 75 % og 25 % sandsynlighed for at blive tilbagehold. Resultaterne for de enkelte de enkelte slæb blev herefter anvendt separat for hver art i en samlet analyse med henblik på at modellere betydningen fangstposens design parametre på størrelsesselektionen. Alle analyser blev foretaget ved anvendelse af selektionsanalyse softwaren ”SELNET” (udviklet af Bent Herrmann). Der blev anvendt en bootstrapping teknik til at udregne middel selektionskurven og usikkerheden på denne inklusiv bidrag for mellem slæb variationen i selektionsprocessen. Inspektion for Signifikant forskelle i selektionen mellem de tre afprøvede design blev testet ved dels at inspicere hvorvidt der er overlap mellem usikkerhedsgrænserne for selektionsparametrene for de tre afprøvede design og mellem deres respektive selektionskurver.

Resultater for torsk.

Nedenfor er vist hovedresultaterne for Torsk (Tabel 1).

Design	Antal slæb	Middel L50 (cm)	Middel SR (cm)
BACOMA120/105	8	39.05 (37.68-41.50)	7.94 (6.70-9.35)
BACOMA120/130	9	41.08 (39.98-41.99)	8.14 (6.65-9.46)
T90 120 S4	8	43.33 (40.92-44.45)	6.22 (5.57-6.89)

Tabel 1. Hovedresultater for torsk. 95 % usikkerhedsintervaller er angivet i ().

Det ses at der er en tendens til højere L50 for T90 sammenlignet med både BACOMA120/105 og BACOMA120/130 men inspektion af usikkerhedsintervallerne viser at forsøget ikke udviser en statistisk signifikant øgning. For SR indikerer forsøget en reduktion i SR for T90 sammenlignet med de to øvrige design. Men reduktionen er ikke statistisk signifikant. For de to BACOMA design er den estimerede SR meget ens og der er ingen indikation på at SR for torsk reduceres ved at øge maskevidden i underpanelet (fra design BACOMA120/105 til BACOMA120/130).

Fig. 1 til 3 viser de estimerede middel selektionskurver for torsk med angivelse af eksperimentelle resultater, størrelsesstruktur i den population der kom ind i fangstposen, samt usikkerhed på selektionskurven.

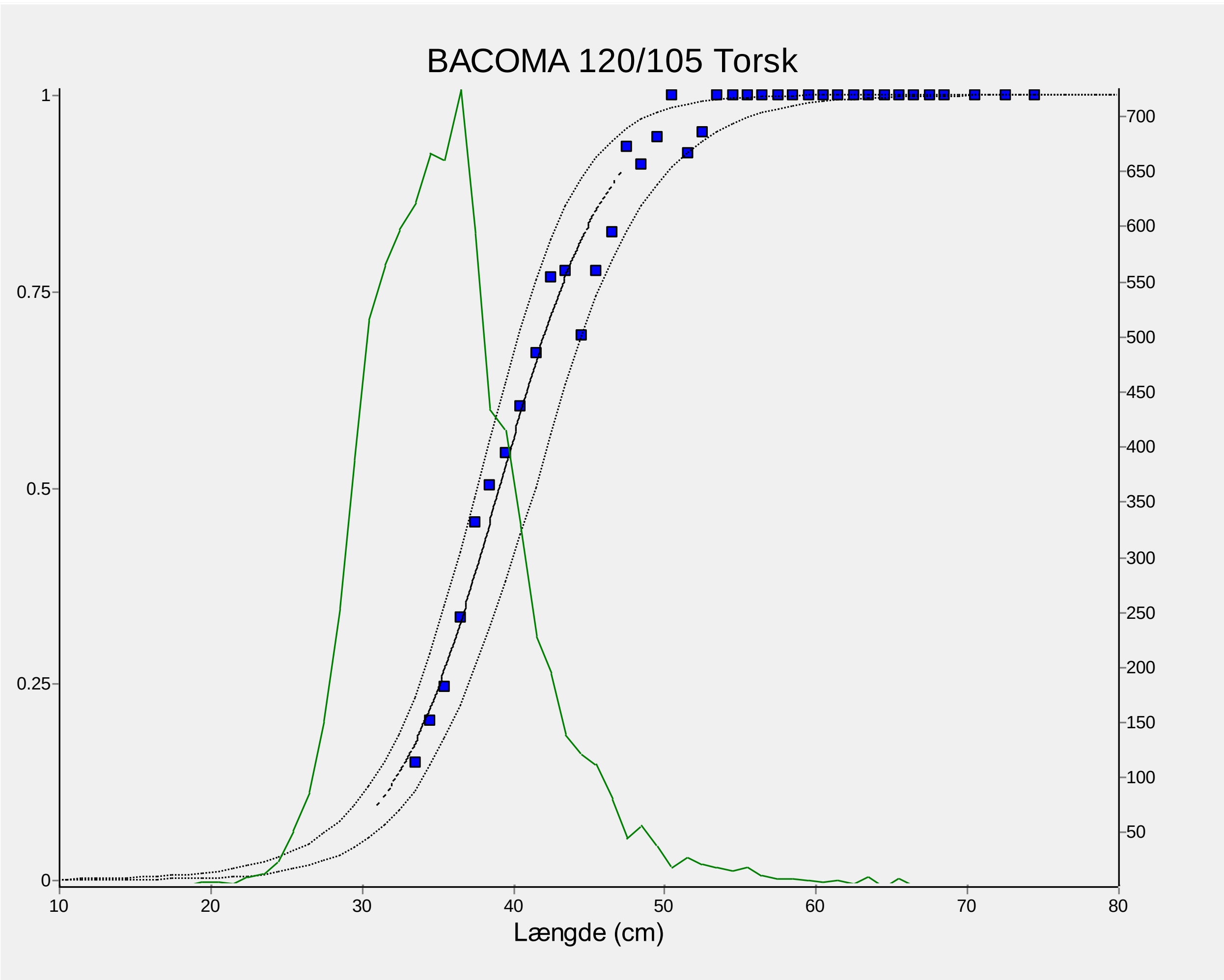


Fig. 1. Selektionskurve for torsk i BACOMA120/105.

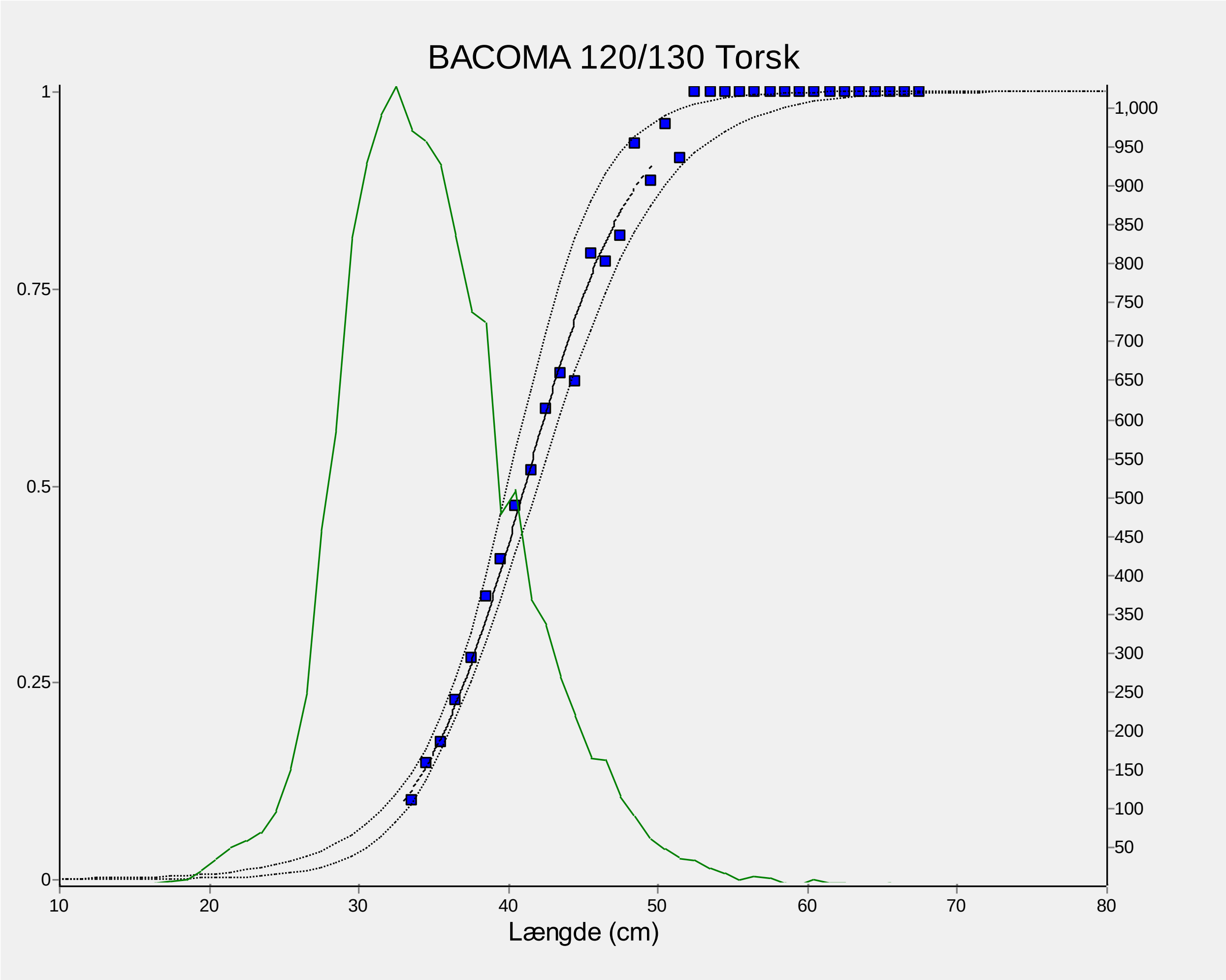


Fig. 2. Selektionskurve for torsk i BACOMA120/130.

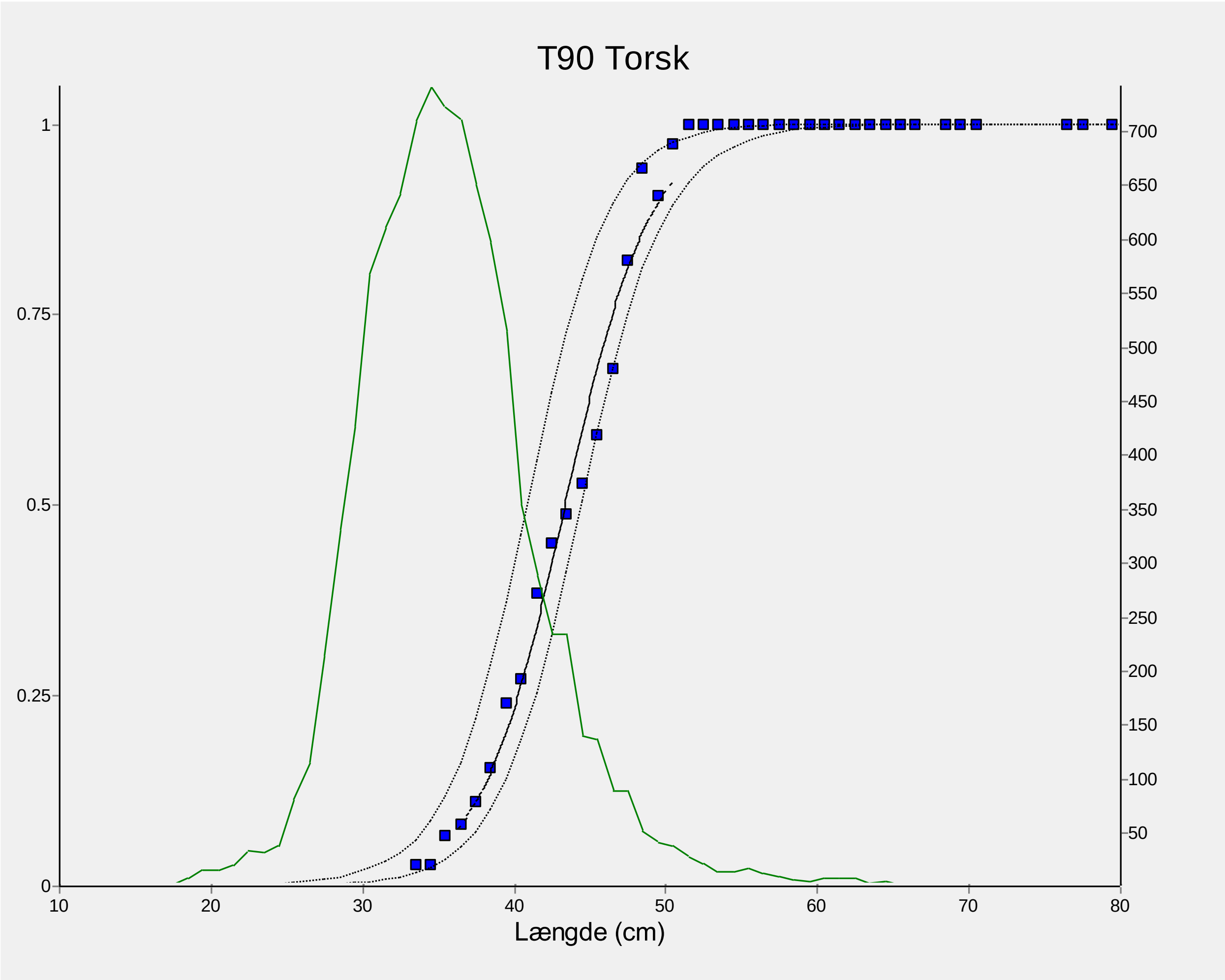


Fig. 3. Selektionskurve for torsk i T90 120 mm 4 mm enkelt tråd.

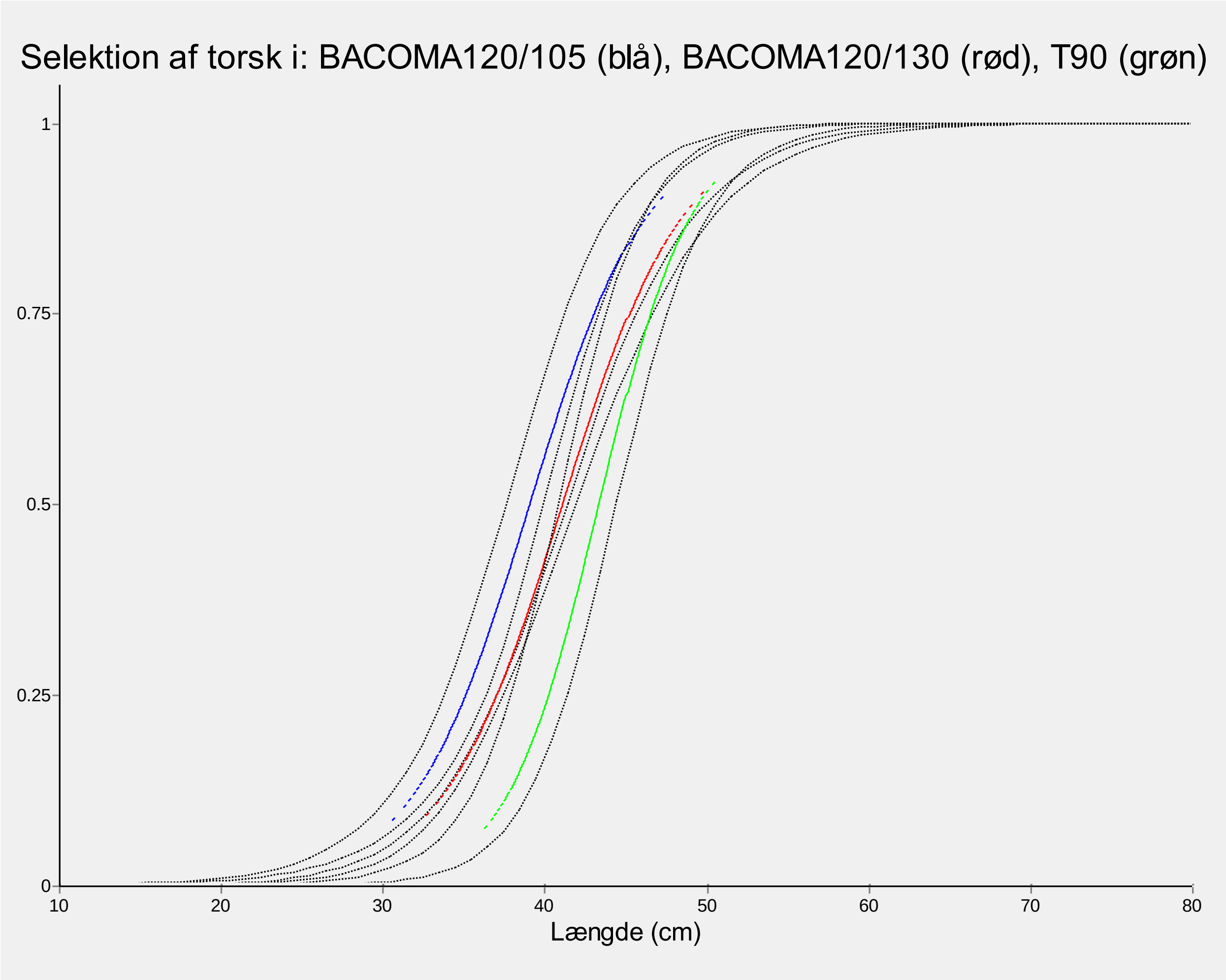


Fig. 4. Selektionskurver for torsk for: BACOMA 120/105 (blå), BACOMA120/130 (rød), T90 (grøn). De stiplede kurver er 95 % usikkerhedsintervaller.

Detaljeret inspektion af usikkerhedsintervallerne for selektionskurverne for torsk (Fig. 4) viser at der ikke er signifikante forskelle mellem kurverne.

Resultater for rødspætte.

Nedenfor er vist hovedresultaterne for rødspætte (tabel 2).

Design	Antal slæb	Middel L50 (cm)	Middel SR (cm)
BACOMA120/105	8	21.49 (20.46-23.01)	2.38 (0.1-4.08)
BACOMA120/130	9	25.01 (24.75-25.44)	3.80 (3.35-4.51)
T90 120 S4	8	24.69 (23.84-25.34)	2.08 (1.31-2.66)

Tabel 2. Hovedresultater for rødspætte. 95 % usikkerhedsintervaller er angivet i ().

Det ses at L50 er signifikant højere for både BACOMA120/130 og T90 sammenlignet med BACOMA120/105. Det vil således være gunstig for selektionen af rødspætter at øge maskevidden i underpanelet i BACOMA120/105 (fra design BACOMA120/105 til BACOMA120/130).

Fig. 5 til Fig. 7 viser de estimerede middel selektionskurver for rødspætte med angivelse af eksperimentelle resultater, størrelsesstruktur i den population der kom ind i fangstposen, samt usikkerhed på selektionskurven.

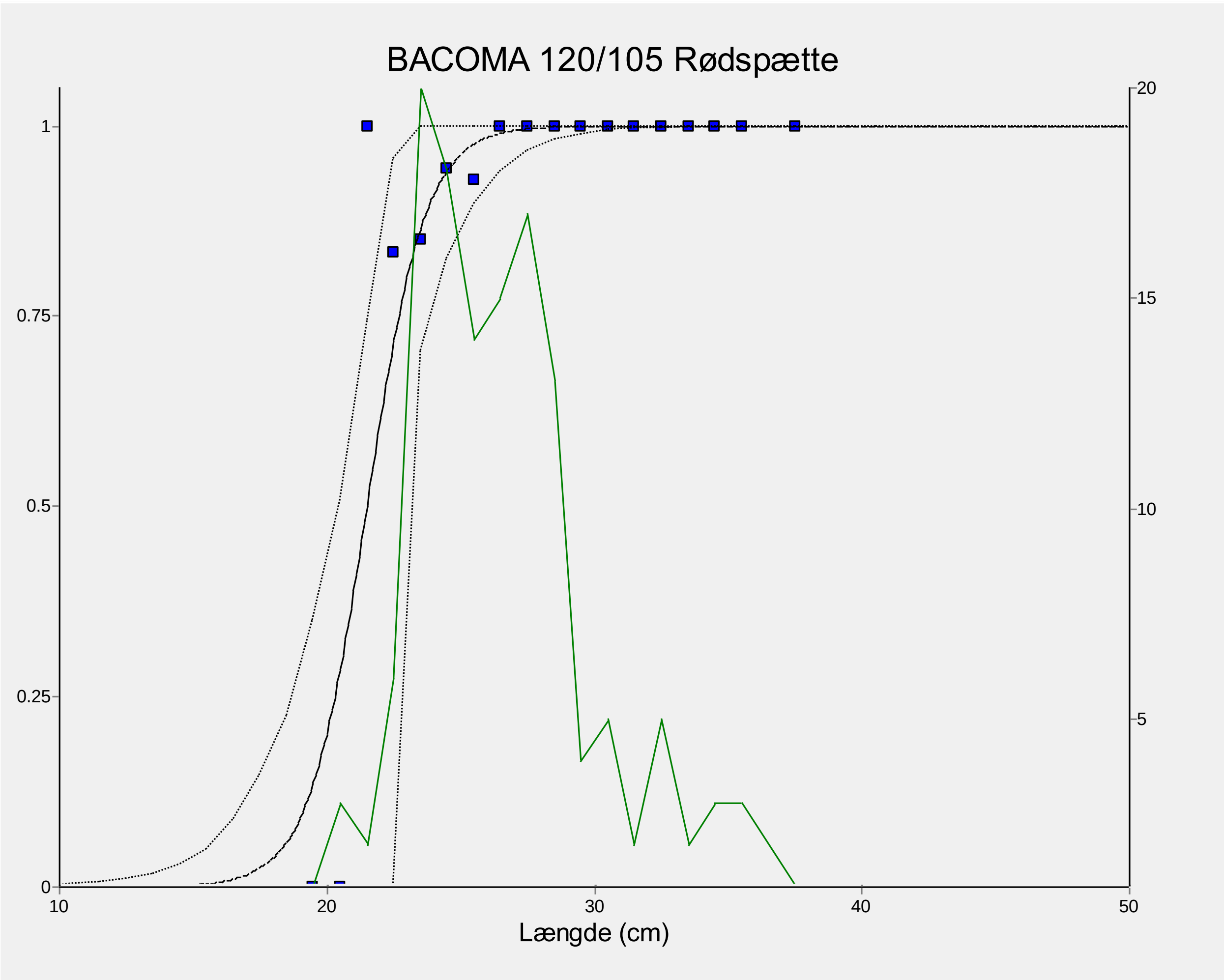


Fig. 5. Selektionskurve for rødspætte i BACOMA120/105

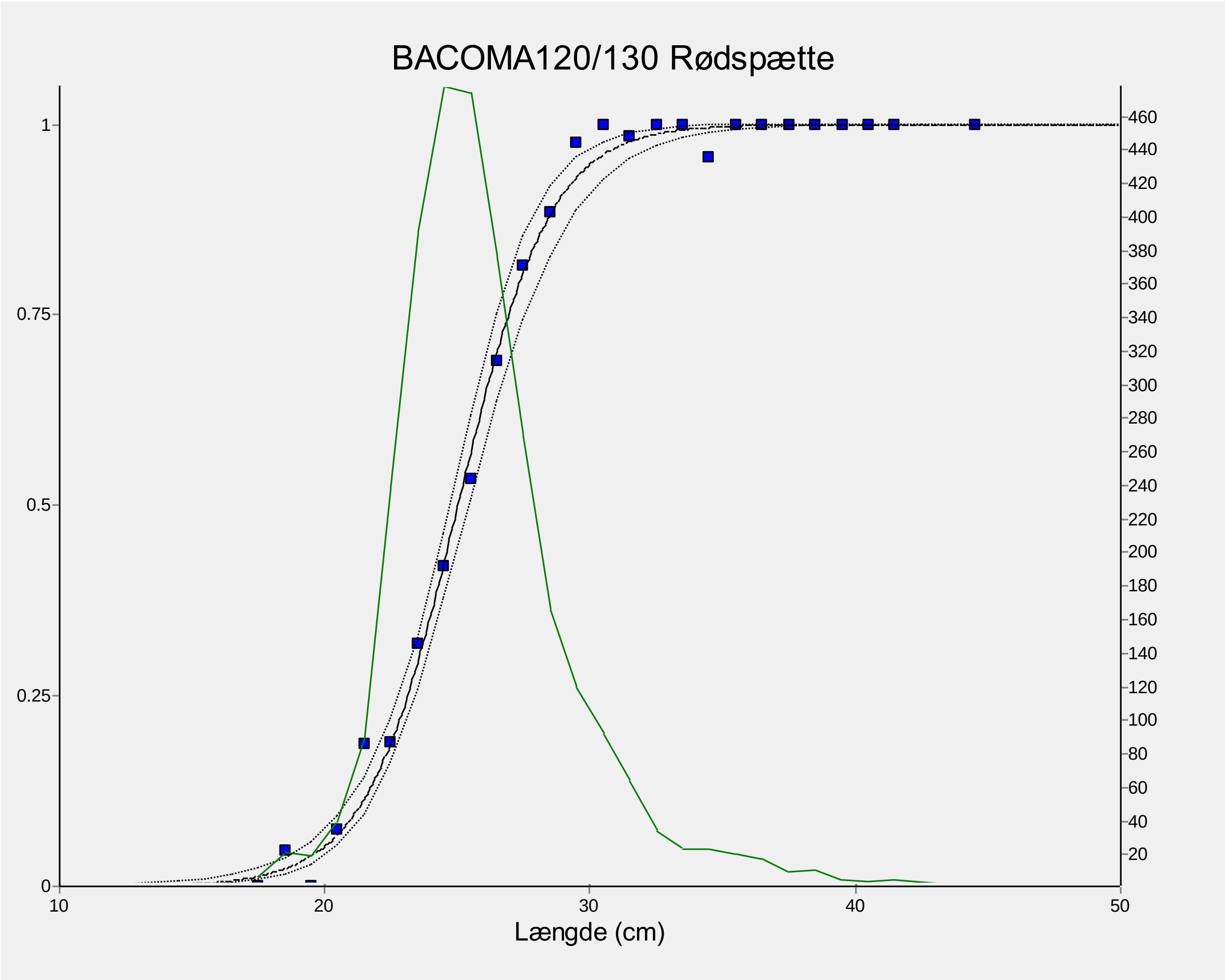


Fig. 6. Selektionskurve for rødspætte i BACOMA120/130.

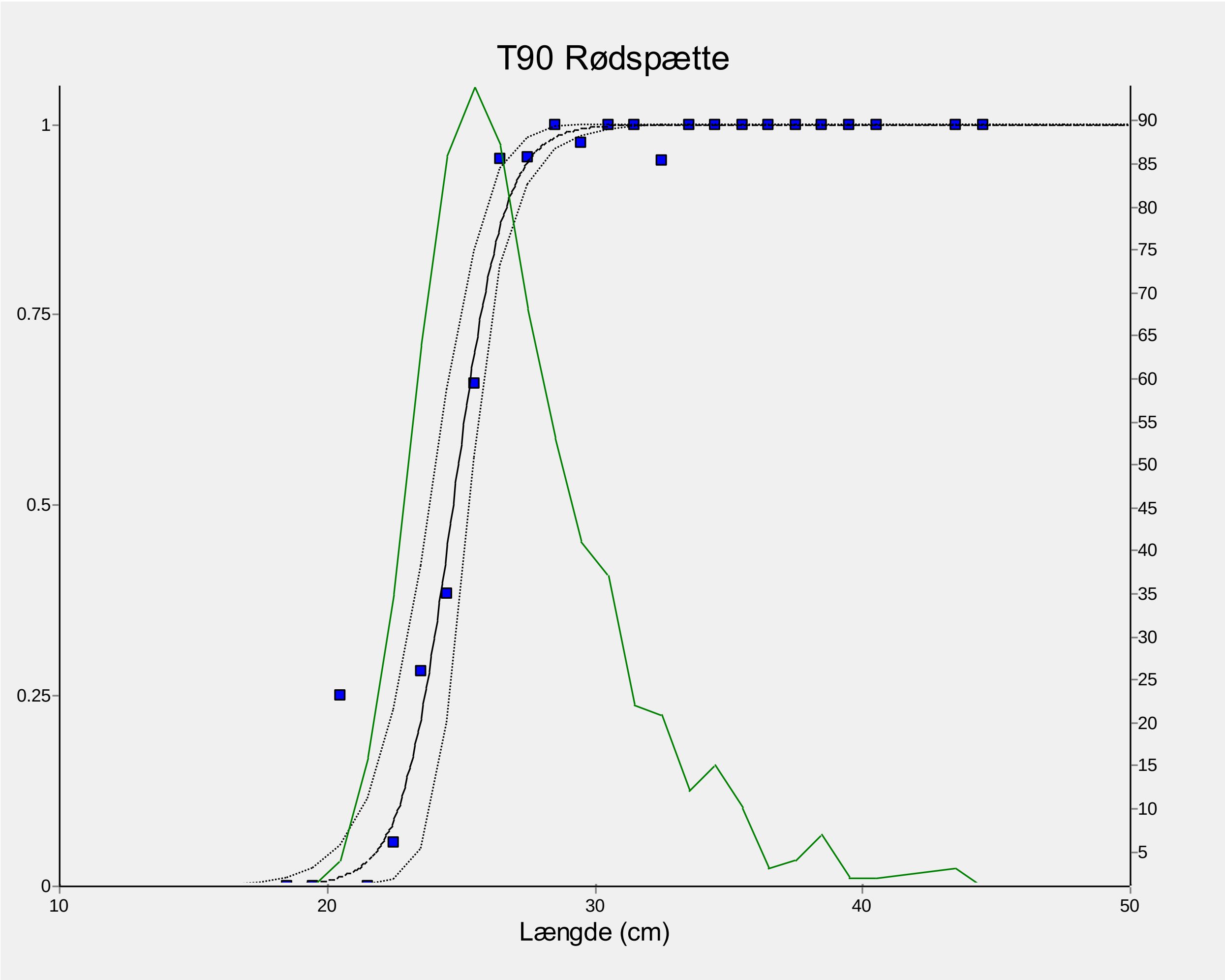


Fig. 7. Selektionskurve for rødspætte i T90 120 mm i net med 4 mm enkelt tråd.

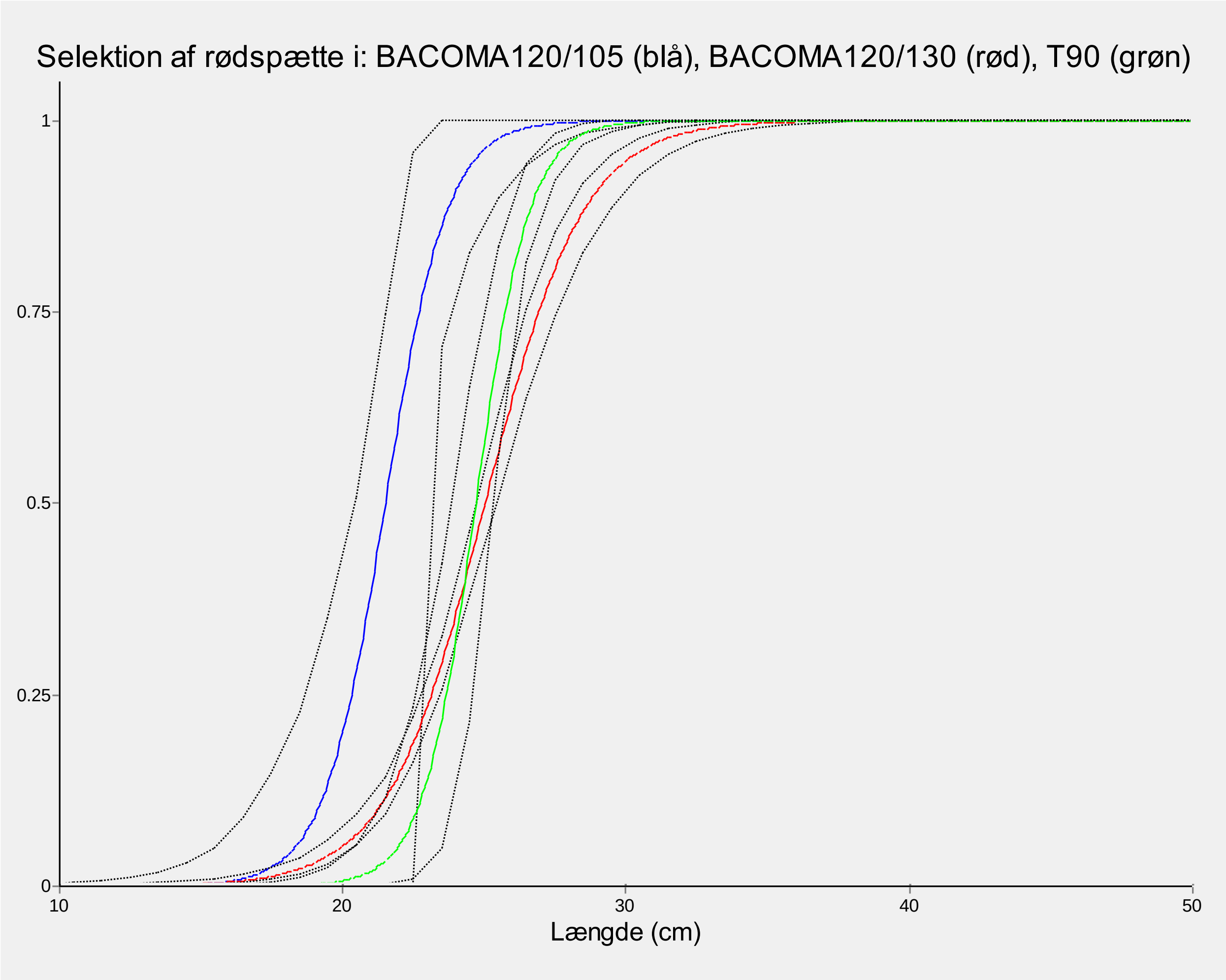


Fig. 8. Selektionskurver for rødspætte for: BACOMA120/105 (blå), BACOMA120/130 (rød), T90 (grøn). De stiplede kurver er 95 % usikkerhedsintervaller.

Inspektion af usikkerhedsintervallerne viser at BACOMA120/130 lader signifikant flere større rødspætter undslippe end begge de to andre designs. For mindre rødspætter (< 25 cm) er der ikke signifikant forskel mellem BACOMA120/130 og T90 i selektionen. BACOMA120/105 har for mange længdeklasser en signifikant større tilbageholdelses sandsynlighed end begge de øvrige designs.

Diskussion

Ovenstående resultater peger på at underpladen på 105 mm diamand masker i BACOMA designet vil kunne ændres til 130 mm uden der opnås et signifikant tab af torsk hvorimod selektionen af rødspætter, og sandsynligvis også andre fladfisk signifikant vil forbedres. I forbindelse med f.eks. et discard forbud, hvor en større fangst af mindre fladfisk vil være uhensigtsmæssigt vil en sådan ændring i BACOMA designet signifikant kunne reducerer denne uønskede fangst.

Del 2 – Kattegat/Skagerrak

Baggrund

Anvendelsen af selektionspaneler, som f. eks. kvadratmaskepaneler, har i dag en betydelig udbredelse både nationalt og internationalt, og er sandsynligvis den mest anvendte selektive anordning i det nordøstlige Atlanterhav. Forskellige selektionspaneler er i dag inkluderet i lovgivningen for Østersøen, Kattegat og Skagerrak samt i dele af Nordsøen. Selektionspaneler er typisk relative små net-paneler i en maskestørrelse og maskeform der muliggør selektion af de arter og størrelser der er behov for i det pågældende fiskeri. Denne type paneler indsættes typisk i redskabets bagerste del (forlængerstykket eller fangstposen) hvor der forventes at kunne opnås en god kontaktsandsynlighed. Andre alternativer til selektionspaneler kan være stormaskede paneler der indsættes i større dele af redskabet, f.eks. store dele af redskabets overside. Appendix 1 beskriver resultaterne der er opnået med et sådant stormasket panel i overpladen på et kombi-trawl anvendt i Skagerrak. Appendix 1 demonstrerer endvidere hvordan stormaskede selektionspaneler kan anvendes til at undersøge fisks adfærd i trawl uden brug af de mere traditionelle optiske systemer, som oftest ikke kan levere gode observationer grundet den dårlige sigt der typisk er i og omkring trawlet i disse fiskerier.

Både nationalt og internationalt har der været foretaget omfattende undersøgelser med forskellige selektionspaneler monteret forskellige steder i forskellige redskaber (f.eks. Norman m.fl., 2003; Krag m.fl., 2008; Madsen m.fl., 2010; Krag m.fl., 2011). Disse forsøg har vist til generelle tendenser, f.eks. vedrørende effekt af placering og udformning af selve selektionspanelet. For at et selektionspanel skal fungere efter hensigten kræver det, at de individer panelet er monteret for at undgå kommer i kontakt med panelet, samt at de kan passere igennem panelet. Sandsynligheden for at en fisk, der er kommet ind i redskabet, kommer i kontakt med selektionspanelet, angiver panelets effektivitet og benævnes her panelets *kontakt sandsynlighed*.

I en gennemgang af undersøgelserne der eksempelvis er udført i Kattegat og Skagerrak viser det sig blandt andet at tilsyneladende ens fangstposer har resulteret i forskellige resultater (Krag m.fl., 2008; Frandsen m.fl., 2009; Krag og Herrmann, 2012). I nogle tilfælde blev der ikke observeret en signifikant effekt af selektionspanelet for torsk i forhold til en standard fangstpose, mens der i andre tilfælde blev opnået en signifikant forbedring (Krag og Herrmann, 2012). I de tilfælde hvor der blev opnået en god selektion af torsk blev der observeret et større tab af jomfruhummere. Disse forsøg understøtter hypotesen om at det ikke alene er panelets placering og udformning i forhold til bindestroppen der er afgørende for panelets selektive effekt samt evne til at tilbageholde f.eks. jomfruhummere. Sådanne resultater indikerer også en mangel i forståelsen omkring hvilke designparametre der er afgørende for et selektionspanels selektive egenskaber, samt at tilsyneladende ens paneler der er implementeret i lovgivningen vil kunne resultere i en selektion, af f.eks. torsk, der kan være forskellig fra de resultater der understøtter implementeringen af panelet. DTU Aqua har foretaget en detaljeret undersøgelse af forskellige fangstposers geometri under en fangstopbygning i prøvetanken i Hirtshals. Resultaterne herfra viser at geometrien i fangstposer med selektionspanel kan være sensitiv til relativt små designændringer i fangstposens udformning (Krag m.fl., 2012). På baggrund af den variation i selektion der kan observeres i tilsyneladende ens fangstposer, hvor ens selektionspaneler monteres i samme afstand til bindestroppen, kan der spekuleres i hvorvidt selve geometrien i panelsektionen har afgørende effekt på kontaktsandsynligheden og dermed panelets effekt.

DTU Aqua har i projektet *Design optimering af SELTRA* (finansieret af EU's fiskerisektorprogram EFF og FødevareErhverv under Ministeriet for Fødevarer, Landbrug og Fiskeri) studeret forskellige designparametres effekt på geometrien i både en 2- og en 4-panels fangstposesektion med et selektionspanel (Krag m.fl., 2012). Fangstposernes geometri blev undersøgt under en fangstopbygning (0 – 700 kg) i fuldskala fangstposer. Undersøgelser i prøvetanken viste at selv små ændringer i designparametrene i en fangstpose kan påvirke redskabets geometri betragtelig. Geometrien forventes at have stor indvirkning på et selektionspanels evne til at selektere fisk, herunder torsk, ud, samt evne til at tilbageholde fangsten af jomfruhummere effektivt. Det betyder at to fangstposer der har identiske selektionspaneler med samme placering i forhold til f. eks. redskabets bindestrop kan have forskellig selektion af fisk og forskellig tilbageholdelse af jomfruhummere. Generelt vil kontakten imellem både fisk og jomfruhummer og selektionspanelet være størst i en fangstpose der har så lav åbning som muligt og være mindst i en fangstpose hvor åbningen er så stor så mulig. Specielt SELTRA-fangstposerne (4-panelsposerne) er sensitivt for mindre ændringer i fangstposens designparametre.

Baseret på de observationer og målinger der blev foretaget i projektet beskrevet i Krag m.fl. (2012) blev det konkluderet at SELTRA-fangstposens net-paneler bør fremstilles i samme længde således at der er ens træk i alle masker i fangstposens omkreds, samt at SELTRA-fangstposen bør monteres til redskabets koniske del da anvendelse af forlængerstykker i mellem SELTRA-fangstposens panelsektion og redskabets koniske del kan resultere i tab af jomfruhummer grundet lav og varierende åbning i selve panelsektionen.

På baggrund af den samlede viden omkring fangstposer med selektionspaneler der de senere år er indsamlet i blandt andet Skagerrak og Kattegat, den kommercielle erfaring fra Kattegat med disse paneltyper, samt at disse paneler pr. 2013 er blevet implementeret i lovgivningen i Skagerrak tages der i dette projekts Kattegat/Skagerrak-del udgangspunkt i en kommerciel afprøvning af netop disse paneler. Designparametrene der kontrollerer panelsektionens geometri varieres således at effekten heraf dokumenteres i forventning om at tilvejebringe en forståelse heraf.

I Kattegat/Skagerrak-delen af dette projekt tages der udgangspunkt i en fangstpose med et SELTRA 270 mm selektionspanel monteret 4-7 meter fra redskabets bindestrop, hvilket svarer til gældende regler for dette panel i Skagerrak.

Der har fra erhvervets side været udtrykt ønske om at generelt kunne placere selektionspaneler længere fremme i redskabet da det frygtes at der ellers kan tabes fangst utilsigtet igennem selektionspanelet. Dette gælder specielt i de fiskerier hvor der kan være større fangster af fisk, f.eks. sej, kuller, rødspætter, samt i blandetarts fiskeriet i den nordlige Nordsø. Større fangster vil kunne resultere i at fangstakkumuleringen i fangstposen kan komme i kontakt med selektionspanelets store masker hvorved der kan ske et utilsigtet tab. Tidligere forsøg har vist at panelets kontaktsandsynlighed reduceres ved at placere selektionspanelet længere fremme i redskaber (Norman m.fl., 2003; Krag m.fl., 2008). Kan kontaktsandsynligheden derimod aktivt stimuleres, vil selektionspanelets evne til at selektere fisk kunne gøres mere uafhængigt af panelets placering i forhold til redskabets bindestrop. Der vil være betydeligt fordele ved at have en panelsektion hvori fisks kontaktsandsynlighed stimuleres således at panelets selektive effekt er uafhængig af panelets placering.

I dette delforsøg undersøges effekten af aktiv stimulering af kontaktsandsynligheden i et selektionspanel, samt effekten af geometri i panelsektionen (åben vs. lukket fangstpose). Dette blev udført som to separate forsøg. Disse forsøgs specifikke udformning, herunder designet af de eksperimentelle fangstposer blev diskuteret med Danmarks Fiskeriforening, fiskere og vodbindere på et møde ved Hanstholm fiskeriforening d. 11.09. 2012.

Materiale og metode

Forsøget blev udført i Skagerrak og Nordsøen i oktober og november 2012 ombord på den kommercielle trawler HM 127 Borkumrif fra Hanstholm. Fartøjet blev identificeret i samarbejde med Danmarks Fiskeriforening (DF) ud fra de specifikationer som var opstillet af DTU Aqua vedrørende praktiske hensyn ombord. Grundet det komplicerede eksperimentelle design blev der fra DTU Aqua stillet krav om af det pågældende fartøj skulle takle fangsten ind på hækken og ikke fremme på styrbord side. HM 127 Borkumrif er udstyret med et 2-trawl system der muliggør at der fiskes med 2 to trawl samtidig og fangsten takles ind på hækken hvor der også var god arbejdsplads. Der blev på begge trawl anvendt opsamlingsposer der opsamlede de individer der undslap igennem fangstposen samt dennes panel (covered codend teknik, se Wileman 1996). De eksperimentelle fangstposer blev monteret på fartøjets egne trawl. De eksperimentelle fangstposer blev monteret på begge kommercielle trawl med ca. lige mange slæb på hvert for at undgå eventuelle systematiske afvig.

Forsøget blev udført som to delforsøg:

i. Aktiv stimulering af kontaktsandsynligheden
ii. Betydning af geometri i fangstposen (åben vs. lukket geometri)

Til forsøg 1 blev der fremstillet to 90 mm fangstposer med et 270 mm diamantmaskepanel monteret i henhold til gældende lovgivning for Skagerrak (3 * 90 mm masker til 1 * 270 mm). Teknisk tegning af dette design er angivet i Appendix A. Bemærk at de eksperimentelle fangstposer var fremstillet i fire-paneler. På den ene fangstpose blev der under selektionspanelet placeret et system af opdriftskugler. Den tilførte opdrift blev kompenseret med blyliner monteret under sektionen således at redskabssektionens samlede opdrift var uændret. Hensigten med designet var at blokere panelsektionens indre volumen således at fisk der passerer sektionen vil formodes at komme i fysisk kontakt med stimuleringssystemet, hvorved der genereres en paniktilstand hos fisk der forventes at give en forbedret kontaktsandsynlighed med selektionspanelet. Selve udformningen af det der skal stimulere fisk til at opsøge selektionspanelet mere aktivt er selvfølgeligt afgørende for effekten af anordningen. Stimuleringsanordningen blev fremstillet således at selve blokeringen af sektionens indre volumen skulle være sammenfaldende med den bagerste kant af selektionspanelet for at etablere panikken under selve selektionspanelet. Der blev monteret undervandskamera omkring selektionspanelet for at dokumentere hvordan stimuleringssystemet fungerede under fiskeri. Det viste sig dog meget vanskeligt at opnå gode optagelser af systemet grundet meget dårlig sigtbarhed i vandet samt mobiliseret sediment fra redskabet (mudderskyer).

Til forsøg 2, betydning af panelsektionens geometri for kontaktsandsynligheden, blev der ligeledes anvendt to eksperimentelle fangstposer. Fangstposen der udgjorde standarden var identisk med den der blev anvendt i forsøg 1. Den anden fangstpose blev fremstillet med kortere sidepaneler i fire-panel konstruktionen således at fangstposen under fiskeri ville lukkes grundet kraftfordelingen i panelsektionen.

Selektionsprocessen i de eksperimentelle fangstposer der afprøves og sammenlignes i både forsøg 1 og i forsøg 2 er koblede processer da der foregår en størrelsesselektion over selektionspanelet og en størrelsesselektion i selve fangstposen. Fisken møder først selektionspanelet og derefter selve fangstposen. Selektionsprocessen i begge forsøg er dermed en sekventiel proces der foregår i en givet rækkefølge. Selektionsanalyserne blev udført i analyseværktøjet SELNET. Der blev anvendt en dual-sequence model der anderkender at processen er sekventiel, samt at der er to selektive bidrag (en fra panelet og en fra fangstposen). Det vil kunne opnås væsentligt andre resultater fra de indsamlede data ved anvendelse af andre modelbeskrivelser. Det er derfor afgørende at modelvalget til beskrivelse af de indsamlede data specifikt er designet til strukturen i de eksperimentelle data.

Resultater

Der blev foretaget 8 valide slæb i forsøg 1 og 12 valide slæb i forsøg 2. Fangsterne af torsk, kuller, jomfruhummer, rødspætter og skærising er vist i Tabel 1 på slæb niveau. Slæb hvor der blev fanget mindre end 10 individer af en art i er ikke medtaget i tabellen eller i analyserne herunder for den art.

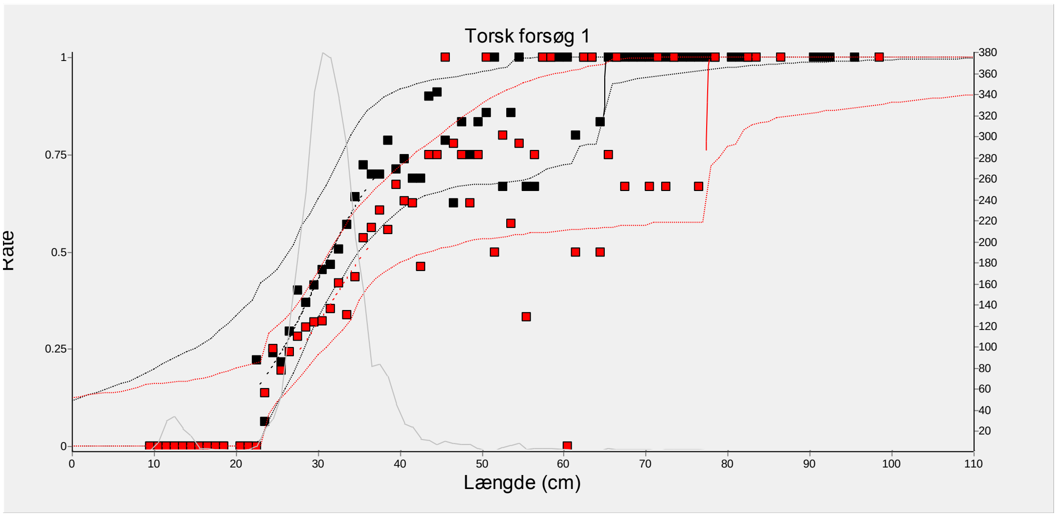
Tabel 1. Oversigt over fangsterne i hvert forsøg. Træk hvori der blev fanget mindre end 10 individer af en art tilsammen i trawl og opsamlingspose blev ekskluderet fra analyserne af den pågældende art. I forsøg 1 er Test1 SELTRA 270 mm, Opsaml1 er opsamlingspose til Test1, Test2 er SELTRA 270 mm med aktiv stimulering og Opsaml2 er opsamlingsposen til Test2. I forsøg 2 er Test1 SELTRA 270 mm med kollapset geometri, Opsaml1 er opsamlingsposen til Test1. Test2 er SELTRA 270 mm med åben geometri, og Opsaml2 er opsamlingsposen til Test2.

	Forsøg 1					Forsøg 2				
Art	**Træk**	**Test1**	**Opsaml1**	**Test2**	**Opsaml2**	**Træk**	**Test1**	**Opsaml1**	**Test2**	**Opsaml2**
Torsk	1	31	94	22	67	10	14	89	45	29
	2	78	63	26	95	11	17	110	53	30
	3	92	40	23	92	12	51	428	87	386
	4	122	12	60	60	13	69	303	136	189
	5	432	359	323	343	14	123	1218	591	658
	6	370	380	276	403	15	455	1076	825	771
	7	515	883	436	935	16	36	160	68	138
	8	218	70	101	113	17	35	245	168	133
						18	12	453	45	373
						19	21	277	55	376
						20	122	1332	588	618
						21	13	72	27	59
Kuller	1	27	51	16	61	12	9	214	5	183
	2	52	24	11	67	13	10	624	123	516
	3	51	15	15	72	14	73	714	91	564
	4	60	22	10	45	15	130	585	146	622
	5	642	945	528	1000	16	35	436	48	456
	6	651	656	606	634	17	17	450	36	465
	7	631	604	606	644	18	0	60	2	73
	8	53	14	45	46	19	9	183	15	161
						20	10	493	71	353
						21	0	64	0	33
Jomfru-hummer	1	904	967	1314	745	10	615	138	504	106
	2	857	258	971	306	11	699	85	265	70
	3	885	293	712	412	12	23	10	14	6
	4	860	131	508	153					
	8	762	395	755	492					
Rødspætte	6	113	6	70	17	14	145	125	249	83
	7	104	30	129	30	15	58	45	28	13
						16	78	48	37	4
						17	240	102	421	59
						18	160	181	260	75
						19	48	109	170	22
						20	94	40	112	52
						21	154	144	206	118
Skærising	1	34	28	38	25	10	9	20	35	6
	2	104	73	78	29	11	35	21	39	13
	3	74	41	77	37	12	12	5	21	5
	4	102	26	83	39					
	8	25	0	15	5					

Selektionsanalyser - aktiv stimulering

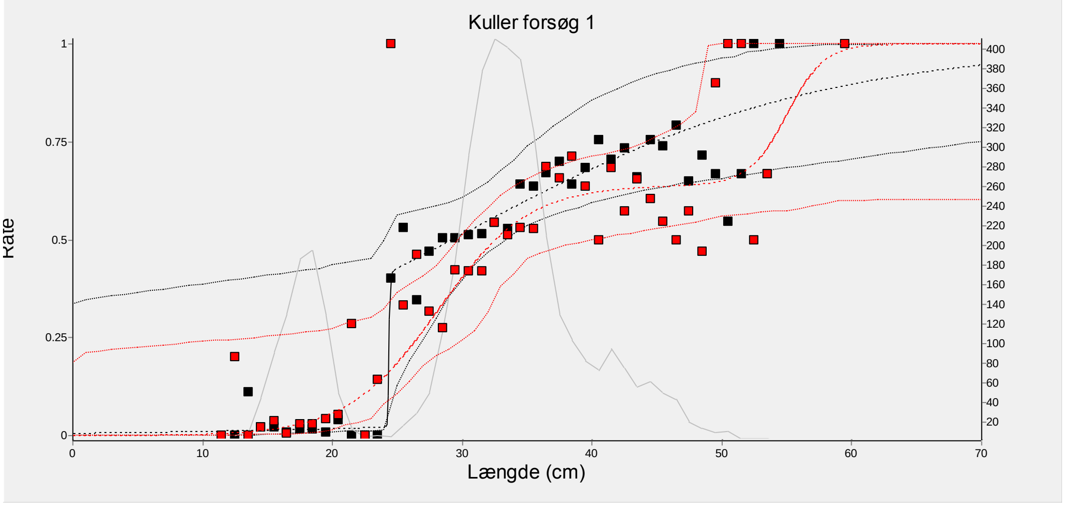
Længde baserede, bias corrected middel-kurver for selektionen i en SELTRA 270 mm med og uden stimulering er vist i Figur 1 til 5. Usikkerhederne på disse kurver er vist som 95 % konfidens bånd basered på bootstrapping. Hvis der ikke er overlap imellem middelkurvernes konfidensbånd, er der en signifikant forskel imellem de to eksperimentelle redskaber.

Analysen for torsk viser at der i vores forsøg ikke var en signifikant forbedret kontaktsandsynlighed ved anvendelse af aktiv stimulering. Der er dog en ikke-signifikant tendens der viser at kontaktsandsynligheden for torsk forbedres med aktiv stimulering.



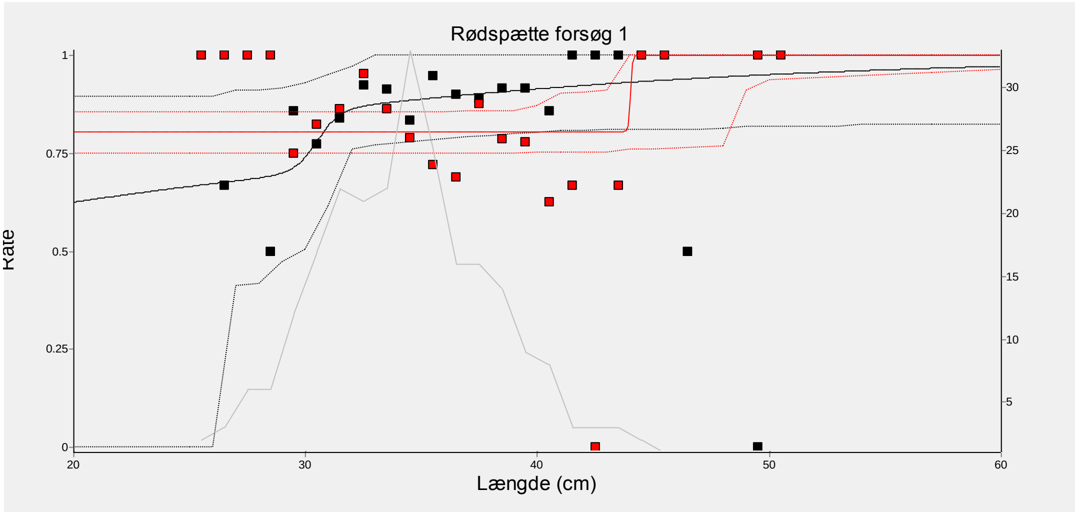
Figur. 1. Selektionsresultater for torsk fra forsøg 1 (stimulering). Retention rate (hel linje) med 95 % konfidence bånd (stiplet linje) for SELTRA 270 mm (sort) og SELTRA 270 mm med aktiv stimulering (rød). Den fiskede population vises i gråt.

For kuller blev der heller ikke observeret en signifikant effekt med aktiv stimulering (Figur 2). Det er for kuller, som for torsk, en tendens til forbedret kontaktsandsynlighed for kuller ved anvendelse af aktiv stimulering.



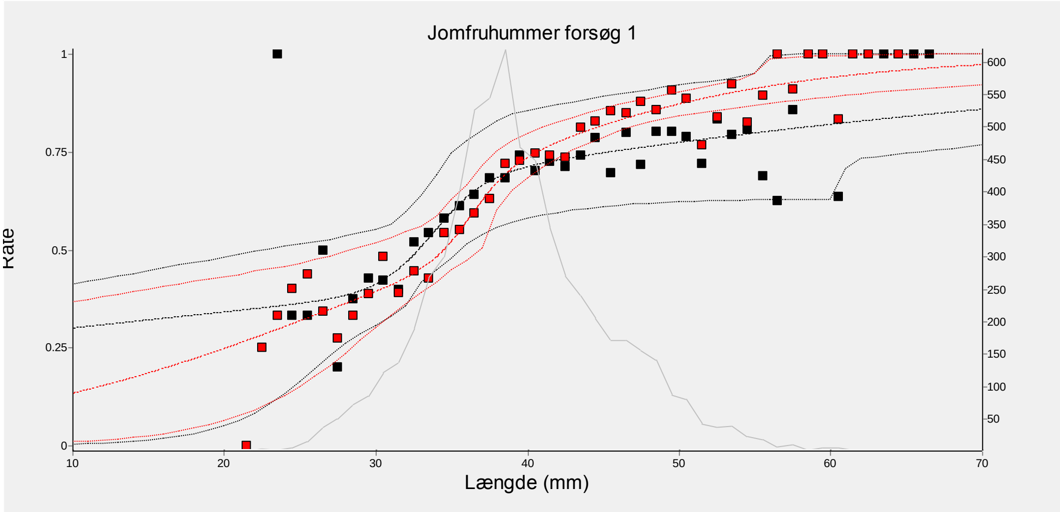
Figur. 2. Selektionsresultater for kuller fra forsøg 1 (stimulering). Retention rate (hel linje) med 95 % konfidence bånd (stiplet linje) for SELTRA 270 mm (sort) og SELTRA 270 mm med aktiv stimulering (rød). Den fiskede population vises i gråt.

Der blev ikke fundet en signifikant forbedret kontaktsandsynlighed for rødspætter med aktiv stimulering. Der er dog, som for torsk og kuller, en tendens til forbedret kontaktsandsynlighed. Dette glæder specielt de større individer af rødspætter.

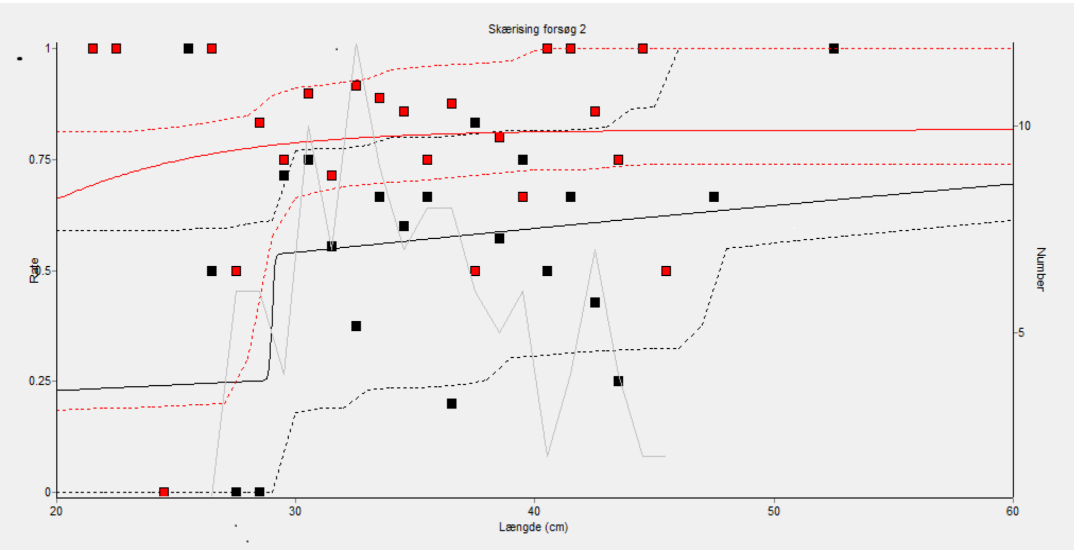


Figur. 3. Selektionsresultater for rødspætte fra forsøg 1 (stimulering). Retention rate (hel linje) med 95 % konfidence bånd (stiplet linje) for SELTRA 270 mm (sort) og SELTRA 270 mm med aktiv stimulering (rød). Den fiskede population vises i gråt.

For jomfruhummer blev det ikke observeret en signifikant effekt af aktiv stimulering. Det var heller ikke forventet at jomfruhummere ville kunne reagere med en egen bevægelse i forhold til stimuleringen der ville kunne påvirke selektionen. Der er en tendens til at fangstposen med stimulering er lidt bedre til at tilbageholde de større jomfruhummere. Denne tendens er dog ikke signifikant.



Figur 4. Selektionsresultater for jomfruhummer fra forsøg 1 (stimulering). Retention rate (hel linje) med 95 % konfidence bånd (stiplet linje) for SELTRA 270 mm (sort) og SELTRA 270 mm med aktiv stimulering (rød). Den fiskede population vises i gråt.

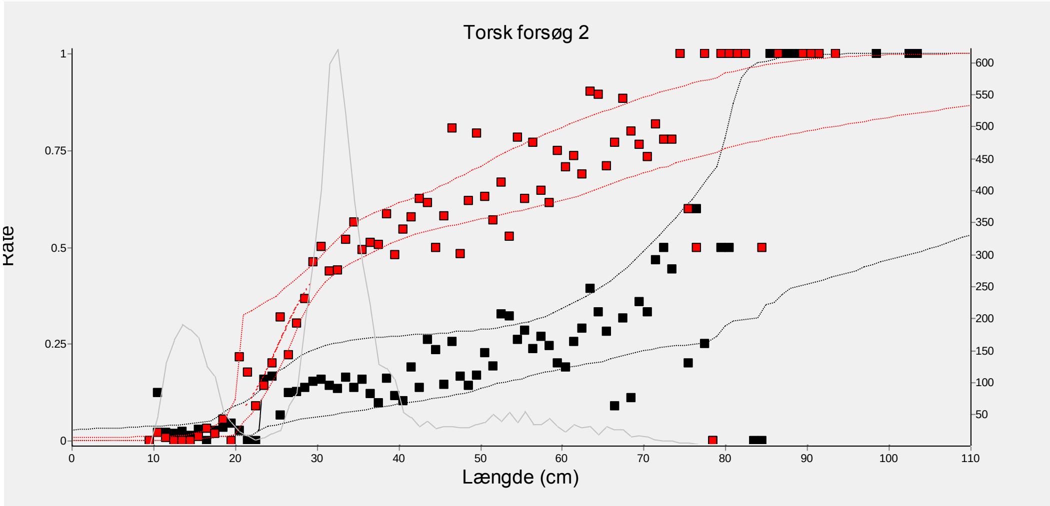


Figur 5. Selektionsresultater for skærising fra forsøg 1 (stimulering). Retention rate (hel linje) med 95 % konfidence bånd (stiplet linje) for SELTRA 270 mm (sort) og SELTRA 270 mm med aktiv stimulering (rød). Den fiskede population vises i gråt.

For skærisinger blev der ikke opnået en signifikant effekt af aktiv stimulering. Det relativt lave antal individer der blev fangst resultere i brede konfidensbånd. Figur 5 indikere at der mistes skærisinger igennem SELTRA panelet både med og uden aktiv stimulering.

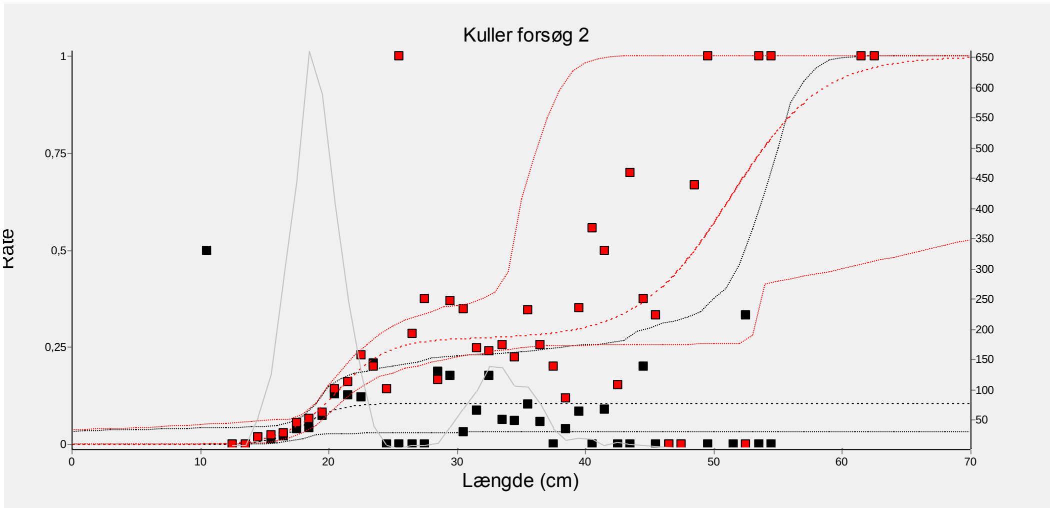
Selektionsanalyser – fangstpose geometri

I figurerne herunder vises en middel selektionskurve indeholdende 95 % usikkerheder for en SELTRA 270 mm (åben geometri) og en SELTRA 270 mm (kollapset geometri). Der er en betydelig og signifikant effekt af SELTRA-panelet for torsk som følge af en reduceret geometri i panelsektionen. Effekten er signifikant i længdeintervallet fra ca. 25 – 75 cm.



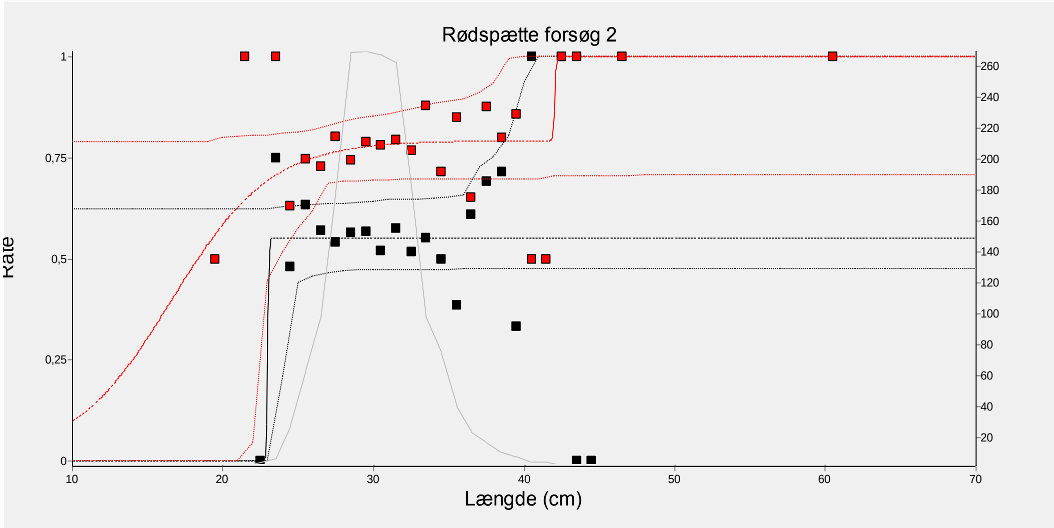
Figur. 6. Selektionsresultater for torsk i forsøg 2. Retention rate (hel linje) med 95 % konfidence bånd (stiplet linje) for SELTRA 270 mm kollaps (sort) og SELTRA 270 mm åben (rød). Den fiskede population vises i gråt.

For kuller er der en signifikant effekt af den reducerede geometri i SELTRA-fangstposen i længdeintervallet fra ca. 30-40 cm. Det bemærkes at der er en betydelig størrelsesselektion af kuller i det almindelige SELTRA 270 mm panel.



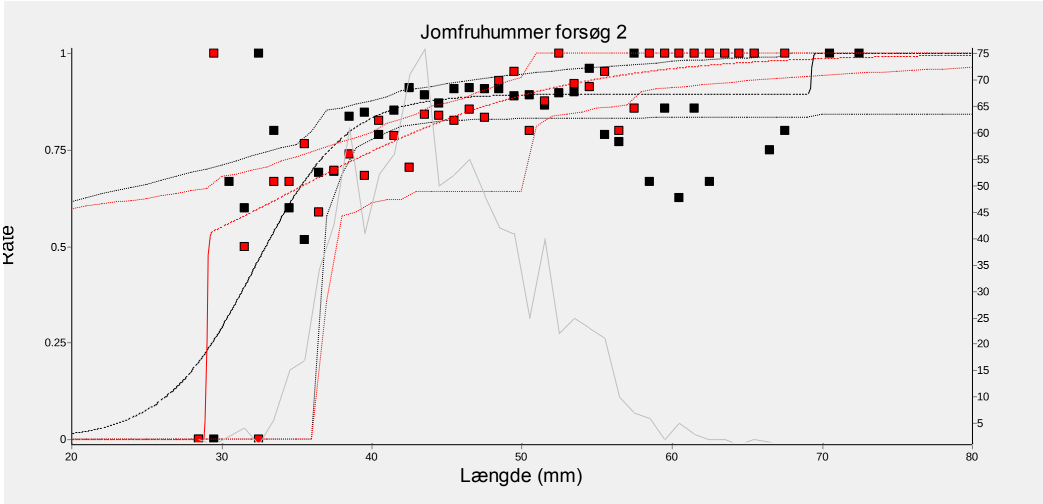
Figur 7. Selektionsresultater for kuller i forsøg 2. Retention rate (hel linje) med 95 % konfidence bånd (stiplet linje) for SELTRA 270 mm kollaps (sort) og SELTRA 270 mm åben (rød). Den fiskede population vises i gråt.

For rødspætter er effekten af at kollapse geometrien i fangstposen signifikant i længdeintervallet 25-35 cm, hvilket også er det interval hvor det primært er fanget fisk i. Figuren for rødspætter viser at selv meget store rødspætter på over 45 cm kan undslippe igennem SELTRA 270 mm selektionspanelet.



Figur 8. Selektionsresultater for rødspætte i forsøg 2. Retention rate (hel linje) med 95 % konfidence bånd (stiplet linje) for SELTRA 270 mm kollaps (sort) og SELTRA 270 mm åben (rød). Den fiskede population vises i gråt.

For jomfruhummere blev der ikke fundet en signifikant effekt af at reducere geometrien i panelsektionen. Der ses dog en ikke-signifikant tendens til at der mistes flere jomfruhummere, specielt af de store individer i den kollapsede fangstpose.



Figur 9. Selektionsresultater for jomfruhummer i forsøg 2. Retention rate (hel linje) med 95 % konfidence bånd (stiplet linje) for SELTRA 270 mm kollaps (sort) og SELTRA 270 mm åben (rød). Den fiskede population vises i gråt.

Selektionsparametrene L50 og SR er angivet i Tabel 2 for de i forsøget afprøvende redskaber. I tillæg til middelestimatet er der angivet 95 % usikkerhedsestimater baseret på bootstrapping i SELNET software.

Tabel 2. Gennemsnit (bias corrected mean) og 95 % konfidence grænser (i parentes) for hver art. For flere arter giver det ikke meget mening at beskrive selektionen i de forskellige SELTRA-fangstposer med de traditionelle selektionsparametre L50 og SR. For rødspætter er retentionen så høj at kurven ikke kommer ned til L50, mens retentionen for kuller er så lav at den ikke kommer op til L50. Det kunne være fordelagtigt at beskrive selektionen i sådanne systemer ud fra den del af selektionskurven der faktisk findes fremfor de traditionelle selektionsparametre (L50 og SR). Dette kan gøres ved at angive tilbageholdelsessandsynlighederne for nogle specifikke størrelser af fisk i stedet.

Forsøg 1	**L_{50} T1C1**	**L_{50} T2C2**	**SR T1C1**	**SR T2C2**
Torsk	$31,52\begin{pmatrix}34,90\\26,45\end{pmatrix}$	$35,64\begin{pmatrix}43,49\\31,39\end{pmatrix}$	$13,82\begin{pmatrix}34,76\\6,55\end{pmatrix}$	$29,86\begin{pmatrix}52,19\\14,64\end{pmatrix}$
Kuller	$29,21\begin{pmatrix}33,57\\24,06\end{pmatrix}$	$32,54\begin{pmatrix}40,06\\29,74\end{pmatrix}$	$20,45\begin{pmatrix}78,01\\11,63\end{pmatrix}$	$27,24\begin{pmatrix}173,32\\17,97\end{pmatrix}$
Jomfruhummer	$32,76\begin{pmatrix}35,54\\22,65\end{pmatrix}$	$34,44\begin{pmatrix}36,91\\28,43\end{pmatrix}$	$47,65\begin{pmatrix}80,70\\11,05\end{pmatrix}$	$20,53\begin{pmatrix}48,38\\13,38\end{pmatrix}$
Rødspætte	$7,77\begin{pmatrix}29,73\\0,12\end{pmatrix}$	$0,12\begin{pmatrix}8,14\\0,12\end{pmatrix}$	$43,80\begin{pmatrix}50,36\\0,12\end{pmatrix}$	$0,16\begin{pmatrix}23,67\\0,13\end{pmatrix}$
Skærising	$26,84\begin{pmatrix}28,24\\17,86\end{pmatrix}$	$21,50\begin{pmatrix}26,57\\9,60\end{pmatrix}$	$13,75\begin{pmatrix}62,50\\2,28\end{pmatrix}$	$14,55\begin{pmatrix}138,80\\7,75\end{pmatrix}$

Forsøg 2	L_{50} T1C1	L_{50} T2C2	SR T1C1	SR T2C2
Torsk	$91{,}89 \binom{105{,}65}{70{,}58}$	$33{,}77 \binom{38{,}00}{31{,}53}$	$72{,}37 \binom{100{,}00}{5{,}64}$	$39{,}09 \binom{54{,}05}{29{,}12}$
Kuller	$184{,}49 \binom{199{,}99}{52{,}43}$	$48{,}45 \binom{66{,}39}{34{,}39}$	$0{,}12 \binom{100{,}00}{0{,}11}$	$28{,}10 \binom{79{,}15}{11{,}16}$
Jomfruhummer	$32{,}91 \binom{36{,}52}{7{,}66}$	$29{,}12 \binom{37{,}08}{7{,}07}$	$7{,}84 \binom{56{,}47}{0{,}15}$	$11{,}21 \binom{59{,}85}{4{,}52}$
Rødspætte	$23{,}08 \binom{174{,}56}{0{,}17}$	$18{,}32 \binom{23{,}51}{0{,}13}$	$164{,}81 \binom{199{,}17}{17{,}99}$	$12{,}05 \binom{124{,}32}{0{,}16}$
Skærising	$21{,}09 \binom{47{,}43}{0{,}19}$	$14{,}72 \binom{28{,}48}{0{,}12}$	$44{,}56 \binom{78{,}25}{0{,}18}$	$17{,}42 \binom{151{,}33}{0{,}15}$

Tabel 3. Fit-statistics for forsøg 1 – aktiv stimulering baseret på estimeringer foretaget i SELNET.

Art	Test	Model	AIC	DEV	DOF	R^2	Contact	P-value
Torsk	Test1	Dual Seq	4755,13	39,54	70	0,9553	0,1498	0,9988
	Test2	Dual Seq	4147	68,79	62	0,7941	0,2414	0,2584
Kuller	Test1	Dual Seq	49.72	36,28	38	0,9299	0,9478	0,5492
	Test2	Dual Seq	49,79	73,97	39	0,6693	0,3600	0,0006
Jomfru-	Test1	Dual Seq	2581,64	44,37	34	0,2809	0,4769	0,1099
hummer	Test2	Dual Seq	2451,84	42,81	33	0,8473	0,7312	0,1179
Skærising	Test1	Dual Seq	571,60	43,55	28	0,2824	0,6233	0,0308
	Test2	Dual Seq	523,17	13,62	24	0,7903	1,0000	0,9548
Sej	Test1	Dual Seq	139,74	53,73	47	0,4445	1,0000	0,2321
	Test2	Dual Seq	245,64	53,44	39	-0,0002	0,6557	0,0616
Rødspætte	Test1	Dual Seq	211,77	20,28	17	-0,2069	0,2162	0,2600
	Test2	Dual Seq	258,70	32,72	20	0,0831	0,1937	0,0362

Tabel 4. Fit-statistic for forsøg 2 – geometri baseret på estimeringer foretaget i SELNET.

Art	Test	Model	AIC	DEV	DOF	R^2	Contact	P-value
Torsk	Test1	Dual Seq	5237,47	74,84	77	0,5106	0,7598	0,4206
	Test2	Dual Seq	7137,89	101,56	75	0,8101	0,6031	0,0223
Kuller	Test1	Dual Seq	2066,29	78,65	37	-0,2135	0,8940	0,0001
	Test2	Dual Seq	2840,20	53,79	38	0,5080	0,7278	0,0463
Jomfru-	Test1	Dual Seq	1279,36	42,20	37	0,5262	0,1047	0,2562
hummer	Test2	Dual Seq	891,19	26,29	33	0,6653	0,7213	0,7729
Skærising	Test1	Dual Seq	147,94	18,90	16	0,0673	0,5281	0,2741
	Test2	Dual Seq	129,44	18,44	18	-0,0129	0,1833	0,4270
Sej	Test1	Dual Seq	219,99	61,45	61	0,0812	0,7014	0,4599
	Test2	Dual Seq	397,61	71,92	63	0,2251	0,5208	0,2066
Rødspætte	Test1	Dual Seq	2444,58	23,73	17	0,1934	0,4480	0,1269
	Test2	Dual Seq	2031,49	25,32	20	0,2541	0,2070	0,1893

Diskussion

Aktiv stimulering

Vores data for torsk og flere andre arter er relativt stærke grundet det høje antal individer der er fanget. Der er en klar tendens til at aktiv stimulering i panel sektionen kan forbedre et selektionspanels selektive egenskaber. Der blev dog ikke observeret en signifikant effekt for de undersøgte arter i dette forsøg. For at kunne vurdere potentialet i aktiv stimulering er det dog afgørende at kunne dokumenteres stimuleringssystemets virke under fiskeriprocessen. I dette forsøg blev der monteret undervandskamera på selve fangstposen for at dokumentere dette. Undervandsoptagelserne var desværre så uklare grundet dårlig sigtbarhed i vandet samt mudderskyer genereret af trawlet at denne dokumentation ikke kunne indsamles.

Umiddelbart vil det forventes at en optimal udformning af en stimulering i forbindelse med f.eks. et selektionspanel vil kunne resultere i en forbedret effekt i forhold til nærværende studie. Et effektivt stimuleringssystem i forbindelse med et selektionspanel vil potentielt kunne minimere effekten af panelsektionens geometri, og vil dermed kunne bidrage til en mere ens effekt af selektionspaneler generelt. Et effektivt stimuleringssystem vil også kunne gøre panelets effekt uafhængigt af panelets placering i redskabet i forhold til bindestroppen, hvilket kunne være en fordel i de fiskerier hvori der opnås større fangster. I et eventuelt fremtidig forsøg på at udvikle et stimuleringssystem med henblik på at opnå en signifikant forbedret kontaktsandsynlighed, kunne det derfor være hensigtsmæssigt at henlægge udviklingen af systemet til en prøvetank således af systemets virke kan dokumenteres og tilpasses.

Afsluttende kan det dog ikke udelukkes at der vil kunne opnås en signifikant effekt af aktiv stimulering med nærende resultater hvis der blev foretaget en koblet analyse der udnytter at de to redskaber i forsøg 1 er fisket parallelt. En sådan koblet analyse kunne f.eks. udnytte at den eneste forskel imellem de to anvendte redskaber var en stimuleringsmekanisme i den ene trawl. Den observerede forskel imellem fangstene i de to redskaber forventes således alene at stamme fra stimuleringsanordningen. Der vil derfor være mulighed for at foretage forskellige analyser der udnytter at den eneste forskel mellem de to redskaber der fiskes parallelt har været stimuleringsanordningen. Således vil det i analysen kunne udnyttes at den eneste væsentlige forskel i selektionen mellem de to redskaber burde være kontaktsandsynlighederne med panelerne.

Fangstpose geometri

Geometrien i panelsektionen påvirker i betydelig grad selektionen af fisk, herunder torsk. Er geometrien åben, er kontaktsandsynligheden lavere end hvis geometrien er mere kollapset. Forskellen er betydelig. Ifølge resultaterne på f.eks. torsk blev der opnået en samlet L50 på ca. 33 cm hvor en SELTRA 270 mm selektionspanel var monteret i en 90 mm fangstpose med en åben geometri, mens L50 øget til over 90 cm da panelsektionen blev kollapset. Det betyder at to tilsyneladende ens selektionspaneler der er monteret lige langt fra redskabets bindestrop kan resultere i vidt forskellig selektion af torsk og andre marine organismer. Den kollapsede fangstpose resulterede også i et tab af jomfruhummere der dog ikke var signifikant. En kollapset panelsektion i en fangstpose vil resultere i en så høj kontaktsandsynlighed, at arter der rent mekanisk kan passere igennem panelets masker med stor sandsynlighed vil gøre dette. Dette kan bevirke større utilsigtet tab i specielt de mere blandede fiskerier.

Del 3 – Nordsøen

Forsøg med anvendelse af fangstposer med forskellig tråd tykkelse

Til diamant maskede fangstposer i Nordeuropæiske trawlfiskerier har der gennem en årrække været en tendens til anvendelse af en større tråd tykkelse og ofte som dobbelt tråd. Det har også været tilfældet i de danske trawlfiskerier. Det har givet anledning til bekymring om hvordan dette kan påvirke størrelsesselektionen herunder af torsk. Et større eksperimentelt baseret studie med forsøgsfiskeri med fangstposer med forskellige tråd specifikationer i form af tråd tykkelse og antal af tråde (enkelt eller dobbelt) i maskernes stolper. Forsøgsfiskeriet blev gennemført af det tyske institut ”Institut für Ostseefischerei” med et internationalt samarbejde herunder med DTU AQUA. Udover forsøg med traditionelt diamant maskede fangstposer omfattede forsøget fangstposer hvor net orienteringen var drejet 90^0 (såkaldt T90-fangstposer) i forhold til traditionel anvendelse of nettet. T90 fangstposerne er inde i lovgivningen for trawlfiskeriet i Østersøen hvor netop forsøgsfiskeriet blev gennemført. Der blev i forsøgsfiskeriet fokuseret på både størrelsesselektion af torsk og af rødspætte for at belyse effekten af tråd karakteristika på størrelsesselektionen af både rundfisk og fladfisk. I Østersøen hvor forsøgsfiskeriet blev gennemført foreskriver lovgivningen at der maksimalt må være 50 åbne masker i omkredsen af fangstposen. Fælles for alle de fangstposer der blev testet var at de overholdt dette design kriterium. Antallet af masker i omkredsen er det halve af hvad der lovgivningsmæssigt er specificeret som maksimal antallet i de fleste andre danske trawlfiskerier. Resultaterne der blev opnået er derfor kun direkte anvendelige for fangstpose design lignende dem der anvendes i Østersøens trawlfiskeri efter torsk men det forventes at tendenserne i resultaterne vil kunne overføres til diamant maskede fangstposer af design der er relevant for andre danske fiskerier.

I alt blev 12 forskellige fangstposer afprøvet ved eksperimentelt fiskeri. Forsøgsfiskeriet foregik fra det tyske forskningsfartøj ”FRV Solea” i perioden 18. marts til 7. april 2011 i Arkona Basin i den vestlige Østersø. De forskellige fangstposer blev fisket enkeltvis monteret i enden af det samme trawl. Mellem enkelt slæb var den anvendte fangstpose den eneste ændring. Der blev anvendt forsøg med små masket dæknet over fangstposen under fiskeri. Torsk og rødspætte fangsten blev opmålt på længde grupper (1 cm) i både dæknet og fangstpose. Fangstdata i dæknet og fangstpose blev på slæbniveau for hver af de to arter anvendt til at estimere selektionskurven som udtrykker den størrelsesafhængige sandsynlighed for en fisk der under fiskeri kommer ned i fangstposen bagerst i trawlen også bliver tilbagehold der. Selektionen blev i de enkelte slæb kvantificeret i form af parametrene

L50 og SR. L50 er i selektionsanalyse defineret som total længden af fisk med 50 % sandsynlighed for at blive tilbageholdt i fangstposen. Mens SR udtrykker forskellen i længde på fisk med henholdsvis 75 % og 25 % sandsynlighed for at blive tilbagehold. Resultaterne for de enkelte de enkelte slæb blev herefter anvendt separat for hver art i en samlet analyse med henblik på at modellere betydningen fangstposens design parametre på størrelsesselektionen. Alle analyser blev foretaget ved anvendelse af selektionsanalyse softwaren "SELNET" (udviklet af Bent Herrmann).

I alt blev der fanget og målt henholdsvis 64376 torsk og 13760 rødspætter som indgik i selektionsanalyserne. Der blev i alt gennemført 43 slæb med en varighed på mellem 90 og 180 minutter. De udførte forsøg, analysearbejdet og resultaterne er gengivet i detaljer i appendiks XX mens hovedtræk er gengivet nedenfor.

Fig. 1 viser de 12 forskellige net konfigurationer der blev anvendt til fangstpose designs.

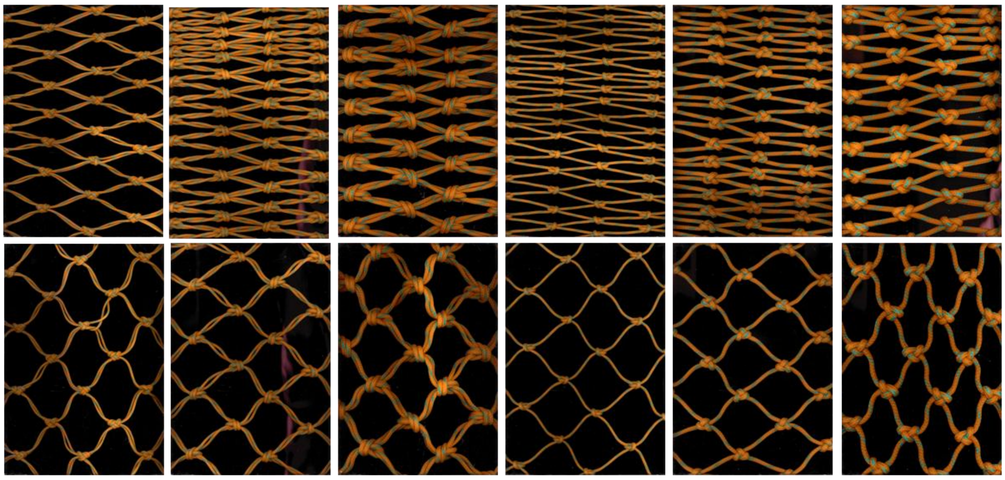


Fig. 1. Net konfigurationer anvendt for de 12 fangstposer. Top: de 6 forskellige net belastet i traditionel diamant pose retning T0. Nederst: de 6 forskellige net belastet i T90 retning. Fra venstre mod højre: dobbelt tråd 3mm (D3), dobbelt tråd 4mm (D4), dobbelt tråd 6mm (D6), enkelt tråd 4mm (S4), enkelt tråd 6mm (S6),enkelt tråd 8mm (S8).

Fig. 2 viser hvordan L50 og SR for torsk afhænger at nettets tråd tykkelse for de 4 forskellige basis design: traditionel net retning i enkelt tråd (T0 single twine), traditionel net retning i dobbelt tråd (T0 double twine), 90^0 drejet net retning i enkelt tråd (T90 single twine), 90^0 drejet net retning i dobbelt tråd (T90 double twine). Den fuldt optrukne kurve viser model estimaterne. Mens de stiplede kurver viser den forventede variation mellem de enkelte slæb. Resultaterne for de enkelte trawl slæb er vist som punkterne i Figuren.

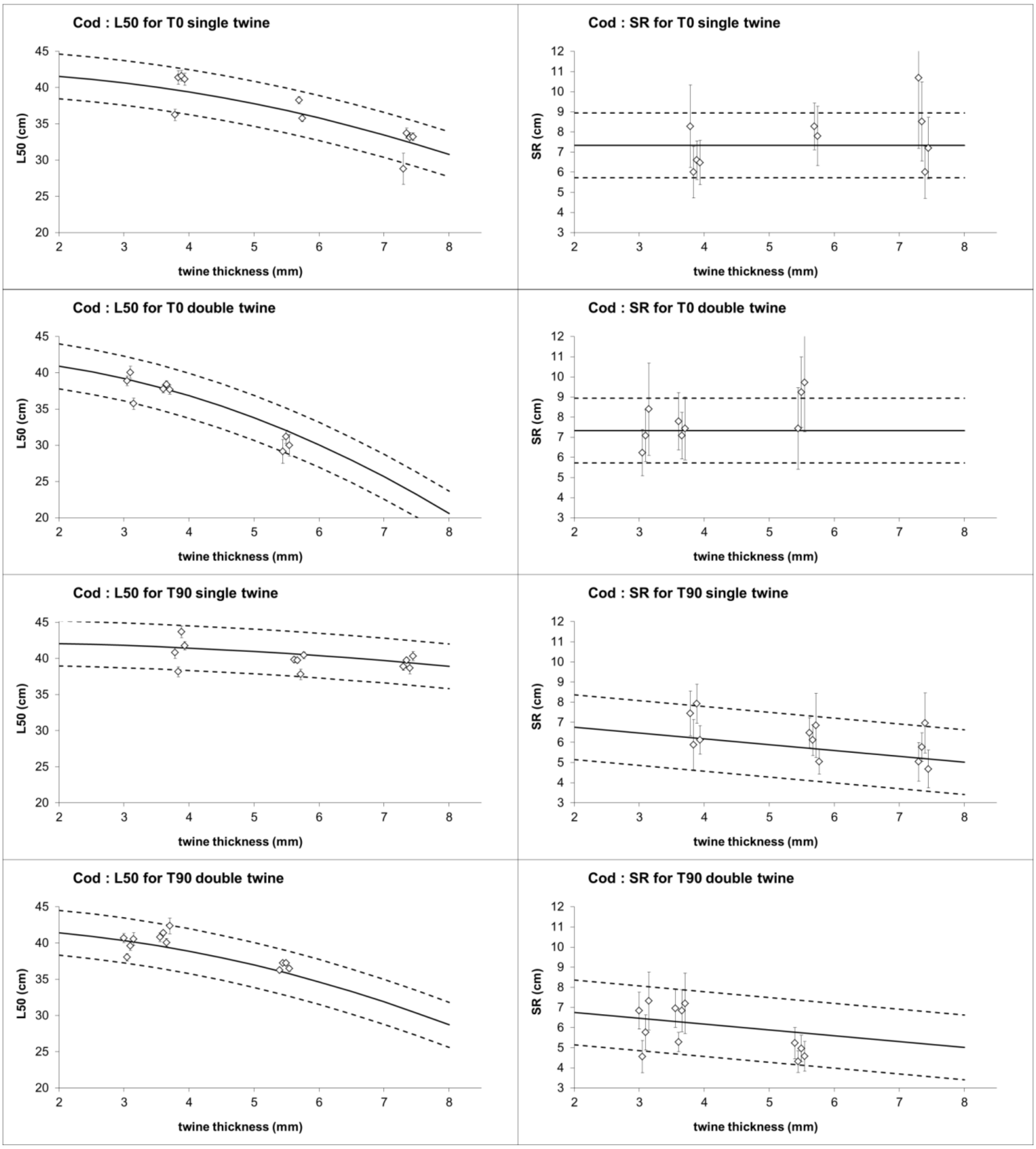


Fig. 2 viser hvordan L50 (til venstre) og SR (til højre) for torsk afhænger at nettets tråd tykkelse for de 4 forskellige basis design: traditionel net retning i enkelt tråd (T0 single twine) (øverst), traditionel net retning i dobbelt tråd (T0 double twine) (næst øverst), 90^0 drejet net retning i enkelt tråd (T90 single twine) (næst nederst), 90^0 drejet net retning i dobbelt tråd (T90 double twine) (nederst). Den fuldt optrukne kurve viser model estimaterne.

Mens de stiplede kurver viser den forventede variation mellem de enkelte slæb. Resultaterne for de enkelte trawl slæb er vist som diamant formede punkter i Figuren.

Figur 2 viser tydeligt at L50 for torsk for traditionelt maskede fangstposer reduceres væsentligt når nettets tråd tykkelse øges. Tendensen er særlig udtalt når der anvendes net med dobbelt tråd som der ofte gøres i danske fiskerier. For 90^0 drejet net i dobbelt tråd findes også en tydelig tendens til at l50 falder med tråd tykkelsen. For 90^0 drejet net i enkelt tråd er L50 langt mindre afhængig af nettets tråd tykkelse. En sammenligning mellem middel estimaterne for selektionsparametrene L50 og SR's afhængighed at fangstpose nettets tråd tykkelse for hver af de 4 basis design er for torsk vist på Fig. 3.

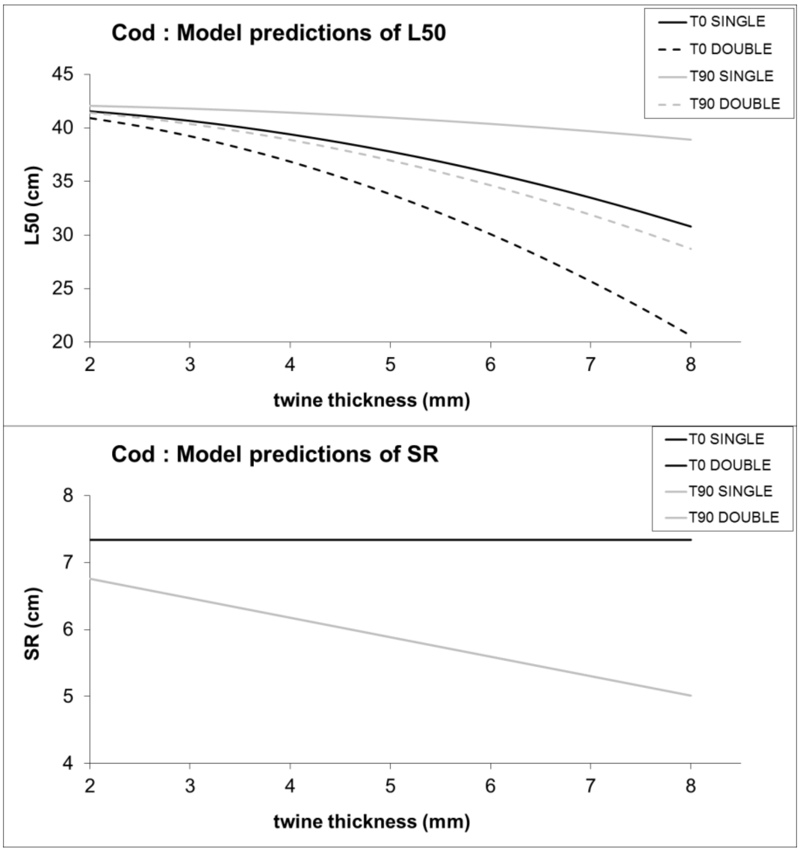


Fig. 3. Selektionsparametrene for torsk L50 (øverst) og SR's (nederst) afhængighed af fangstposens tråd tykkelse.

Fig. 4 viser hvordan L50 og SR for rødspætte afhænger at nettets tråd tykkelse for de 4 forskellige basis design: traditionel net retning i enkelt tråd (T0 single twine), traditionel net retning i dobbelt tråd (T0 double twine), 90^0 drejet net retning i enkelt tråd (T90 single twine), 90^0 drejet net retning i dobbelt tråd (T90 double twine). Den fuldt optrukne kurve viser model estimaterne. Mens de stiplede kurver viser den forventede variation mellem de enkelte slæb. Resultaterne for de enkelte trawl slæb er vist som punkterne i Figuren.

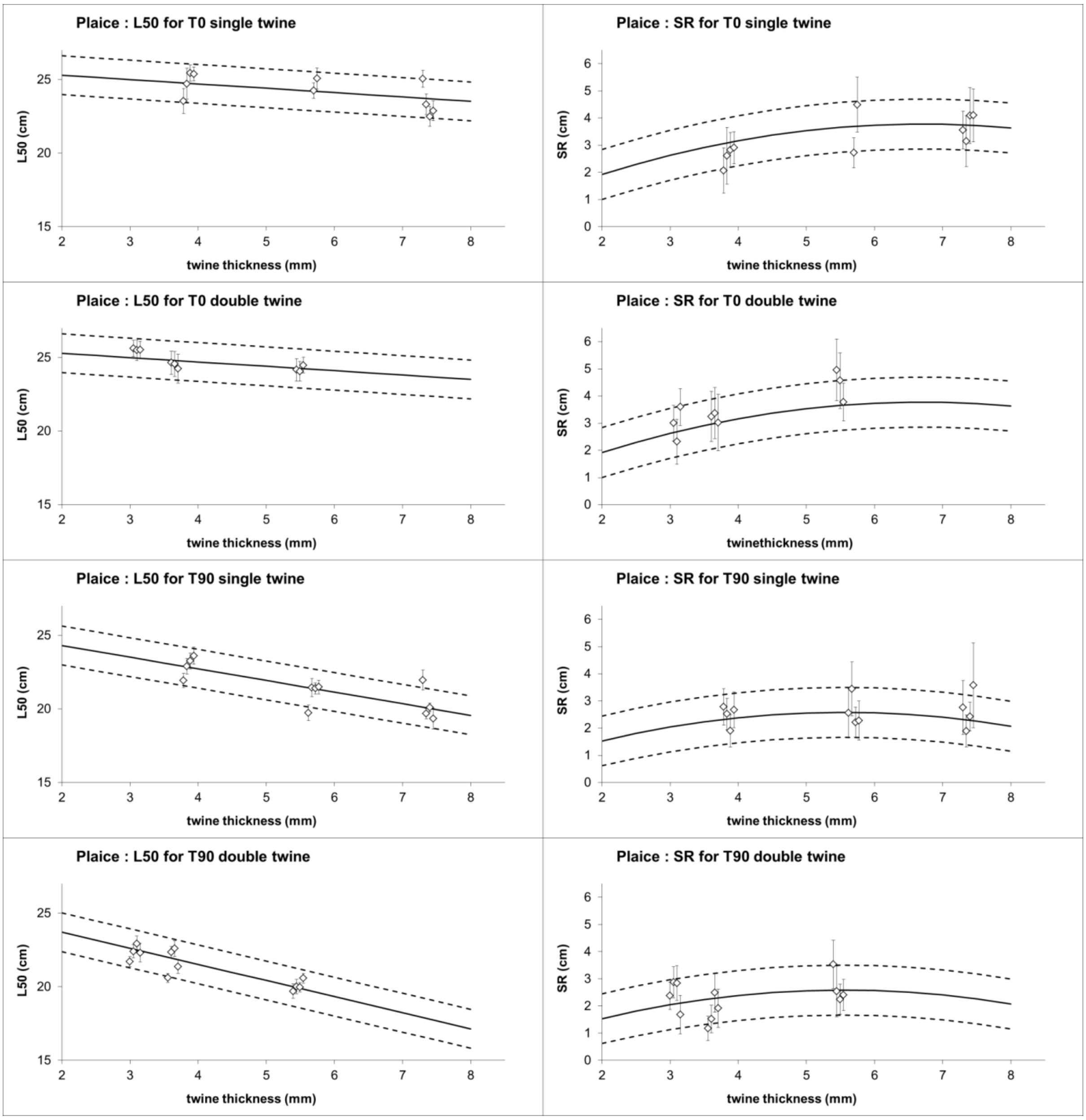


Fig. 5 viser hvordan L50 (til venstre) og SR (til højre) for rødspætte afhænger at nettets tråd tykkelse for de 4 forskellige basis design: traditionel net retning i enkelt tråd (T0 single twine) (øverst), traditionel net retning i dobbelt tråd (T0 double twine) (næst øverst), 90^0 drejet net retning i enkelt tråd (T90 single twine) (næst nederst), 90^0 drejet net retning i dobbelt tråd (T90 double twine) (nederst). Den fuldt optrukne kurve viser model estimaterne. Mens de stiplede kurver viser den forventede variation mellem de enkelte slæb. Resultaterne for de enkelte trawl slæb er vist som diamant formede punkter i Figuren.

Figur 5 viser at L50 for rødspætte for traditionelt maskede fangstposer reduceres når nettets tråd tykkelse øges.. For 90^0 drejet net i dobbelt tråd findes også en tydelig tendens til at l50 falder med tråd tykkelsen. For 90^0 drejet net er denne effekt endnu kraftigere og den er særligt udtalt for dobbelt tråds fangstposer. En sammenligning mellem middel estimaterne for selektionsparametrene L50 og SR's afhængighed at fangstpose nettets tråd tykkelse for hver af de 4 basis design er for rødspætte vist på Fig. 6.

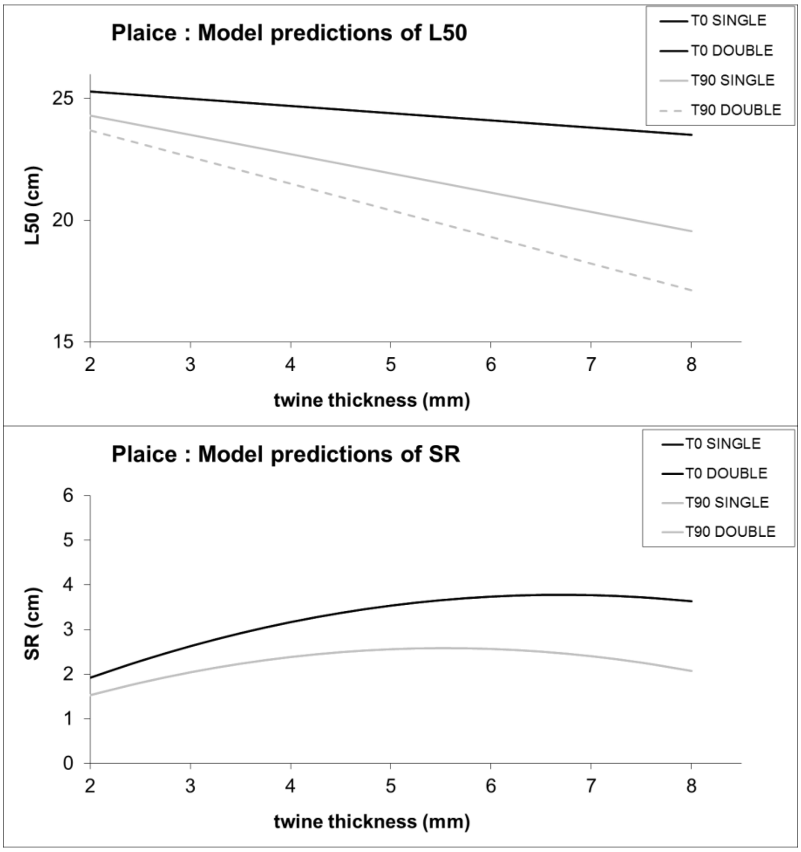


Fig. 6. Selektionsparametrene for rødspætte L50 (øverst) og SR's (nederst) afhængighed af fangstposens tråd tykkelse.

Konklusion.

Den udførte forsøgsrække viser vigtigheden også at overveje fangstpose nettets tråd tykkelse for diamant maskede fangstposer med hensyn til at opnå en tilsigtet selektion af rundfisk som torsk og af fladfisk som rødspætter. Generelt ses at for traditionel diamant maskede fangstposer så reduceres L50 betydeligt med øgning i fangstposens nets tråd tykkelse. For 90^0 drejet net er virkningen ikke helt ens for rundfisk og fladfisk.

Anvendelsen af dobbelttråd i fangstposen kan reducerer L50 signifikant sammenlignet med anvendelse af enkelttråd. Selektionen af fisk vil således signifikant kunne forbedres i flere tilfælde ved at anvende enkelt tråds fangstposer fremfor de dobbelt trådet fangstposer der anvendes kommercielt i dag.

Det omfattende studie der laver på tråd tykkelse, antal tråde samt orienteringen af nettet effekt på selektionen er i detalje beskrevet i Appendix 2.

Appendiks A: Largemesh paper

Quantifying fish escape behaviour in trawls based on catch comparison data: Model development and a case study from Skagerrak

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Key words: Fish behaviour, Trawl, Size selectivity, Catch comparison, Cod (*Gadus morhua*), Haddock (*Melanogramus aeglefinus*), mixed species fishery

Abstract

Fish react with a series of behavioural patterns, often species and size specific, towards a trawl during the fishing process. Thorough understanding fish behaviour in relation to fishing gear is therefore fundamental to support the increased demand for more efficient, selective and environmentally friendly trawls designs and the scientific understanding of different designs ability to utilize or stimulate different behavioural patterns in the catching process. Large effort has been put into behavioural studies using optical and acoustic observation systems. Harsh observation conditions on the fishing grounds however often hamper the direct observation of fish behaviour in relation to fishing gear.

Based on catch data, we developed and applied a new model to extract detailed and quantitative information about species- and size-dependent escape behaviour in towed fishing gear as trawls. We used catch comparison data collected with a twin trawl setup, where the only difference between the two trawls was that a 12 meter long upper section was replaced with 800 mm diamond meshes in one of them. Based on this very large mesh size, we assumed that all individuals that came in contact with the panel would be able to escape through it. We applied the new method to investigate the length-based escape behaviour for cod, haddock, saithe, witch, and lemon sole and to quantify the extent to which behavioural responses set limits for the large mesh panel's efficiency for each species. We demonstrated the need to account for the potential selectivity in the trawl body and show how this size selection otherwise can bias the assessment of length-based escape behaviour. Our indirect assessment of fish behaviour, which can be applied under all fishing

conditions, was in good agreement with the direct observations made for the same species in a similar section of the trawl body reported in the literature.

Introduction

For centuries, fishermen have been perfecting fishing gear to catch fish more efficiently. During especially the last decades, more advanced and sophisticated trawl designs have been developed as a result of the need for improved species and size selectivity and to meet stricter bycatch reductions. The major challenge with such designs is to improve selectivity, typically for one or two focus species, and at the same time maintain high catch efficiency for target species and sizes. A critical component in this dual purpose optimisation of trawl designs is an understanding of fish behaviour in relation to the gear. The process by which fish are caught by a trawl involves a complex sequential process of behavioural responses to the different parts of the trawl gear [1]. Understanding these behaviour patterns for the relevant species and sizes and the factors affecting these patterns is critical for designing economically profitable trawl systems with improved selectivity.

Extensive research has been devoted to understanding fish behaviour in relation to fishing gear to aid the development of more efficient species or size selective fishing gears [1-3]. Behaviour patterns of several species have been described qualitatively for trawls at different stages of the catching process. The main conclusions are outlined and reviewed in Wardle [1] and He [3]. There is an overall understanding of the behavioural pattern through the catching process in trawl gear for a few important commercial species such as haddock (*Melanogramus aeglefinus*), cod (*Gadus morhua*), whiting (*Merlangius merlangus*), and some flatfish species [1,3-4]. However, information about the behaviour of many other bycatch and commercial species, which are important for the management of fish stocks, is too limited to be utilised directly in gear development.

Understanding of fish behaviour is often synthesised from observations of different trawl designs in different areas. However, a fish may behave differently when it encounters different trawl designs. Thus, there is a need to assess fish behaviour not in trawl gear in general but more specifically for a given design category. Ideally, fish behaviour should be mapped in a quantitative way for a given gear design in a given area under the conditions in which the gear is used. This, however, is not the case today. Observation cruises are expensive and the observation conditions are harsh. Poor, inconclusive, or biased results are often obtained, although the quality of underwater cameras and other observation equipment has improved greatly during the last decade [2,5]. Another obstacle is that optical observations can only be made during the day when there is sufficient light at observation depth. Commercial fishing is often conducted around the clock, and experimental fishing has demonstrated that fish behaviour in relation to fishing gear varies between day and night for several species [5-7].

Today, a variety of different optical and acoustic observation equipment and techniques is available to researchers. The often more robust acoustic techniques, which are independent of visibility and light at depth, still depend on optical species recognition and therefore face the same limitation as direct observation techniques. In addition to direct optical or acoustic observations, fish behaviour can be studied indirectly by reconstructing the behaviour process based on the catch composition e.g., using spatially divided gear designs. Examples of such designs are separator trawls [8-10] and similar experimental designs in which the trawl cavity is divided into separate collecting bags [5,11-14]. However, installing separating panels or other separating devices inside the trawl body introduces new structures that can affect fish behaviour [5].

In this paper, we studied behaviour of six commercial species in the *Nephrops* (*Nephrops norvegicus*) directed fishery in Skagerrak. This fishery is conducted in relatively deep waters on muddy grounds where the traditional observation techniques repeatedly have failed. Our behaviour study was conducted without any direct observations and without any spatially divided gear designs. The study was based solely on analysis of catch data collected using a paired gear setup in which the experimental trawl was equipped with an 800 mm diamond mesh panel in the top side of the entire aft tapered section of the trawl. We assumed that all fish that came in contact with the panel were able to escape through these large meshes. Under this assumption, the contact probability when fish encounter the large mesh panel equals the escape behaviour and the available selection [15]. Initial catch comparison analyses indicated that size selectivity was occurring in the trawls' nominal 120 mm mesh size. We demonstrated how the traditional catch comparison modelling of such data can lead to biased interpretations of fish behaviour and also how to account for selectivity that occurs in the trawl body. We present a new structural model to describe and quantify fish behaviour indirectly based on analysis of catch data alone. Using this method, we quantified the length-dependent behavioural response for cod, haddock, saithe (*Pollachius virens*), lemon sole (*Microstomus kitt*), and witch flounder (*Glyptocephalus cynoglossus*) in relation to the large mesh panel in the experimental trawl cavity.

The analysis was subdivided into two iterations. The first was the traditional catch comparison analysis of the collected paired trawl data. The results of this analysis, however, led to further research questions, as it was difficult to provide a biologically meaningful explanation for some of the results. In the second iteration, we developed the new structural based model. Using this model, we generated simulations in search of an explanation for the unexpected structure of the results obtained from the traditional catch comparison analysis, and we developed a structural based assessment of fish escape behaviour in relation to the large mesh panel. Due to the iterative structure of this study, each of these two steps requires its own materials and methods and results section.

The aim of this work was to investigate fish behaviour in relation to towed fishing gear quantitatively based on catch data, as a supplement or as an alternative to the traditional optic systems which are costly and can have a low success rate in poor observation conditions which often is encountered on commercial fishing grounds. We develop and demonstrate an indirect quantitative method to study fish behaviour based on catch data alone which can be used under all observation conditions and in all parts of the trawl cost efficiently.

Material and methods

Ethics statement

This study did not include endangered or protected species. Experimental fishing was conducted onboard a Danish commercial trawler in accordance with the fishing permit given by the Danish AgriFish Agency (J. no. 2004-243-120). No other permit was required to conduct the study.

Experimental setup for data collection

Two identical *Cosmos Combi* trawls (540 meshes of 120 mm (PE) in the fishing circle circumference) were made. In one of the trawls (i.e., the experimental trawl), an 800 mm diamond mesh panel was installed from selvedge to selvedge in the entire upper panel in the aft tapered section (13.8 m stretch length). The extension and codend in both trawls was made of 45 mm meshes (Figure 1).

Experimental fishing was conducted on a commercial trawler (511 KW). The vessel's twin trawl system with three towing warps was used. The twin rig was spread with two 244 cm Thyborøn V-doors and a 1200 kg rolling centre clump. The sweeps were 204 m in 50 mm Taifun single sweeps with a 5 m backstrop behind the doors. The trawl doors and clump were equipped with distance sensors, which provided information about the basic geometry of the front part of both trawls during towing. The total catch of fish was length measured to the nearest cm below and *Nephrops* to the nearest mm below. For subsequent data analysis, 0.5 cm was added to each measured fish length and 0.5 mm to each measured *Nephrops* carapace length. The two trawls were interchanged halfway through the experiment to compensate for any systematic effects between the two gears.

Iteration 1: Traditional catch comparison analysis

Because the two trawls were fished side by side in a twin rig, comparable size distributions for the different species were available from the catch in two codends (Figure 1). The number of individuals in each length class collected in the two codends was used to evaluate the length-dependent relative catching efficiency of the two trawls by species. Because the constructions of the two trawls were identical except for the section containing the large mesh panel, the relative length-dependent catch efficiency expressed the effect of introducing the large mesh panel in a section of the experimental trawl compared to the standard trawl. This relative length-dependent catch efficiency between the two trawls deployed simultaneously side by side was closely related to the so-called catch comparison [16]. On a haul-by-haul basis, the experimental catch comparison rate, $rate_l$, for each of the species separately was given by:

$$rate_l = \frac{nr1_l}{nr1_l + nr2_l} \qquad (1)$$

where $nr1_l$ is the number of fish of length *l* of the given species collected in codend 1 and $nr2_l$ is the number collected in codend 2. Traditionally, in catch comparison analysis the experimental $rate_l$ is often modelled by the function *rate(l)* of the following form [16]:

$$rate(l, q_0..q_j) = \frac{exp(f(l, q_0..q_j))}{1 + exp(f(l, q_0..q_j))} \quad (2)$$

where *f* is a polynomial of order *j* with coefficients q_0 to q_j. Thus, $rate(l,q_0..q_j)$ expresses the likehood of finding a fish of length *l* in the large mesh panel trawl codend given that it is found in one of the two codends. One advantage of applying a model of the form (2) to model this length-dependent likelihood is that it is naturally constrained to the interval [0.0;1.0], which is independent of the value of the polynomial *f* and therefore *a priori* fulfills this basic criterion to model a likelihood. A value of 0.5 for *rate* would mean that the likelihood of finding the fish in one of the two codends is equally high, therefore implying that introducing the large mesh panel in the trawl would not have any effect on the catch efficiency. In contrast, a value of 0.3 for *rate* would mean that the likelihood of finding the the fish in the large mesh trawl codend would be 30% and the likelihood for it being found in the codend of the standard trawl would be 70%. This would imply that the experimental trawl (i.e., with the large mesh panel) would only retain 43% (0.43 ≈ 0.3/0.7) of a given fish species at a given length compared to the standard trawl. Thus, the effect would be a 57% reduction in the catch efficiency compared to the standard trawl. Herein, we applied the traditional catch comparison rate to investigate the effect of the large mesh panel on catch efficency.

On a haul-by-haul level, the values of the parameters describing *rate(l)* in formula (2) can be estimated by minimising the following equation, which is similar to maximising the likelihood of the observed experimental data assuming that the model *rate(l)* adequatly describes the catch comparison rate between the two trawls:

$$-\sum_l \{nr1_l \times ln(rate(l)) + nr2_l \times ln(1.0 - rate(l))\} \quad (3)$$

where the summation is over the length classes in the experimental data.

To model the catch comparison *rate(l)* between the two trawls we applied formula (2). We considered *f* up to an order of 4 with parameters q_0, q_1, q_2, q_3, and q_4. Leaving out one or more of the parameters $q_1..q_4$ led to an additional 31 models that were considered as potential models for the catch comparison *rate(l)* between the two trawls. Selection of the best model for *rate(l)* among the 32 competing models was based on a comparison of the AIC values for the models. The model with the lowest AIC value was selected [17].

Often the catch comparison curve is estimated for each haul separately, and the results from single hauls are then applied in a two-step procedure to estimate a mean curve while considering between-haul variations in the catch comparison rate [18]. However, in this study we did not have any particular interest in the between-haul variation in the catch comparison rate between the two trawls; instead, we were interested in estimating an average catch comparison rate for the trawls based on all of the available hauls. Therefore, we used another approach that involved applying formula (3) summed over hauls and estimating an average curve based on formula (2). We used a double bootstrap approach with 2000 bootstrap repetitions to estimate the Efron percentile 95% confidence limits [19] for $q_0..q_4$ and *rate(l)* for all relevant length values. This approach, which avoided underestimating confidence limits when averaging over hauls without using the traditional two-step procedure, is similar to the one described in Sistiaga et al. [15] and Herrmann et al. [20], and more details about the approach can be found in these references. Traditionally, the confidence limits for a curve and for the parameter values describing this curve are estimated without accounting for potentially increased uncertainty resulting from uncertainty in selection of the model used to describe the curve [21]. In this study, we accounted for this additional uncertainty in the catch comparison curve by incorporating into each of the 2000 bootstrap repetitions an automatic model choice that was based on which of the 32 models produced the lowest AIC.

The catch comparison analyses were performed using of the computer software SELNET. More information about SELNET can be obtained by consulting the descriptions in [15,20,22-24].

Results from iteration 1: Traditional catch comparison analysis

A total of 25 valid hauls were conducted in June in Skagerrak on commercial grounds typically used by the Danish mixed species fleet (Figure 2). All hauls were made during daylight hours between sunrise and sunset. The nominal mesh size both in the standard and the experimental trawls was 120 mm full mesh. Table 1 lists results of mesh measurements in the codend and large mesh panel. The 800 mm mesh size in the large mesh panel could not be measured with the traditional mesh measurement tools and therefore is given as the nominal mesh size.

Towing time was about 3 h. Additional operational conditions are summarised in Table 2. The two trawls were interchanged in the middle of the cruise to compensate for any systematic effects. Cod, haddock, saithe, *Nephrops*, lemon sole, and witch flounder were caught in sufficient numbers and were included in the analysis. All *Nephrops* were measured, except for in haul no. 8, which was subsampled due to large catch size. In this haul, 41% of the individuals were measured in the control trawl and 47% in the experimental trawl.

The polynomial models used in the catch comparison analysis are very flexible and should therefore only be used within the length range for which data are available. Figure 3 shows the population structure for all species along with results of the traditional catch comparison analysis shown as length-dependent mean values ± 95% confidence limits. The large mesh panel significantly reduced the catch of saithe, haddock, and cod, as indicated by the catch comparison rate being significantly lower than 0.5 for a large range of length classes (Figure 3). Among the gadoid species, the effect was strongest for saithe and weakest for cod. For witch flounder and plaice, there was a length-dependent escape behaviour of the large mesh panel, which was significant for the larger individuals. There was no significant difference between the standard and the experimental trawl for the catch of *Nephrops*, as 0.5 was within the confidence band for all length classes. It should be noted that the confidence bands were very narrow for carapace length between 30 and 60 mm.

The fit statistics (Table 3) show that the model applied was able to describe the experimental data sufficiently well, as the model's P-values were > 0.05 for all species except for cod. In the residuals [25] for cod, no structure was detected in the deviations between data and the model. Therefore, we were confident in applying the model for all species investigated.

The shape of the catch comparison curve for cod and haddock displayed a peculiar cup-shaped curve, which, when interpreted as escape behaviour, would mean that small and large fish behaved similarly but medium-sized fish behaved differently (Figure 3). From a biological point of view, we would expect a more monotonous progression of the catch comparison curve, which would indicate a pattern in which the behaviour of small fish gradually changed over length or alternatively no length-dependent effect. Such a pattern could have a biological explanation, such as improved swimming ability with increasing length, which could lead to increased panel contact for larger individuals. It is difficult to provide a conceivable explanation for the cup-shaped pattern observed for cod and haddock. Therefore, in the next step we examined potential causes of this unexpected cup-shaped curve.

Materials and methods for iteration 2: Model development and simulation

We assumed that all sizes of fish caught during the sea trials could escape with ease through the large 800 mm meshes size if they contacted this panel. How this assumption could result in the cup-shaped catch comparison curves observed for cod and haddock in Figure 3 is intriguing. Is it a valid description of the length-dependent behaviour of these species in relation to the large mesh panel, with middle-sized fish being better at contacting the large mesh panel compared to both smaller and larger individuals, or is there another, less exotic mechanism affecting our catch comparison analysis? Could the results be caused by the size selective properties of other netting panels in the two trawls rather than the large mesh panel? To address these questions, we developed a special structural model to analyse the catch comparison rate between the two trawls. This new model considers the potential size selection in all mesh panels in all sections of the two trawls from which the length-dependent catch are compared.

The development of this new model is thoroughly described in the Appendix. Formula A5 (derived in Appendix) expresses the theoretical catch comparison rate R_l in terms of the size selection of the two trawls exclusively in the section where the large mesh panel is integrated and by the sharing rate (split) between the two trawls of the fish entering the trawl. In the standard trawl, this section consisted of an upper and lower panel made of the same 120 mm diamond mesh netting (Figure 1). In the large mesh panel trawl, the upper 120 mm panel was replaced by the 800 mm mesh size panel. Thus, the potential size selection through the 120 mm section in the standard trawl that corresponds to the 800 mm section in the experimental trawl should be accounted for in the catch comparison rate.

To get a first impression of what kind of curve we could expect for the catch comparison rate if there was size selection in the standard trawl, we conducted a simple parametric simulation to estimate the theoretical catch comparison R_l for such an experimental setup. We used parametric simulation facilities built into the software tool SELNET to model equation (A5) in the appendix. In the simulation, we assumed that the likelihood of fish contacting the upper panel in the section had the same length dependency for both trawls. We assumed that the fish showed a kind of avoidance response to the upper panel, which depended on the size of the fish. For small fish, for example, we simulated that 50% would come in contact with the upper panel in the relevant section in both trawls. For larger fish we assumed that the avoidance response would be greater due to increased swimming ability with increasing length. Thus, for very big fish we assumed that the avoidance would be nearly 100%. This kind of behavioural modelling is described in formula (A5). We used these assumptions in the SELNET simulation with the following parameter values: $c_1 = 0.5$, $c_2 = 0.0$, $L50_c = 65\ cm$, and $SR_c = 15\ cm$ (see Appendix for a description of these parameters). For the fish that contacted the panel nettings and thus had a length-dependent chance of escaping through it, we assumed that the process could be modelled by a *logit* function with parameters $L50_p$ and SR_p [25]. For the 120 mm panel we assumed $L50_p = 30\ cm$ and $SR_p = 5\ cm$, whereas for the large mesh panel we used values that would result in the release of cod of every size that was simulated to contact the panel ($L50_p >> 120\ cm$). We assumed that entry into the two trawls was equally high (split = 0.5). To make the simulations as realistic as possible, we applied a size structure similar to the one we observed in the experimental data for cod. The SELNET simulation resulted in a virtual dataset for cod, which then was analysed in SELNET using the same method that was applied for the experimental data (see Traditional catch comparison analysis section above; Figure 3). Figure 4 (top) shows the results for this theoretical catch comparison rate R_l from the simulation and a comparison with the experimentally obtained results for cod (also shown in Figure 3).

Comparison of the curve for the experimentally obtained catch comparison rate with the simulated data assuming size selection in the standard trawl revealed cup-shaped curves for both (Figure 4, top). Thus, size selection in the standard trawl could well explain the cup-shaped nature of the catch comparison curve without having to assume exotic length-dependent fish behaviour. To further demonstrate that size selection in the standard trawl resulted in the cup-shaped catch comparison curve, we conducted an additional simulation in SELNET with the same parameters, except that we used values of $L50_p$ and SR_p that simulated no selection in the panel in the standard trawl. Results from this simulation show that the cup-shaped nature of the curve has disappeared (Figure 4, bottom). Almost no fish outside the range of 20 to 80 cm were present in the simulation (population structure curve in the plot), and therefore the actual shape of the catch comparison curves should not be applied outside this range. The models applied to analyse the data are not structurally bounded in any way and therefore the results cannot be extrapolated. Figure 4 (bottom) also shows the panel contact curve that was applied in both simulations, which demonstrates an increased avoidance response with increasing fish size.

The lesson learned from the analysis described above is that two factors affected the nature of the catch comparison curve in this study: fish behaviour in relation to the large mesh panel and the selective properties of the corresponding panel in the standard trawl. The next issue we addressed is the extent to which can we learn something about the length-dependent response in relation to the large mesh panel for different species from the respective experimental catch comparison rates. A simple approach would be to restrict the analysis of the catch comparison data to sizes above which the 120 mm panel would potentially select out some individuals. This approach was applied to develop a model for the expected catch comparison rate R_l for sizes above the selective range of the 120 mm panel up to sizes where the large mesh panel can be assumed to release fish attempting to pass through it (see Appendix for model development):

$$R_l = \frac{sp \times (1 - c(l))}{1 - sp \times c(l)} \qquad (4)$$

where *sp* is the assumed length-independent entry likelihood (split) of a fish into the trawl containing the large mesh panel given that it enters one of the two trawls that fished simultaneously. Thus, the likelihood of entering the standard trawl will be *1.0 – sp*. *c(l)* is the length-dependent contact likelihood of a fish with the large mesh panel given that it enters the section in the experimental trawl where the large mesh panel was inserted. A flexible model for *c(l)* which enable constant, increasing or decreasing contact likelihood with the large mesh panel:

$$c(l) = c_1 + (c_2 - c_1) \times logit(L_{50_c}, SR_c, l) \qquad (5)$$

where c_1 and c_2 are constants that both are constrained to the interval *[0.0;1.0]*. $L50_c$ is the midpoint fish length at which the value of the contact likelihood will be the mean of c_1 and c_2. The value of SR_c defines how quickly the contact shifts from a value close to c_1 to a value close to c_2 with increasing fish length in the vicinity of $L50_c$. Thus, if the value of SR_c is close to 0.0, the change in the contact likelihood will appear over a small length range, whereas a value far from 0.0 will result in a change that will cover a wider length span. Herein we applied formula (5), which we named *model M1*, to describe the large mesh panel contact likelihood. Estimation of the parameter values of c_1, c_2, $L50_c$, and SR_c was conducted species by species applying formula (5) for *c(l)* in formula (4) and then using R_l for *rate(l)* in (3), but constraining the length classes used in the experimental data to the interval above which the 120 mm panel can be selective and below which the large mesh panel can begin to be selective. Based on formula (5), a number of simpler models can be derived with fewer parameters. Thus, in addition to using formula (5) to model the length-dependent panel contact, we also considered three simpler models (Table 4).

Selection of the best model among *M1, M2, M3*, and M4 was carried out for each species individually by selecting the model that produced the lowest AIC value. Confidence intervals for the rate curve R_l and for the contact curve *c(l)* were evaluated using the same double bootstrap technique described above for iteration 1 and applied for the evaluation of the traditional catch comparison curve.

To identify the length limit below which we needed to cut-off the experimental data in order to estimate the length-dependent large mesh panel contact likelihood for each species, we used realistic mesh openings based on flume tank measurements of the mesh openings in the net section of interest. We then applied the FISHSELECT methodology [26] to estimate the maximum size of the individual species that can penetrate such mesh openings. The maximum mesh opening was found in the forward end of the panel with an opening angle of about 30°. The mesh opening angle was based on flume tank measurements of a 1:8 scale model. Using FISHSELECT, we then estimated the maximum size of cod that can pass through a 120 mm mesh with an opening angle of 30°. For haddock we used values found in Krag et al. [27], and for *Nephrops* we used values from Frandsen et al. [28]. We used unpublished morphology-based FISHSELECT data for lemon sole. No morphology measurements were available for saithe and witch flounder, so we assumed that saithe morphology was similar to that of cod and witch morphology was similar to lemon sole. Single hauls with fewer than 10 individuals of each species were excluded from the analysis.

Results from iteration 2: Model development and simulation

For each species, the length classes that could pass through the nominal 120 mm mesh size were excluded. Excluding the potential selectivity that can occur in the gears' nominal mesh size reduced the number of individuals in the populations of the different species. For cod and haddock, a large proportion of the caught populations were excluded due to large numbers of relatively small individuals. In contrast, only a few individuals were excluded for saithe, lemon sole, and witch flounder. Table 5 lists the adjusted (cut-off) minimum lengths. All sizes of *Nephrops* could escape through the 120 mm meshes, thus *Nephrops* was not included in this part of the analysis.

Choice of model was based on fit statistics for the four evaluated models used to describe the experimental data (Table 6). In cases where two models resulted in rather similar fit statistics (difference in AIC < 1.0), we selected the simplest model.

The data show that all saithe below 40 cm and about 85% (mean) of the large sizes escaped through the large mesh panel (Figure 5). Escapement of haddock through the large mesh panel was about 80% (mean), with no length dependency. About 44% (mean) of witch flounder and about 55%

(mean) of lemon sole escaped through the large mesh panel, and neither species exhibited length dependency. Both flatfish species had relatively wide confidence limits compared to saithe and haddock. The mean length-dependent escape curves for saithe, haddock, witch flounder, and lemon sole all exhibited a gradual monotonous progression (Figure 5 & 6).

The pattern for cod differed from those of the other fish species. Figure 5 & 6 illustrate a knife-edge change in the mean length-dependent escape curve for cod at one specific length (68 cm). This is unexpected from a biological point of view and gives an unrealistic description of cod behaviour. One potential explanation is that this result is an artefact caused by working with few data with large variation. Cutting off the data for cod at 33 cm left only 31% of the original data. To investigate this possibility, we used SELNET to simulate the following three datasets using the same population structure as that found in the experimental data: i) with the same population size as in the experimental data; ii) five times the size of the population in the experimental dataset; iii) and 100 times the size of the population in the experimental dataset. We applied the same method described to estimate the length-dependent contact response of cod for each of these datasets.

The results of these simulations indicate that the knife-edge change with length in the escape curve seen in the original dataset was an artefact of using a sparse dataset (Figure 7). For population sizes 5 and 100 times larger, we were able to "re-estimate" results that appeared very similar to the length-dependent contact likelihood we actually simulated the datasets with (see Figure 4, bottom).

Discussion

In this study we quantified the length-dependent escape behaviour of five commercial fish species in the mixed demersal fishery in Skagerrak in relation to a large mesh panel placed in the last tapered section of a trawl. This assessment of fish behaviour was made without traditional direct observations and without dividing the trawl gear into different compartments, which potentially could affect the behaviour of the fish species in question. The indirect method applied in our structural model can include every fish in the analysis, in contrast to optical observation techniques [5], and can be used under all physical conditions (e.g., independent of light and turbidity levels). Furthermore, this indirect quantitative method enabled us to describe behaviour patterns for all species caught and included uncertainties of the estimates, which is not possible with direct observation techniques. The method developed in this study to estimate the escape behaviour of fish over a large section in the main body of a trawl can be used to make a survey of escape behaviour along e.g., along the full length of a trawl. This type of survey could provide detailed quantitative descriptions of behaviour, including uncertainties about the estimates from the main body of the trawl, which can be difficult to collect with direct observation techniques. A further advantage of the described method is that detailed information about fish behaviour can be collected at low cost and during existing codend selectivity studies as additional and valuable information. Sections of large meshes in the forward part of the trawl are commonly used, especially in pelagic and semi-pelagic fisheries, to guide fish into the narrower and smaller mesh aft part of the trawl. However, little quantitative information is available about the guiding effect of large meshes in the forward part of trawls (e.g., large pelagic designs). The method presented herein could be used to conduct quantitative studies of escape behaviour in these very large trawls.

The traditional catch comparison technique used in iteration 1 led to an unexpected cup-shaped catch comparison curve for cod and haddock, which, when interpreted as fish behaviour, resulted in an exotic length dependency in the escape behaviour. Thus, it was important to understand and subsequently account for additional selectivity occurring in the section of the standard trawl that corresponds to the experimental section (i.e., the large mesh panel). Controlling for this selectivity is important in order to avoid misinterpreting peculiar results, as fish do escape in the main body of the trawl and not only through the codend.

The advantage of the results found in the current study, was that we used the commercial trawl design which we aim at modifying. However, the results showed that when using the commercial mesh size (120 mm), we needed to account for the selectivity occurring in the net section corresponding to the large mesh panel in the standard trawl. This issue could be avoided by replacing the 120 mm nominal mesh size with a small non-selective mesh size, with the cost of not having a commercial design any more. One consequence of using a large commercial mesh size was that we had to exclude all individuals in the population that were able to escape through it. This weakened the data, as observed for cod in the current study. Due to exclusion of most of the individuals, the data showed a knife-edge pattern of the escape behaviour for cod, which indicated that all length dependency in the escape behaviour occurred at one length; this pattern, however, has little biological meaning. We could have used data or model smoothing, but we chose not to as this is not recommended for the type of analysis we applied [29].

Behavioural studies of what occurs in the trawl mouth have shown that haddock and, to a lesser extent, saithe rise above the ground gear as they tire, whereas flatfish, cod, and *Nephrops* enter the trawl close to the sea bed [8,11,14,31-34]. These observations are similar to the patterns we found in the current study. The tendency of fish to exhibit varying degrees of rising in the trawl has led to the development of multi-level trawls, with horizontal separators and multiple codends, which allow partial segregation of the catch by species [5,8-10,13-14,31]. The rather limited observations of cod in trawl nets indicate that they drift slowly back towards the codend, staying stationary in the net for long periods of time [35-36]. Based on underwater observations, Thomsen [34] reported that once inside the trawl, cod tended to rise, as did other gadoids such as haddock and whiting, although the rate of ascent for cod was far slower and further aft in the trawl. Krag et al. [5,13] conducted behaviour studies with trawl designs identical to those used in the current study with the aid of both direct and indirect observations. These behaviour studies were conducted where the aft tapered section is joined to the extension, which is equivalent to where the aft end of the large mesh panel was situated in the current study. Krag et al. [13] divided the extension into three vertically stacked compartments. In the upper half of the extension (upper compartment), 54% of the cod, 87% of the haddock, and 50% of the lemon sole were caught. The same separation device was used by Krag et al. [5] in a study comparing direct and indirect observations of fish behaviour. Similar catch proportions were found, with 57% of the cod, 73% of the haddock, and 39% of the lemon sole caught in the upper compartment. However, length-dependent catch values were not given in either study. Compared to the escape behaviour values (contact likelihood) found in the current study for the large mesh panel, the catch values reported in Krag et al. [5,13] for the upper half of the extension are very similar. The similarity between these species separation successes and the panel escapement found in our study supports the assumption that not all fish come in contact with the large mesh panel. The comparable catch and escape proportions between Krag et al. [5,13] and the current study indicate that the fish that meet the panel escape through it.

For a fish to escape through a large mesh panel (or similar selective devices), it needs to come in contact with the panel. The 800 mm mesh size used in this study indicated the selective potential for large mesh panels in the aft tapered section of the trawl, as fish of all sizes could escape with ease. In general, there was a large effect of the panel for gadoids, a smaller effect for flatfish, and no effect for *Nephrops*. Relatively large by-catches in the *Nephrops* directed fisheries are a common problem [37-38]. The results of this study were in line with earlier reports of *Nephrops* behaviour [32,39], which stated that *Nephrops* are associated with the gear's lower part and often are observed rolling along the lower panel in the trawl. *Nephrops* use most of their energy in front of the trawl trying to out-swim the trawl using rapid tail flicks [40], which may explain the more passive selectivity process for *Nephrops* once they are inside the net. The selectivity of *Nephrops* in the trawl body seems to be determined solely by the trawl's lower panel, whereas the opposite may be true for most fish. In areas and fisheries where the catch of *Nephrops* makes up the majority of the catch value, large meshes could be used in the entire upper panel of the trawl body and wings. Such a design would improve the species selectivity in the fishery and reduce the drag of the gear, thereby saving fuel without a significant effect on the catch of *Nephrops.* However, as *Nephrops* of all sizes potentially can escape through the 120 mm mesh size in the panel of the standard trawl that corresponds to the large mesh panel in the experimental trawl, our approach, in which the selectivity in the 120 mm is excluded, cannot be used for *Nephrops.*

This study investigated the fish behaviour in the aft tapered section of the trawl, which generally is the transition part of the trawl where its inner volume is reduced from a relatively large open cone to a narrow cylindrical section leading to the codend. This volume reduction means that only fish in the centre of the volume of the trawl section can end up in the codend without either coming into contact with the gear's netting or actively avoiding this contact by swimming away from the netting. Observation studies of fish behaviour in trawls have shown that fish choose to avoid even large meshes and are herded by panels of netting when a clearer path is available [7]. Glass et al. [7] further observed that fish will penetrate the meshes surrounding them when alternative paths are blocked. In this study, the position of the large mesh panel just ahead of the extension may have created the illusion for the fish that their path was blocked and could therefore have triggered an active escape reaction. Attempts to further improve the contact likelihood between panel and fish could include experiments with stronger stimuli beneath the panel (e.g., mechanical blocking by netting or floats). Such experiments would be very relevant, as most of the selective devices implemented in European and other waters are square or large mesh panels for which the selective effect is given by the contact likelihood and the mesh size used.

The large mesh panel in this study was 12 m long (stretched length) and covered the length of the entire aft tapered trawl section. This section was gradually reduced from a diameter of about 1.4 m to about 0.7 m in diameter. Thus, the cross-section area of the inner volume was reduced by more than 75%. This substantial but gradual reduction should have given most sizes of fish an opportunity to escape through the large meshes. If the fish felt threatened in the aft tapered section and perceived the large meshes as an escape opportunity, we would have caught very few fish. However, this was not the case. The fish were apparently more herded by than drawn to the large meshes. It might be that the more ordered herding process, whereby the fish orientate themselves relative to the netting and keep a safe distance, might break up in small volumes (e.g., at the end of the aft tapered trawl section) and be replaced by a panic reaction. There are several unknown factors in the behavioural process, which, if known in greater detail, could be used to improve the efficiency of selective devices. Quantitative indirect behaviour studies such as this one in combination with direct observation techniques have the potential to generate this information.

Acknowledgements

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Appendix

Catch is collected separately in each of the two codends in a twin trawl. Except for one section, the design of the two legs in the twin trawl is identical (Figure 1).

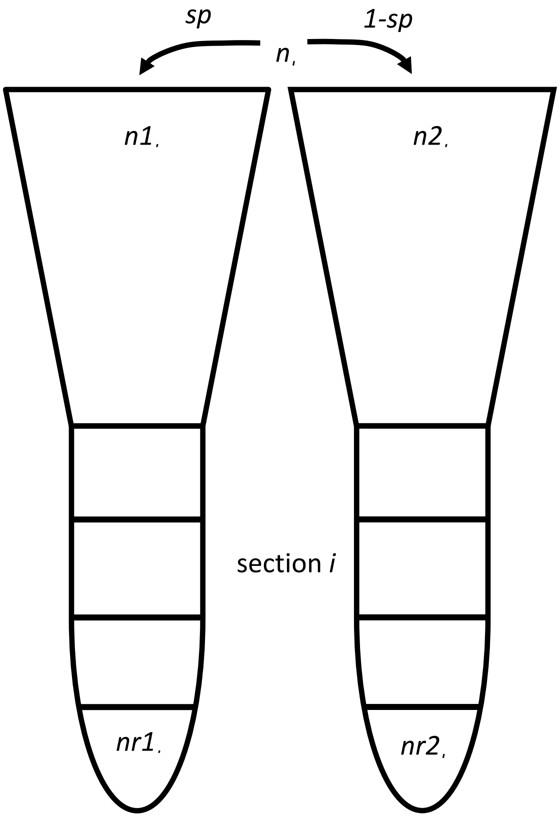


Figure 1. Drawing of the experimental twin trawl design of the.

Entry in the two legs is defined by the assumed length-independent split, sp:

$$n1_l = sp \times n_l$$

(A1)

$$n2_l = (1.0 - sp) \times n_l$$

The retained numbers are the numbers retained in each of the q-sections in the corresponding leg:

$$nr1_l = n1_l \times \prod_{i=1}^{q} r1_{il} = n_l \times sp \times \prod_{i=1}^{q} r1_{il}$$

(A2)

$$nr2_l = n2_l \times \prod_{i=1}^{q} r2_{il} = n_l \times (1 - sp) \times \prod_{i=1}^{q} r2_{il}$$

Where $r1_{il}$ is the retention likelihood for a fish entering section i in leg 1 given that it enters the section.

Comparing the catch in the two legs leads to the catch comparison, R_l:

$$R_l = \frac{nr1_l}{nr1_l + nr2_l} = \frac{sp \times \prod_{i=1}^{q} r1_{il}}{sp \times \prod_{i=1}^{q1} r1_{il} + (1-sp) \times \prod_{il}^{q2} r2_{il}} \qquad \text{(A3)}$$

Except for section j, the designs in the two legs are identical. Therefore we can assume:

$$r1_{il} = r2_{il} \; ; \; \forall \, i \neq j \qquad \text{(A4)}$$

This leads to:

$$R_l = \frac{sp \times r1_{jl}}{sp \times r1_{jl} + (1-sp) \times r2_{jl}} \qquad \text{(A5)}$$

Thus, the problem is reduced to modelling the size selection in section j of the two legs in the twin trawl. In leg 1, section j consists of an upper and a lower panel. Thus, for a fish to be retained during its passage in section j towards the codend, it must not escape through the upper or the lower panel. For a fish to escape through the upper panel, two conditions need to be fulfilled:

a) It comes into contact with the panel. Contact likelihood, $c1_{up_l}$.
b) It is morphologically able to pass through a mesh in the panel given that it contacts it. This morphological condition is described by the contact selectivity of the panel, $rc1_{up_l}$.

Thus, the escape likelihood for fish of length l through the upper panel of section j given that it enters section j is given by:

$$p1_{up_l} = c1_{up_l} \times (1 - rc1_{up_l}) \tag{A6}$$

Given that the fish does not escape through the upper panel, it has a secondary chance to do so through the lower panel. This likelihood can be modelled by:

$$p1_{low_l} = \left(1 - p1_{up_l}\right) \times c1_{low_l} \times \left(1 - rc1_{low_l}\right) \tag{A7}$$

$$p1_{low_l} = c1_{low_l} \times \left(1 - rc1_{low_l}\right) - p1_{up_l} \times c1_{low_l} \times \left(1 - rc1_{low_l}\right)$$

$$p1_{low_l} = c1_{low_l} \times \left(1 - rc1_{low_l}\right) - c1_{up_l} \times c1_{low_l} \times \left(1 - rc1_{up_l}\right) \times \left(1 - rc1_{low_l}\right)$$

Fish that do not escape through either the upper or lower panel in a section are retained. Thus, $r1_{il}$ is modelled by:

$$r1_{il} = 1 - p1_{up_l} - p1_{low_l}$$

$$r1_{il} = 1 - c1_{up_l} \times \left(1 - rc1_{up_l}\right) - c1_{low_l} \times \left(1 - rc1_{low_l}\right) + c1_{up_l} \times c1_{low_l} \times \left(1 - rc1_{up_l}\right) \times \left(1 - rc1_{low_l}\right) \tag{A8}$$

Similarly, for side 2 we get:

$$r2_{il} = 1 - c2_{up_l} \times \left(1 - rc2_{up_l}\right) - c2_{low_l} \times \left(1 - rc2_{low_l}\right) + c2_{up_l} \times c2_{low_l} \times \left(1 - rc2_{up_l}\right) \times \left(1 - rc2_{low_l}\right) \tag{A9}$$

Together, (A5), (A8), and (A9) form the basic modelling for the catch comparison.

We next look for a situation where the $rc1_{up}(l) \cong 0.0$ for all lengths up to a very large length, $l1_{up_{zero}}$, and where $rc1_{low}(l) \cong 1.0$, $rc2_{up}(l) \cong 1.0$, and $rc2_{low}(l) \cong 1.0$ for all lengths above a length $l1_{low_{max}}$.. Thus, for $l \in \left[l1_{low_{max}}; l1_{up_{zero}}\right]$, equations (A8) and (A9) simplify to:

$$r1_{jl} = 1 - c1_{up_l}$$

(A10)

$$r2_{jl} = 1$$

Insertion into equation (A5) then leads to:

$$R_l = \frac{sp \times (1 - c1_{up_l})}{1 - sp \times c1_{up_l}} \quad \text{(A11)}$$

which is similar to formula (4) in the main paper.

Tables

Table 1. Nominal and measured mesh sizes for the standard and experimental trawl.

Trawl	Gear section	Nominal mesh size (mm)	No. of meshes measured	Average mesh size (mm) ± SD	
				ICES 4 kg	EU 5 kg
Experimental	Large mesh panel	800	*	*	*
Experimental and standard		120	50	115.35 ± 2.56	119.79
Experimental	Codend	42	50	41.39 ± 1.10	43.05
Standard	Codend	42	50	41.66 ± 0.85	43.33

*The instruments available for measuring meshes in trawls were not capable of measuring such large meshes.

Table 2. Operational conditions during experimental fishing.

	Depth (m)	Door spread (m)	Wire length (m)	Speed (knots)	Wind (m/s)
Average	169.49 ± 35.69	200.78 ± 14.92	514.80 ± 64.09	2.85 ± 0.20	4.44 ± 4.27
Min–Max	24.6–213.8	144.6–210.4	232–556	2.0–3.2	0–16

Table 3. Fit statistics for the traditional catch comparison analysis.

Species	P-value	Deviance	DOF
Saithe	0.9511	47.35	65
Haddock	0.6622	37.65	42
Cod	0.0053	114.74	79
Witch flounder	0.9733	15.45	28
Lemon sole	0.2661	25.67	22
Nephrops	0.6765	41.12	46

DOF= degrees of freedom

Table 4. Simpler models derived from model 1 (*M1*). See text for details.

Model name	Equation
M2	$c(l) = c_2 \times logit(L_{50_c}, SR_c, l)$
M3	$c(l) = logit(L_{50_c}, SR_c, l)$
M4	$c(l) = c_1$

Table 5. Maximum lengths of fish that can escape through the 120 mm diamond panel in the standard trawl, which is equivalent to the large mesh panel section in the experimental trawl. The

values were based on mesh opening measurements made from flume tank observations combined with morphology-based FISHSELECT estimates of selectivity.

Species	**Maximum escape length**	**Reference**
Cod	33 cm	Herrmann et al. (2009)
Haddock	33 cm	Krag et al. (2011)
Saithe	33 cm	no data, used data for cod
Nephrops	all sizes can escape	Frandsen at al. (2010)
Witch flounder	28 cm	no data, used data for lemon sole
Lemon sole	28 cm	unpublished data

Table 6. Fit statistics and choice of model.

		Cod	**Haddock**	**Saithe**	**Witch flounder**	**Lemon sole**
Hauls excluded		none	1,2,3,4,5,7,8,9,19,21,24	8,21	5,6	none
Length range (cm)		34–112	34–61	34–112	28–50	28–35
AIC	M1	2618.49	205.33	**873.26**	600.30	111.73
	M2	**2616.49**	205.57	918.15	599.65	109.73
	M3	2628.93	**203.57**	916.15	597.65	107.73
	M4	2631.82	**203.14**	931.76	**596.84**	**105.94**
P-value	M1	0.0098	0.8319	0.6535	0.9018	0.6698
	M2	0.0124	0.7623	0.0006	0.8794	0.7839
	M3	0.0008	0.8073	0.0008	0.9103	0.8663
	M4	0.0004	0.7731	0	0.8963	0.9057
Deviance	M1	84.82	15.67	52.25	11.60	3.20
	M2	84.82	17.91	99.14	12.95	3.20
	M3	99.27	17.91	99.14	12.95	3.20
	M4	104.15	19.47	116.75	14.14	3.41
DOF	M1	57	22	57	19	5
	M2	58	23	58	20	6
	M3	59	24	59	21	7
	M4	60	25	60	22	8

Hauls that were excluded from the analysis due to low number of individuals are listed for the individual species. The model used in subsequent analysis is indicated in bold. For further description of models (M1–M4), see the text and Table 4. For lemon sole, a single bootstrap technique that did not account for between-haul variation was used due to weak data on the haul level. Thus, no hauls were excluded for lemon sole.

Figures:

Figure legends

Figure 1. (A) The upper panels in the experimental setup of the standard trawl (left) and the experimental trawl (right). Both trawls' lower sections are similar to the upper panel for the standard trawl. (B) The 800 mm large mesh panel inserted in a similar trawl design in a scale model (1:8) in the flume tank. See text for further explanation.

Figure 2. A map of Skagerrak showing the starting position of each trawl tow (black dots).

Figure 3. Traditional catch comparison analysis and populations retained in both the experimental and standard trawls. Solid lines are mean estimates and dotted lines indicate 95% confidence bands.

Figure 4. Top: Experimental data showing unexpected cup-shaped structure for cod and simulated data using the same population assuming selectivity in the 120 mm mesh panel of the standard trawl that corresponds to the large mesh panel in the experimental trawl. Bottom: Models assuming presence and absence of selectivity in the 120 mm mesh panel of the standard trawl that corresponds to the large mesh panel in the experimental trawl based on simulated data similar to the top plot. The contact with the large mesh panel (panel contact) is also included.

Figure 5. Estimated average escape behaviour (solid black curve) ± 95 % confidence limits (broken black curves),estimated mean retention (grey curve), and length based retention data (black dots). Length classes that could escape through the 120 mm nominal mesh size were excluded (see the text; Table 5). Only length classes included in the catch were included in the modelling for all species.

Figure 6. Length-based escape behaviour for all species (mean values).

Figure 7. Stochastic simulation of large mesh panel contact and escape behaviour through this panel using the population of cod above 33 cm long (see the text) (left plot), 5 times this population size (middle plot), and 100 times this population size (right plot).

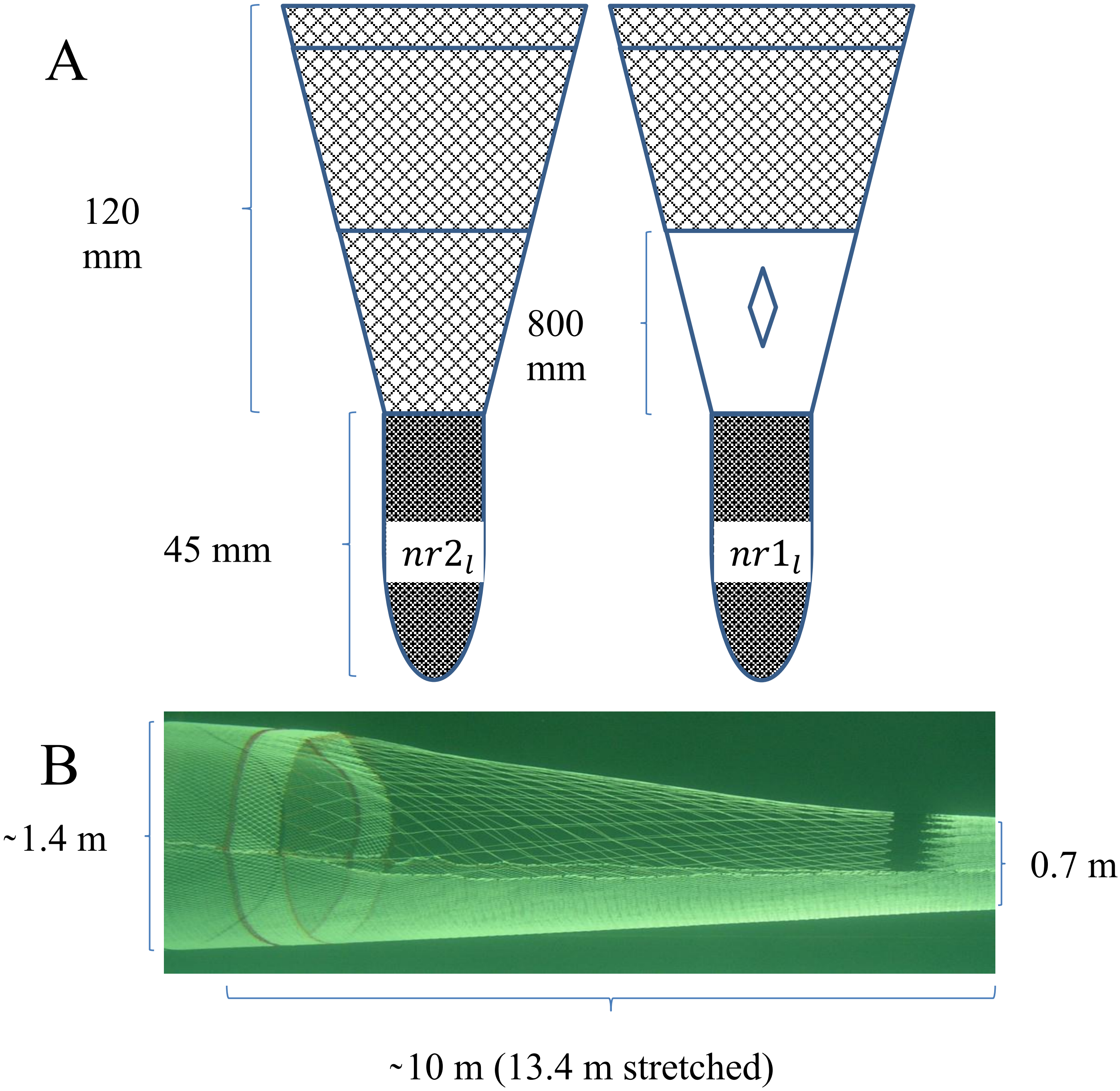


Figure. 1.

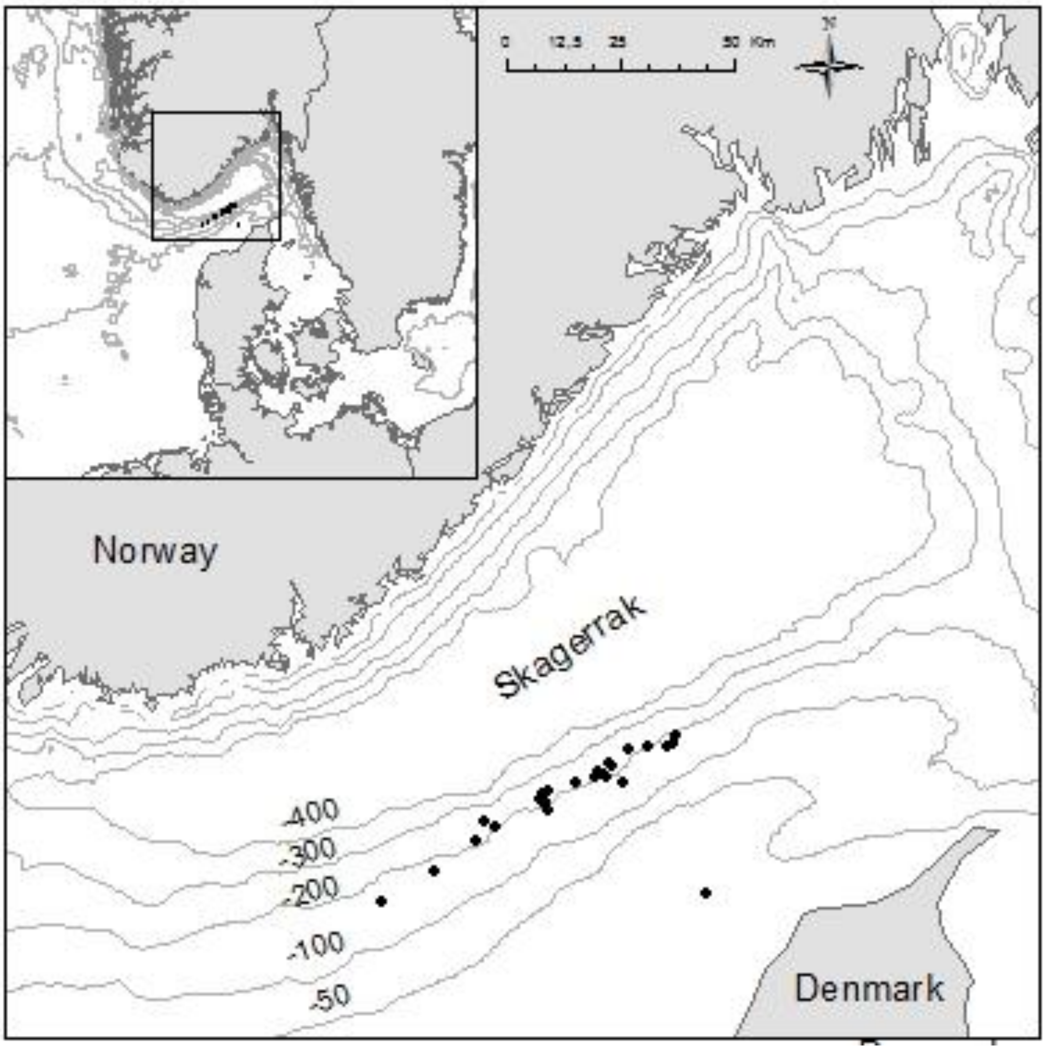
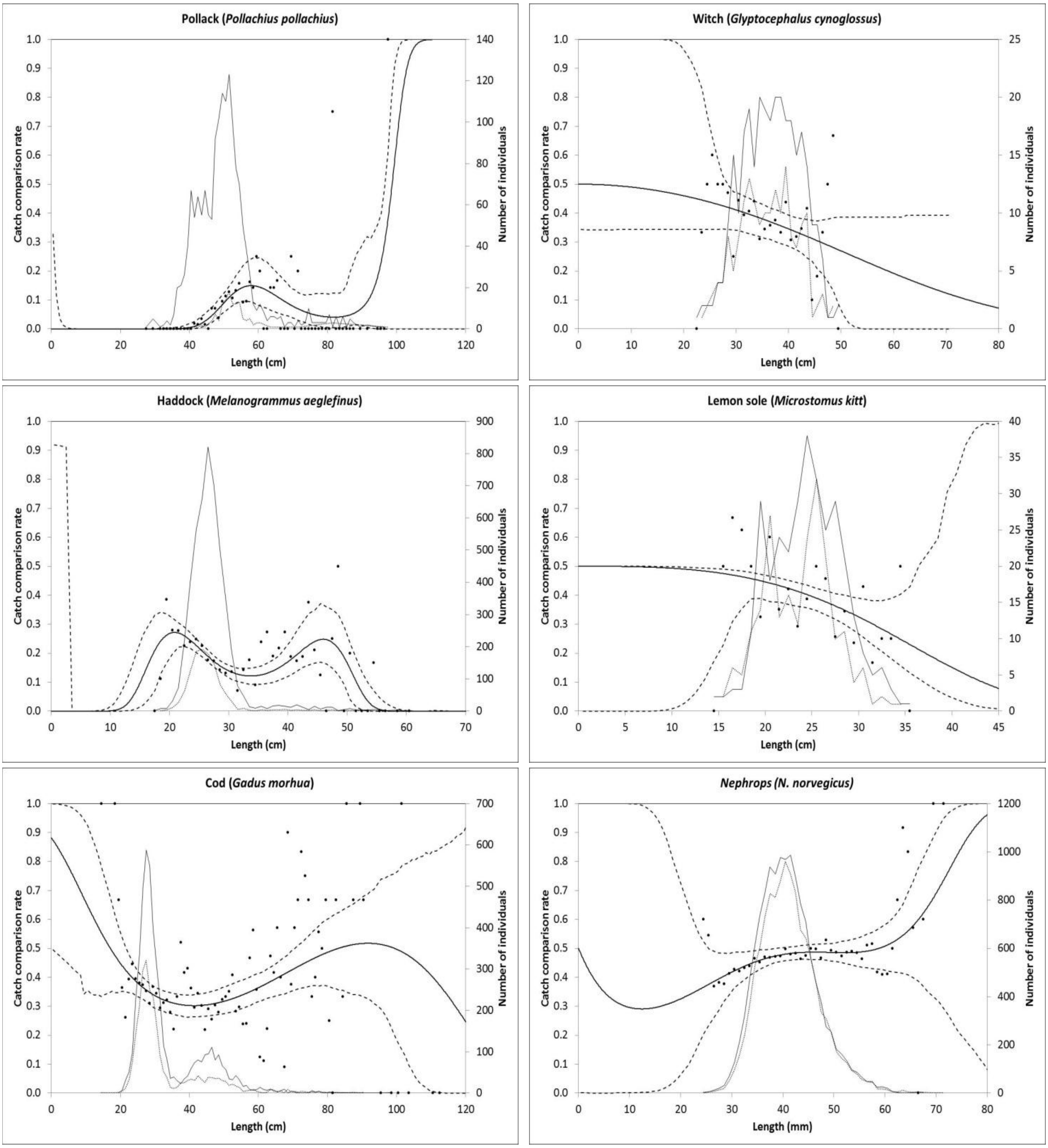


Figure. 2.



Pollack (Pollachius pollachius)
Witch (Glyptocephalus cynoglossus)
Haddock (Melanogrammus aeglefinus)
Lemon sole (Microstomus kitt)
Cod (Gadus morhua)
Nephrops (N. norvegicus)
Catch comparison rate
Number of individuals
Length (cm)
Length (mm)

Figure. 3.

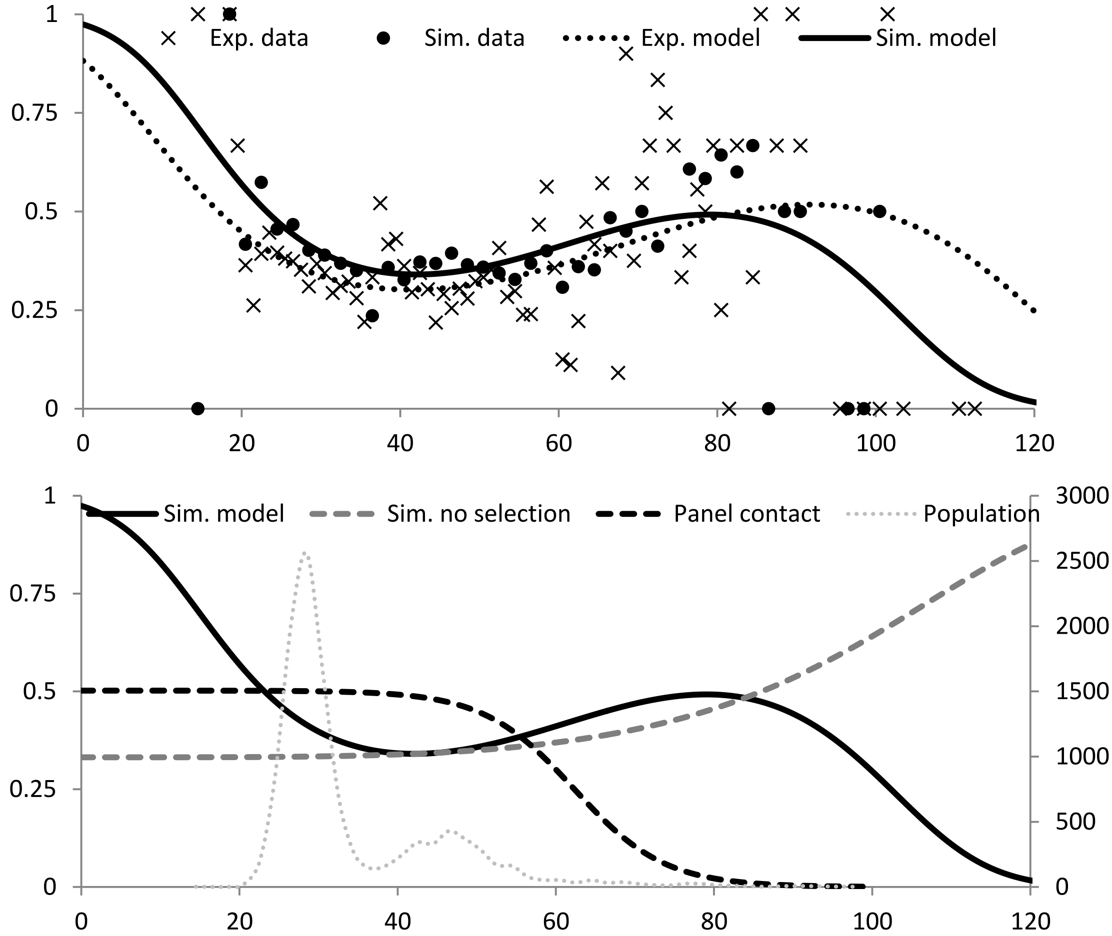
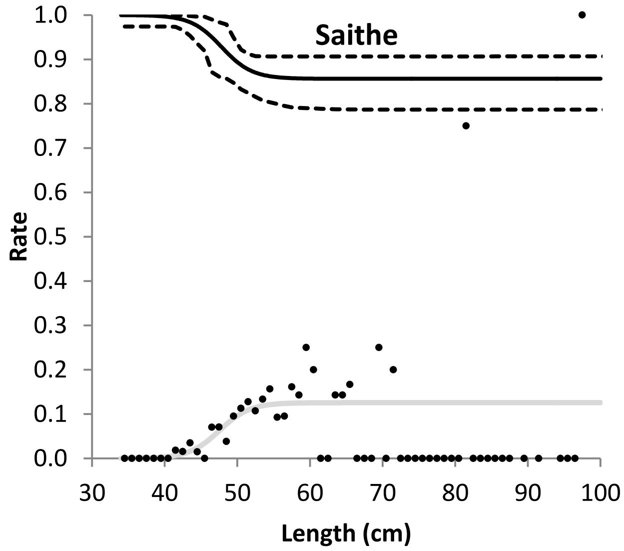
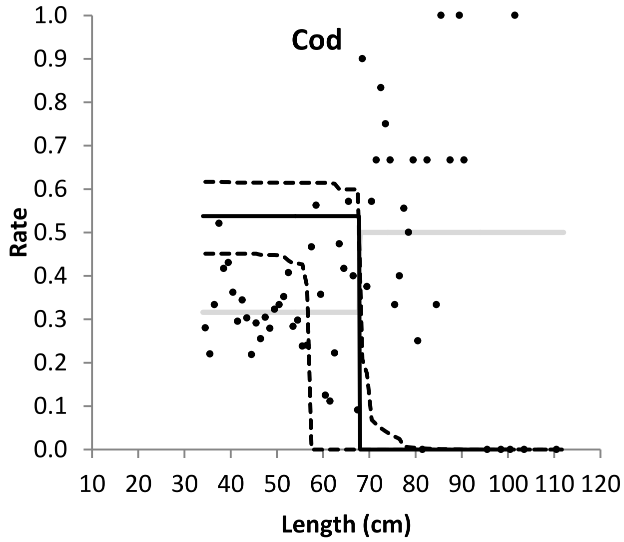
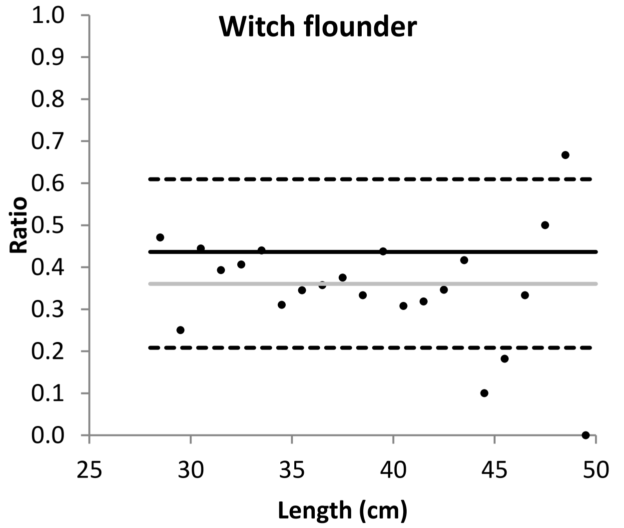
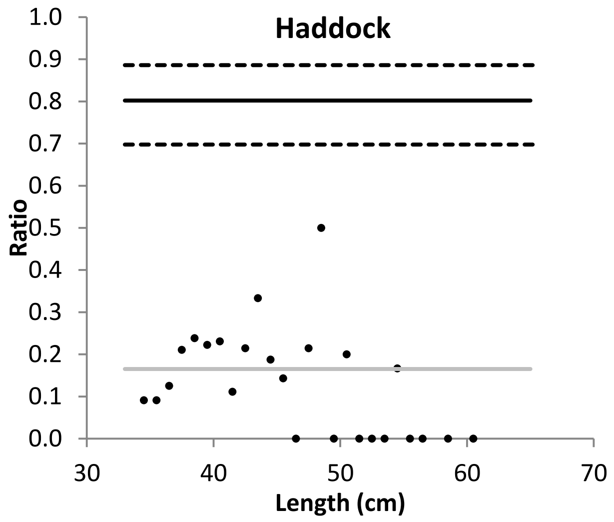

Exp. data
Sim. data
Exp. model
Sim. model
Sim. model
Sim. no selection
Panel contact
Population
0
0.25
0.5
0.75
1
0
20
40
60
80
100
120
0
500
1000
1500
2000
2500
3000

Figure. 4.


Saithe
Rate
Length (cm)


Cod
Rate
Length (cm)


Witch flounder
Ratio
Length (cm)


Haddock
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Ratio
30
40
50
60
70
Length (cm)

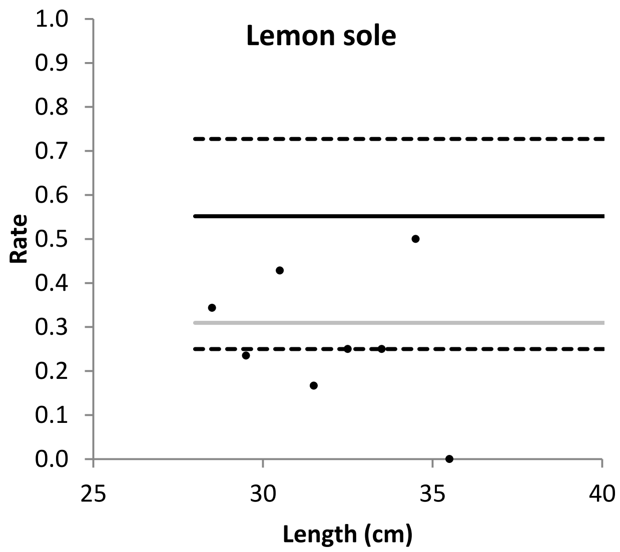

Lemon sole
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Rate
25
30
35
40
Length (cm)

Figure. 5.

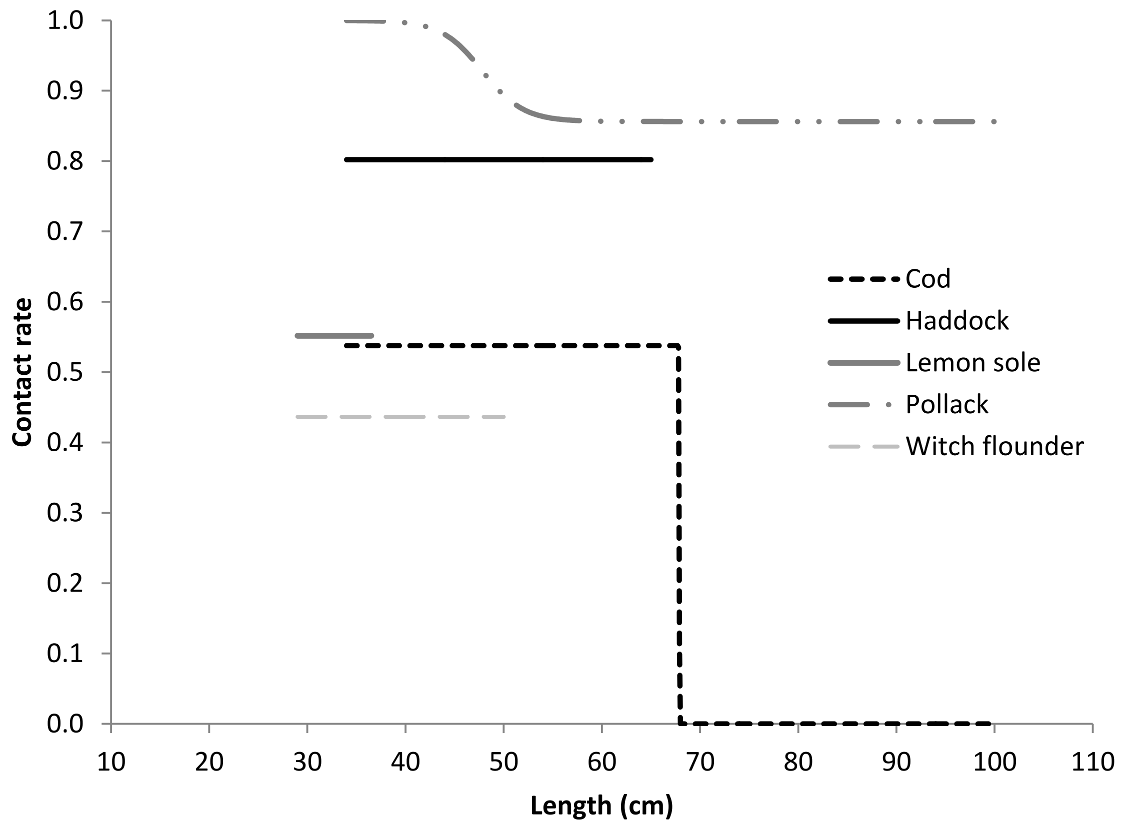

1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Contact rate
10
20
30
40
50
60
70
80
90
100
110
Length (cm)
Cod
Haddock
Lemon sole
Pollack
Witch flounder

Figure. 6.

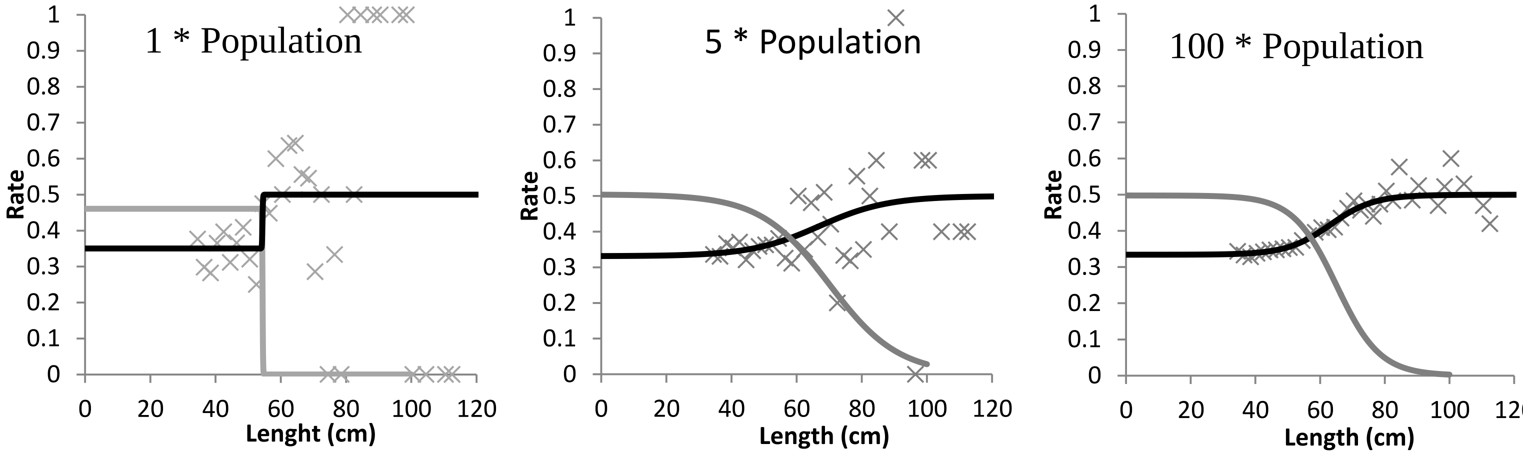

1 * Population
5 * Population
100 * Population
Rate
Lenght (cm)
Length (cm)
Length (cm)

Figure. 7.

Appendiks B: Twine-paper

The influence of twine thickness, twine number and netting orientation on codend selectivity

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Abstract

Based in an experimental Baltic trawl fishery, we tested diamond mesh codends with different twine thicknesses, twine numbers (single or double), and netting orientation (T0 or T90) to quantify the effects of the twine characteristics on the size selection of cod (*Gadus morhua*) and plaice (*Pleuronectes platessa*). For a given twine thickness: going from T0 to T90 increases selectivity of cod; while going from single to double reduce it. Increasing twine thickness reduces selection but the extent depends on whether the twine is single or double and whether the netting orientation is T0 or T90. In general, the results demonstrate the benefit of using a relatively thin single twine netting to ensure the appropriate size selection with round fish and the best results were obtained using netting with a T90 orientation. For a given twine thickness going from T0 to T90 decreases selectivity of plaice. Increasing twine thickness reduces selection for plaice. Our results demonstrate that very different selectivity results can be obtained using the same mesh size, simply by varying the twine thickness, the twine number, and the netting orientation. In some fisheries, the size selectivity could be improved considerably by adjusting these simple design parameters alternatively to produce more advanced and complex designs.

Keywords: cod, codend selectivity, diamond mesh, plaice, SELNET, size selectivity, T0, T90, twine thickness, twine number

1. Introduction

Because of its simplicity of construction and ease of operation, diamond mesh codends have traditionally been used to fish for round fish such as cod and haddock (*Melanogrammus aeglefinus*), and flatfish species such a plaice, at the aft end of demersal trawls in northern European fisheries (Graham et al., 2007; O'Neill and Herrmann, 2007; Krag et al., 2008). In recent years, the fishing industry has introduced stronger, stiffer, and thicker twines, which are often used as double twine netting, particularly in the designs of diamond mesh cod-ends used by many European trawl fisheries (Herrmann and O'Neill, 2006). Concerns about their effect on codend size selectivity led to restrictions on the maximum twine thickness and twine number allowed onboard EU fishing vessels. EU regulations, such as 850/1998 and 1967/2006, define the maximum twine thickness permitted in codends used in European waters. The maximum thickness of diamond meshes is 6 mm for double twines and 8 mm for single twine in northern European waters while it is 3 mm in the Mediterranean area. For the size selection of haddock , experimental studies (Lowry and Robertson, 1996; Kynoch et al., 1999) and theoretical studies (Herrmann and O'Neill, 2006; O'Neill and Herrmann, 2007) have demonstrated a significant decrease in the 50% retention length (*L50*) with increasing netting twine thickness for double twine diamond mesh codends. In particular, Herrmann and O'Neill (2006) formulated a set of hypotheses, using the simulation tool PRESEMO (Herrmann, 2005a), to investigate mechanisms that might potentially explain and quantify the effect of twine thickness on haddock size selection using traditional double twine diamond mesh codends (T0 cod-ends). The authors reported that an increase in twine thickness could lead to a reduction in selectivity, because: (i) the internal lateral mesh opening of meshes made of thicker twine would be smaller with the same knot-centre to knot-centre lateral mesh opening; (ii) the increased twine bending stiffness of thicker twines would increase the mesh resistance to opening; (iii) it would be more difficult for fish to deform and escape via partly open meshes compared with those made from stiffer twine; and (iv) netting made from thicker twine would present a greater visual barrier to fish, which may discourage them from making escape attempts. Thus, the effect of twine thickness on haddock size selection using traditional double twine diamond mesh codends have been well described in the scientific literature, based on experimental and theoretical investigations. From a mechanistic perspective, the effect of twine thickness on haddock size selection using double twine diamond mesh codends can probably be extrapolated to predict and understand the size selection of morphologically similar round fish species such as cod. However, this extrapolation is less likely to be applicable to flatfish species such as plaice, which has a very different cross-sectional shape compared with round fish species. In Baltic Sea trawl fisheries that target cod, the codends made solely from traditional diamond mesh netting has been banned in the legislation since 2003, while it is legal to use diamond mesh netting in combination with square meshes in the BACOMA design and codends where the diamond mesh netting direction is turned 90° (T90)(EU Regulation no. 2187/2005). The T90 codend, which for cod, is believed to have better size selectivity properties compared with the traditional T0 cod-end (Dahm, 2004), was introduced as a legal alternative to the BACOMA codend in the Baltic Sea cod trawl fishery during 2005. For a specific type of single twine netting, Wienbeck et al. (2011) have documented improved cod size selective properties when using T90 cod-ends compared with similar T0 cod-ends. However, Wienbeck et al. (2011) cautioned that their results are specific to the type of netting used for the cod-ends in their experiments and they recommended that a systematic study should be conducted to investigate the effects of twine parameters such as thickness and twine number on the size selectivity of T0 and T90 codends. Furthermore, the legislation describing the construction of T90 codends for the Baltic Sea trawl fishery did not define a specific twine thickness, although an upper limit of twine thickness for single and double twine codends was specified (EU Regulation no. 2187/2005 and EU Reg. No 686/2010). It is unknown to what extent the size selectivity properties of the T90 codend vary within the legal ranges for twine thickness below this maximum thickness and to what extent the twine number in the netting is important.

During trawl fishing, the codend meshes are stretched by hydrodynamic drag forces that act primarily on the accumulated catch in the aft (Herrmann, 2005b; Herrmann et al., 2006). However, difference in mechanical properties of the T0 and T90 codends mean that the shapes of their meshes can be very different during fishing, which can influence their size selectivity properties. According to Herrmann et al. (2007), the bending stiffness of the T0 codends mesh bar, which depends on the twine thickness, tends to keep the meshes closed. By contrast, an increased twine bending stiffness will increase the resistance against mesh closing with the T90 netting. Furthermore, the netting knot size, which increases with twine thickness, may also contribute to the benefit of turning the netting by 90°. These effects seem to favor the use of T90 constructions made of thick twine to achieve high L50 values.

However, some mechanisms that influence the effect of the twine thickness on size selection were described by Herrmann and O'Neill (2006), such as the ability of fish to partly deform the mesh bars during escape attempts and the visual barrier, which favors constructions based on thinner twine netting. These potentially counteracting mechanisms make it difficult to predict the overall effect of changing the twine characteristics (twine thickness and number) on the size selectivity of T0 and T90 cod-ends for round and flatfish species.

Given this lack of knowledge, the main aim of this study was to investigate and quantify the effect of twine thickness, twine number (single or double), and the netting orientation on size selectivity. Therefore, we formulated the following research questions: (i) to what extent does the twine thickness in the codend affect the size selection of round fish (cod) and flatfish (plaice)?; (ii) does it matter whether the codend is made of single or double twine netting?; (iii) do these twine characteristics affect the size selectivity of cod and plaice in different ways with the T0 and T90 codends?

2. Material and methods

2.1 Experimental design

To investigate the research questions regarding the effect of twine characteristics on codend size selection, we tested a total of 12 different codends made of six different commercial netting types (Fig. 1). All codends were made of polytit COMPACT netting (EuroRed S.L., Callosa de Segura, http://www.eurored.org). A T0 and a T90 codend were made from each netting type, resulting in six pairs of codends. Three pairs of nets were made of double twine netting (nominal twine diameter 3, 4, and 6 mm), and three pairs were made of single twine netting (nominal twine diameter 4, 6, and 8 mm). The actual twine diameter was estimated by scanning sample pieces of the different nets using a high resolution flatbed scanner and the image analysis facilities in the FISHSELECT program (Herrmann et al., 2009).

All codends were constructed with 50 open meshes in the circumference to comply with the current legislation for the Baltic Sea trawl fishery regarding this design parameter for T90 codends. A symmetrical two-panel construction with identical upper and lower panel was used for all codends. All codends had the same number of meshes in the two selvedges (three). We attempted to keep the mesh size identical for all codends (approximately 123 mm), although it differed slightly between the different nettings. The mesh size was measured using an OMEGA-gauge (Fonteyne et al., 2007; Council Regulation (EC) No 517/2008 of 10 June

2008). Based on their construction and twine characteristics, all of the T90-codends described in Fig. 1 can be used legally in the demersal Baltic Sea trawl fishery.

Each of the 12 codends was fished alternately, one at a time, while attached to the same trawl and the same extension piece. The trawl used was a "Codhopper," which has a circumference of 530 meshes and a 160 mm mesh size in the belly. The trawl was spread using two 3.5 m^2 Bison trawl doors. The extension piece was a T90 construction with 50 open meshes around and 50 meshes in length, made of nominal 120 mm single 5 mm netting using the same polytit COMPACT netting that was used for the codends. The codend was the only change in gear between the individual tows.

The covered codend method (Wileman et al., 1996) was applied. Supporting hoops were applied to keep the cover netting clear of the test codend. The cover was connected to the extension piece two mesh rows before the codend. The cover was 238 meshes long. The 2.6 m diameter of the cover hoops ensured that the diamond shaped cover meshes were almost open like square meshes. The cover was a two panel construction with a total of 264 meshes in circumference. The cover mesh size was 80 mm because previous experience during experimental fisheries in the same region demonstrated that fishing with a smaller cover mesh size was impossible because of the retention of large amounts of herring in the cover (Wienbeck et al., 2011). Compared with the recommendations of Wileman et al. (1996), this cover mesh size was rather large compared with the test codend mesh sizes (Table 1). Therefore, special attention was given in the analysis to remove length classes where the selection of cover and test codend potentially overlapped. The experimental fishing was conducted onboard the German Fishery Research Vessel (FRV) "Solea" (total length = 42 m, 950 kW). To make the conditions as similar as possible for each codend, all hauls were conducted on the same fishing ground.

2.2 Data analysis

To model the size selection of cod and plaice for the individual hauls, we used a logistic curve described by the parameters *L50* and the selection range *SR* (= *L75* - *L25*) (Wileman et al., 1996). The capacity of the logistic curve for modeling the data from individual hauls was inspected based on the fit statistics, i.e., the *p*-value and model deviance versus the DOF degrees of freedom (DOF), following the procedures described by Wileman et al. (1996). In case of a poor fit statistic (*p*-value > 0.05; deviance >> DOF), the residuals were inspected to determine whether the poor result was due to structural problems when modeling the experimental data using the logistic curve or if it was due to the overdispersion of the data. To be able to quantify the strength of the data linked to the amount of binominal noise within it, the R^2-values were also calculated to the ability of the logistic model to describe the experimental data. The R^2-value quantifies the ratio of the variation in the data explained by the model to the total amount of variation in the data. To avoid potential bias in the analysis due to cover selection, the data for length classes below 33 cm were not used for cod, following the procedure described by Wienbeck et al. (2011).

The same method for checking the potential bias due to the cover selection, which as described for cod by Wienbeck et al. (2011), was also applied to plaice prior to the experiments. This found that it is unlikely that any of the available sizes of plaice (> 14 cm) would have passed through the cover meshes. Therefore, no plaice length classes were eliminated from the data analysis. To account for the effect of minor differences in mesh sizes between the different codends (Table 1), the analysis was based on the selection factor *SF* (= *L50/mesh size*) and selection ratio *SFA* (= *SR/mesh size*), instead of *L50* and *SR*. Therefore, the results from single hauls were transformed from an L50-SR domain to an SF-SFA domain, before the next steps in the analysis (Herrmann and O'Neill, 2006). After the last step in the analysis, the results can be transformed back to the traditional L50-SR domain by multiplying with the specific mesh size. This makes the results directly comparable for the different codends with the different twine characteristics (twine thickness, twine number, and netting orientation).

The data were analyzed using the software tool SELNET. SELNET is a flexible software tool that was developed to acquire and analyze size selectivity and catch data for towed fishing gears, both at the haul level and for a group of hauls. The methods implemented in SELNET comply with the recommendations for the analysis of size selectivity data, which were described by Wileman et al. (1996) and in Fryer (1991). SELNET was developed by the corresponding author of the current study and additional information on SELNET can be obtained directly from him or by consulting the following references (Sistiaga et al., 2010; Wienbeck et al., 2011; Frandsen et al., 2011; Eigaard et al., 2011; Herrmann et al., 2012).

The analysis applied considered the between-haul variation in the selection process and the effect of codend design parameters, following the procedure described by Fryer (1991). This involves a two-step procedure, as follows. First, analyzing the hauls individually by fitting a logistic curve to the data, as described above. The second step uses the results from all the individual hauls simultaneously for the *SF* and *SFA*, together with their covariance matrix and information on the values of the design parameters *td (twine thickness in mm)*, *DO (double twine:0.0 for single twine netting; 1.0 for double twine netting)*, and *T90* (T90 orientation: 0.0 for T0 orientation netting; 1.0 for T90 orientation netting) for the codends used in each of the hauls. The data were analyzed species by species, while considering the codend design parameters *td*, *DO*, and *T90* as potential fixed effects for *SF* and *SFA* (see Table 1). A special model with the following form was constructed and applied in SELNET (see appendix for model development and justification).

$$SF = f_0 + f_1 \times td + f_2 \times td^2 + f_3 \times T90 \times td + f_4 \times DO \times td + f_5 \times T90 \times DO \times td + f_6 \times T90 \times td^2 + f_7 \times DO \times td^2 + f_8 \times T90 \times DO \times td^2 + f_9 \times w$$

$$SFA = g_0 + g_1 \times td + g_2 \times td^2 + g_3 \times T90 \times td + g_4 \times DO \times td + g_5 \times T90 \times DO \times td + g_6 \times T90 \times td^2 + g_7 \times DO \times td^2 + g_8 \times T90 \times DO \times td^2 + g_9 \times w$$

(1)

Compared with equation (A2) in the appendix, this equation: (1) includes additional linear terms ($f_9 \times w$ and $g_9 \times w$) to model the potential general linear effect of the codend catch weight on the codend size selection. W is the total codend catch weight at end of the haul. The codend catch weight is included in the model as a potential fixed effect because it is expected to vary between individual hauls and because some authors have found that it can potentially affect the codend size selection in diamond mesh codends (O'Neill and Kynoch, 1996; Herrmann, 2005b). Thus, equation (1) is used to model the effect of the twine characteristics on the *SF* and *SFA* for different codends, while accounting for the potential general effect of the codend catch weight. The species-specific parameters $f_0 \ldots f_9$ and $g_0 \ldots g_9$ have to be estimated while fitting the model to datasets with values for SF and SFA, based on the experimental selectivity results from the individual hauls. Model selection was performed for each species separately based on the AIC value (Akaike, 1974), while considering every possible simpler sub-model following the procedure described in Wienbeck et al. (2011). This resulted in a total of 1048576 models that needed to be run and tested for each species in SELNET.

Before making conclusions regarding the effects of twine thickness and twine number for cod and plaice based on the selected models, it was important to check that the models agreed with the results from the individual hauls, on which they were based. Thus, we considered the uncertainty of the individual results and inspected whether the model prediction appeared to reflect the main trends for the effects of twine thickness on the results for each codend category: $T0_{single}$ (DO=0;T90=0), $T0_{double}$ (DO=1;T90=0), $T90_{single}$ (DO=0;T90=1), and $T90_{double}$ (DO=1;T90=1) (see Table 1). The individual codends used in the experiments did not have the same mesh opening. Therefore, it was also necessary to follow the trends in the L50 and SR values for the individual codends to calculate the corresponding *L50* and *SR* values for a theoretical 120-mm mesh opening simply by multiplying the individual *SF* and *SFA* values by 12. The corresponding confidence limits (CI) for the individual codends were also determined simply by multiplying the lower and upper limit values for the *SF* and *SFA* by 12. The estimates for a mesh size of 120 mm were of particular interest for the Baltic Sea trawl fishery, because this is the minimum legal mesh opening for the T90 codend used in that fishery. After inspecting whether the results from the individual hauls conflicted with the model predictions, it was necessary to consider the estimates of the between-haul variation in the selection process in addition to the uncertainty of the haul results. Therefore, the individual haul results were plotted for the *L50* and *SR* with 95% CI versus the mean model estimated values and the predicted 95% CI for the between-haul variation. The lower and upper 95% CI for the estimated between-haul variation in the selection parameters (lim L50, lim SR) for a mesh size of 120 mm were calculated by:

$$lim\ L50 = 12 \times \left(SF \pm 1.96 \times \sqrt{D_{11}}\right)$$

$$lim\ SR = 12 \times \left(SFA \pm 1.96 \times \sqrt{D_{22}}\right) \qquad (2)$$

where *SF* and *SFA* are the predictions based on the selected submodel based on (1), and D_{11} and D_{22} are the diagonal elements in the estimated between haul-variation matrix for the selected model (for details see Fryer, 1991).

The effect of turning the net orientation by 90° from T0 to T90 with the different codend categories ($T0_{single}$, $T0_{double}$, $T90_{single}$ and $T90_{double}$) was given as a percentage effect (p_T90) for the 120 mm nominal mesh opening. The mean percentage effect for L50 (p_T90_{L50}) was predicted using the resulting submodels (1) with the parameters DO and T90 for a range of twine thickness values *td* to estimate the pairs of *L50* for the T0 and T90 designs:

$$p\_T90_{L50} = \frac{L50_{T90} - L50_{T0}}{L50_{T0}} \times 100 \quad (3)$$

A similar approach was used for *SR*.

3. Results

3.1. Collection of selectivity data

The experimental fishing trials were conducted between 18 March and 7 April 2011 in the Arkona Basin, western Baltic Sea. The water depths varied between 32 and 49 m in the fishing grounds. The average towing speed (GPS speed over ground) was 3.4 knots (range of 3.2–3.6 knots). The haul duration was between 90 and 180 min (mean = 150.2 min). The size selectivity data for cod and plaice were collected from a total of 43 valid hauls. The catch information for each haul are described in Table 2. In addition to cod and plaice, the most abundant catch species in the codend catch was flounder (*Platichthys flesus*) while the cover catch also contained large quantities of herring and sprat. The total catch weight in the codend varied from 180 to 1266 kg. A total of 64376 cod measuring between 13 and 103 cm were caught and their lengths were measured to the nearest cm. We used 47276 cod measuring >33 cm and their data in the analysis. For plaice the length span was 14 to 50 cm and a total of 13760 were caught and measured. The total number of cod (>33 cm) in the test codend ranged from 130 to 1370 individuals, and from 155 to 2253 in the cover. The number of plaice in the test codend ranged from 42 to 319 and from 52 to 420 in the cover. The high number of target species (cod and plaice) caught in most hauls, combined with no subsampling provided strong data for cod in particular, with very little binominal noise in the size selection data.

3.2 Analysis of the cod data

As described in section 2.2, a logistic curve was fitted to data from individual hauls to estimate the selectivity parameters (L50 and SR) and the corresponding SF and SFA values. Table 3 summarizes the results from individual hauls of cod. Inspection of fit statistics indicated that there were no problems with using a logistic curve to describe the selection data for all hauls, except for haul no. 4 (p-value = 0.02). The inspection of the residuals for haul 4 did not indicate any structural problems with using the logistic curve to model the experimental data. Therefore, we considered that the lack of fit was caused by overdispersion of the data so we were confident about applying the logistic curve to model the size selection of cod in all hauls. In general, high R^2-values were obtained, i.e., all but one was >0.8 and only 4/43 were <0.90 (Table 3). In addition to the capacity of the model for describing the data, these high R^2-values also highlighted the low binominal noise in the data as a consequence of strong data acquisition because many cod were measured and no subsampling was applied.

The values for L50 ranged from 29.84 cm to 45.63 cm, which did correspond to the SF values of 2.40 and 3.64. The highest values were obtained for hauls 7 (T90S4), 1–4 (T90D4), 8 (T90S4), 17 (T90D3), and 29–31 (T0S4) (Table 3). By contrast, low L50 and SF values were determined for haul 35 (T0S8) and hauls 39–41 (T0D6). The range of values for SR and SFA were 4.43 cm to 11.08 cm and 0.36 to 0.89, respectively. Thus except for codend T0D6 the data included in the analysis covered most of the selective range (from zero retention (r(l) = 0.0) to full retention (r(l)=1.0). For T0D6 detail inspection of results showed the data coverage at the lowest length class (33 cm) varied from r = 0.55 to r = 0.70. This increase the uncertainty when evaluating the validity of the logit curve to model the size selection of the full selection curve for this codend design and increase confidence limits for the estimated SF and SFA values (link Table 2 and 3). But given the fact that none of the results for the other codends indicated problems by applying the logit curve to model the size selection in individuals we assume that is this also valid for the T0D6 design even if the SF and SFA values are based on extrapolation of the estimated logit curve. Therefore despite of the poor coverage of the selective range for the hauls with the T0D6 codend we have chosen also to use the results for this codend in the further analysis. This is further defended by that in the further step of the analysis is the uncertainties in the individual hauls accounted for. Specifically is the uncertainty in the individual haul *SF* and *SFA* values modeled as within haul variation and therefore automatically accounted for in the analysis (see Fryer (1991) for further details on this).

To estimate the general effects of the design parameters *td*, DO, and T90 on the codend size selection of cod, we analyzed model (1) and each simpler submodel that could be derived from this model, before comparing them. This evaluation was based on the results for the SF and SFA for all 43 hauls, as described in section 2.2. For cod, this resulted in the following model (model (4)).

$$SF = f_0 + (f_2 + f_6 \times T90 + f_7 \times DO) \times td^2$$

$$SFA = g_0 + g_3 \times T90 \times td \qquad (4)$$

Model (4) shows that all three design parameters, i.e., *td*, DO, and T90, were estimated to affect the SF and thus the L50. For SFA, the design parameter DO, which quantified the difference between using single and double twine netting, was absent from the best model. Table 4 lists the details of model (4).

Because f_2 was significantly less than zero (see Table 4), an increase in the twine thickness resulted in a decrease in SF, and thus L50. This effect was much stronger for double twine nettings because the parameter f_7 was close to the value of f_2 and it was also significantly less than zero. Based on the estimated f_6 value, which was significantly larger than zero, turning the netting by 90° would reduce the negative effects of the twine thickness and twine number on the SF and L50. Nevertheless, this T90 effect was not sufficiently strong to fully compensate for both negative effects. Consequently, the overall effect would be a slight decrease in the SF with an increase in the twine thickness.

However, inspecting the confidence intervals for f_2 and f_6 showed that the predicted decrease in SF with an increase in twine thickness for single twined T90 codends was not significant because the upper limit for f_6 was more than the limit for f_2, which was closest to zero. By contrast, for double twine codends, the confidence interval for f_6 did not overlap with the confidence interval for the combined negative effect of f_2 and f_7. Thus, for double twine T90 codends, we estimated that there was a significant decrease in SF with an increase in twine thickness. Because the sum of f_6 and f_7 is also negative, the model predicts a lower SF for a double twine T90 codend compared with a similar T0 single twine with the same twine thickness. This effect was not statistically significant according to Table 4.

For SFA and thus also SR, model (4) predicted no effect of twine thickness for T0 codends ($T0_{single}$ and $T0_{double}$) and no difference in the values for single and double twined T0 codends. For T90 codends, there was a significant decrease in SFA with an increase in twine thickness. The model predicted that this effect would be identical for single and double twine T90 codends. Fig. 2 shows the predicted mean effect on the L50 and SR, depending on the twine thickness for cod in a codend with a 120-mm mesh size based on model (4). Table 4 shows the four different codend categories based on the predicted values for SF and SFA with corresponding rescaling to the L50-SR domain for a mesh size of 120 mm (see section 2.2).

Fig. 3 shows the L50 and SR values (rescaled to 120 mm) for the individual hauls for the four different codend categories, depending on the codend twine thickness. The CI for the individual haul parameters are indicated, as well as the predicted between-haul variation in the selection process (see model (2) and Table 4).

For all four codend categories, model (4) could reproduce the main trends of the effect of the twine thickness on L50 and SR, which was found in the experimental results (Fig. 3). None of the results for any of the 43 hauls were found to be in direct conflict with the models for either L50 or SR after inspecting the CI for the estimated values in the individual hauls and for the predicted between-haul variation in the selection process. Thus, we were confident when applying the model to make predictions.

Model (4) was used to predict the effect of an increase in twine thickness on the mean values for L50 and SR with a 120-mm codend mesh size (Table 5). In addition, the percentage effect of turning the netting by 90° (from (T0 to T90) was estimated for different twine thicknesses (see formulae (3))

The percentage effect on L50 by going from T0 to T90 orientation increased with the twine thickness. This was found to have a more profound effect with double twine netting compared with single twine netting. For twine thickness at 2 mm the effect is predicted to be 1.22% for single twine and 1.24% for double twine. For twine thickness at 8 mm the effected is predicted to be 26.33% for single twine and 39.34% for double twine. According to the model, however, this positive effect could not compensate for the negative effect that the increased twine thickness had on the T0 baseline value. For cod, therefore, the model predicted a decrease in the L50 with an increase in the codend twine thickness for T0 and T90 codends. Nevertheless, this effect was not significant for the T90 single twine codends. For the codend category T0 with a single twine, the effect of increasing the twine thickness from 2 mm to 8 mm was predicted to reduce the L50 from 41.56 cm to 30.80 cm. This was a drop of 10.76 cm, which corresponded to >25%. This effect was more profound with double twine T0 codends, where increasing the twine thickness from 2 mm to 6 mm reduced the L50 by >26%.

For SR, the percentage effect of turning the netting to T90 increased with the twine thickness (Table 5). Thus, using a thicker twine tended to decrease the SR with T90 codends.

3.3 Analysis of the plaice data

As with cod, a logistic curve was fitted to the size selection data for plaice captured in individual hauls to estimate the selectivity parameters (L50 and SR) and the corresponding SF and SFA values for individual hauls. Table 6 summarizes results for individual hauls of plaice. An inspection of the fit statistics indicated that there was no problem with using a logistic curve to describe the selection data for all hauls, except for hauls no. 14 and no. 40 with *p*-values of 0.0029 and 0.0035, respectively. An inspection of the residuals for hauls 14 and 40 did not indicate any structural problems with using the logistic curve to model the experimental data in either of these hauls. Therefore, we considered that the lack of fit was caused by overdispersion of the data so we were confident about using the logistic curve to model the size selection of plaice in all individual hauls. Furthermore, the high R^2-values, where the lowest value was 0.74 and only 3/43 values were <0.91, highlighted the power of the data based on the very low binominal noise.

To estimate the general effect of the design parameters *td*, DO, and T90 on the codend size selection of plaice, model (1) and all simpler submodels were analyzed and compared. This evaluation was based on the results for the SF and SFA for all 43 hauls we conducted (see section 2.2). For plaice, this resulted in the following model (model (5)).

$$SF = f_0 + f_1 \times td + f_3 \times T90 \times td + f_5 \times T90 \times DO \times td$$

$$SFA = g_1 \times td + g_2 \times td^2 + g_3 \times T90 \times td$$

(5)

Model (5) shows that all three design parameters, i.e., td, DO, and T90, were estimated to affect the SF and thus the L50. For SFA, the design parameter DO, which quantified the difference between using single and double twine netting, was absent from the best model. Table 7 shows the details for model (5).

Table 7 shows that an increase in the twine thickness (TD) tended to decrease the SF, and thus the L50, for all four categories of codends, because parameter f_1 was significant less than zero. For the T0 types of codends ($T0_{single}$ and $T0_{double}$), the effect was predicted to be identical. For T90 codends, the decrease in SF with an increase in the twine thickness would be even bigger because f_3 and f_5 were significantly less than zero. Thus, the biggest decrease in SF with an increase in the twine thickness was found with the codend type $T90_{double}$ whereas the lowest was with the two T0 codend types.

For visualization purposes, the predicted SF values were transformed to L50 values for the 120 mm nominal mesh size, as for cod. The increase in the L50 with increasing twine thickness is shown in Fig. 4 for the four different codend categories. The L50 tended to decrease monotonically for all four codend categories with a twine thickness in the range of 2 mm to 8 mm (Fig. 4).

For the SFA model (5) containing first order and second order terms for the effect of twine thickness (g1 and g2) with opposite signs, this relationship was more complex and it need to be inspected for specific values of twine thickness. However, turning the netting orientation to a T90 orientation tended to decrease the SFA and this effect increased with the twine thickness because g_3 was significantly less than zero (Table 7). Fig. 4 plots the predicted effect of the twine thickness on SR with a 120-mm codend mesh size.

Fig. 5 shows the rescaled (for a 120-mm mesh size) L50 and SR values for plaice in the individual hauls for the four different codend categories, which depended on the codend twine thickness. The CI for the individual haul parameters are shown, as well as the predicted between-haul variation in the selection process (see formula (2) and Table 7).

For all four codend categories, model (5) reproduced the main trends of the effect of twine thickness on the L50 and SR, which were found in the experimental results (Fig. 5). For plaice, none of the results for any of the 43 hauls were in direct conflict with the model for either the L50 and SR, after inspecting the CI of the estimated values in the individual hauls and the predicted between-haul variation in the selection process. Thus, we can be confident when applying the model for plaice predictions.

Model (5) was used to predict the effect of an increase in the twine thickness on the mean value for L50 and SR with a 120-mm codend mesh size (Table 8). In addition, the percentage effect of turning the netting by 90° (from T0 to T90) was estimated for different twine thickness (see formulae 3, section 2.2).

In contrast to cod, the percentage effect of changing the netting orientation to T90 decreased with the increasing twine thickness for plaice. In addition, the effect was more profound for double twine netting compared with single twine netting. The effect with 2 mm twine was predicted to be -3.91% and -6.31% for single and double netting, respectively, but this effect increased to -16.83% and -27.15%, respectively, after increasing the twine thickness to 8 mm. For both T0 codend categories, increasing the twine thickness from 2 mm to 8 mm was predicted to reduce the L50 from 25.30 cm to 23.52 cm, which corresponded to a drop of 7%. The effect was more pronounced with T90 codends.

For SR, the percentage effect of turning the netting to T90 increased with the twine thickness (Table 8). This was based on the increase of the SR with thicker twine when applied in T0 codends. By contrast, the SR tended to be less dependent on the twine thickness with T90 codends.

4. Discussion

This research addresses the effects of codend twine thickness and twine number on the size selectivity for round fish and flat fish species when using traditional T0 codends and T90 codends. This investigation is based on a case study of cod and plaice with experimental fishing in the Baltic Sea where both species are important for trawl fisheries (Probst et al., 2011). Based on an assumption that the fish morphology has a major role in the codend size selection process (Herrmann, et al., 2009; Frandsen et al., 2010; Krag et al., 2011; Herrmann et al., 2012), we expected that the trends in the results obtained for cod could be extrapolated to other round fish such as haddock due to similarities in their morphology (Sistiaga et al., 2011). Similarly, we expected that the trends in the results for plaice could be extrapolated to other flat fish species. This extrapolation relies on morphological similarities and it might be affected by differences in fish behavior.

For cod, the results for single and double twine T0 codends documented that the L50 decreased with increases in the twine thickness. This effect was more pronounced for double twine T0 codends. These results are in agreement with previously reported results for haddock (Lowry and Robertson, 1996; Kynoch et al., 1999; Herrmann and O’Neill, 2006; O’Neill and Herrmann, 2007) and they follow the same pattern as that observed in a Mediterranean study of other species (Sala et al., 2007). Our results for cod show that turning the netting orientation from T0 to T90, both for single and double twine netting, provided a significant increase in the L50 values and this effect increased with the twine thickness. These findings are logical when we consider the mechanical-based explanation given by Herrmann et al. (2007) to account for the effect of turning a diamond mesh netting by 90° (T90). For the double twine T90 codends, however, this positive effect was more than compensated for by the negative effect that an increase in the twine thickness had on the baseline T0 codend. Consequently, the L50 values decreased significantly with increasing twine thickness for double twine T90 codends. Thus, despite the positive effect of turning the netting, there was a decrease in the L50 values for cod with an increase in the twine thickness for double twined T90 codends.

In addition to the positive effect of increasing the twine thickness on the size selectivity with a T90 construction, this result highlights the importance of considering the other, and potentially counteracting, mechanisms described by Herrmann and O'Neill (2006). For the T90 single twine codends, our results indicate that these counteracting mechanisms can almost compensate for each other, resulting in only a slight decrease in the predicted L50 for cod with an increase in the twine thickness. Furthermore, the predicted decrease was not significant. Therefore, it cannot be ruled out that the counteracting mechanisms completely compensated for each other with this type of codend, resulting in a size selection process that did not depend on the twine thickness for cod. For cod, and potentially other round fish in general, the results obtained using double twine codends showed there was a significantly reduced size selection with T0 and T90 codend constructions. Therefore, improved size selectivity could be obtained by simply changing from double twine, which is the current commercial practice, to single twine codend netting. In general, our results demonstrated that using nets with a thinner twine in a single twine codend construction provided the highest L50 values. In the current experiments, the best results were obtained with a single twine T90 codend construction. Furthermore, the performance of this codend type appeared to be highly insensitive to the choice of twine thickness.

In addition to improved selectivity based on L50 estimates, the T90 constructions were predicted to allow a more acute size selection with smaller SR values. This appears to favor this type of codend for size selection with round fish. This effect may be because the meshes in the T90 codends are predicted to open more uniformly further ahead of where the catch accumulates compared with the T0 codends. The mesh opening was also less dependent on the size of the catch (Herrmann et al., 2007). One effect of a more uniform mesh opening could be a reduction in the SR in individual hauls (Herrmann, 2005b; Herrmann and O'Neill, 2005; Herrmann et al., 2009).

Initially, it was questioned whether the codend twine characteristics would affect the size selection of round fish and flat fish in the same direction and to the same extent. After we compared the results for cod and plaice, we concluded that there were some similarities but also major differences in the effects of the twine characteristics on size selection in both species. An increase in the twine thickness tended to decrease the L50 for cod and for plaice, whereas this effect was far less pronounced for plaice with T0 constructions. For example, we predicted that increasing the twine thickness from 2 mm to 8 mm for a single twine L50 would lead to decreases of 7% and 25% for plaice and cod, respectively. In contrast to cod, we found no evidence of any difference in performance between single and double twine T0 codends for plaice. Changing the netting orientation from T0 to T90 was predicted to affect the size selection for plaice in the opposite direction compared with cod. The percentage T90 effect for plaice significantly decreased with increasing twine thickness and the lowest values were obtained for the double twine T90 codend. It is possible that the differences in the effects on cod and plaice may be linked to differences in their morphology because the shape of plaice would require a diamond mesh with a relative small opening angle to pass though, whereas the shape of cod would benefit from a more open diamond mesh. This mechanism could potentially explain the different effects of increasing the twine thickness and turning the netting orientation

Our results were based on sea trials conducted using codends with a nominal mesh size of 120 mm. Thus, the results are most relevant to codend constructions with similar mesh sizes, which are used widely in North East Atlantic commercial fisheries. Based on the mechanisms described in Herrmann and O'Neill (2006) and Herrmann et al. (2007), we expect larger effects with smaller mesh sizes, because of the greater influence of a shorter mesh bar with increasing twine thickness. This mechanism also influences the T90-effect, so we also expect a larger T90 effect with smaller mesh sizes. By contrast, we would expect a very small T90 effect when using a relatively big mesh compared with the twine thickness and, therefore, the knot size in a T90 configuration. As a consequence, it may be possible to obtain stronger effects than the trends we observed based on the effects of the twine characteristics on codend size selection with smaller mesh sizes, and lower effects with bigger mesh sizes.

It is commercial practice in some fisheries to use different codend attachments such as chafers, round straps, or protective bags. The results presented here are based on codends with no such attachments. It is known that attachments such as round straps affect the codend shape (Herrmann et al., 2006) and devices that cover some of the codend meshes will affect the size selectivity of the codend (Kynoch et al., 2004). Consequently, these attachments might also influence the degree of the effects of the twine thickness and netting orientation.

We used the method described by Fryer (1991) to model size selection in the codends based on the effects of the codend netting design parameters (Table 1) and we assumed that the between-haul variation in the selection process could be modeled in a similar way for all of the codends we investigated. This is a usual approximation for this type of model, but it neglects potential differences in the between-haul characteristics of the different codends investigated (Wienbeck et al., 2011). However, to account for this would require far more hauls for each codend design. Additionally, the potential effect of codend catch weight on size selection (O'Neill and Kynoch, 1996 ;Herrmann, 2005b) is taken into account in model (1) by linear terms and by such approximated to affect the codend size selection independent of twine characteristics. This was omitted for SF and SFA in the resulting models (4) and (5) for cod and plaice, respectively. Thus, the results did not indicate any general trend in the effect of catch weight on the size selection of cod and plaice and we are confident in applying models (4) and (5) because a potential non-general effect of the codend catch weight is explicitly included in the between-haul variation modeling.

For the "T90 effect," it is important to note that our results are based on using new netting materials and we do not know if the effect of turning the codend netting orientation to T90 would disappear with the material relaxation caused by tension during fishing operations over some time (Herrmann et al., 2007). This would require a special experimental study to analyze any potential material-ageing effect.

The results presented in this study have some potential implications for fisheries management in different areas. The current legislation often permits the use of a relatively wide range of twine characteristics for codend constructions in many management areas. The current study showed that this has a potentially dramatic effect on the size selectivity of codends. Further, it is possible that the increasing trend to use thicker and double twined netting for T0 and T90 codends has created an artificial need for more sophisticated selective devices. These devices often include square mesh panels such as the BACOMA design (Madsen et al., 2002; Wienbeck et al., 2011) and other square mesh panel designs, such as those described by Madsen et al. (2010). The use of such constructions is often aimed at releasing juvenile round fish, such as cod. Based on the results obtained in the research reported here, we may question whether a simpler alternative could be used by some fisheries such as the deployment of diamond mesh codends (in T0 or T90 configuration) made of thinner single twine netting.

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Appendix: Model development

In this section, we describe the development of the model that was used to quantify the effect of twine thickness *td* in the netting used for codend construction on the size selection of a specific species. A general model for each of SF and SFA to order td^2 can be expressed on the form (shown only for *SF*):

$$SF \sim 1 + T90 + DO + DO \times T90 + \ (1 + T90 + DO + DO \times T90) \times td + (1 + T90 + DO + DO \times T90) \times td^2 \quad \text{(A1)}$$

One way to argue for the model (A1) is that it can be derived by the following steps: (i) first formulating individual models for *SF* and *SFA* for each of the four codend categories ($T0_{single}$, $T0_{double}$, $T90_{single}$, and $T90_{double}$; Table 1) as functions of *td*; (ii) then approximating each of these functions by second order Taylor-expansions (see Bers and Karal (1976) for details on this kind of expansions) with *td* = 0.0 as the expansion point; (iii) then arguing that the same coefficients belonging to the models for the different codend categories can be expressed by the same function in *T90* and *DO* since it is the values of these parameters which makes the codend categories different; (iv) then using a simple linear model in *T90* and *DO*, including an interaction term, to approximate the relationship between the values of the coefficients in models for the four different codend categories, which finally enable aggregating the codend models into to one having the form of model (A1).

We will require that our model for the selective characteristics (*SF* and *SFA*) should be independent of *T90* and *DO* as td goes to 0. Since this can only be achieved if the coefficients of *T90*, *DO* and *DO*×*T90* in model (A1) are 0, we constrain the model to fulfill this asymptotic condition. The arguments for the asymptotic constraint are based on a mechanical point of view. The following argument can be used: according to Herrmann et al. (2007), the knot size and the mesh bar bending stiffness potentially leads to differences in the SF and SFA values for the T0 and T90 codends made of the same netting material while the other design parameters remained identical. Based on simple geometrical consideration can it be expected that the knot size would increase approximately linearly with increase in twine diameter. Therefore, a gradual decrease in twine thickness towards zero should result in a gradual decrease in the knot size towards zero. A gradual degrease in the mesh bars bending stiffness towards zero with gradual degrease in twine thickness towards zero is also expected since this is well known from the thin beam theory (Timoshenko and Goodier, 1982). As a consequence of the above argumentation, a gradual decrease in twine thickness towards zero, should lead to a gradual decrease in the differences in the *SF* and *SFA* values for T0 and T90 codends towards zero. A similar type of argument can be applied to the asymptotic differences in the *SF* and *SFA* values for single or double twine codends, because their bending stiffness will affect the inner mesh aperture geometry, through which the fish try to attempt, which decreases with the twine thickness. Based on the above argument, it was assumed that it was a reasonably good approximation to eliminate coefficients for *T90*, *DO* and *DO*×*T90* in model (A1). This then enable us to write the models for SF and SFA on the following form:

$$SF = f_0 + f_1 \times td + f_2 \times td^2 + f_3 \times T90 \times td + f_4 \times DO \times td + f_5 \times T90 \times DO \times td + f_6 \times T90 \times td^2 + f_7 \times DO \times td^2 + f_8 \times T90 \times DO \times td^2$$

$$SFA = g_0 + g_1 \times td + g_2 \times td^2 + g_3 \times T90 \times td + g_4 \times DO \times td + g_5 \times T90 \times DO \times td + g_6 \times T90 \times td^2 + g_7 \times DO \times td^2 + g_8 \times T90 \times DO \times td^2$$

(A2)

Model (A2) was used to model the influence of the twine thickness on the SF and SFA for codends with different designs. As described in section 2.2 was model (A2) and all submodels which could be derived from it by leaving of one or more terms at the time tested against each other. The model resulting in the lowest AIC value was then chosen to model the influence of twine characteristics on the size selection.

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Tables:

Table 1: Specification of the different cod-ends used in this experiment. Each codend name is based on the netting orientation (T0 or T90) and the twine characteristics (see Fig. 1). The parameters TD, DO, T90, and codend category were used in the analysis.

Codend	Mesh size (mm)	td : twine diameter (mm)	DO : double twine	T90 : netting turned 90°	CC: codend category
T0S4	125.4	3.89	0	0	$T0_{single}$
T0S6	124.2	5.72	0	0	$T0_{single}$
T0S8	124.4	7.40	0	0	$T0_{single}$
T0D3	125.3	3.10	1	0	$T0_{double}$
T0D4	123.4	3.66	1	0	$T0_{double}$
T0D6	123.2	5.49	1	0	$T0_{double}$
T90S4	125.4	3.89	0	1	$T90_{single}$
T90S6	124.2	5.72	0	1	$T90_{single}$
T90S8	124.4	7.40	0	1	$T90_{single}$

T90D3	125.3	3.10	1	1	$T90_{double}$
T90D4	123.4	3.66	1	1	$T90_{double}$
T90D6	123.2	5.49	1	1	$T90_{double}$

Table 2: Catch data for individual hauls

			Cod								Plaice							
Haul No.	Codend	Total codend catch (kg)	Codend catch (kg)	No. length classes	Min length (cm)	Max length (cm)	Total no.	No in codend	No. in cover	Codend catch (kg)	No. length classes	Min length (cm)	Max length (cm)	Total no.	No. in Codend	No. in cover
1	T90D4	422	321	34	33.5	80.5	1201	370	831	33	25	16.5	44.5	217	152	65
2	T90D4	844	727	36	33.5	79.5	3057	804	2253	30	24	16.5	39.5	264	152	112
3	T90D4	375	269	33	33.5	102.5	1118	364	754	18	21	16.5	39.5	262	99	163
4	T90D4	251	171	29	33.5	64.5	965	209	756	21	23	17.5	46.5	181	99	82
5	T90S4	427	271	30	33.5	72.5	1362	340	1022	34	25	17.5	46.5	303	159	144
6	T90S4	284	135	23	33.5	62.5	521	188	333	29	24	15.5	40.5	380	125	255
7	T90S4	434	329	32	33.5	74.5	1851	350	1501	21	24	16.5	39.5	209	88	121
8	T90S4	423	300	29	33.5	65.5	1598	358	1240	23	21	15.5	36.5	282	105	177
9	T90D6	572	357	22	33.5	58.5	1053	549	504	53	26	15.5	42.5	423	314	109
10	T90D6	546	424	32	33.5	72.5	1250	571	679	31	23	16.5	46.5	232	172	60
11	T90D6	631	404	29	33.5	74.5	1251	557	694	52	24	15.5	47.5	438	327	111
12	T90D6	461	288	25	33.5	58.5	788	405	383	41	24	16.5	42.5	392	233	159
13	T90S6	595	478	29	33.5	72.5	1909	608	1301	25	26	16.5	45.5	192	134	58
14	T90S6	573	410	30	33.5	71.5	1638	523	1115	48	23	16.5	41.5	475	263	212
15	T90S6	281	153	22	33.5	54.5	503	216	287	33	24	16.5	40.5	343	191	152
16	T90S6	346	284	28	33.5	71.5	1881	384	1497	21	23	16.5	40.5	224	98	126
17	T90D3	430	283	26	33.5	58.5	1460	349	1111	44	26	16.5	43.5	439	222	217
18	T90D3	299	149	24	33.5	79.5	618	205	413	36	22	15.5	37.5	429	188	241
19	T90D3	386	227	30	33.5	80.5	951	264	687	30	25	16.5	42.5	371	135	236
20	T90D3	219	159	27	33.5	66.5	589	185	404	13	23	17.5	42.5	123	52	71
21	T90S8	243	176	26	33.5	61.5	526	209	317	22	28	16.5	44.5	198	90	108
22	T90S8	529	418	31	33.5	63.5	1539	479	1060	41	27	16.5	43.5	290	218	72
23	T90S8	315	160	26	33.5	67.5	672	221	451	44	21	15.5	37.5	474	302	172
24	T90S8	713	147	27	33.5	65.5	512	155	357	23	24	17.5	42.5	177	125	52
25	T0D4	364	305	27	33.5	74.5	874	410	464	20	25	17.5	46.5	199	73	126
26	T0D4	428	348	28	33.5	61.5	965	447	518	23	28	15.5	48.5	213	78	135
27	T0D4	280	224	26	33.5	63.5	567	293	274	16	24	17.5	42.5	157	57	100
28	T0S4	273	233	27	33.5	62.5	488	295	193	12	21	17.5	37.5	137	47	90
29	T0S4	180	123	25	33.5	92.5	516	130	386	11	23	17.5	39.5	113	42	71
30	T0S4	363	245	28	33.5	71.5	1343	273	1070	26	23	16.5	39.5	360	103	257
31	T0S4	302	176	27	33.5	63.5	817	192	625	34	27	14.5	43.5	450	137	313
32	T0D3	272	192	21	33.5	55.5	837	255	582	26	26	16.5	42.5	397	102	295
33	T0D3	234	180	27	33.5	60.5	792	227	565	14	22	16.5	39.5	219	49	170

34	T0D3	326	187	24	33.5	76.5	505	270	235	32	25	14.5	40.5	500	130	370
35	T0S8	798	542	29	33.5	68.5	1055	836	219	28	25	16.5	43.5	457	120	337
36	T0S8	474	384	28	33.5	63.5	862	561	301	16	25	16.5	42.5	214	152	62
37	T0S8	598	401	30	33.5	83.5	792	577	215	35	26	15.5	42.5	339	250	89
38	T0S8	604	423	26	33.5	72.5	975	641	334	24	25	17.5	43.5	365	272	93
39	T0D6	922	717	30	33.5	65.5	1250	1095	155	25	25	15.5	49.5	396	124	272
40	T0D6	1266	937	31	33.5	73.5	1810	1370	440	49	25	16.5	41.5	683	263	420
41	T0D6	1057	788	29	33.5	69.5	1338	1055	283	33	26	14.5	41.5	477	158	319
42	T0S6	586	479	28	33.5	73.5	1618	662	956	27	24	15.5	38.5	413	124	289
43	T0S6	461	360	26	33.5	60.5	1059	552	507	24	24	16.5	46.5	353	110	243

Table 3: Estimation of the selection parameters and fit statistics for individual hauls of cod

Haul No.	Codend	L50 (cm)	SR (cm)	SF	SFA	*P*-value	Deviance	DOF	R^2-value
1	T90D4	41.94	7.21	3.40 (3.35-3.45)	0.58 (0.50- 0.67)	0.9709	18.66	32	0.9823
2	T90D4	42.54	5.38	3.45 (3.42- 3.47)	0.44 (0.40- 0.47)	0.7917	27.15	34	0.9941
3	T90D4	41.22	6.99	3.34 (3.29- 3.39)	0.57 (0.48- 0.65)	0.5890	28.62	31	0.9759
4	T90D4	43.61	7.43	3.53 (3.44- 3.63)	0.60 (0.47- 0.73)	0.0202	44.10	27	0.9045
5	T90S4	42.58	7.79	3.40 (3.34- 3.46)	0.62 (0.53- 0.72)	0.9008	18.91	28	0.9734
6	T90S4	39.86	6.16	3.18 (3.12- 3.24)	0.49 (0.39- 0.60)	0.9833	9.63	21	0.9646
7	T90S4	45.63	8.31	3.64 (3.57- 3.70)	0.66 (0.58- 0.75)	0.5403	28.57	30	0.9688
8	T90S4	43.62	6.43	3.48 (3.43- 3.52)	0.51 (0.45- 0.57)	0.8521	19.47	27	0.9867
9	T90D6	37.21	5.37	3.02 (2.99- 3.05)	0.44 (0.37- 0.50)	0.7376	15.66	20	0.9834
10	T90D6	38.24	4.43	3.10 (3.08- 3.13)	0.36 (0.31- 0.40)	0.9999	8.92	30	0.9954
11	T90D6	38.23	5.10	3.10 (3.07- 3.13)	0.41 (0.36- 0.47)	0.9292	17.08	27	0.9852
12	T90D6	37.45	4.70	3.04 (3.01- 3.07)	0.38 (0.32- 0.44)	0.9943	9.43	23	0.9873
13	T90S6	41.25	6.69	3.32 (3.29- 3.36)	0.54 (0.48- 0.60)	0.7697	21.35	27	0.9850
14	T90S6	41.22	6.29	3.32 (3.28- 3.35)	0.51 (0.45- 0.57)	0.9575	16.52	28	0.9905
15	T90S6	39.09	7.04	3.15 (3.09- 3.21)	0.57 (0.44- 0.70)	0.1606	26.16	20	0.8517
16	T90S6	41.83	5.19	3.37 (3.33- 3.41)	0.42 (0.37- 0.47)	0.9397	15.85	26	0.9748
17	T90D3	42.48	7.18	3.39 (3.34- 3.44)	0.57 (0.49- 0.65)	0.7752	18.56	24	0.9789
18	T90D3	39.71	4.81	3.17 (3.13- 3.21)	0.38 (0.31- 0.45)	0.5560	20.43	22	0.6846
19	T90D3	41.33	6.03	3.30 (3.25- 3.35)	0.48 (0.41- 0.56)	0.7348	22.96	28	0.9768
20	T90D3	42.37	7.68	3.38 (3.31- 3.46)	0.61 (0.49- 0.73)	0.9416	14.99	25	0.9466
21	T90S8	40.36	5.19	3.24 (3.20- 3.29)	0.42 (0.34- 0.49)	0.9835	11.66	24	0.9892
22	T90S8	41.21	5.92	3.31 (3.28- 3.35)	0.48 (0.42- 0.53)	0.5791	26.86	29	0.9792
23	T90S8	40.04	7.20	3.22 (3.15- 3.28)	0.58 (0.46- 0.70)	0.9049	15.51	24	0.9540
24	T90S8	41.82	4.80	3.36 (3.31- 3.42)	0.39 (0.31- 0.46)	0.9008	16.45	25	0.9835
25	T0D4	38.88	7.96	3.15 (3.10 - 3.20)	0.65 (0.53- 0.76)	0.9990	8.69	25	0.9816
26	T0D4	39.51	7.25	3.20 (3.16- 3.24)	0.59 (0.49- 0.68)	0.4697	25.88	26	0.9188
27	T0D4	38.79	7.69	3.14 (3.09- 3.20)	0.62 (0.49- 0.76)	0.9990	8.09	24	0.9812
28	T0S4	37.91	8.65	3.02 (2.95- 3.09)	0.69 (0.52- 0.86)	0.3923	26.29	25	0.8903
29	T0S4	43.21	6.21	3.45 (3.37- 3.52)	0.50 (0.39- 0.60)	0.9967	8.76	23	0.9711
30	T0S4	43.50	6.84	3.47 (3.41-3.53)	0.55 (0.47- 0.62)	0.4783	25.72	26	0.9800

31	T0S4	43.03	6.81	3.43 (3.36- 3.50)	0.54 (0.45- 0.64)	0.7792	19.37	25	0.9518
32	T0D3	40.57	6.46	3.24 (3.18- 3.29)	0.52 (0.42- 0.61)	0.7316	14.86	19	0.9712
33	T0D3	41.83	7.43	3.34 (3.27- 3.41)	0.59 (0.48- 0.70)	0.9435	14.91	25	0.9501
34	T0D3	37.32	8.74	2.98 (2.91- 3.04)	0.70 (0.51- 0.89)	0.7853	16.59	22	0.9255
35	T0S8	29.84	11.08	2.40 (2.22- 2.57)	0.89 (0.60- 1.18)	0.5030	26.28	27	0.8110
36	T0S8	35.00	8.86	2.81 (2.75- 2.88)	0.71 (0.55- 0.88)	0.7583	20.68	26	0.9401
37	T0S8	34.33	6.25	2.76 (2.70- 2.81)	0.50 (0.39- 0.61)	0.9980	11.19	28	0.9713
38	T0S8	34.51	7.44	2.77 (2.73- 2.82)	0.60 (0.47- 0.72)	0.9822	11.79	24	0.9637
39	T0D6	29.97	7.67	2.43 (2.29- 2.57)	0.62 (0.45- 0.79)	0.9999	8.35	28	0.9689
40	T0D6	32.06	9.54	2.60 (2.52- 2.68)	0.77 (0.62- 0.92)	0.9562	17.36	29	0.9628
41	T0D6	30.76	9.98	2.50 (2.38- 2.62)	0.81 (0.61- 1.01)	0.9713	14.86	27	0.9249
42	T0S6	39.60	8.59	3.19 (3.15- 3.23)	0.69 (0.59- 0.79)	0.9320	16.17	26	0.9759
43	T0S6	37.07	8.08	2.98 (2.94- 3.03)	0.65 (0.53- 0.77)	0.3524	26.01	24	0.9414

Table 4: Results for combined model (4) with fixed and random effects using the method described in Fryer (1991). D_{11}, D_{12}, and D_{22} quantify the between-haul variation in the SF and SFA (for details see Fryer (1991)).

		Multiplier	Value	SE	95% confidence limits	*P*-value
SF	f_0	intercept	3.5228	0.0453	3.4326 – 3.6129	3.8074e-77
	f_2	td^2	-0.0149	1.4441e-3	-0.0178 − -0.0121	2.0449e-16
	f_6	$T90 \times td^2$	0.0106	1.3343e-3	0.0079 – 0.0132	1.2046e-11
	f_7	$DO \times td^2$	-0.0133	1.8633e-3	-0.0170 − -0.0096	4.1584e-10
SFA	g_0	intercept	0.6116	0.0199	0.5720 – 0.6513	5.2094e-46
	g_3	$T90 \times td$	-0.0242	4.8565e-3	-0.0339 − -0.0146	3.4547e- 6
Between	D_{11}	1.7361e-2				
-haul	D_{12}	-2.4980e-3				
variation	D_{22}	4.6925e-3				
Model	Log-likelihood					-303.57
statistics	AIC-value					661.14
	Delta log-likelihood for the estimate					7.5773e-15
	Number of hauls					43

Table 5: Model predictions for the influence of twine thickness on the size selection of cod in Baltic trawl fisheries and the percentage T90 effect. 95% confidence limits for the mean L50 are given in parentheses.

	L50 Single Twine			L50 Double Twine			SR Single Twine			SR Double Twine		
td (mm)	T0 (cm)	T90 (cm)	T90 effect %	T0 (cm)	T90 (cm)	T90 effect %	T0 (cm)	T90 (cm)	T90 effect %	T0 (cm)	T90 (cm)	T90 effect %
2.0	41.56 (40.57-42.54)	42.06 (41.07-43.05)	1.22	40.92 (40.02-41.82)	41.43 (40.52-42.33)	1.24	7.34 (6.86-7.82)	6.76 (6.23-7.29)	-7.92	7.34 (6.86-7.82)	6.76 (6.23-7.29)	-7.92
2.5	41.15 (40.21-42.09)	41.94 (40.99-42.90)	1.92	40.16 (39.35-40.97)	40.95 (40.12-41.77)	1.97	7.34 (6.86-7.82)	6.61 (6.06-7.17)	-9.91	7.34 (6.86-7.82)	6.61 (6.06-7.17)	-9.91
3.0	40.66 (39.77-41.55)	41.80 (40.88-42.72)	2.80	39.23 (38.51-39.94)	40.37 (39.61-41.12)	2.91	7.34 (6.86-7.82)	6.47 (5.88-7.06)	-11.89	7.34 (6.86-7.82)	6.47 (5.88-7.06)	-11.89
3.5	40.08 (39.24-40.91)	41.63 (40.72-42.53)	3.87	38.13 (37.49-38.76)	39.68 (38.96-40.40)	4.07	7.34 (6.86-7.82)	6.32 (5.70-6.95)	-13.87	7.34 (6.86-7.82)	6.32 (5.70-6.95)	-13.87
4.0	39.40 (38.61-40.20)	41.43 (40.52-42.35)	5.14	36.86 (36.26-37.45)	38.88 (38.13-39.64)	5.50	7.34 (6.86-7.82)	6.18 (5.51-6.84)	-15.85	7.34 (6.86-7.82)	6.18 (5.51-6.84)	-15.85
4.5	38.64 (37.88-39.41)	41.21 (40.23-42.18)	6.64	35.42 (34.78-36.06)	37.98 (37.10-38.86)	7.24	7.34 (6.86-7.82)	6.03 (5.32-6.74)	-17.83	7.34 (6.86-7.82)	6.03 (5.32-6.74)	-17.83
5.0	37.79 (37.02-38.56)	40.96 (39.88-42.03)	8.38	33.81 (33.03-34.59)	36.98 (35.89-38.06)	9.37	7.34 (6.86-7.82)	5.89 (5.13-6.64)	-19.81	7.34 (6.86-7.82)	5.89 (5.13-6.64)	-19.81
5.5	36.85 (36.04-37.66)	40.68 (39.45-41.91)	10.40	32.03 (31.04-33.03)	35.86 (34.51-37.22)	11.96	7.34 (6.86-7.82)	5.74 (4.94-6.54)	-21.79	7.34 (6.86-7.82)	5.74 (4.94-6.54)	-21.79
6.0	35.82 (34.92-36.72)	40.38 (38.96-41.80)	12.73	30.09 (28.82-31.36)	34.65 (32.96-36.33)	15.16	7.34 (6.86-7.82)	5.59 (4.75-6.44)	-23.77	7.34 (6.86-7.82)	5.59 (4.75-6.44)	-23.77
6.5	34.70 (33.67-35.73)	40.05 (38.39-41.71)	15.43	27.97 (26.38-29.56)	33.32 (31.27-35.38)	19.14	7.34 (6.86-7.82)	5.45 (4.56-6.34)	-25.75	7.34 (6.86-7.82)	5.45 (4.56-6.34)	-25.75
7.0	33.49 (32.29-34.68)	39.69 (37.76-41.63)	18.54	25.69 (23.74-27.63)	31.89 (29.42-34.36)	24.17	7.34 (6.86-7.82)	5.30 (4.36-6.24)	-27.73	7.34 (6.86-7.82)	5.30 (4.36-6.24)	-27.73
7.5	32.19 (30.79-33.59)	39.31 (37.07-41.55)	22.14	23.23 (20.89-25.57)	30.36 (27.44-33.28)	30.67	7.34 (6.86-7.82)	5.16 (4.17-6.15)	-29.72	7.34 (6.86-7.82)	5.16 (4.17-6.15)	-29.72
8.0	30.80	38.90	26.33	20.61	28.72	39.34	7.34	5.01	-31.70	7.34	5.01	-31.70

	(29.17-32.43)	(36.33-41.48)	(17.84-23.37)	(25.31-32.12)	(6.86-7.82)	(3.97-6.06)	(6.86-7.82)	(3.97-6.06)

Table 6: Estimation of the selectivity parameters and the fit statistics for individual hauls of plaice

Haul No.	Codend	L50 (cm)	SR (cm)	SF	SFA	*P*-value	Deviance	DOF	R^2-value
1	T90D4	21.17	1.20	1.72 (1.69- 1.74)	0.10 (0.06- 0.13)	0.9999	5.56	23	0.9929
2	T90D4	22.97	1.56	1.86 (1.83- 1.89)	0.13 (0.08- 0.17)	0.9999	5.28	22	0.9928
3	T90D4	23.22	2.56	1.88 (1.84- 1.93)	0.21 (0.15- 0.27)	0.9994	4.99	19	0.9941
4	T90D4	21.97	1.96	1.78 (1.74- 1.82)	0.16 (0.10- 0.22)	1.0000	1.61	21	0.9971
5	T90S4	22.92	2.91	1.83 (1.79- 1.87)	0.23 (0.18- 0.29)	0.2811	26.43	23	0.9614
6	T90S4	23.91	2.63	1.91 (1.86- 1.95)	0.21 (0.16- 0.26)	0.9846	10.18	22	0.9841
7	T90S4	24.30	1.99	1.94 (1.89- 1.98)	0.16 (0.11- 0.21)	0.9978	7.74	22	0.9917
8	T90S4	24.68	2.80	1.97 (1.92- 2.02)	0.22 (0.17- 0.28)	0.798	13.75	19	0.9899
9	T90D6	20.21	3.62	1.64 (1.60- 1.68)	0.29 (0.22- 0.37)	1.0000	4.33	24	0.9928
10	T90D6	20.54	2.60	1.67 (1.63- 1.71)	0.21 (0.13- 0.29)	0.9831	9.65	21	0.9748
11	T90D6	20.49	2.30	1.66 (1.64- 1.69)	0.19 (0.14- 0.23)	1.0000	4.61	22	0.9965
12	T90D6	21.12	2.46	1.71 (1.69- 1.74)	0.20 (0.15- 0.25)	0.6758	18.5	22	0.9710
13	T90S6	20.41	2.66	1.64 (1.60- 1.69)	0.21 (0.14- 0.29)	0.9967	9.37	24	0.9658
14	T90S6	22.21	3.56	1.79 (1.74- 1.84)	0.29 (0.20- 0.37)	0.0029	43.3	21	0.9373
15	T90S6	22.15	2.30	1.78 (1.75-1.81)	0.18 (0.14- 0.23)	0.9698	11.33	22	0.9914
16	T90S6	22.24	2.35	1.79 (1.75- 1.83)	0.19 (0.13- 0.25)	0.2676	24.54	21	0.9472
17	T90D3	22.66	2.47	1.81 (1.78- 1.84)	0.20 (0.16- 0.24)	0.9996	7.34	24	0.9916
18	T90D3	23.39	3.00	1.87 (1.83- 1.90)	0.24 (0.19- 0.29)	0.6152	17.58	20	0.9813
19	T90D3	23.94	2.97	1.91 (1.87- 1.95)	0.24 (0.18- 0.29)	1.0000	3.18	23	0.9963
20	T90D3	23.29	1.75	1.86 (1.81- 1.91)	0.14 (0.08- 0.20)	0.9978	7.17	21	0.9682
21	T90S8	22.77	2.86	1.83 (1.77- 1.89)	0.23 (0.15- 0.31)	0.9953	11.07	26	0.9706
22	T90S8	20.39	1.96	1.64 (1.61- 1.67)	0.16 (0.11- 0.21)	1.0000	5.02	25	0.9624
23	T90S8	20.83	2.52	1.67 (1.65- 1.70)	0.20 (0.16- 0.25)	0.9235	11.01	19	0.9879
24	T90S8	20.05	3.71	1.61 (1.55- 1.67)	0.30 (0.17- 0.43)	0.9570	12.02	22	0.8886
25	T0D4	25.35	3.34	2.05 (1.99- 2.12)	0.27 (0.19- 0.35)	0.9987	7.77	23	0.9747
26	T0D4	25.25	3.47	2.05 (1.98- 2.12)	0.28 (0.20- 0.36)	0.0657	37.61	26	0.7384
27	T0D4	24.93	3.11	2.02 (1.94- 2.10)	0.25 (0.17- 0.34)	0.7760	16.77	22	0.9369
28	T0S4	24.60	2.16	1.96 (1.89- 2.03)	0.17 (0.10- 0.24)	0.9957	6.70	19	0.9756
29	T0S4	25.82	2.73	2.06 (1.97- 2.15)	0.22 (0.13- 0.30)	0.9758	10.23	21	0.9177
30	T0S4	26.58	2.95	2.12 (2.07- 2.17)	0.24 (0.18- 0.29)	0.9803	9.89	21	0.9894

31	T0S4	26.52	3.04	2.11 (2.08- 2.15)	0.24 (0.19- 0.29)	0.5398	23.65	25	0.9838
32	T0D3	26.75	3.14	2.14 (2.09- 2.18)	0.25 (0.20- 0.30)	0.4914	23.48	24	0.9846
33	T0D3	26.63	2.42	2.13 (2.07- 2.18)	0.19 (0.12- 0.26)	0.6289	17.37	20	0.9675
34	T0D3	26.65	3.76	2.13 (2.08- 2.17)	0.30 (0.24- 0.36)	0.2007	28.41	23	0.9778
35	T0S8	25.96	3.69	2.09 (2.04- 2.14)	0.30 (0.24- 0.35)	0.2664	26.76	23	0.9825
36	T0S8	24.17	3.26	1.94 (1.89- 2.00)	0.26 (0.18- 0.34)	0.9852	10.79	23	0.9783
37	T0S8	23.31	4.24	1.87 (1.82- 1.93)	0.34 (0.25- 0.43)	0.8855	16.07	24	0.9663
38	T0S8	23.71	4.25	1.91 (1.85- 1.96)	0.34 (0.26- 0.42)	0.7351	18.41	23	0.9131
39	T0D6	24.81	5.09	2.01 (1.95- 2.08)	0.41 (0.32- 0.51)	0.1542	29.84	23	0.9142
40	T0D6	24.71	4.69	2.01 (1.95- 2.06)	0.38 (0.30- 0.47)	0.0035	45.41	23	0.9649
41	T0D6	25.13	3.88	2.04 (2.00- 2.08)	0.32 (0.26- 0.37)	0.1031	33.05	24	0.7546
42	T0S6	25.10	2.81	2.02 (1.98- 2.07)	0.23 (0.18- 0.27)	0.9930	9.06	22	0.9840
43	T0S6	25.95	4.65	2.09 (2.03- 2.15)	0.37 (0.29- 0.46)	0.1314	29.49	22	0.9392

Table 7: Results for combined model (5) with fixed and random effects using the method described in Fryer (1991) where D_{11}, D_{12}, and D_{22} quantify the between-haul variation in the size selection process

		Multiplier	Value	SE	95% CI	*P*-value
SF	f_0	intercept	2.1575	0.0343	2.0893 – 2.2257	2.9273e-69
	f_1	td	-0.0247	6.8768e-3	-0.0384 − -0.0110	5.6158
	f_3	T90×td	-0.0412	4.0824e-3	-0.0493 − -0.0331	7.1936e-16
	f_5	T90×DO×td	-0.0253	5.417e-3	-0.0361 − -0.0145	1.2313e-5
SFA	g_1	td	0.0941	6.2664e-3	0.0816 – 0.1065	7.4037e-25
	g_2	td^2	-7.0250e-3	9.9873e-4	-0.0090 − -0.0050	6.4346e-10
	g_3	T90×td	-0.0163	3.048e-3	-0.0223 − -0.0102	8.7512e-7
Between	D_{11}	3.1507e-3				
Haul	D_{12}	3.1263e-4				
Variation	D_{22}	1.5233e-3				
Model	Log-likelihood				-246.78	
Statistics	AIC-value				563.55	
	Delta log-likelihood for the estimate				4.2050e-15	
	Number of hauls				43	

Table 8: Model predictions for the influence of twine thickness on the size selection of plaice in Baltic trawl fisheries and the percentage T90 effect. 95% confidence limits for the mean L50 are given in parentheses.

	L50 Single Twine			L50 Double Twine			SR Single Twine			SR Double Twine		
td (mm)	T0 (cm)	T90 (cm)	T90 effect %	T0 (cm)	T90 (cm)	T90 effect %	T0 (cm)	T90 (cm)	T90 effect %	T0 (cm)	T90 (cm)	T90 effect %
2	25.30 (24.76-25.83)	24.31 (23.70-24.92)	-3.91	25.30 (24.76-25.83)	23.70 (23.18-24.22)	-6.31	1.92 (1.61-2.23)	1.53 (1.18-1.88)	-20.33	1.92 (1.61-2.23)	1.53 (1.18-1.88)	-20.33
2.5	25.15 (24.68-25.62)	23.91 (23.33-24.50)	-4.92	25.15 (24.68-25.62)	23.15 (22.67-23.64)	-7.93	2.29 (1.89-2.70)	1.81 (1.36-2.25)	-21.26	2.29 (1.89-2.70)	1.81 (1.36-2.25)	-21.26
3	25.00 (24.58-25.42)	23.52 (22.94-24.09)	-5.93	25.00 (24.58-25.42)	22.61 (22.13-23.08)	-9.57	2.63 (2.13-3.12)	2.04 (1.50-2.58)	-22.28	2.63 (2.13-3.12)	2.04 (1.50-2.58)	-22.28
3.5	24.85 (24.48-25.22)	23.12 (22.54-23.70)	-6.97	24.85 (24.48-25.22)	22.06 (21.56-22.55)	-11.24	2.92 (2.32-3.52)	2.23 (1.58-2.89)	-23.42	2.92 (2.32-3.52)	2.23 (1.58-2.89)	-23.42
4	24.70 (24.36-25.04)	22.72 (22.12-23.33)	-8.01	24.70 (24.36-25.04)	21.51 (20.97-22.05)	-12.92	3.17 (2.46-3.88)	2.38 (1.62-3.15)	-24.67	3.17 (2.46-3.88)	2.38 (1.62-3.15)	-24.67
4.5	24.55 (24.23-24.88)	22.33 (21.69-22.97)	-9.06	24.55 (24.23-24.88)	20.96 (20.36-21.57)	-14.62	3.37 (2.54-4.20)	2.49 (1.60-3.38)	-26.06	3.37 (2.54-4.20)	2.49 (1.60-3.38)	-26.06
5	24.41 (24.07-24.74)	21.93 (21.25-22.62)	-10.13	24.41 (24.07-24.74)	20.42 (19.74-21.10)	-16.35	3.54 (2.58-4.49)	2.56 (1.54-3.58)	-27.61	3.54 (2.58-4.49)	2.56 (1.54-3.58)	-27.61
5.5	24.26 (23.90-24.62)	21.54 (20.80-22.28)	-11.21	24.26 (23.90-24.62)	19.87 (19.10-20.64)	-18.09	3.66 (2.56-4.75)	2.58 (1.42-3.75)	-29.36	3.66 (2.56-4.75)	2.58 (1.42-3.75)	-29.36
6	24.11 (23.71-24.51)	21.14 (20.34-21.95)	-12.31	24.11 (23.71-24.51)	19.32 (18.46-20.18)	-19.86	3.74 (2.50-4.98)	2.57 (1.25-3.88)	-31.35	3.74 (2.50-4.98)	2.57 (1.25-3.88)	-31.35
6.5	23.96 (23.50-24.42)	20.75 (19.87-21.62)	-13.42	23.96 (23.50-24.42)	18.77 (17.82-19.73)	-21.65	3.77 (2.37-5.18)	2.51 (1.03-3.98)	-33.63	3.77 (2.37-5.18)	2.51 (1.03-3.98)	-33.63
7	23.81 (23.30-24.33)	20.35 (19.40-21.30)	-14.54	23.81 (23.30-24.33)	18.23 (17.17-19.29)	-23.46	3.77 (2.20-5.34)	2.40 (0.75-4.05)	-36.26	3.77 (2.20-5.34)	2.40 (0.75-4.05)	-36.26
7.5	23.66 (23.08-24.25)	19.96 (18.93-20.98)	-15.67	23.66 (23.08-24.25)	17.68 (16.52-18.84)	-25.29	3.72 (1.97-5.47)	2.26 (0.43-4.09)	-39.34	3.72 (1.97-5.47)	2.26 (0.43-4.09)	-39.34
8	23.52	19.56	-16.83	23.52	17.13	-27.15	3.63	2.07	-42.99	3.63	2.07	-42.99

(22.86-24.17)	(18.45-20.67)	(22.86-24.17)	(15.86-18.40)	(1.69-5.57)	(0.05-4.10)	(1.69-5.57)	(0.05-4.10)

Figures:

Fig. 1: Nettings used for the 12 codends. Top: the six different nettings stretched in the T0 direction. Bottom: the six different nettings stretched in the T90 direction. From left to right: double twine 3 mm (D3), double twine 4 mm (D4), double twine 6 mm (D6), single twine 4 mm (S4), single twine 6 mm (S6), and single twine 8 mm (S8).

Fig. 2: Predicted mean L50 and SR values for cod, depending on the twine thickness. The SF and SFA values were rescaled for a 120-mm mesh size, according to the procedure described in section 2.2. For SR, both T0 and both T90 curves (single and double) are identical according to the model predictions.

Fig. 3: L50 and SR values for cod from single hauls with the different cod-end categories. Results from single hauls with the same twine thickness are shown slightly translated around the true value to make it possible to distinguish individual results and their confidence limits. The results are based on the SF and SFA values, which have been rescaled to a 120-mm mesh size.

Fig. 4: Predicted mean L50 and SR values for plaice, depending on the twine thickness. The SF and SFA values were rescaled to a 120-mm mesh size, according to the procedure described in section 2.2, for the different codend categories. The model-predicted L50 curves for T0 single and T0 double are identical. This also applies to both T0 and both T90 curves for the SR predictions.

Fig. 5: The L50 and SR values for plaice from single hauls using the four cod-end categories. Results from single hauls with the same twine thickness are shown slightly translated around the true value to make it

possible to distinguish individual results and their confidence limits. The results are based on the SF and SFA values, which were rescaled to a 120-mm mesh size.

Fig. 1

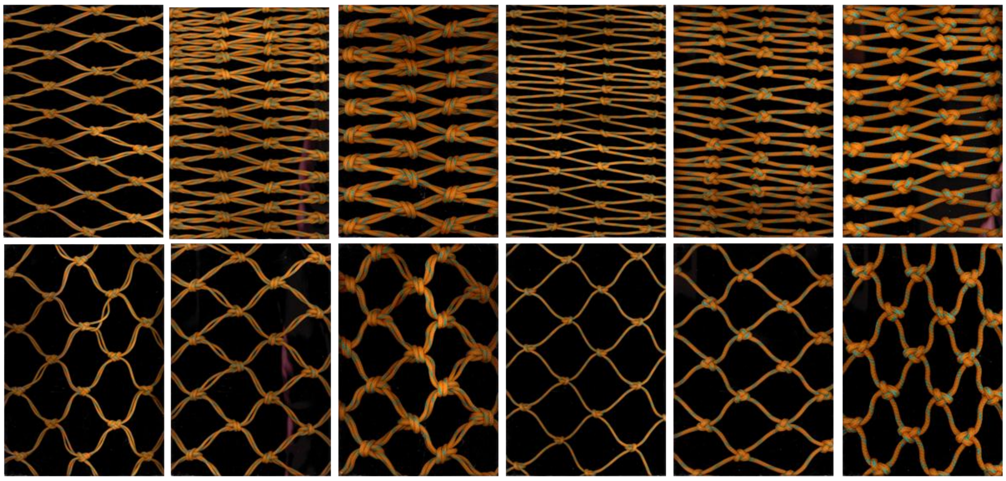


Fig. 2

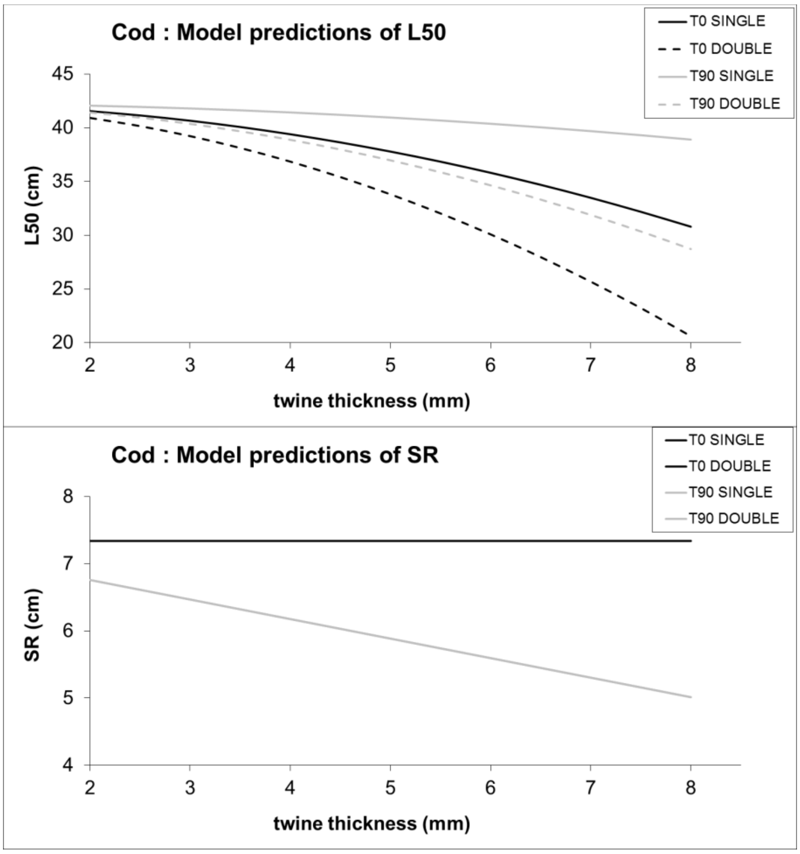

Cod : Model predictions of L50
T0 SINGLE
T0 DOUBLE
T90 SINGLE
T90 DOUBLE
L50 (cm)
45
40
35
30
25
20
2
3
4
5
6
7
8
twine thickness (mm)
Cod : Model predictions of SR
T0 SINGLE
T0 DOUBLE
T90 SINGLE
T90 DOUBLE
SR (cm)
8
7
6
5
4
2
3
4
5
6
7
8
twine thickness (mm)

Fig. 3

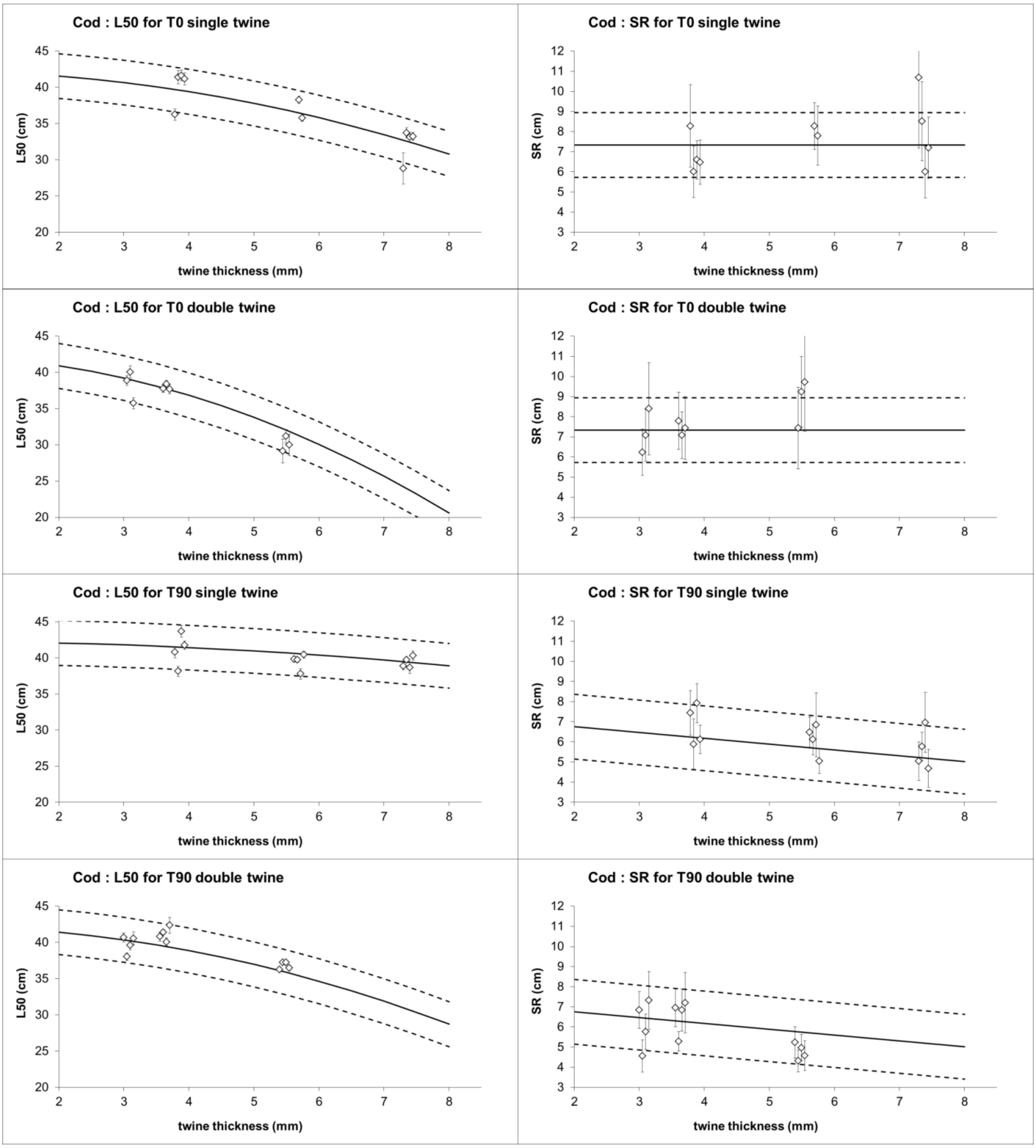

Cod : L50 for T0 single twine
Cod : SR for T0 single twine
Cod : L50 for T0 double twine
Cod : SR for T0 double twine
Cod : L50 for T90 single twine
Cod : SR for T90 single twine
Cod : L50 for T90 double twine
Cod : SR for T90 double twine
L50 (cm)
SR (cm)
twine thickness (mm)

Fig. 4

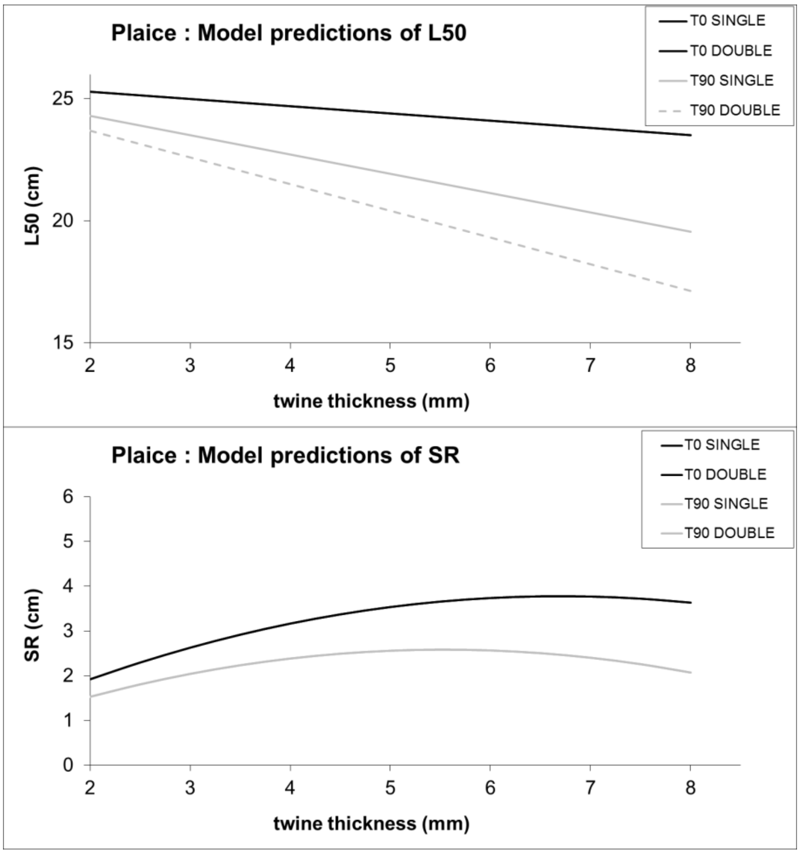
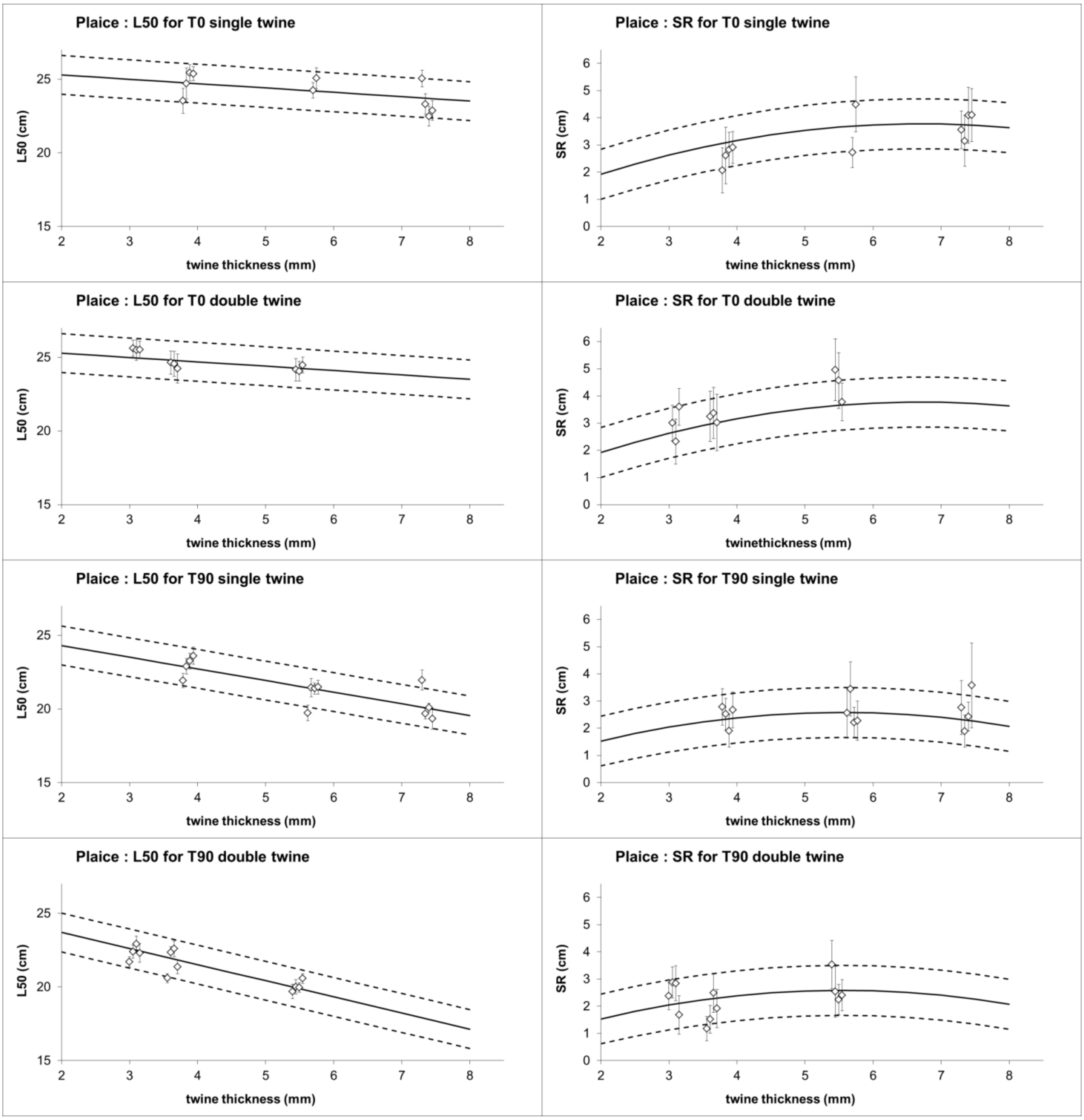

Plaice : Model predictions of L50
T0 SINGLE
T0 DOUBLE
T90 SINGLE
T90 DOUBLE
L50 (cm)
25
20
15
2
3
4
5
6
7
8
twine thickness (mm)
Plaice : Model predictions of SR
T0 SINGLE
T0 DOUBLE
T90 SINGLE
T90 DOUBLE
SR (cm)
6
5
4
3
2
1
0
2
3
4
5
6
7
8
twine thickness (mm)

Fig. 5



Plaice : L50 for T0 single twine
L50 (cm)
15
20
25
2
3
4
5
6
7
8
twine thickness (mm)
Plaice : SR for T0 single twine
SR (cm)
0
1
2
3
4
5
6
2
3
4
5
6
7
8
twine thickness (mm)
Plaice : L50 for T0 double twine
L50 (cm)
15
20
25
2
3
4
5
6
7
8
twine thickness (mm)
Plaice : SR for T0 double twine
SR (cm)
0
1
2
3
4
5
6
2
3
4
5
6
7
8
twinethickness (mm)
Plaice : L50 for T90 single twine
L50 (cm)
15
20
25
2
3
4
5
6
7
8
twine thickness (mm)
Plaice : SR for T90 single twine
SR (cm)
0
1
2
3
4
5
6
2
3
4
5
6
7
8
twine thickness (mm)
Plaice : L50 for T90 double twine
L50 (cm)
15
20
25
2
3
4
5
6
7
8
twine thickness (mm)
Plaice : SR for T90 double twine
SR (cm)
0
1
2
3
4
5
6
2
3
4
5
6
7
8
twine thickness (mm)